RadioNet has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730562

HI absorption towards low luminosity radio AGNs of different accretion modes and WISE colours

HI absorption 2017: A workshop on the status of and preparation of upcoming surveys , ASTRON, Dwingeloo

Yogesh Chandola

National Astronomical Observatories, Chinese Academy of Sciences (NAOC), Beijing, China

yogesh.chandola@gmail.com, yogesh.chandola@nao.cas.cn

June 15, 2017

Outline

Outline

Introduction

Radio AGNs: a brief introduction

- Radio AGNs: radio properties
- Radio AGNs: different accretion modes
- Radio AGNs: fuelling and feedback

Associated H I absorption towards radio AGNs

Radio AGNs

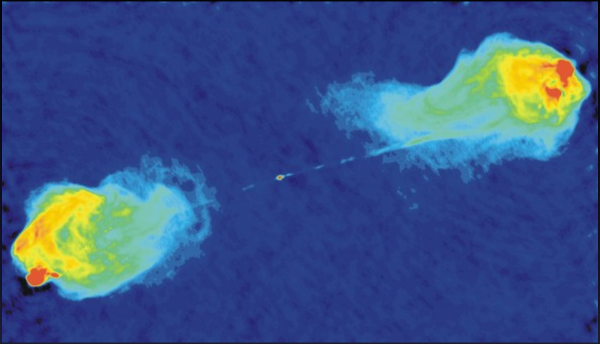


Figure: Cygnus A (R. Perley, C. Carilli & J. Dreher, ApJ, 285, L35,1984), Image courtesy of NRAO/AUI

- All massive galaxies have central supermassive black hole (Kormendy & Ho 2013).
- But not all have radio AGN activity ($P_{1.4\mathrm{GHz}} > 10^{23}$W Hz^{-1}).
- What triggers the radio AGN activity ? What are the fuelling mechanisms ? How radio sources affect their host galaxies and vice-versa ? How radio sources and their immediate environment evolve over time ?
- All these questions can be only answered by comprehensive study of radio sources, their central engines, host galaxies and environment.

Radio continuum surveys

- Radio surveys at metre wavelengths.
  - VLSS (Lane et al. 2014)
  - TGSS (Sirothia et al. 2009, Intema et al. 2016)
  - MWA GLEAM (Wayth et al. 2015, Hurley-Walker et al. 2016)
  - LOFAR MSSS (Heald et al. 2015)
- Radio surveys at cm wavelengths
  - NVSS(Condon et al. 1998)
  - FIRST (Becker et al. 1995)
  - SUMSS (Mauch et al. 2003)
  - WENSS (Rengelink et al. 1997)
- High frequency radio surveys/studies
  - GB6 (Green Bank 4.85 GHz; Gregory et al. 1996)
  - AT20G (ATCA 20 GHz; Murphy et al. 2010)

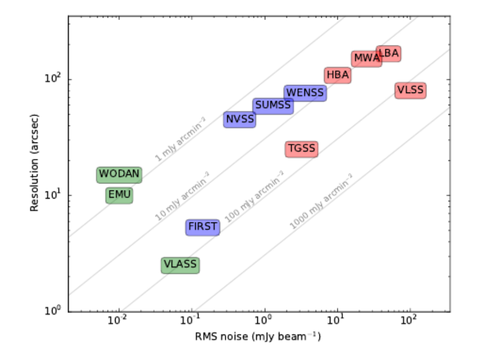
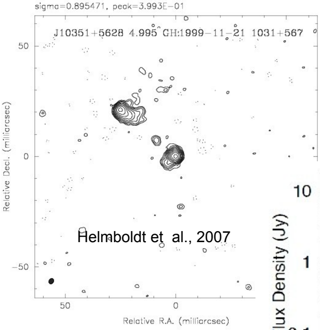


Figure: Angular resolution vs. sensitivity of large area sky surveys. Figure from Intema et al. 2016. Red (<300 MHz), blue and green (>300 MHz).

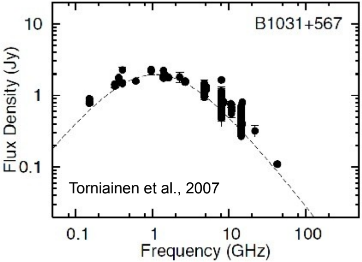
Radio AGNs: radio properties

Radio source linear sizes, spectra, luminosities and morphologies

Gigahertz Peaked Spectrum (GPS) radio sources



- Projected linear sizes < 1kpc
- Dynamical ages ~ $10^{2\text{-}3}$ yrs .
- Radio spectrum peaks at ~ 1 GHz
- VLBA image of B1031+567 (J1035+5628) ==> Compact Symmetric Objects (Wilikinson et al. 1994) morphology



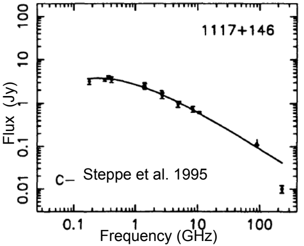
- Diverse population of radio AGNs differing in their linear sizes, spectras, luminosities and morphologies have been revealed by radio surveys and studies done at multiple scales and wavelengths !!

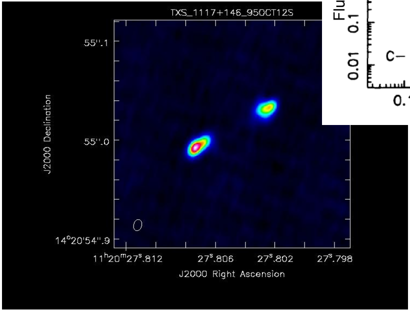
Radio AGNs: radio properties

Radio source linear sizes, spectra, luminosities and morphologies

Compact Steep Spectrum (CSS) radio sources

- Projected linear sizes 1-15 kpc
- Dynamical ages ~ $10^{3\text{-}6}$ yrs
- Radio spectrum peaks at < 500 MHz
- Spectral index steep (> 0.5) for higher frequency





VLBA image of CSS source 4C +14.41 or TXS 1117+146 at 2.3 GHz (Fey & Charlot 1997, ApJS, 111, 95); Image courtesy United States Naval Observatory (USNO) Radio Reference Frame Image Database (RRFID)

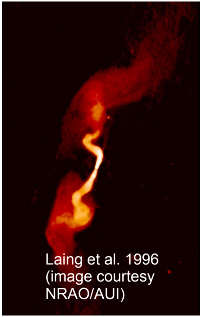
- Diverse population of radio AGNs differing in their linear sizes, spectras, luminosities and morphologies have been revealed by radio surveys and studies done at multiple scales and wavelengths !!

Radio AGNs: radio properties

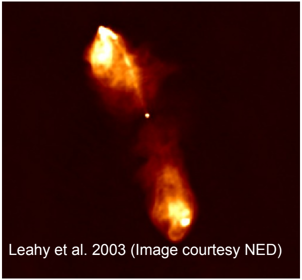
Radio source linear sizes, spectra, luminosities and morphologies

FR I radio sources

- Symmetrical radio jets which eventually expands into diffuse plumes
- Radio power 1.4 GHz < 10^{25} W/Hz
- Example: 3C31



Laing et al. 1996 (image courtesy NRAO/AUI)



Leahy et al. 2003 (Image courtesy NED)

FR II radio sources

- Have powerful collimated radio jets which eventually power lobes and hot spots.
- Radio power at 1.4 GHz > 10^{25} W/Hz
- Example: 3C98

- Diverse population of radio AGNs differing in their linear sizes, spectras, luminosities and morphologies have been revealed by radio surveys and studies done at multiple scales and wavelengths !!

Radio AGNs: radio properties

Radio source linear sizes, spectra, luminosities and morphologies

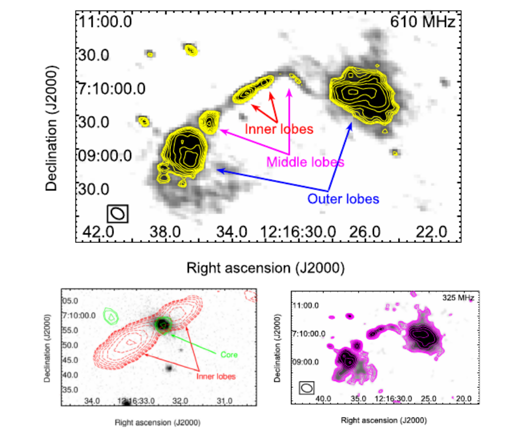


Figure: Triple double radio galaxy J1216+0709 (Singh et al. 2016, ApJ, 826, 132)

- Diverse population of radio AGNs differing in their linear sizes, spectras, luminosities and morphologies have been revealed by radio surveys and studies done at multiple scales and wavelengths !!

Radio AGNs: radio properties

Radio source linear sizes, spectra, luminosities and morphologies

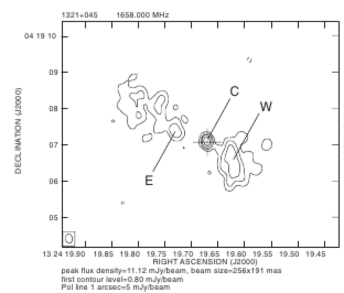


Figure: Bazrazewska et al. 2010, MNRAS, 408, 2261

- Bazrazewska et al. 2010 presented low luminosity ($L_{1.4\mathrm{GHz}} < 10^{26}$ W /Hz) CSS sample, mostly with disrupted jets; early stage counterpart of FR I objects ?
- More low luminosity objects by Sadler et al. (2014) & Baldi et al. (2015); termed as FR 0 sources.

Radio AGNs: radio properties

Radio source linear sizes, spectra, luminosities and morphologies

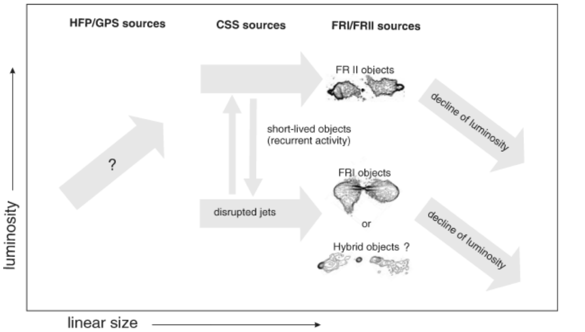


Figure 5. Evolutionary scheme of radio-loud AGNs.

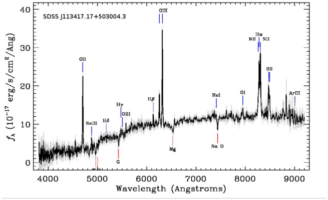
Figure: Bazrazewska et al. 2010, MNRAS, 408, 2261

- Bazrazewska et al. 2010 presented low luminosity ($L_{1.4\mathrm{GHz}} < 10^{26}$ W /Hz) CSS sample, mostly with disrupted jets; early stage counterpart of FR I objects ?
- More low luminosity objects by Sadler et al. (2014) & Baldi et al. (2015); termed as FR 0 sources.

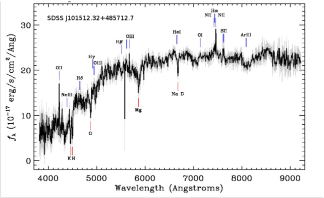
Radio AGNs: different accretion modes

Central engine and optical emission line characteristics: Shakura & Sunayev (1973), Novikov & Thorne (1973), Narayan & Yi (1994,1995), Yuan & Narayan (2014), Hine & Longair (1979), Buttiglione et al. 2010, Best & Heckman (2012), Heckman & Best (2014)

HERG: High Excitation Radio Galaxy



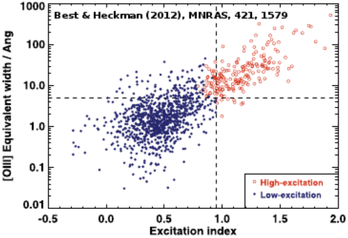
LERG: Low Excitation Radio Galaxy



Excitation Index (EI) defined by Buttiglione et al. (2010)

EI = log10([O III]/Hβ) − 1/3[log10 ([N II]/Hα) + log10([S II]/Hα) + log10 ([O I]/Hα)]

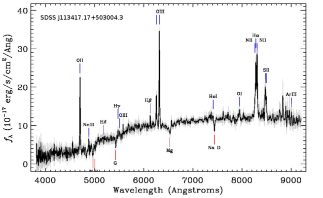
Best & Heckman (2012)
HERG: EI > 0.95 + 1 σ , OIII EQW > 5 Ang
LERG: EI < 0.95 - 1 σ , OIII EQW < 5 Ang



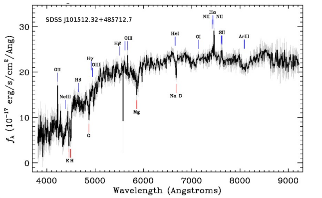
Radio AGNs: different accretion modes

Central engine and optical emission line characteristics: Shakura & Sunayev (1973), Novikov & Thorne (1973), Narayan & Yi (1994,1995), Yuan & Narayan (2014), Hine & Longair (1979), Buttiglione et al. 2010, Best & Heckman (2012), Heckman & Best (2014)

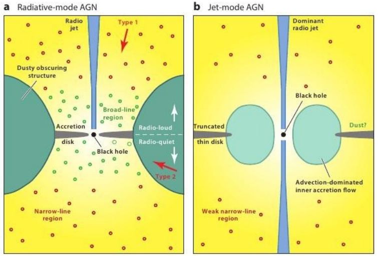
HERG: High Excitation Radio Galaxy



LERG: Low Excitation Radio Galaxy



	HERG	LERG
Optical lines	Strong emission lines	Weak emission lines
Eddington Ratio	> 1%	< 1 %
Radio Luminosity	Dominant $L_{1.4GHz} > 10^{26}$ W/Hz	Mainly below 10^{26} W/Hz
FR I/II	Mainly FRIIs	Mix of FRI & FRII
Fueling process	Mainly mergers	Accretion of hot halo gas
Feedback mechanism	Radiative	Jet-mode



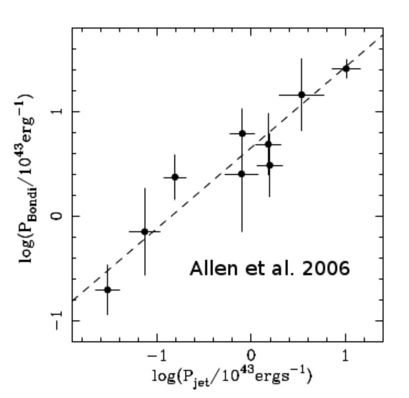
Heckman & Best (2014)

Figure 3

Schematic drawings of the central engines of radiative-mode and jet-mode AGNs (not to scale).

Radio AGNs: different accretion modes and fuelling mechanisms

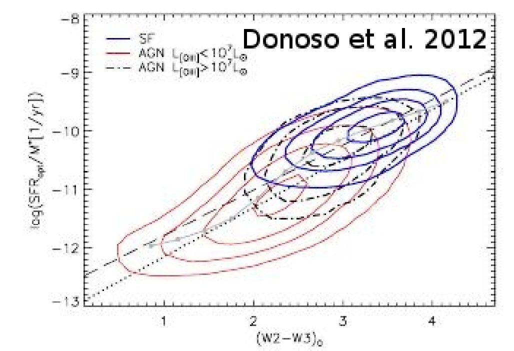
Allen et al. (2006), Balmaverde et al. (2008)

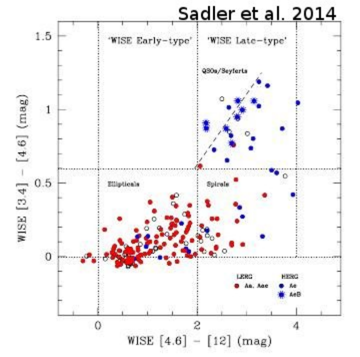


- Low radio power or low excitation radio AGNs undergo Bondi accretion of hot halo gas (Allen et al. 2006; Balmaverde et al. 2008).

Radio AGNs: different accretion modes, WISE colours and star formation rates

Donoso et al. (2012), Sadler et al.(2014), Pace & Salim (2016), Ellison et al. (2016)

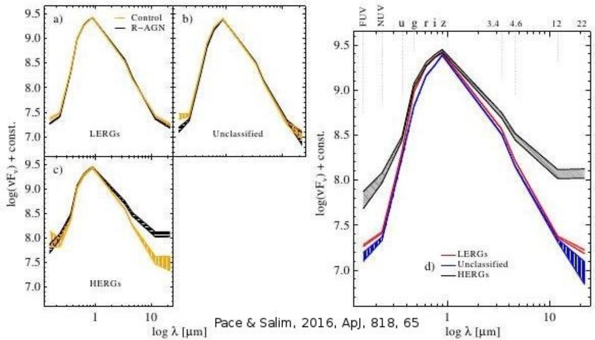




Sadler et al. 2014; sources from AT20G-6dFGS survey at 20 GHz. W2−W3>2 : 57% HERGs W2−W3<2 : 93% LERGs.

Radio AGNs: different accretion modes, WISE colours and star formation rates

Donoso et al. (2012), Sadler et al.(2014), Pace & Salim (2016), Ellison et al. (2016)



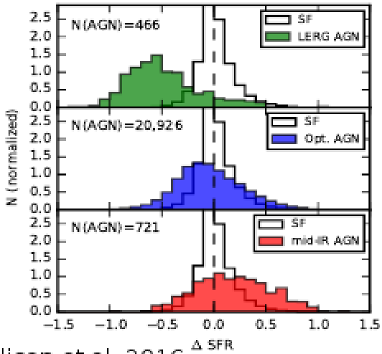
Pace & Salim, 2016, ApJ, 818, 65

Pace & Salim (2016) investigated radio AGN feedback to the hosts using SED in UV (GALEX) to mid-IR (WISE) region.

LERGs show lower UV/mid-IR emission compared to control sample while HERGs show excess. This indicate suppressed star-formation in LERGs.

Radio AGNs: different accretion modes, WISE colours and star formation rates

Donoso et al.(2012), Sadler et al. (2014), Pace & Salim (2016), Ellison et al. (2016)



Ellison et al. 2016

- Ellison et al. 2016 compared SFR derived from total IR luminosity for LERGs, optical AGNs (using BPT diagram), mid-IR AGN (W1-W2 > 0.8) with normal SF galaxies.
- LERGs show low SFR while IR selected AGNs show slightly higher SFR as compared to SF galaxies.

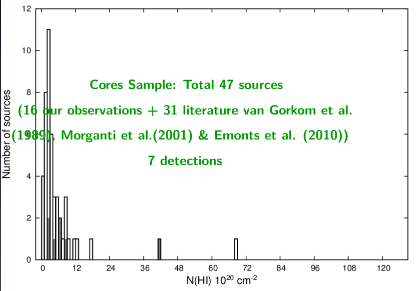
Since cold gas is fuel reservoir for SF activity and HI is a tracer for cold diffuse ISM, it is important to study HI in hosts of radio AGNs of different radio properties, WISE colours and accretion modes in order to better understand the feedback and fueling processes.

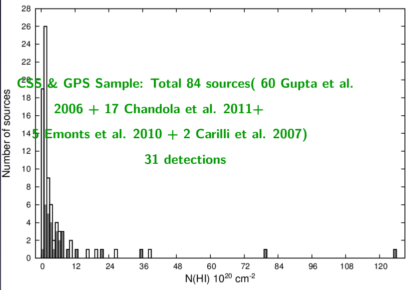
Outline

Differences in circumnuclear HI gas properties of compact and large radio sources

Chandola, Gupta & Saikia, 2013, MNRAS, 429, 2380

- The detection rate for cores sample is rather low (7/47 ; ∼15 %) as compared with the detection rate for compact CSS & GPS sources (28/49; ∼ 57 %). For the entire 'CSS & GPS' sample this rate is (31/84; ∼ 37%).
- HI is detected in absorption towards 4/32 (∼13 %) FR I objects, compared with 3/15(∼20 %) for the FR II sources. Within statistical errors, there is no significant difference.

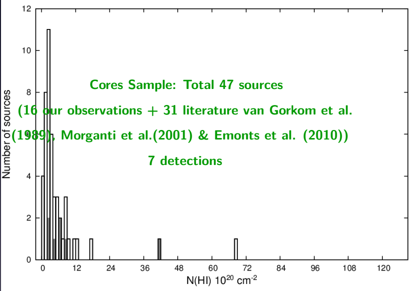


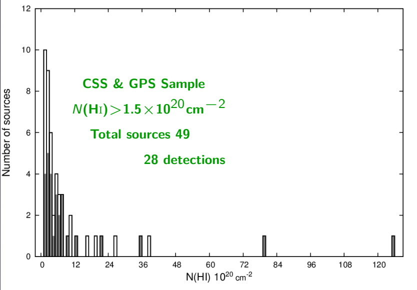


Differences in circumnuclear HI gas properties of compact and large radio sources

Chandola, Gupta & Saikia, 2013, MNRAS, 429, 2380

- The detection rate for cores sample is rather low (7/47 ; ∼15 %) as compared with the detection rate for compact CSS & GPS sources (28/49; ∼ 57 %). For the entire 'CSS & GPS' sample this rate is (31/84; ∼ 37%).
- HI is detected in absorption towards 4/32 (∼13 %) FR I objects, compared with 3/15(∼20 %) for the FR II sources. Within statistical errors, there is no significant difference.

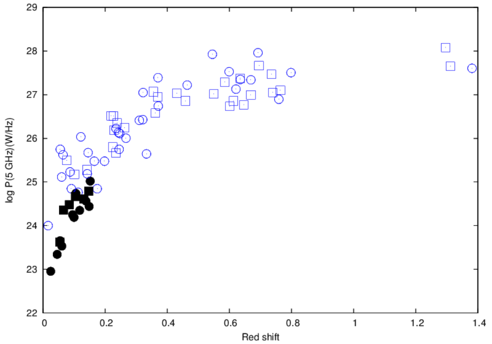




HI gas properties in compact radio sources of different luminosities

Chandola, Sirothia & Saikia, 2011, MNRAS, 418, 1787

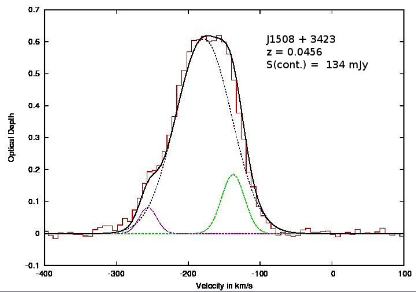
- Sample of 18 sources known as CORALz (**CO**mpact **RA**dio sources **A**t **L**ow red-shift) core sample **(Snellen et al. 2004)**: $S_{1.4GHz}$>100mJy, Angular size < 2 arcsec, Red-shift range 0.024-0.152, ∼100 times weaker than those studied by **Gupta et al. 2006**.
- GMRT observations during Dec. 2009 - Feb. 2010, Baseband Bandwidth 4 MHz (∼ 900 km/s), Spectral channels 128 (velocity resolution ∼ 7 km/s), observation time ∼3-4 hrs per source.

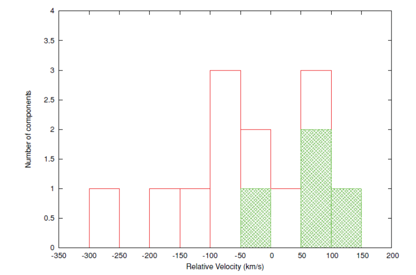


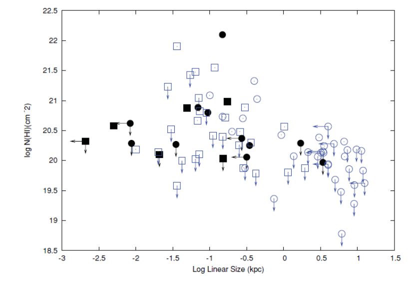
HI gas properties in compact radio sources of different luminosities

Chandola, Sirothia & Saikia, 2011, MNRAS, 418, 1787

- Detection rate: 7/18 detections (over all ∼40 %, 50 % for GPS, 33 % CSS)
- Relative velocity : Blue shift upto −300 km/s, unlike upto − 1000 km/s in **Gupta et al. 2006**.
- Column density-linear size anti-correlation consistent with **Pihlström et al. 2003, Gupta et al. 2006**.



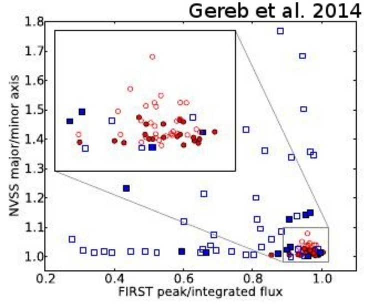




HI absorption towards low luminosity radio AGNs

Emonts et al. 2010; Chandola et al. 2011; Geréb et al. 2014, 2015

- Sensitivity issues and flux density limited samples; earlier absorption studies mainly towards higher luminosity radio sources except a few towards low luminosity radio sources e.g. Emonts et al. (2010).
- Chandola, Sirothia & Saikia (2011) studied HI absorption towards low luminosity sample of 18 compact radio sources by Snellen et al. 2004.
- Geréb et al. (2014, 2015): **WSRT** observations, **101 sources** with $\mathbf{S_{1.4} > 50}$ **mJy**, **z** $\lesssim$ **0.2**, radio structural classification based on NVSS major/minor axis and FIRST peak/integrated flux (in the **figure below, extended: blue, compact: red**), 32 HI detections (filled symbols in figure below).



HI absorption towards low luminosity radio AGNs of different accretion modes & *WISE* colours

Chandola & Saikia, 2017, MNRAS, 465, 997

How does the HI detection rate and other gas properties vary with radio source properties, host galaxy properties and central AGN characteristics?

Geréb et al. (2014, 2015): HI absorption data, radio structural classification
Best & Heckman (2012): Classification of nearby radio AGNs (FIRST radio survey) according optical emission line properties (SDSS) and excitation index (Buttiglione et al. 2010).
Cutri et al. (2013): WISE data for host galaxy property in mid-IR.

Sample: Total 100 sources. Of which 91 classified as 80 LERGs and 11 HERGs.

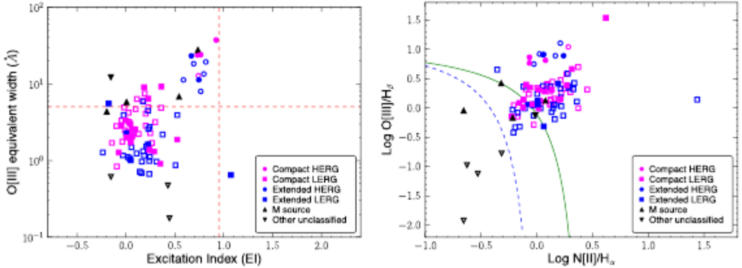
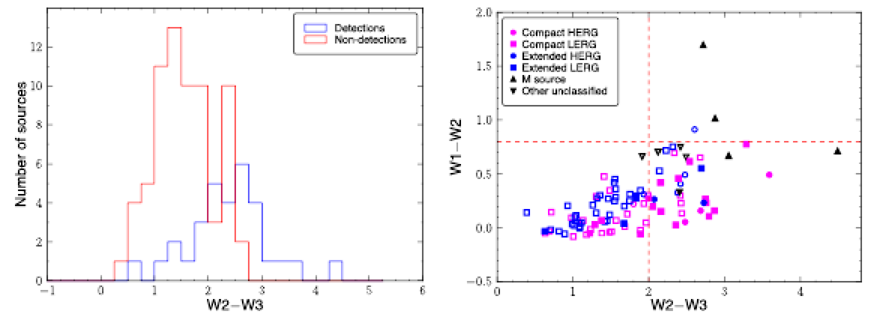


Figure 1. Left: O [III] equivalent width versus excitation index (for 91 sources with all six emission lines) with filled symbols (detections) and empty symbols (non-detections). The vertical line represents EI = 0.95, while the horizontal line is for O [III] equivalent width = 5 Å. Right: log O [III]/Hβ versus log N [II]/Hα (for 99 sources with at least four emission lines). The solid green curve is the Kewley et al. (2001, 2006) dividing line between AGNs and composite (SF+AGN) galaxies, while the dashed blue curve is the Kauffmann et al. (2003) dividing line between star-forming and composite galaxies.

HI absorption towards low luminosity radio AGNs of different accretion modes & *WISE* colours

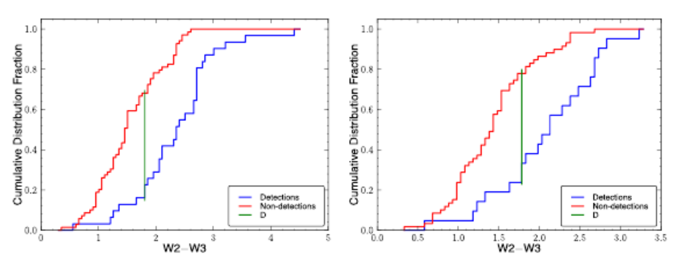
Chandola & Saikia, 2017, MNRAS, 465, 997



- Detection rates: HERG (5/11; 45.5 ± 20.3 %), LERG (21/80; 26.3±5.7%)
- **Although there is suggestion of higher detection rates for HERGs, statistical errors are also high due to small numbers. It would be useful to investigate this futher with observation of similar sensitivity toward larger number of HERGs.**
- Observations with the GMRT towards 30 mid-IR bright radio AGNs in last two semesters.

H I absorption towards low luminosity radio AGNs of different accretion modes & *WISE* colours

Chandola & Saikia, 2017, MNRAS, 465, 997



Cumulative Distribution Fraction of WISE colours for all sources with H I detections and non-detections at left and LERGs at right.

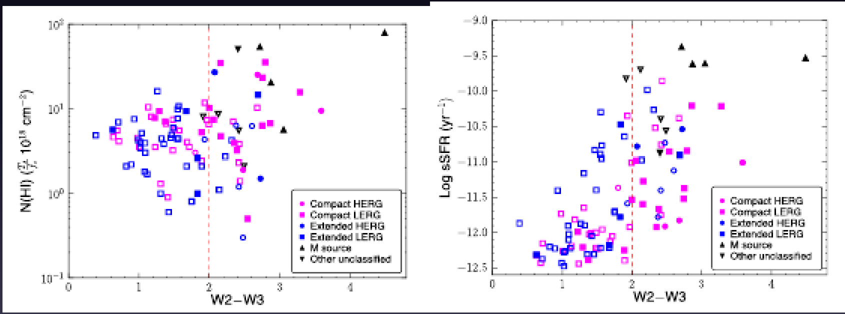
- Taking radio structural classification along with optical classification into account
  Compact: LERGs+HERGs (19/46; 41.3±9.5%), LERGs (16/42; 38.1±9.5%)
  Extended: LERGs+HERGs (7/45; 15.6±5.9%), LERGs (5/38; 13.2±5.9%)
- Taking WISE colours and optical classification, independent of radio structure
  (1) W2−W3 > 2 : LERGs (13/21; 61.9±17.2%), HERGs (5/9; 55.6±24.8%)
  (2) W2−W3 < 2 : LERGs (8/59; 13.6± 4.8%), HERGs (0/2)
- Taking WISE colours and radio structure, independent of optical classification
  (1) W2−W3 > 2 : Compact (15/20; 75± 19.4%), Extended (3/10; 30±17.3%)
  (2) W2−W3 < 2: Compact (4/26; 15.4±7.7%), Extended (4/35; 11.4±5.7%)

Strong dependence of detection rate on WISE W2-W3 colour. Sources with compact radio size and W2−W3 >2 have highest detection rate!

HI absorption towards low luminosity radio AGNs of different accretion modes & *WISE* colours

Chandola & Saikia, 2017, MNRAS, 465, 997

HERGs are known to have dusty tori which could be heated due to AGN and star-formation ==> most of them have W2−W3 >2, but LERGs don't have tori but still some have high column density gas!



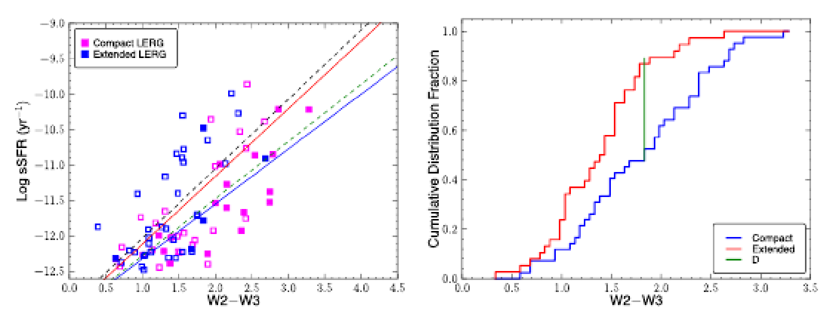
Individual gas cloud or gas in ISM ?? Specific star formation rate (sSFR from MPA-JHU group online data (Kauffman et al. 2004); Higher sSFR for LERGs W2−W3> 2 (although an order of magnitude less than star-forming galaxies) ==> absorber is gas-dust rich ISM with significant star-formation in some cases

HI absorption towards low luminosity radio AGNs of different accretion modes & *WISE* colours

Chandola & Saikia, 2017, MNRAS, 465, 997

But what is source of ISM dust or gas for LERGs with W2−W3>2 ?

(1) Gas rich mergers are less likely in LERGs (Ellison et al. 2015) + most of LERG sources in our sample have W1−W2 $<$ 0.8 implying less mergers (Ellison et al. 2016)
(2) Compact radio sources (slope:0.81±0.12) and the detections (slope:0.78±0.16) have similar flatter slopes while extended sources (slope:0.98±0.19) and the non-detections (slope:0.96±0.14) have similar and and somewhat steeper values. Distribution of WISE colours for compact and extended sources differ significantly.



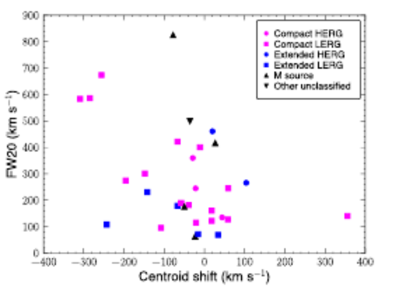
Likely that LERGs are following evolutionary path where star-formation started in a dusty gas-rich environment and decreased at later stages due to scarcity of fuel, combined with possible feedback from a radio source.

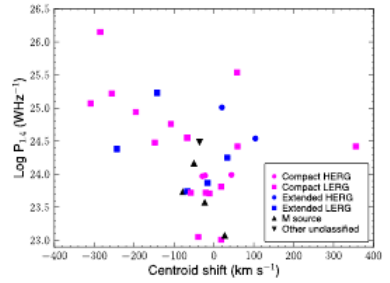
H I absorption towards low luminosity radio AGNs of different accretion modes & *WISE* colours

Chandola & Saikia, 2017, MNRAS, 465, 997

But what is source of ISM dust or gas for LERGs with W2−W3>2 ?

(1) Gas rich mergers are less likely in LERGs (Ellison et al. 2015) + most of LERG sources in our sample have W1−W2 < 0.8 implying less mergers (Ellison et al. 2016)
(2) Compact radio sources (slope:0.81±0.12) and the detections (slope:0.78±0.16) have similar flatter slopes while extended sources (slope:0.98±0.19) and the non-detections (slope:0.96±0.14) have similar and and somewhat steeper values. Distribution of WISE colours for compact and extended sources differ significantly.

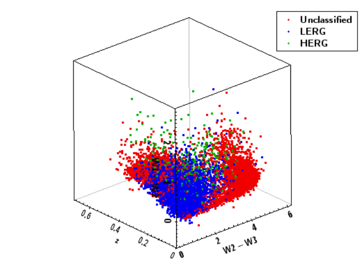


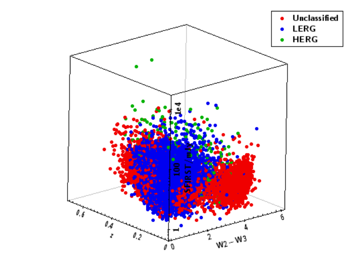


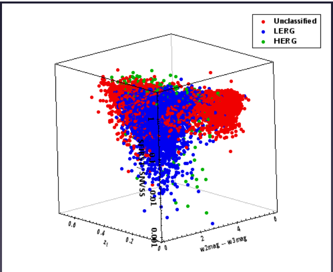
Likely that LERGs are following evolutionary path where star-formation started in a dusty gas-rich environment and decreased at later stages due to scarcity of fuel, combined with possible feedback from a radio source.

HI absorption surveys with SKA pathfinders

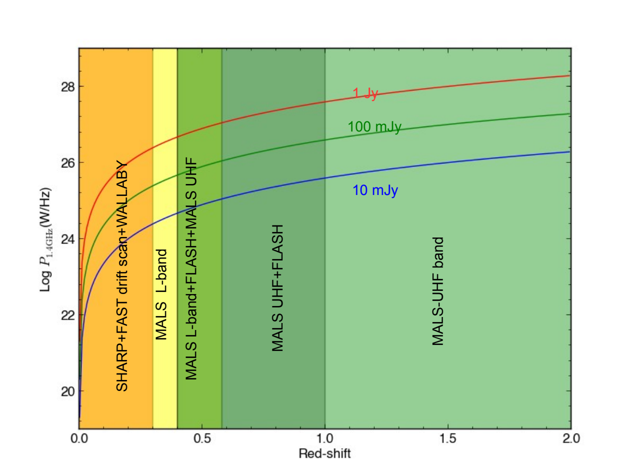
Radio sources from Best & Heckman (2012): SDSS DR 7+ NVSS+FIRST ($\sim$18000 sources have WISE counterparts).







HI absorption surveys with SKA pathfinders



Summary

- H I absorption detection have significant dependence on mid-IR WISE colour W2−W3.
- We have shown that considering galaxies with **WISE infrared colour W2−W3 $>$ 2, which is typical of gas-rich systems, along with a compact radio structure leads to high detection rates of over 70 per cent**.
- It is likely that the **LERGs are following a secular evolutionary process** and some of these started their evolution with higher gas/dust content and may have also undergone a minor merger at some stages of their evolution, but **feedback from the radio source appears to be playing a role in affecting and suppressing star formation at later stages**.
- Future sensitive H I absorption surveys in combination with WISE data, optical data and VLBI follow up important to learn more about fuelling and feedback mechanisms in different radio AGNS.

Thanks for your attention !! Comments and suggestions are welcome !!