Collaborators

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Outline of talk

- What triggers star formation in the void regions?
- The molecular gas disk in CG910 and its HI content: could there be gas accretion?
- Low frequency radio emission around void galaxies – searching for diffuse emission at 610 and 150MHz with GMRT.
What we expect in voids ...

- CDM predicts that voids are populated by low luminosity galaxies such as dwarf spheroidals and low surface brightness (LSB) galaxies (Peebles 2001).
- Galaxy morphology-density theory also predicts that low density regions such as voids will contain late type only and generally low luminosity system.
- But in last two decades several studies have shown that void galaxies show star formation and nuclear activity (e.g. Moorman et al. 2016, Beygu et al. 2016, Kreckel et al. 2012, Grogin and Geller 2000).
- Their star formation maybe driven by close galaxy interactions in the overall underdense void environment.
Void Galaxies

- They are gas rich, late type disk galaxies that lie within voids. Usually spirals and irregulars; ellipticals less common.
- Relatively blue and show signs of star formation. In the smaller voids the galaxies are usually low luminosity dwarfs or irregulars but the larger voids also have galaxies that show signatures of star formation (Kreckel et al. 2011; Cruzen et al. 2002; Grogin and Geller 2001; Szomoru et al. 1997).

Gas rich dwarf galaxies in the Lynx Cancer void (Chengalur & Pustilink 2013)

SDSS images of some bright galaxies in larger voids: SBS1428+529, VG_06, CG693 - they show star formation and even AGN activity
Groups/Interacting Pairs: Signatures of Void Substructure?

There are many examples of interacting pairs, polar ring galaxies and even small groups of galaxies residing in voids. These galaxies may have formed when smaller voids merged to form larger voids. This merging process can lead to the formation of filaments within larger voids – thus creating a void substructure.
Star Formation in Void Galaxies

In several surveys, void galaxies are found to be blue in color signifying star formation. Hα images and optical spectra also show signs of star formation in the gas rich spirals.

When plotted on the color magnitude diagram for galaxy evolution, they fall mainly on the blue cloud. Thus void galaxies are not low luminosity systems as predicted but are slowly evolving galaxies.

Color magnitude diagram for galaxies in the Void galaxy Survey (Kreckel et al. 2012).
Signatures of more evolved void galaxies: bulges and AGN

- Star formation will result in gas infall and the growth of bulges and AGN. The Bootes void has examples of more evolved void galaxies that show AGN-bulge evolution.

SBS 1428+529  SBS1325+597

CG692-CG693

I Band

B Band
AGN and Black Hole Masses in Void galaxies

- Bulges appear less prominent in void galaxies and AGN are not common (Liu et al. 2015).
- However, of the few that have AGN, the black hole masses are a few times $10^7$ solar masses and show activity similar to galaxies in normal environments.

The spectral decomposition of the Halpha line in CG693 and Mrk845. The black hole mass lies on M-σ relation.

(Subramaniam et al. 2016, in prep.).
Cold Gas in Void galaxies

- Void galaxies have large HI masses (Szomoru et al. 1996; Kreckel et al. 2012) but their molecular gas (H\(_2\)) content is not well studied.

- Early studies of a few Bootes void galaxies detected CO emission from 4 galaxies (of which 2 are very strong). Recent detection was from an interacting system in a nearby void (VGS_31 system, Beygu et al. 2013).

- The detected galaxies all had high far infrared fluxes or showed signatures of star formation associated with interactions.

The molecular gas masses are in the range 10\(^8\) to 10\(^9\) solar masses. Suggests that the larger void galaxies have significant gas and dust.
Goals of Our Study: Molecular Gas and star formation in void galaxies

- Detection of molecular gas in void galaxies. Is molecular gas common in these galaxies? Or are they usually devoid of $\text{H}_2$? What are the molecular gas masses? How do they compare with HI gas masses?
- What is the $\text{H}_2$ gas morphology?
- What are the star formation rates (SFR) and star formation efficiencies? How do they compare with normal galaxies?
- Are disky void galaxies similar to low surface brightness galaxies (LSB galaxies are low in star formation, low metal content and dark matter dominated)?
- Is the star formation in void galaxies different from normal field galaxies? What triggers the star formation in the isolated void environment?
Sample galaxies were observed in April 2013 with the 45m Nobeyama telescope. In March 2014, we observed again but due to poor weather conditions, we could not obtain any more data.

Three of the sample galaxies were mapped in Halpha emission with HCT.

We observed the galaxy CG910 with CARMA in May 2014 for mapping CO emission.

We observed CG910 with GBT in Feb 2016 for HI emission.

Observed Bootes void galaxies at low frequency 610 and 240MHz.
Sample Galaxies, the Observations at NRO and HCT

• We had a sample of 12 spiral galaxies that were from nearby voids and a few from the Bootes void (e.g. Szomoru et al. 1996; Kreckel et al. 2011). The galaxies were selected based on their relatively high IRAS fluxes or strong Hα line emission.

• We could only observe 5 out of 12. Due to bad weather the remaining were not done. Observation carried out in April 2013 and March 2014. All the galaxies were regular spirals. All 5 appeared to be isolated.

<table>
<thead>
<tr>
<th>galaxy name</th>
<th>$D_L$ (Mpc)</th>
<th>redshift (z)</th>
<th>type</th>
<th>$g$ magnitude</th>
<th>void name</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBS 1325+597</td>
<td>70.4</td>
<td>0.016</td>
<td>Sm, HII</td>
<td>16.0</td>
<td>Ursa Minor I</td>
</tr>
<tr>
<td>SDSS 143052</td>
<td>76.6</td>
<td>0.018</td>
<td>Extend.</td>
<td>76.0</td>
<td>Ursa Minor I</td>
</tr>
<tr>
<td>SDSS 153821</td>
<td>97.6</td>
<td>0.022</td>
<td>Sd</td>
<td>15.3</td>
<td>....</td>
</tr>
<tr>
<td>CG 598</td>
<td>248.0</td>
<td>0.057</td>
<td>HII, Sbbrst</td>
<td>16.4</td>
<td>Bootes</td>
</tr>
<tr>
<td>SBS 1428+529</td>
<td>191.0</td>
<td>0.044</td>
<td>Sb, Sy 2</td>
<td>15.2</td>
<td>Bootes</td>
</tr>
</tbody>
</table>

• We detected CO(1-0) line emission from the galaxies and estimated the H$_2$ masses from the line fluxes.

• Three of the detected galaxies were imaged in Hα emission at HCT in April 2014. For the other two, we did not have suitable filters.
CO(1-0) Detections

SBS1325+597 (VGS_34)

CG 598

SDSS1430+5514 (VGS_44)

SDSS1538+3311 (VGS_57)
CO Luminosities, Masses and Total Gas Content from the detections

<table>
<thead>
<tr>
<th>galaxy name</th>
<th>$t_{obs}$ (hours)</th>
<th>$S_{CO}$ $\Delta v$ (K km s$^{-1}$)</th>
<th>$L_{CO}(10^8)$ (K km s$^{-1}$ pc$^2$)</th>
<th>$H_2$ Mass ($10^9$ $M_\odot$)</th>
<th>Surface density $\Sigma_{H_2}$ ($M_\odot$ pc$^{-2}$)</th>
<th>HI mass ($10^9$ $M_\odot$)</th>
<th>$M(H_2)/M(HI)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBS 1325+527</td>
<td>1h 12m</td>
<td>10.7 ± 0.2</td>
<td>$(3.1 \pm 0.1)$</td>
<td>1.5 ± 0.03</td>
<td>12.4 ± 0.3</td>
<td>2.4 ± 0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>SDSS 143052</td>
<td>1h 16m</td>
<td>7.0 ± 0.2</td>
<td>$(2.4 \pm 0.1)$</td>
<td>1.1 ± 0.03</td>
<td>27.5 ± 0.7</td>
<td>0.60 ± 0.1</td>
<td>2.3</td>
</tr>
<tr>
<td>SDSS 153821</td>
<td>1h 31m</td>
<td>6.4 ± 0.2</td>
<td>$(3.5 \pm 0.1)$</td>
<td>1.7 ± 0.05</td>
<td>29.9 ± 0.9</td>
<td>0.7 ± 0.2</td>
<td>2.5</td>
</tr>
<tr>
<td>CG 598</td>
<td>2h 26m</td>
<td>5.2 ± 0.1</td>
<td>$(18.0 \pm 0.3)$</td>
<td>8.5 ± 0.1</td>
<td>3.8 ± 0.1</td>
<td>5.3 ± 0.8</td>
<td>1.6</td>
</tr>
<tr>
<td>SBS 1428+529</td>
<td>0h 25m</td>
<td>&lt; 0.6</td>
<td>&lt; 1.23</td>
<td>&lt; 0.6</td>
<td>...</td>
<td>2.0 ± 0.4</td>
<td>&lt; 0.4</td>
</tr>
</tbody>
</table>
The galaxy has a small optical size of ~10.7kpc at a distance of 70.4Mpc but has a very massive HI disk; \( M(\text{HI}) = 23.9 \times 10^8 \) solar mass (Kreckel et al. 2011). \( M(\text{H}_2) = 1.5 \times 10^9 \) solar mass. The ratio \( M(\text{H}_2)/M(\text{HI}) = 0.6 \) and is high.

The profile has a prominent double horned structure which shows that the molecular gas is in a rotating disk. The velocity separation is ~250km/s. Hence after including disk inclination the rotation velocity ~125km/s.

\[ V_0 = 49566 \text{ km/s} \]
SBS1325+597 : Hα Imaging and UV emission

- The Hα distribution is in a ring about galaxy center. Much like the CO distribution. The GALEX near UV image shows emission that has a scale slightly larger than the g band image of the galaxy. The peak emission is slightly off from the galaxy center.
- From the Hα flux we obtain a SFR=0.20 solar mass/year (Kennicutt 1998).

The SDSS B band image (top left) and HCT Hα image (top right) of SBS1325+597.

Extreme left shows the GALEX UV images and the right shows HCT Hα image with GALEX contours of SBS1325+597 superposed.

Note: the UV disk is more extended.
This is a relatively small galaxy at a distance of 76 Mpc and has a stellar disk of \( \sim 15 \text{kpc} \). Disturbed isophotes in B band. Maybe an interacting system.

- \( \text{M}(\text{H}_2) = 1.1 \times 10^9 \) solar mass. The ratio \( \text{M}(\text{H}_2)/\text{M}(\text{HI}) = 2.3 \). The gas surface density appears to be very high – but the galaxy size may be underestimated. The profile is one-sided – the other half of gas emission from the disk is weak.

- The GALEX UV emission is more extended than the B band emission. Maybe a resolution effect or could be real.
SDSS143052.33+551440.0 : Hα Image

The Hα emission gives a SFR=0.60 solar mass/year. This is similar to low luminosity spirals such (e.g. BCDs).

The SFE=0.2, which is high. Gas is rapidly being used up in star formation.

Hα on left and SDSS g band image on right. Emission is little lopsided.
The molecular gas mass is \( M(\text{H}_2) = 1.7 \times 10^9 \) solar masses and the \( M(\text{HI}) \) mass is \( \sim 0.7 \times 10^9 \) solar masses. The gas mass ratio of molecular to HI is very high at 2.5. SFR = 1.0 solar mass/yr, highest amongst 5 galaxies.

The CO(1-0) emission is sharply peaked and has a width \( \sim 250 \text{ km/s} \) which suggests a disk rotation velocity of \( \sim 125 \text{ km/s} \). Galaxy has a bar and distinct spiral arms. Gas driven into center by bar. Star formation mainly along bar.
This is a distant galaxy lying in the Bootes void (z~0.05). It appears disky in all images but not much structure can be seen, it is however large in optical size ~52.5kpc.

- The molecular gas mass is $M(H_2)=4.6\times10^8$ solar mass, which is quite large. The $M(HI)$ mass is $\sim3.6\times10^9$ solar masses. The gas mass ratio is 0.13. The $H_2$ gas surface density appears to be high – at least on one side of the galaxy.
- The profile is one sided – the other half of gas emission from the disk is weak.
The molecular gas CO(1-0) spectrum. The gas is asymmetric about the systemic velocity suggesting lopsided molecular gas disk. It could be due to the interaction.

The NUV image (left) and the g- band sdss image (right) shows that the galaxy has significant star formation. The rate is 1.5 solar mass yr\(^{-1}\). The size is more extensive than optical.

- This is a distant galaxy lying in the Bootes void (z\approx0.05). It appears disky in all images but not much structure can be seen. It is however large in optical size \(\sim\)52.5kpc.
- The molecular gas mass is \(M(H_2) = 8.5\times10^9\) solar mass, which is quite large. The M(HI) mass is \(\sim3.6\times10^9\) solar masses. The gas mass ratio is 1.6.
- The g- band sdss image shows that the galaxy is accreting a smaller companion. Hence the larger size and slightly off-center \(H_2\) distribution. The interaction leads to star formation and NUV emission.
Comparison of our $\text{H}_2$ detection with previous three detections

- Our CO detection matches well with two earlier studies (Sage et al. 1997 and Beygu et al. 2013).
- Thus molecular gas is not uncommon in voids and star formation can be supported.

(Das et al. 2015)
What triggers star formation in void galaxies?

1. They could be interacting with close neighbours or with HI dominated galaxies that we do not see in optical images. The interactions trigger the star formation.

2. Gas accretion onto galaxy disks can shock gas and trigger star formation. Or cold gas accretion makes the disks unstable and results in onset of star formation.

3. Void merging can result in more gas accretion (e.g. Polar ring galaxy in void wall).
Gas Flow along Void Substructure

There could be gas flowing along the void filaments that accrete onto galaxies. This may trigger star formation as well as cool the gas disks and results in star formation. As a result, the galaxies grow in mass and evolve.

Gas accreting onto galaxies will appear as abnormal velocities in the HI position velocity plots. It has been detected in VGS_31 system (left and below) and in the Local Void galaxy NGC6946.

(Beygu et al. 2013)
Mapping the Molecular Gas in CG910: is there gas accretion?

Galaxy is at z=0.044. Relatively isolated. Disk size 19 Kpc (21") and is inclined at 60 degrees. CO emission has double horned profile, suggest a rotating disk with $v=140$ km/s. Nuclear emission in radio but optical spectrum suggests star formation rather than AGN activity.

Aim: To map the molecular gas disk, understand star formation in voids.

SDSS z and g band image of CG910. The bulge is prominent and disk inclined. Its IRAS flux is high suggeting relatively high star formation. In g band the emission is lopsided.

The IRAM spectrum of CO(1-0) emission (Sage et al. 1997). The mass of molecular gas is $3.8 \times 10^8$ solar mass.
CARMA CO(1-0) Map of CG910

- The CO emission is distributed out to 7 to 8Kpc. Gas surface density is very high. Peak emission slightly off-center.
- Velocity field shows signs of non-circular gas flow which maybe due to a small bar.
The position velocity plot of the CO emission traces the velocity of the cold gas along the disk.

In CG910 we find some gas at large radii – around 20 to 24 kpc. This may represent gas flowing into the disk and cooling to form molecular hydrogen gas.

Such gas can later become unstable and lead to star formation.

To see signatures of gas accretion or interaction with a low luminosity companion, HI observations are essential.
We observed CG910 over 3 days with the GBT from Jan 31\textsuperscript{st} to Feb 3\textsuperscript{rd}, 2016. Total time of observation was \sim hours.

The HI flux is \sim0.4Jykm/s which gives an HI mass of $3.3\times10^9$ solar mass using a distance of 188Mpc.

There is some emission off the velocity center. Maybe due to gas accretion or HI interaction with a low luminosity companion which is not detected in optical images?

Preliminary results, data not yet fully analysed.
Low frequency radio observations of the Bootes void with the GMRT

- We have done 610 and 240 MHz observations of the radio emission around the 4 bright AGN host galaxies in the Bootes void.
- Our aim is to map the radio emission due to star formation and AGN activity around these galaxies and compare with field galaxies.
- We will especially look for diffuse emission that could be due to filaments in the void region.
- Ongoing work ....
610 and 150 MHz emission around CG692-693

At 610 MHz, CG692 is prominent but the companion CG693 is weak.

In the Chandra image the emission is concentrated on CG693 and associated with the AGN (Sy1 nucleus).
TGSS 150 MHz Images: for spectral index and identifying diffuse emission

Comparing with the TGSS 150MHz image we find that the emission is extended and has a spectral index of ~ -1.0.

We have no confirmed diffuse extended emission yet.
Summary

• We have searched for CO(1-0) emission from 5 void galaxies with the 45m NRO millimeter telescope. We have detected molecular gas in 4 out of the 5 galaxies. Earlier detections were in 3 other galaxies. We studied their SFRs with HCT.

• There is moderate ongoing star formation in void galaxies. In our 3 studies the star formation rates are in the range 0.2 to 1 solar mass/year. Void galaxies are evolving but at a rate slower than normal environment galaxies.

• The star formation may be triggered by close interactions in some cases. But gas accretion along void filaments may also be important..

• They are not predominantly LSB galaxies; moderate SF present and molecular gas detected.

• We have detected radio emission from void galaxies at low frequencies.