AGN, Jets and Molecular Gas in Nearby Radio Galaxies

Mousumi Das, RRI, Bangalore

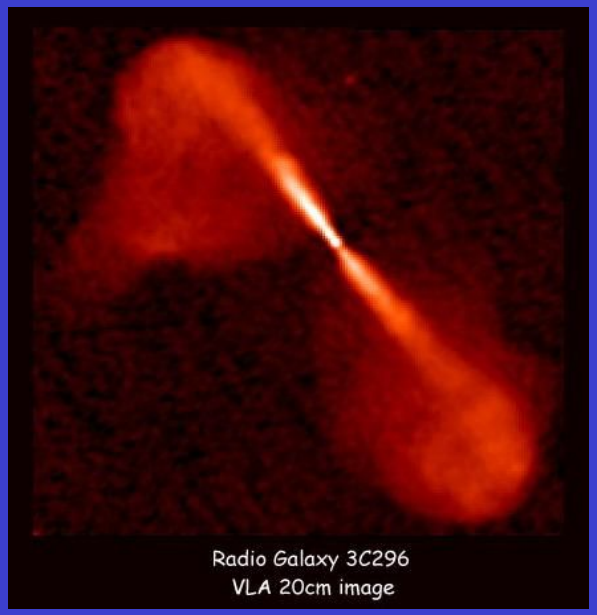
Co-Investigators : S.N.Vogel (UMD)
G.A.Verdoes-Kleijn (ESO)
C.P.O'Dea (RIT)
S.A.Baum (RIT)

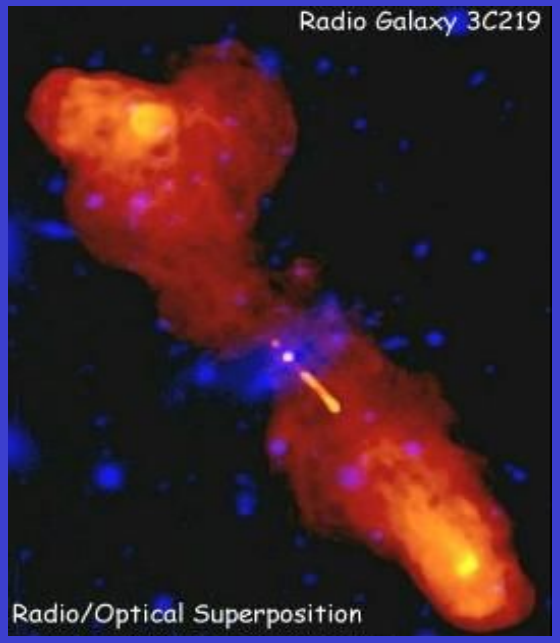
IIA, January 2006

Radio Galaxies : AGN activity and Jets

Radio Galaxies are luminous early type galaxies that host active galactic nuclei (AGN). Many have radio lobes or jets.

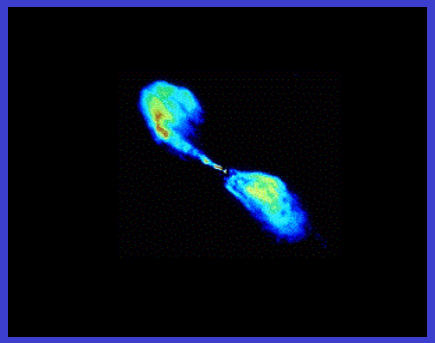
Depending on jet morphology they are called FR I or FR II type sources.





Radio Galaxies have been studied at various wavelengths .....

Radio (VLA)



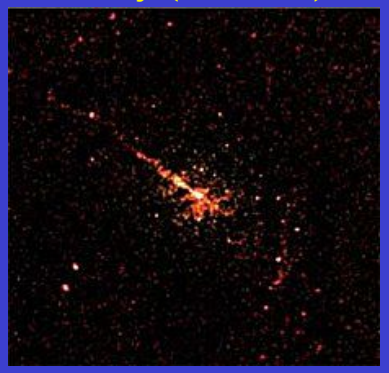
Mid-IR (Spitzer)

Near-IR (2MASS)

Visible (DSS)

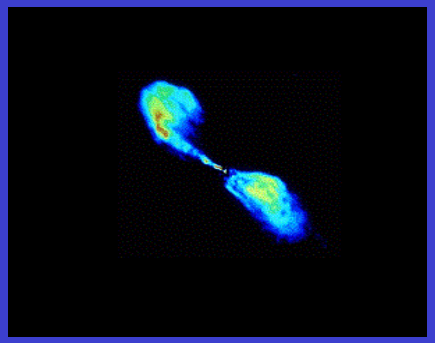
UV (Galex)

X-ray (Chandra)



Radio Galaxies have been studied at various wavelengths .....

Radio (VLA)



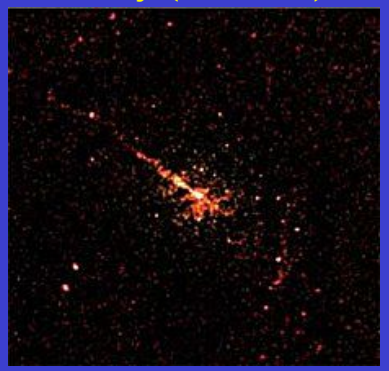
Mid-IR (Spitzer)

Near-IR (2MASS)

Visible (DSS)

UV (Galex)

X-ray (Chandra)



But millimeter continuum observations of radio galaxies is rare. Only a handful have been studied e.g. 3C 20 and 3C 123.

Molecular Gas in Radio Galaxies

Molecular gas has been detected in several radio galaxies so far (e.g. Lim et al. 2003, Leon et al. 2003). Masses are of order 10^8 to 10^10 M_sun.

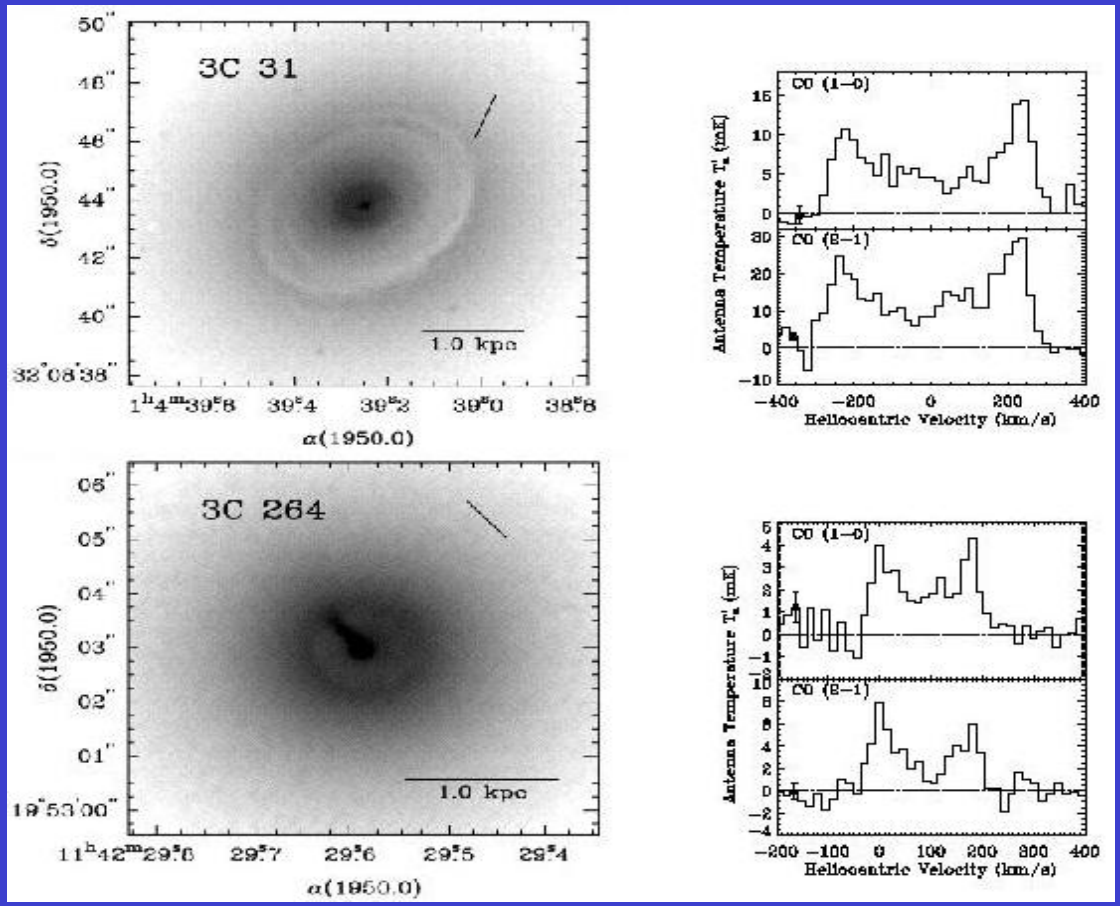
But the gas distribution has been mapped in very few cases. Examples are Cen A, 3C 84, 3C 293 and 3C 31. In these cases the gas is in a disk and has a disturbed morphology.

The molecular gas may provide a reservoir for fueling the AGN and powering the radio jets in these galaxies.

The radio jets may also interact with the gas disk in these galaxies.

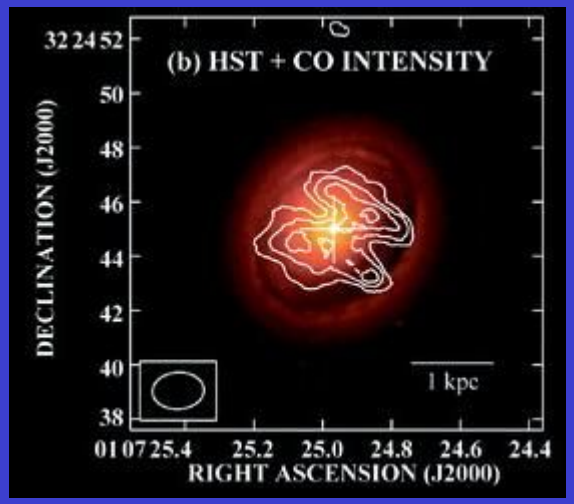
Molecular Gas Observations : Examples

CO single dish detection of molecular gas



Lim et al. (2000)

CO Map of Gas Disk



Okuda et al. 2005

The questions we are asking .....

Continuum emission

What is the radio morphology of the core and jet structure of the AGN at millimeters (~100 Ghz)?

What is the flux and how does the spectral index of the core and jets change with frequency?

How are the radio jets oriented relative to the gas disks in radio galaxies?

Why are only some active galaxies bright at millimeters?

Molecular gas distribution

What is the morphology of the gas distribution in radio galaxies?

Does it have a regular disk structure or is it perturbed?

Are the gas kinematics similar to that seen in nearby disk galaxies?

What is the origin of the molecular gas in these galaxies?

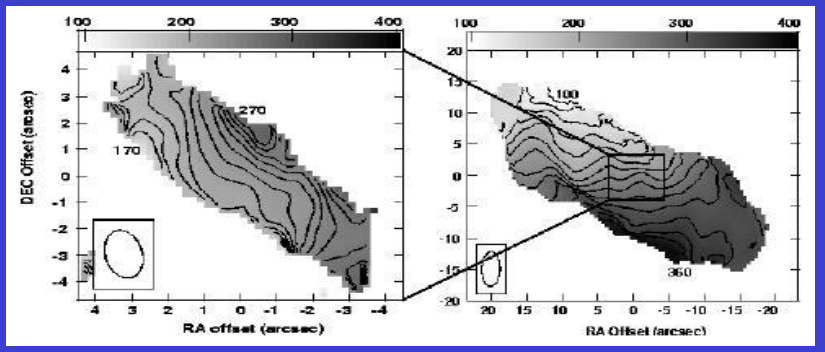
Does the gas feed the AGN? How is the gas transported to the AGN?

Do radio jets interact with the gas disk?

Gas Fueling in Barred Galaxies : Examples

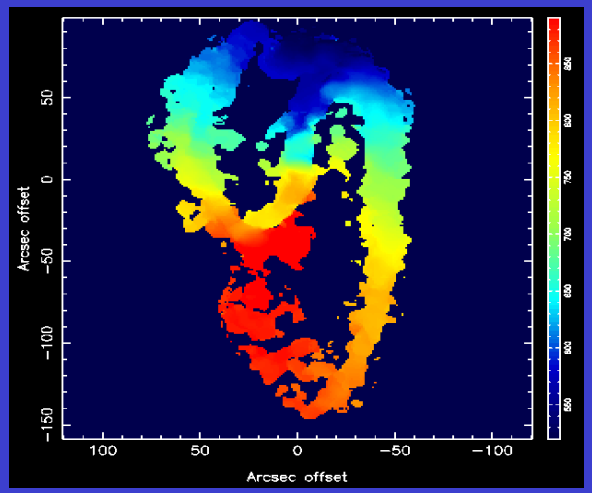
NGC 253

Velocity Field in NGC 253

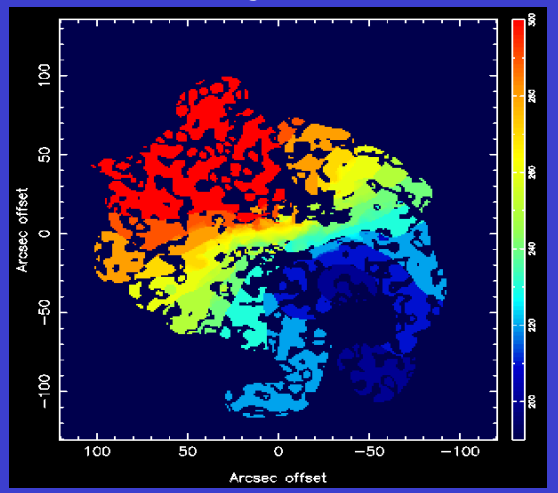


(Das et al. 2001)

CO Velocity Field in NGC 3627



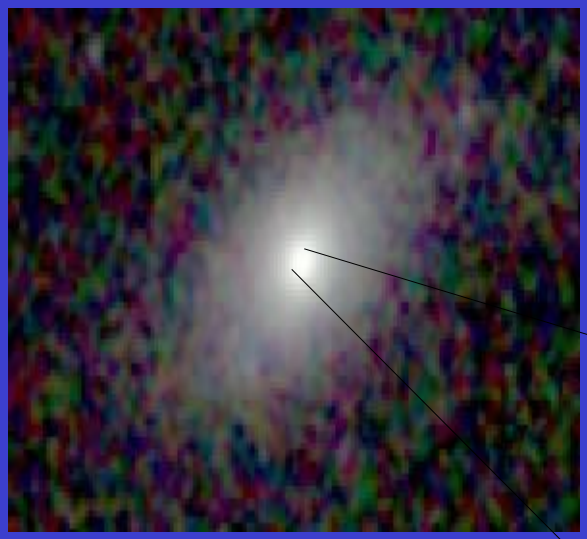
CO Velocity Field in M101



(Das et al.2003)

Galaxies in our study

NGC 3801 (UGC 06635)



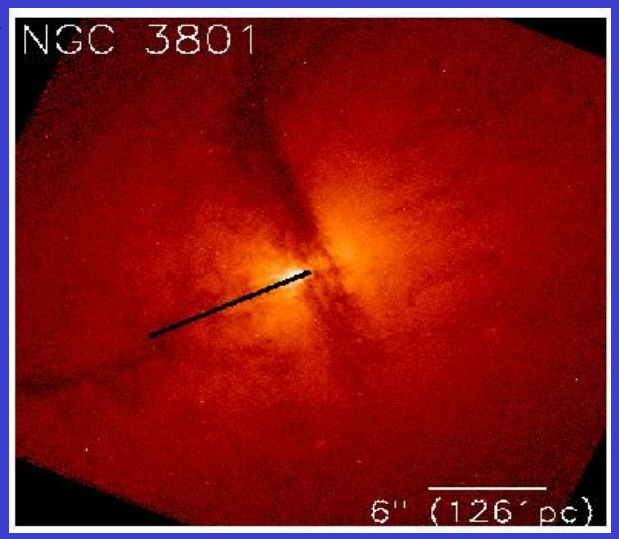
2MASS JHK image

Distance : 48 Mpc (Vsys=3451 km/s)

galaxy type : SO/a , FR I radio source

P.A. Dust Lane : 24 degrees

P.A. Radio jets : 120 degrees

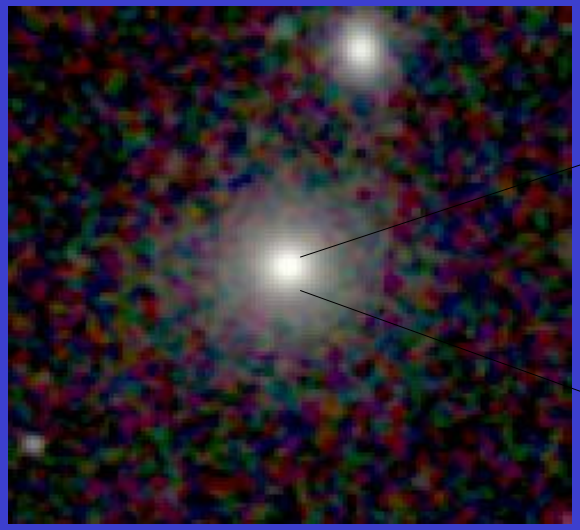


HST V band image

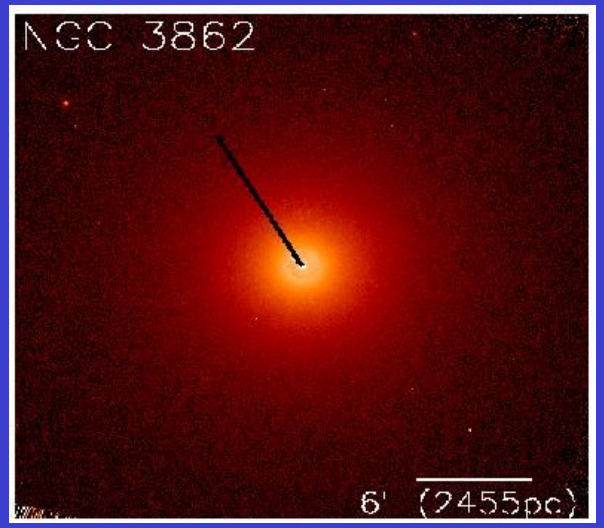
NGC 3801 is part of a group of 10 galaxies.

It has a prominent dust lane with knots of star forming regions associated with the dust lane.

NGC 3862 (3C 264 or UGC 06723)



2MASS image of NGC 3862



Radio and HST optical images of NGC 3862

Distance : 90 Mpc, vsys = 6511 km/s

type : E, FR I radio source

The galaxy lies close to center of the cluster A1367.

Both optical and radio jets observed.

Observations :

The observations were done using the BIMA millimeter wave interferometer at Hat Creek in N. California in late 2003.

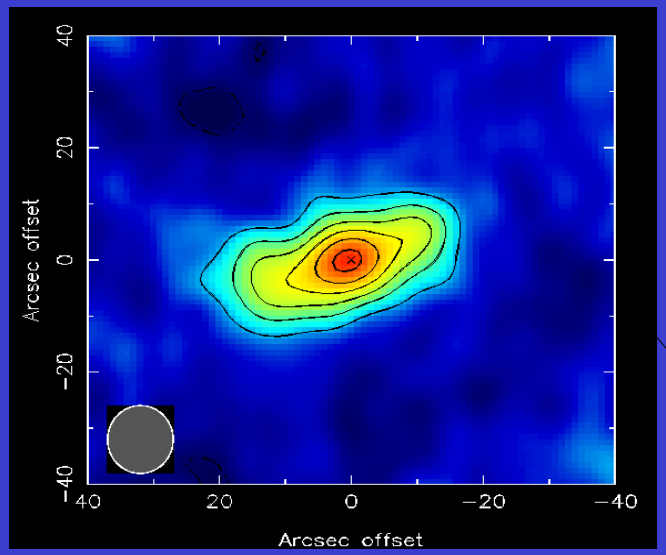
We did single pointing observations with the CO(1-0) line in the upper sideband. 3C273 was used as a flux calibrator. Large velocity range of ~ 2000 km/s was used.

We seperated the line and continuum emission by flagging out the CO line and computing the continuum source. Then we subtracted the continuum source to derive the molecular gas distribution.

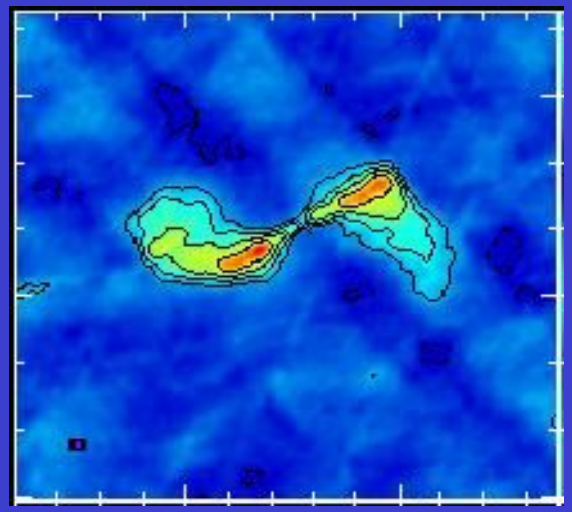
We did additional observations of NGC 3801 at 86 GHz and 110 GHz to derive the spectral index of the core and jets.

Results for NGC 3801

Radio Continuum at 2.7mm



Radio Continuum at 20cm

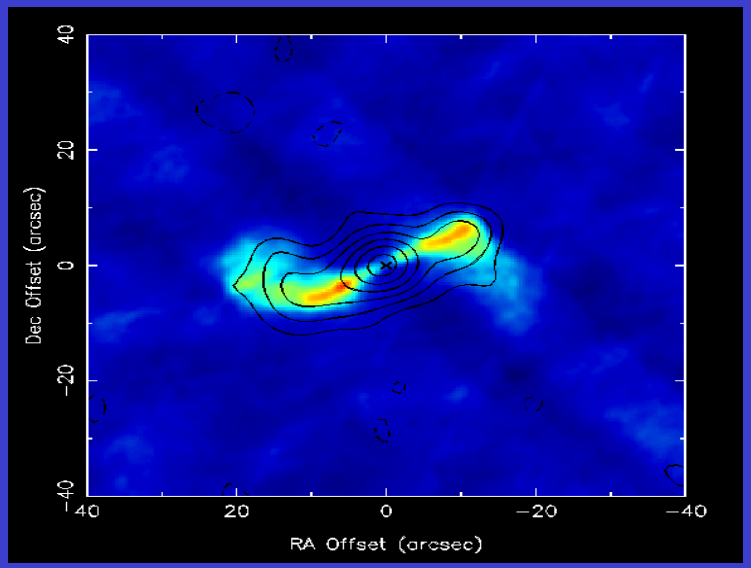


Our BIMA 2.7mm maps trace the radio jets mapped at lower frequency VLA observations.

The radio jets have P.A. 120 degrees and radius approximately 3.5 kpc (15”). Jets are curved, perhaps due to precession or interaction with ISM..

The millimeter observations are able to detect the radio core which is self absorbed at lower frequencies.

BIMA map with VLA contours overlaid



Spectral index maps and core-jet decomposition:

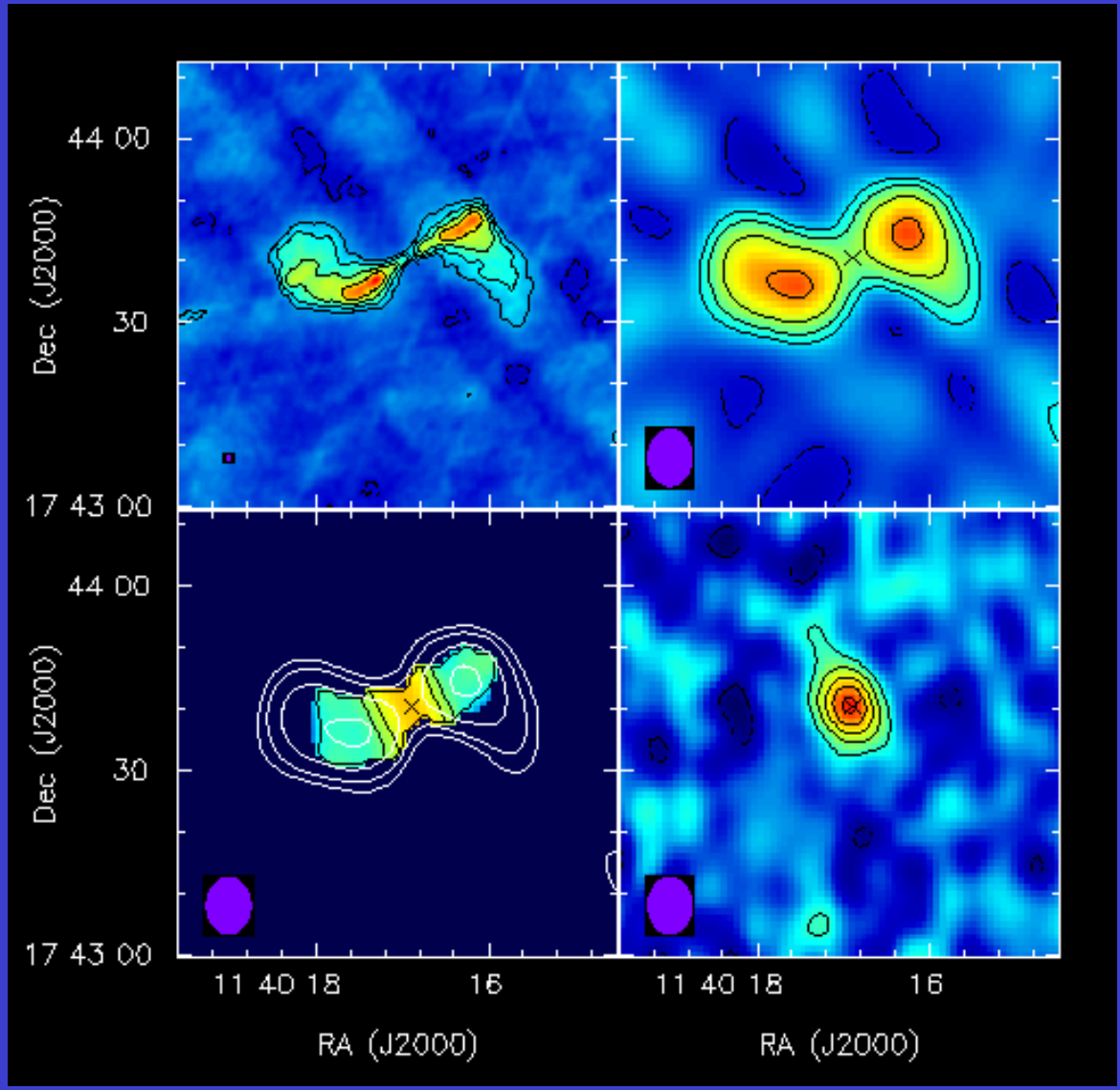
We used the VLA 1.5 Ghz maps to derive the spectral index map of NGC 3801 between 20cm and 2.7mm.

The core is not detected at 1.5 GHz. Upper limit to the flux of the core is 0.8 mJy.

The lobes have a mean spectral index of -0.76.

We used the VLA 1.5 Ghz observations to seperate out the core from the jet.

The core has a flux of 15mJy.

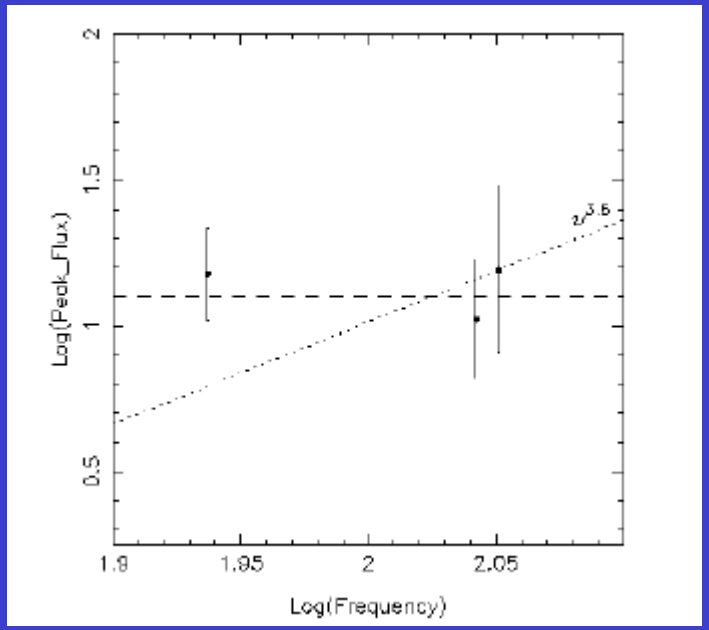


Spectral Index of the Core :

We did additional observations at 86 Ghz and 110 Ghz to see if the core has a flat spectrum.

All observations at 86, 110 and 112 Ghz were smoothed to the same resolution and then compared.

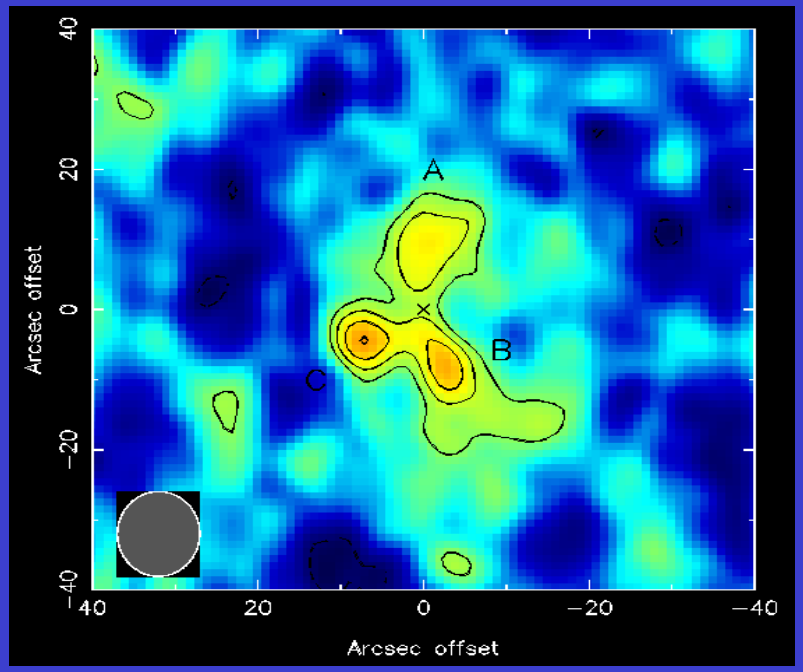
Within errors the spectrum is flat. The dotted line is the power law expected from dust emission.



The continuum emission is hence due to the AGN in the galaxy. The radio synchroton emission is optically thick at millimeter wavelengths in NGC 3801.

Molecular Gas Morphology in NGC 3801

CO (1-0) Map of the Gas Distribution in center of NGC3801



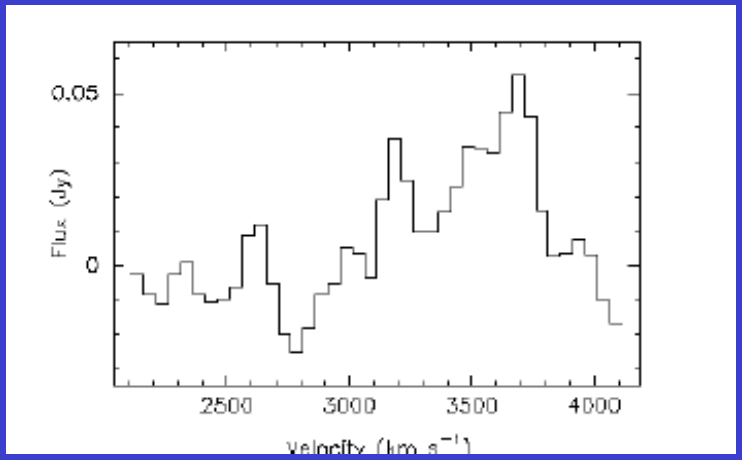
(The 2MASS center of the galaxy is marked with a cross).

The molecular gas is distributed in 3 main clumps : A, B and C. The gas lies along the dust lane in the galaxy center.

The morphology is close to an edge on rotating gas disk in the center of the galaxy. The emission extends across 30" (7kpc).

The BIMA CO spectrum is similar to the single dish IRAM spectrum. Total gas mass is ~ 5x10^8 M_sun.

The CO (1-0) emission spectrum summed over 30x40”box.



Position Velocity plot of NGC 3801 :

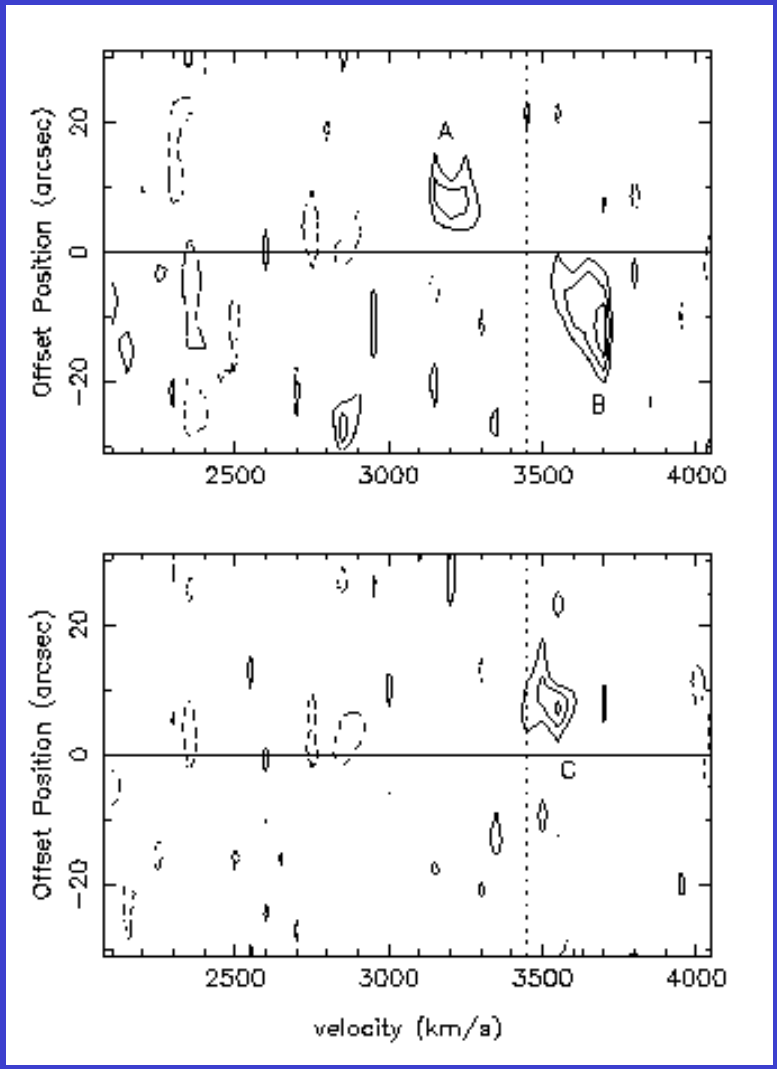
Velocity Cuts along the dust lane (top) and normal to the dust lane (bottom).

We did 2 position velocity plots along and normal to the dust lane through the center of the galaxy.

The velocity extent of CO emission is similar to the HI 21cm profile. There is an HI absorption line that corresponds to the velocity range of clump C, which overlaps with the near jet.

The PV plot represents a rotating disk of radius 3.5 kpc. The flat rotation velocity is 250 km/s .

Clumps A and B are rotating in a disk whereas clump C is falling towards the galaxy center.



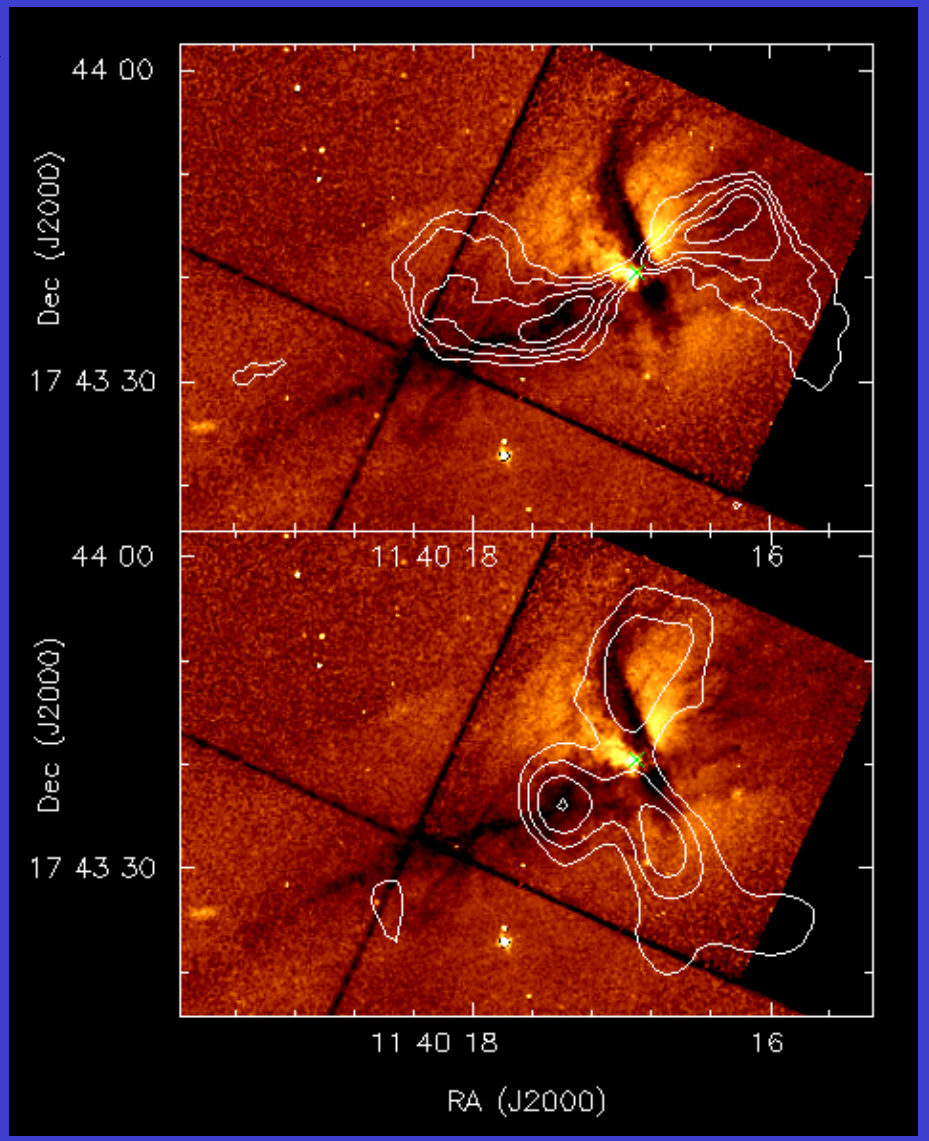
Comparison of HST, VLA and CO observations :

BIMA radio continuum and C(1-0) emission maps superimposed on the HST F555W image of NGC3801.

Both the radio jet and the molecular clump C lie on the dust filament normal to the main dust lane of the galaxy.

The molecular clumps A and B lie close the main dust lane. Since molecular gas traces dust galaxies, the gas probably lies in a disk normal to the radio jets.

The radio jet on the near side of the galaxy may be interacting with the infalling clump of molecular gas.



Main Results for NGC 3801

Continuum Source:

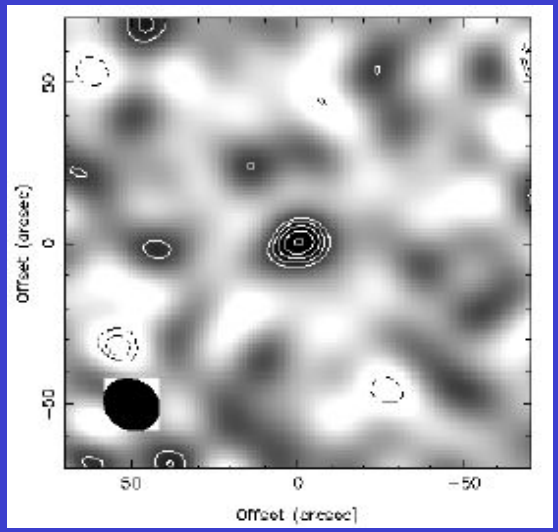
1) We have detected 3mm continuum emission from the core and radio jets in NGC 3801.

2) The bright radio core was not detected in 20cm VLA observations but is strong at 3mm. This maybe because the synchroton emission is self absorbed at lower frequencies but optically thin at 3mm.

3) The core spectrum is flat at 3mm. Hence the core emission is due to the AGN. The core is dense and compact.

4) AGN activity at millimeter wavelengths has been detected in very few galaxies (e.g. UGC 6614, 1300+0144).

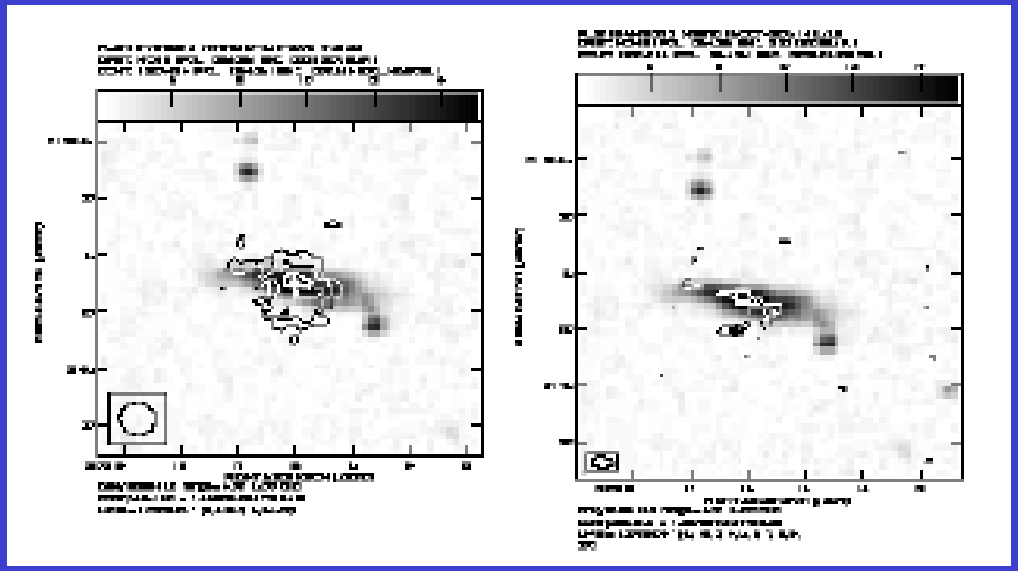
UGC 6614 :



BIMA 3mm observations of the radio continuum in the LSB giant UGC 6614

(Das et al. 2006)

1300 + 0144:



GMRT 1.4 Ghz observations of the radio continuum in 1300+0144

(Das et al. 2006)

Main Results Continued :

5) The radio jets have a spectral index of -0.76 and are optically thin.

6) The nearer jet lies along the dust lane normal to the main disk in the galaxy. Its position coincides with one of the gas clumps (clump C).

7) The nearer radio jet may be interacting with the infalling gas clump. The jet is probably entraining gas from the infalling clump.

8) The nearer radio jet may also be causing the absorption line in the HI 21cm spectrum of the galaxy.

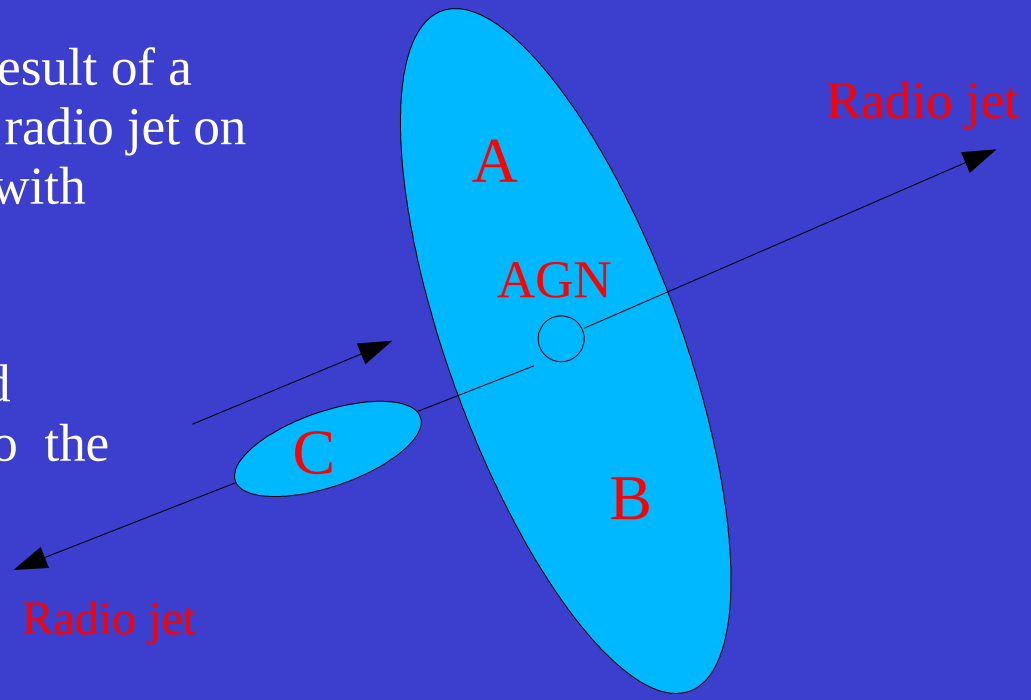
The Molecular Gas Disk in NGC 3801:

1) Two of the gas clumps are in a gas disk rotating at 250 km/s. The third is falling towards the center of the galaxy.

2) The gas cloud C may be interacting with the radio jet.

3) The gas clump C may be the result of a recent merger in the galaxy. The radio jet on the near side may be interacting with infalling gas.

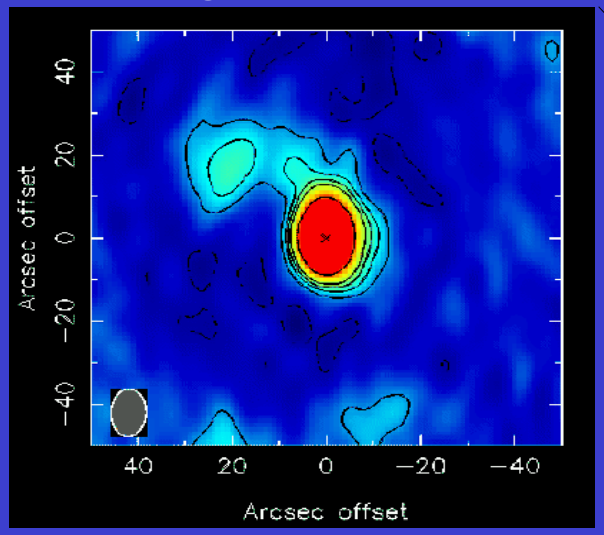
4) The gas disk is not regular and somewhat warped. May be due to the interaction/merger event.



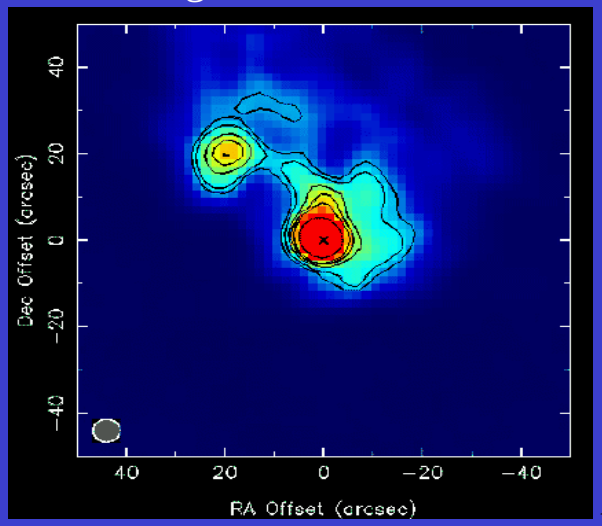
Results for NGC 3862 (3c264)

Continuum Emission

BIMA image at 111.2 GHz

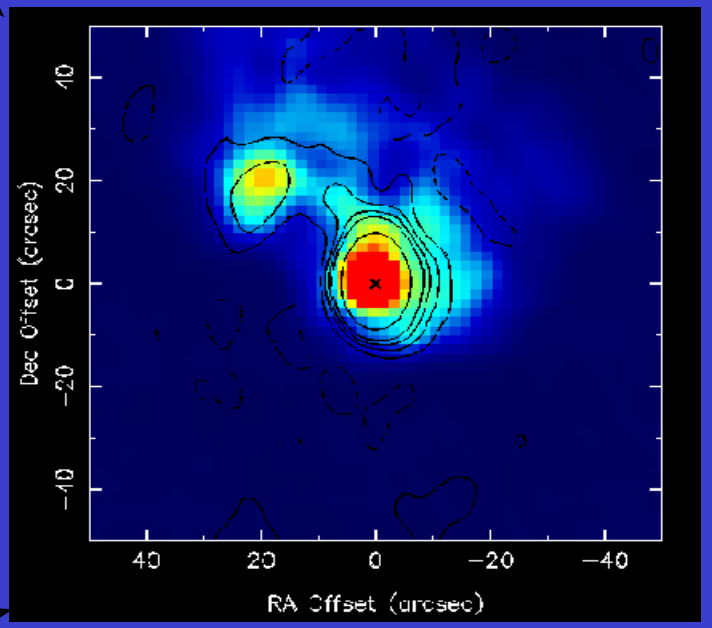


VLA image at 1.4 GHz



It has a one sided jet that is seen both at 1.4 Ghz VLA observations and our 111.2 Ghz observations. Jet is inclined 50 degrees to our line of sight.

Radio jet also seen in optical emission. Jet interacts with the ISM in the galaxy



VLA image of the core and jet with BIMA contours overlaid

Continuum Emission in NGC 3862 :

1) The flux at 3mm (111.2 Ghz) is 128 mJy.

2) The spectral index of the core between 1.4 Ghz and 111 Ghz is -0.35. Hence core is not flat spectrum.

3) There is a one sided jet at 3mm which traces the lower frequency 1.4 Ghz jet.

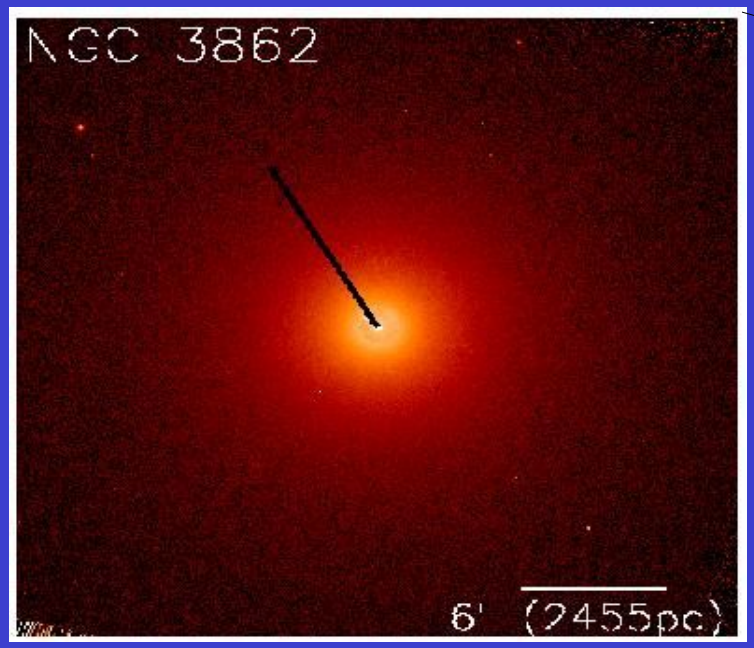
4) The peak of the continuum emission matches the 2MASS near IR peak.

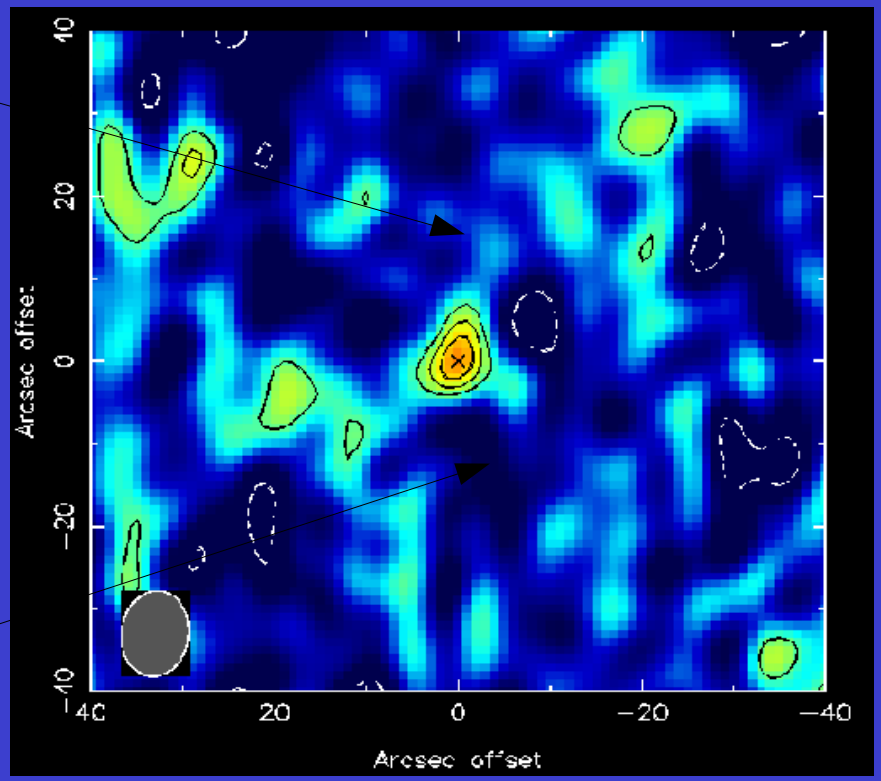
Molecular Gas Distribution in NGC 3862

The molecular gas disk lies in the region of the dust emission in the galaxy.

The mass of molecular gas is 10^9 M_sun. The gas is concentrated in the nuclear region.

The size of the molecular gas disk is about 4.5 kpc.





Summary

1) We have detected and mapped molecular gas in 2 FR I type radio galaxies. Both galaxies have significant amounts of molecular gas concentrated in their centers.

2) The molecular gas disk in one galaxy is perturbed and undergoing a merger. This is true for other FR I galaxies that have molecular gas disks as well. This could mean that the cold gas in FR I sources is externally accreted and not due to cooling flows as previously thought.

3) We have detected 3mm emission from the jet and core of both galaxies.

4) There is indication of jet-ISM interaction in NGC 3801; the jet maybe entraining gas from the infalling clump.

For reference see : Das et al. 2005, ApJ, 629, 757