Searching for Dual AGN in Galaxies using Radio Observations

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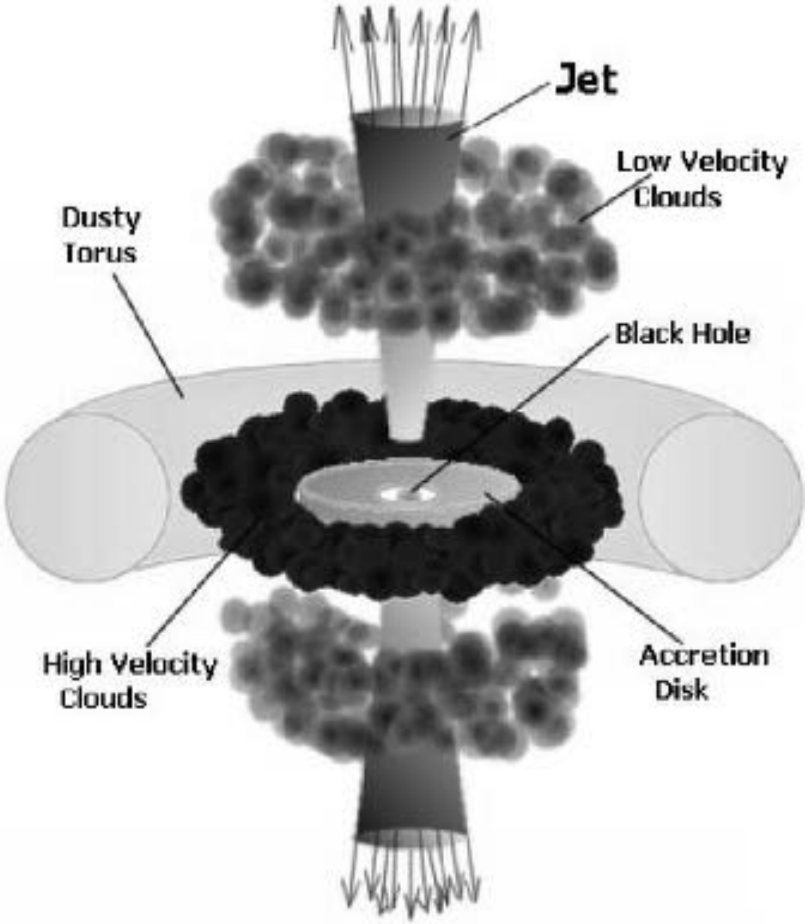
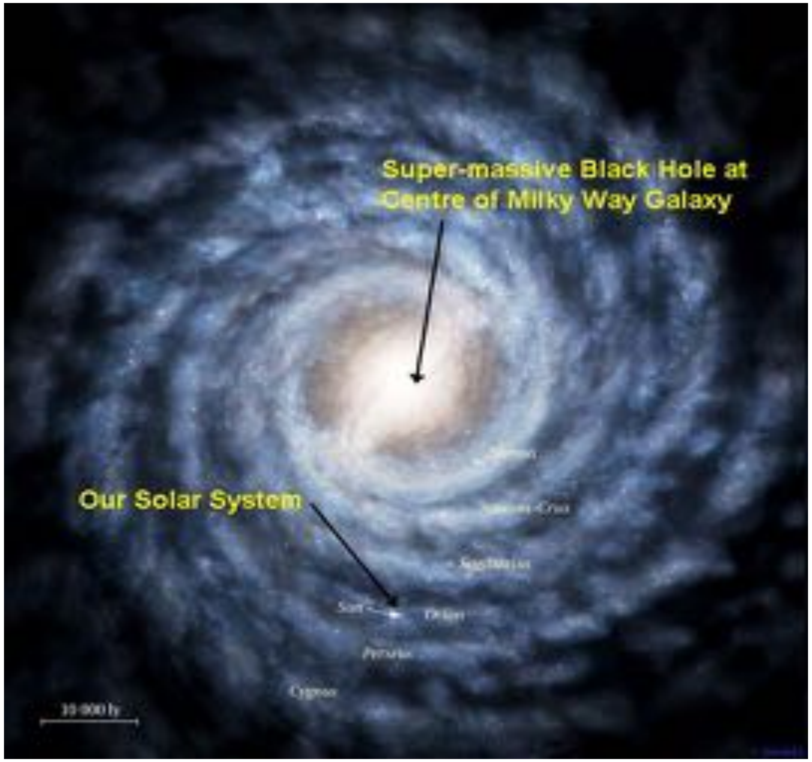
Active Galactic Nuclei (AGN)

- Nuclei of some galaxies have a much higher luminosity which can not be explained by stellar emission.
- These extra luminous nuclei are called active galactic nuclei (AGN) .
- AGN emit a huge amount of energy from a small region at the center of the host galaxy.
- The energy from the central engine is due to accretion onto a central super massive black hole (SMBH).



AGN Pair : Why we expect them at the centers of galaxies?

- Observations show almost all galaxies have central SMBHs



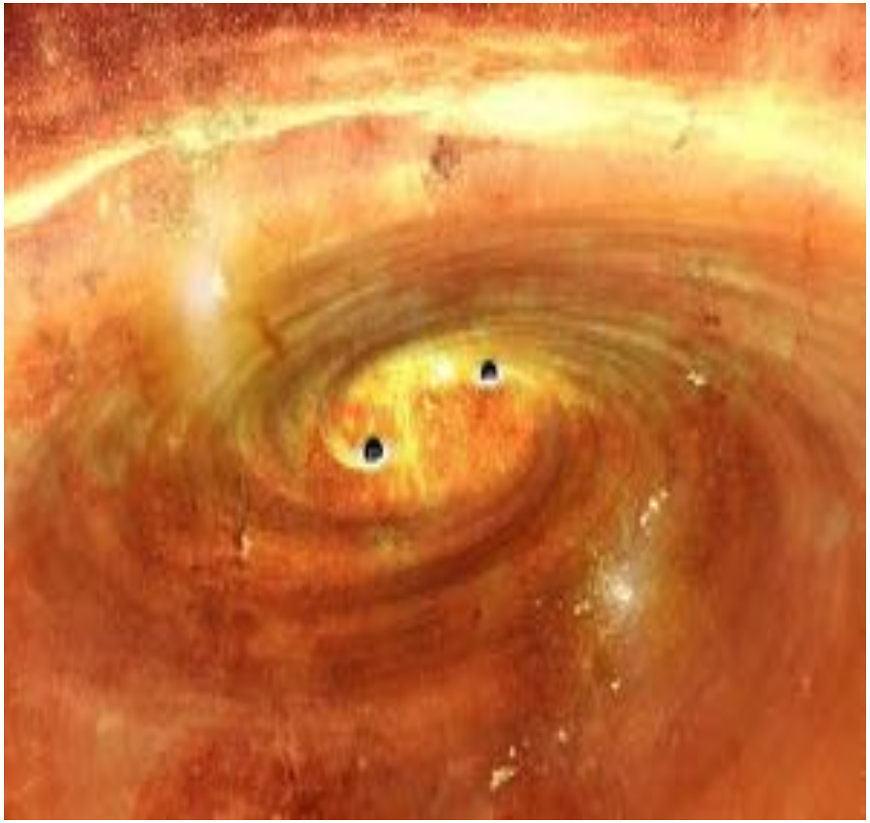
hipacc.ucsc.edu

- According to hierarchical models of galaxy formation, galaxies formed from mergers

transudationism.blogspot.com

How do AGN pairs form in the centers of galaxies?

- During mergers SMBHs sink to the centre of the merger remnant, finally resulting in gravitationally bound SMBH binary systems
- Simulations show that mergers cause gas accretion onto the SMBHs which can ignite AGN activity in the BH pair



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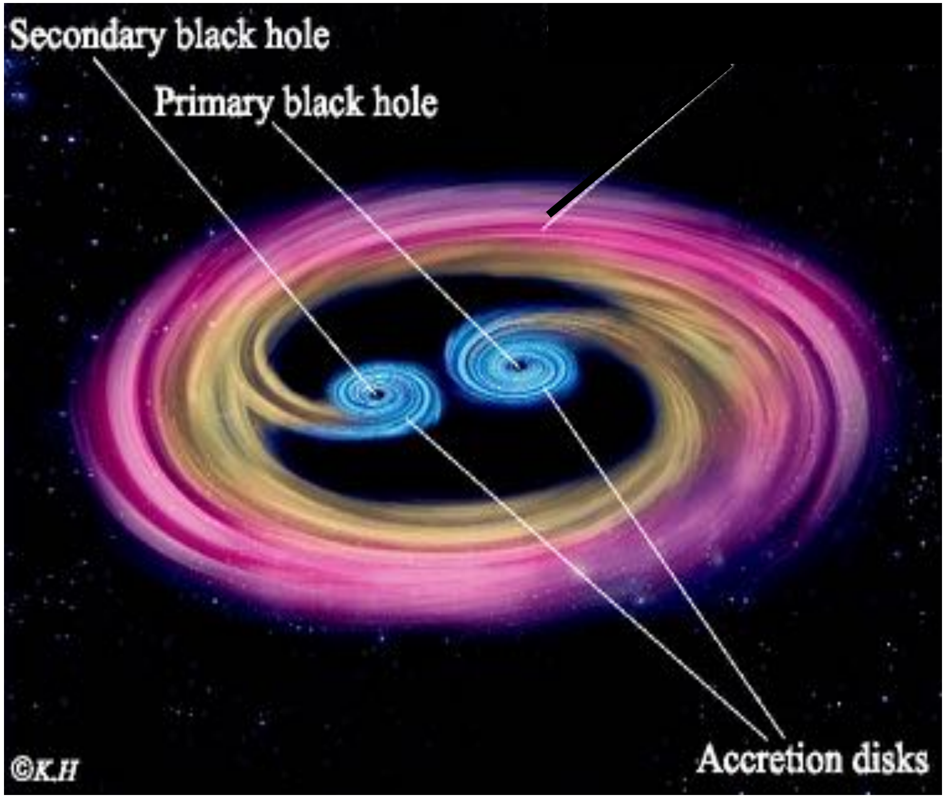


Google.com

Motivation

- Our main aim is to understand the end stage of galaxy mergers – how the nuclei of the individual galaxies settle into the final remnant, how they affect the surrounding stars and gas and vice versa.
- Dual AGN is one way we can trace the end state of mergers.
- As a first step we want to detect dual AGN systems.

Dual/binary AGN : Direct detections

1. Two cores in radio image

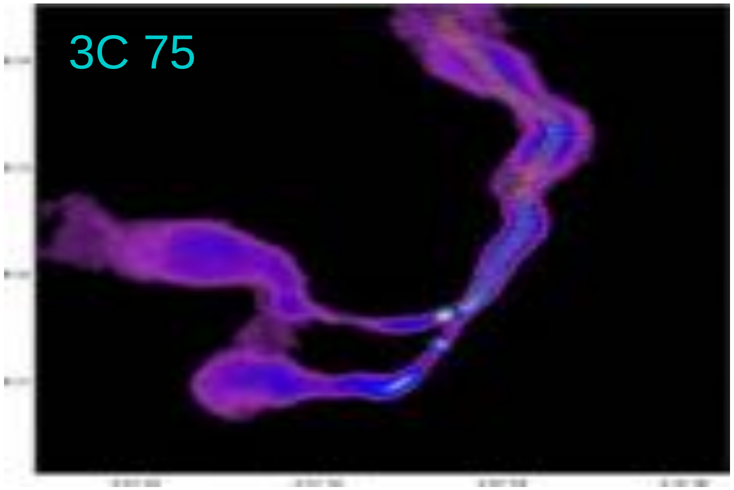
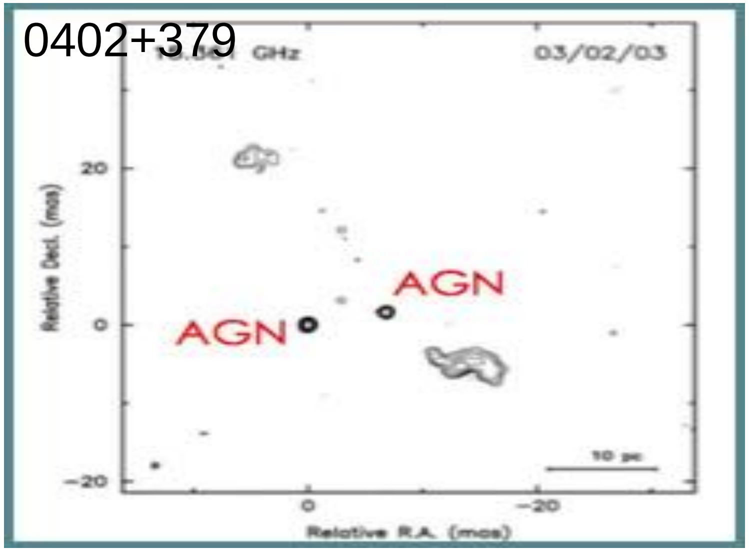


Image courtesy: NRAO and F.N. Owen et al

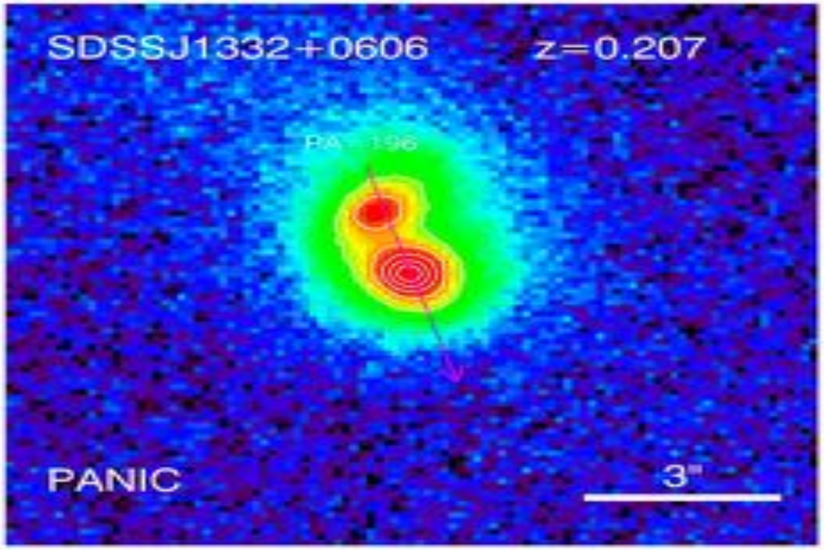
2. Two cores in X-ray map

Koss et al 2011



Rodriguez et al (2006)

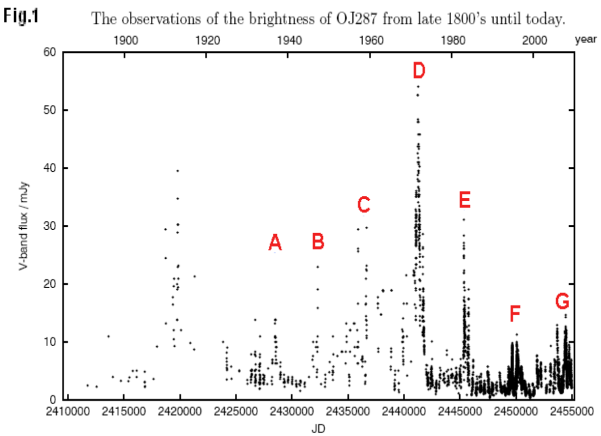
3. Two cores with distinct spectra in optical/IR



Liu et al 2013

Indirect Signatures :

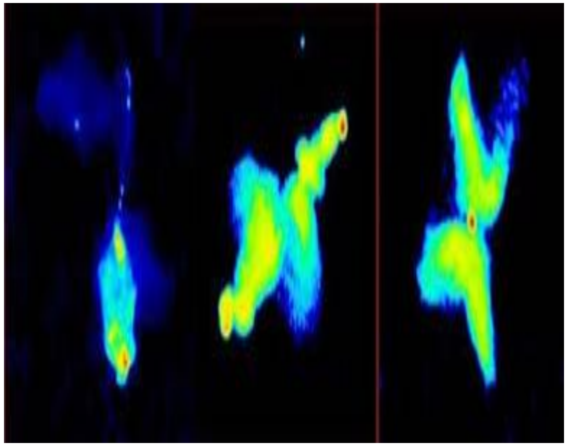
1. Periodicity in flux variability



arXiv:0809.1280,

www.astro.utu.fi

2. X- or S-shaped radio galaxies



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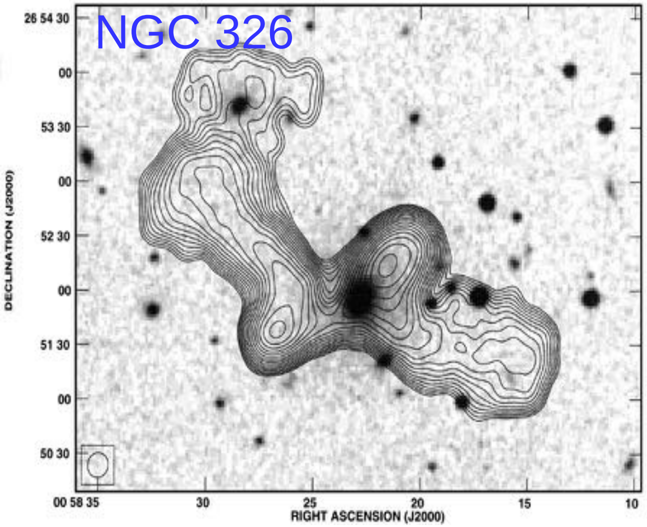
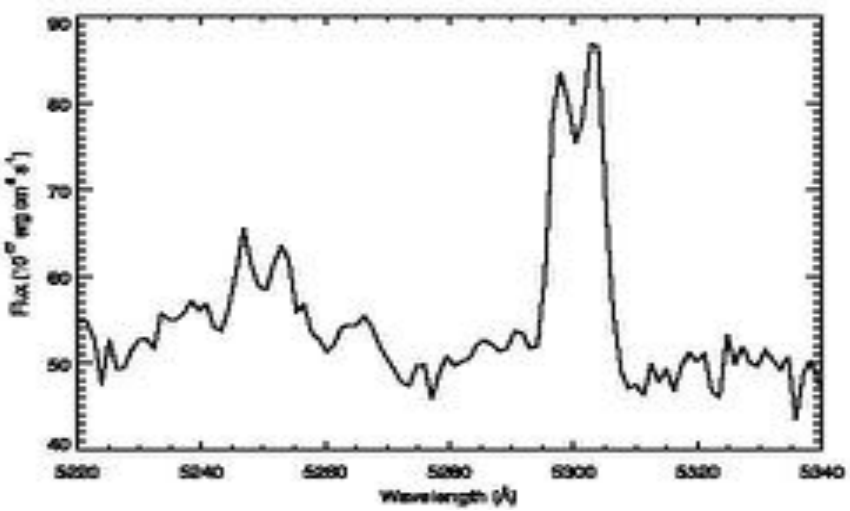


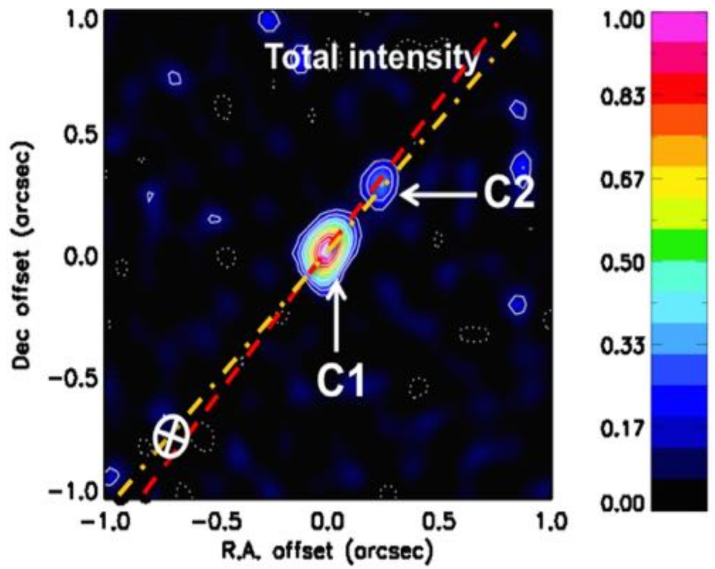
Ekers 1978

3. Double-peaked emission line in optical spectra ([OIII] emission lines)

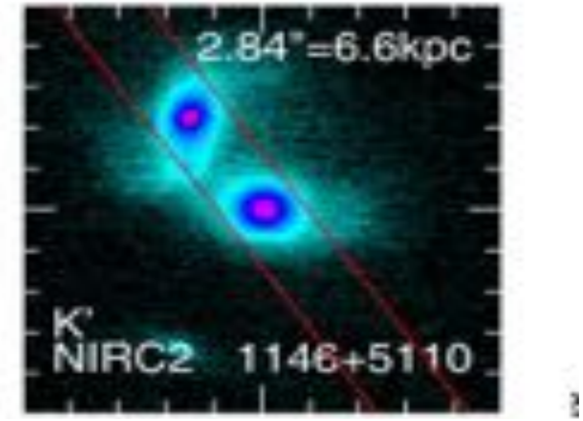


Detected Binary/dual AGN

- From theoretical models we expect a large number of dual/binary AGN.
- To date the confirmed binary AGN is only 23~25.
- One of the reasons for low detection rates could be the lack of high resolution observations that are required in radio or X-ray.



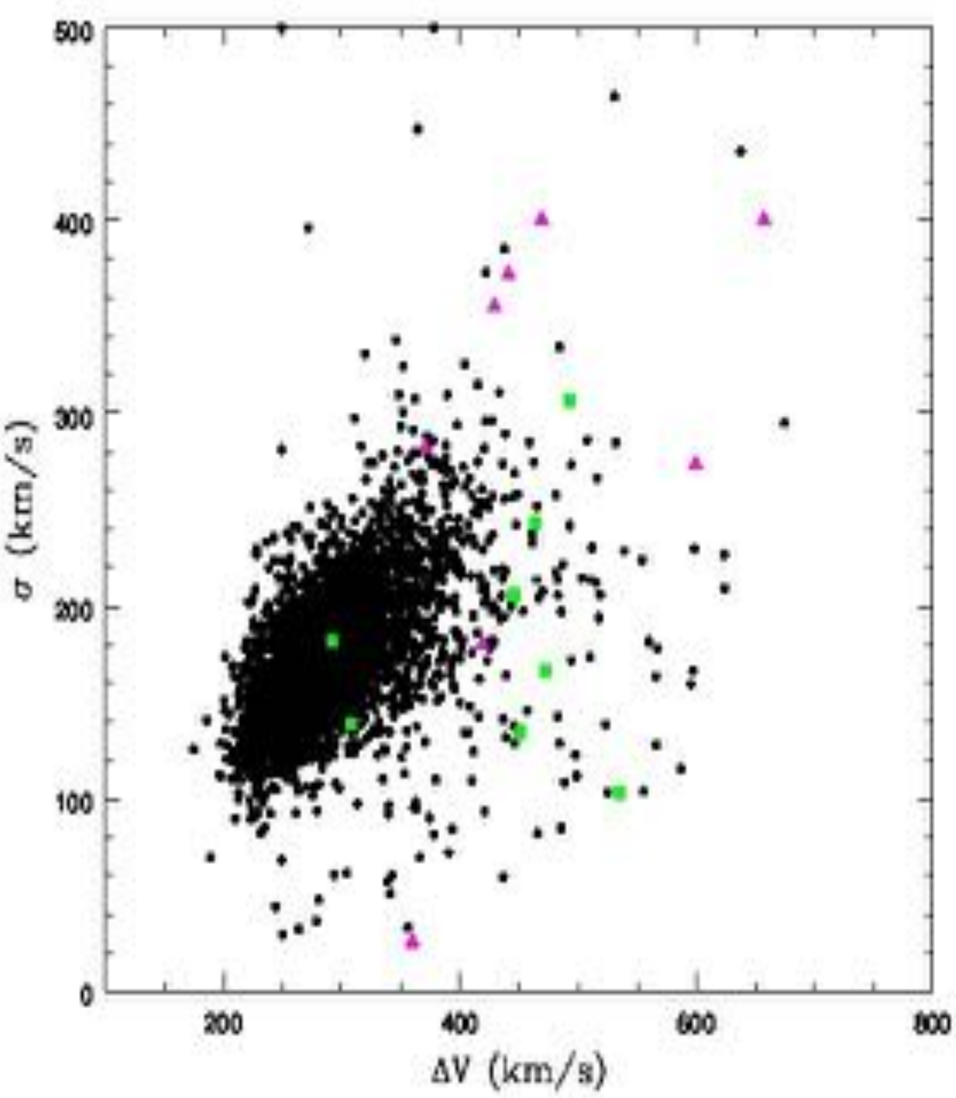
Muller et al 2015



McGruk et al 2015

Sample selection for VLA proposal : dual AGN in minor mergers

- We started with 3030 Double-peaked emission lines galaxies from Ge et al. (2012) choosing z<0.1.
- We plotted Δv vs σ where Δv is the Doppler separation of the [OIII] emission line and σ is the stellar velocity dispersion of the bulge.
- We selected outliers in Δv in the plot i.e those that had Δv > 400 km/s.
- All have radio detection in NVSS or FIRST survey.
- Disky in optical image.
- We selected 6 galaxies from Ge et al.
- To increase our sample, we also took 2 disky galaxies from Fu et al (2012) that radio emission.



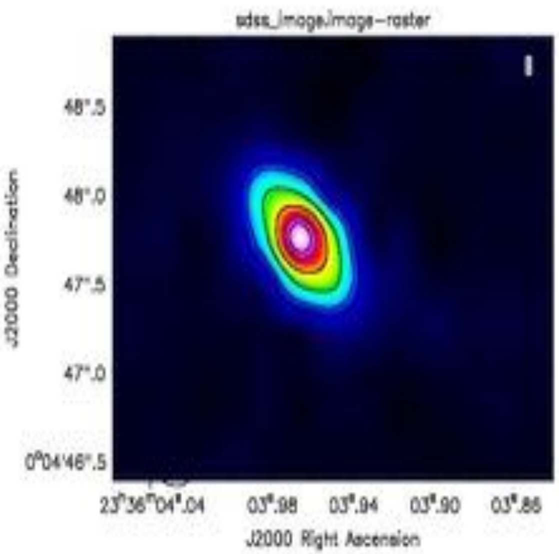
Observation

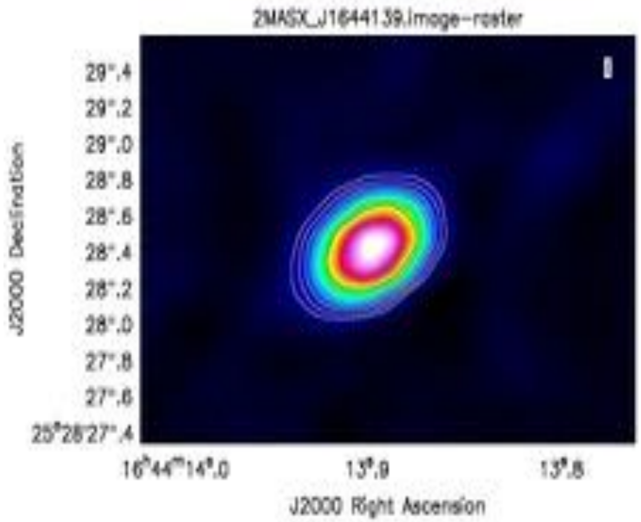
images.nrao.edu

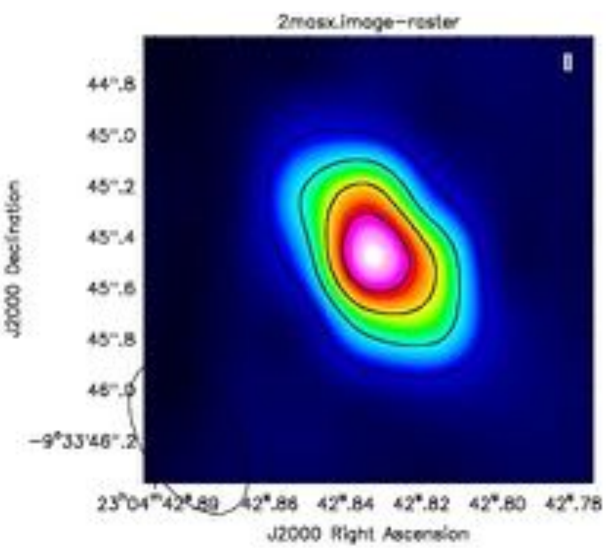
- Telecope: EVLA
- Frequency: 6 GHz
- Array: A
- Date of Observations: June, July 2015
- Expected Resolution :0.33''
- Data analysis with CASA

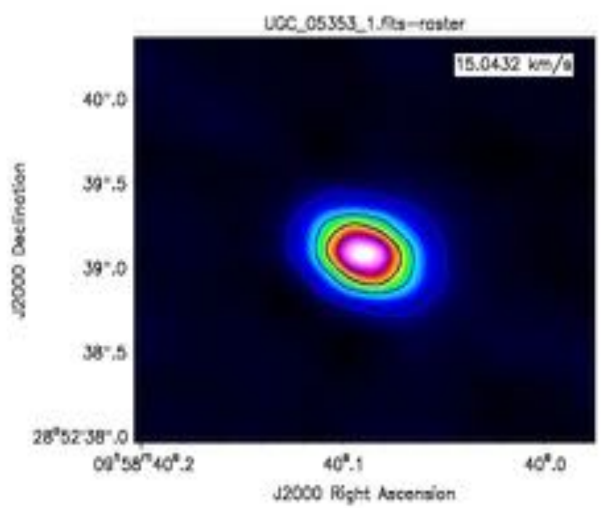
Results of EVLA 6 GHz Observations : Single Cores

Single Core Extended Structure galaxies

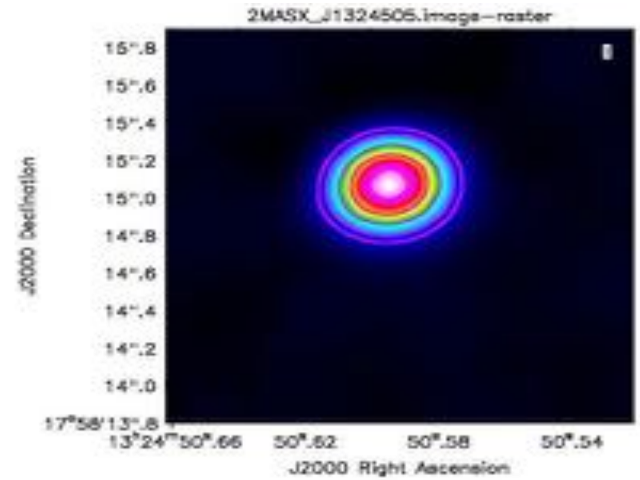


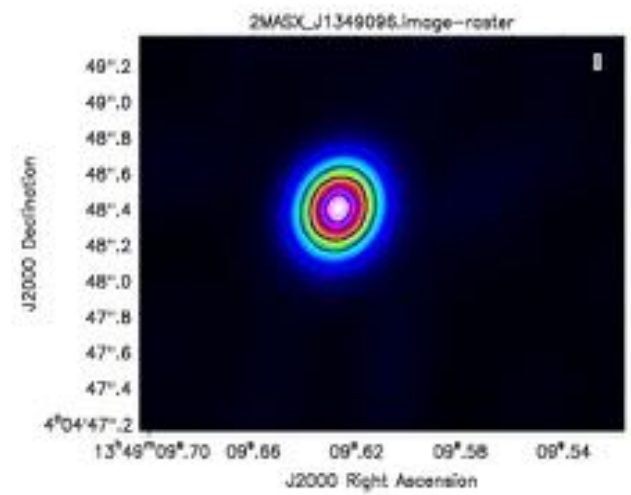






Single core Compact galaxies

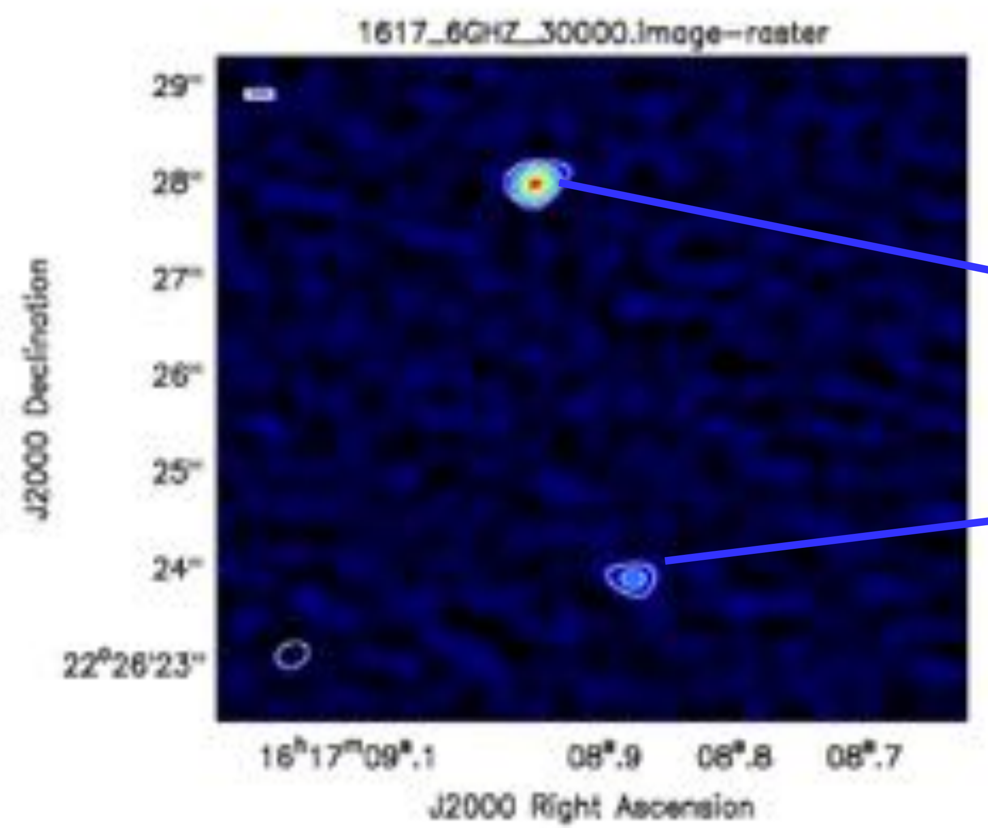




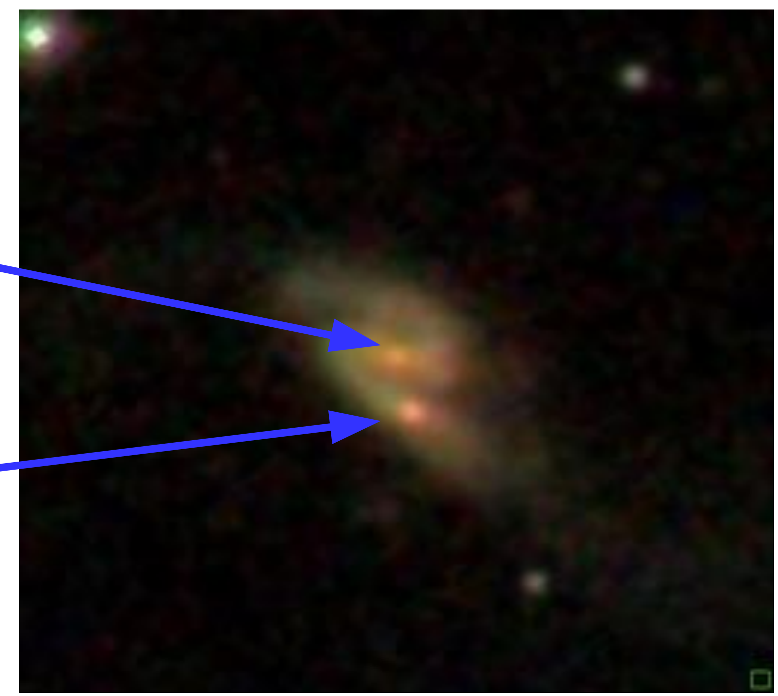
EVLA 6GHz Results : Dual Core galaxies

1. J1617: appears to be an ongoing minor merger

6 GHz radio image



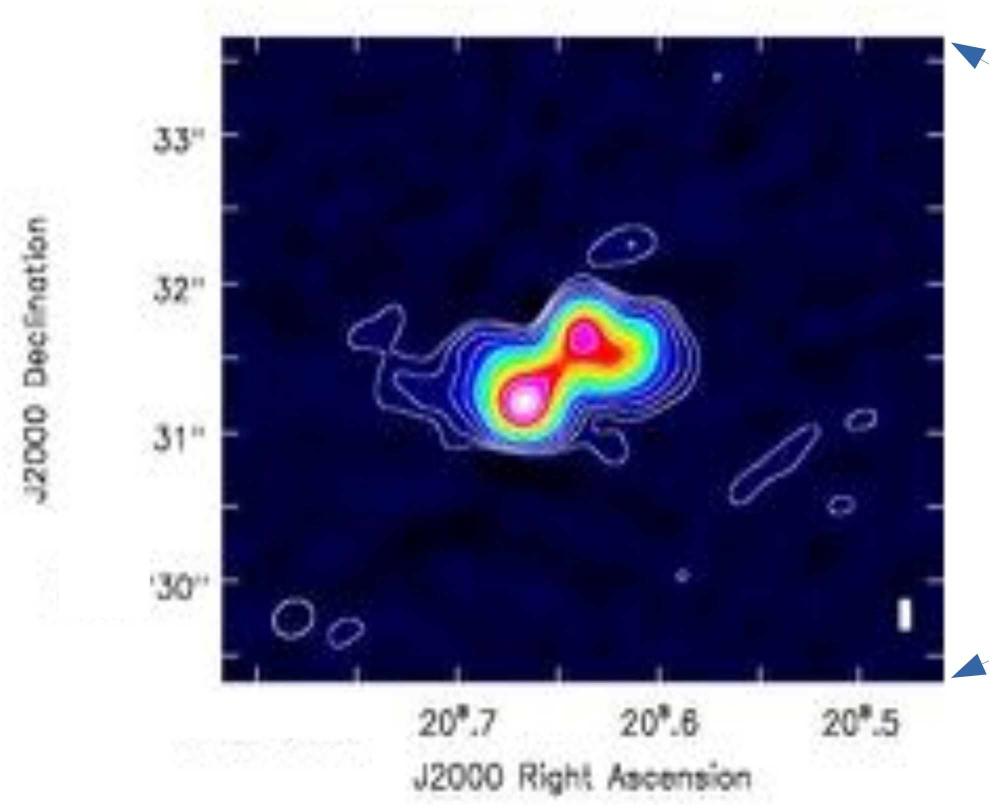
SDSS image

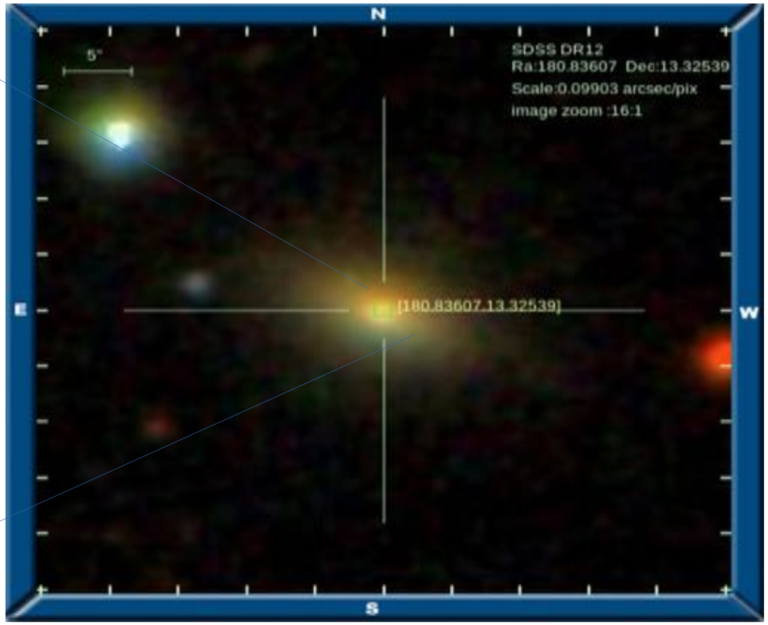


Separation: 5.6 kpc

Dual Core galaxies : with optical images

2. J1203 : Separation ~0.7kpc

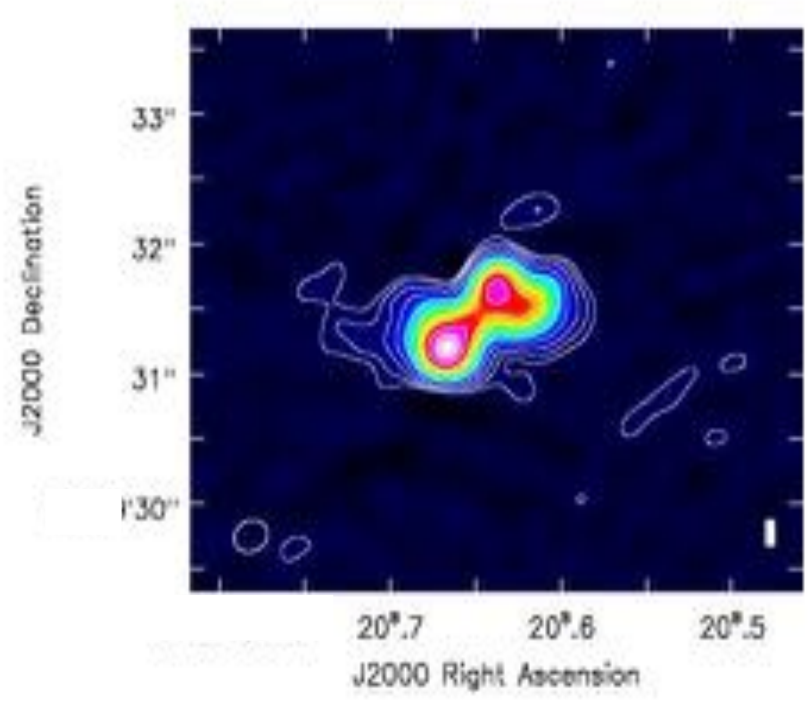




SDSS image

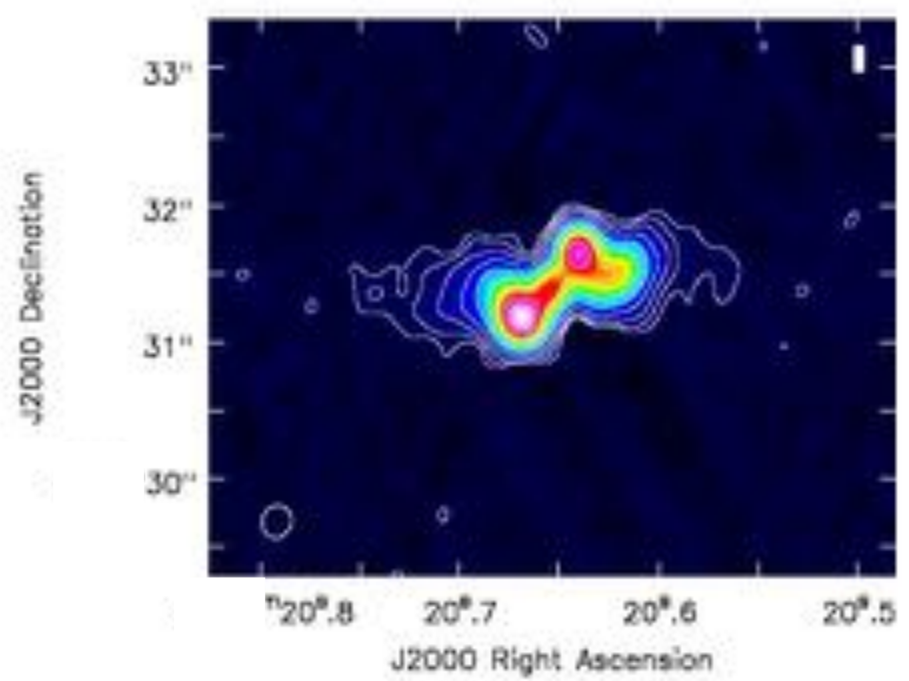
J1203 : Archival Data

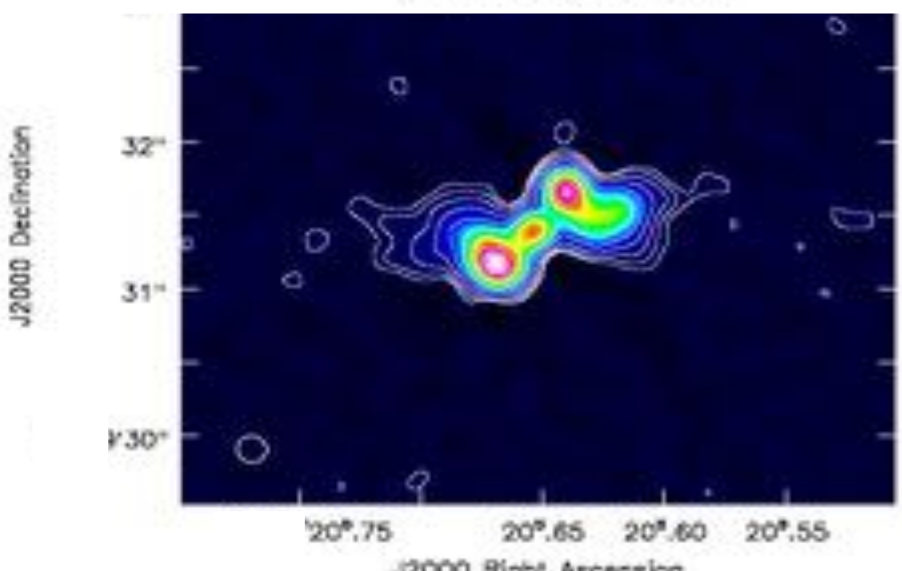
- We obtained EVLA archival data on the source J1203 (that showed two cores at 6 GHz) in October 2015.
- The archival data was X band data centered at 8.5 and 11.5 GHz at A array.
- We found that the source had an interesting structure and hence followed it up separately.



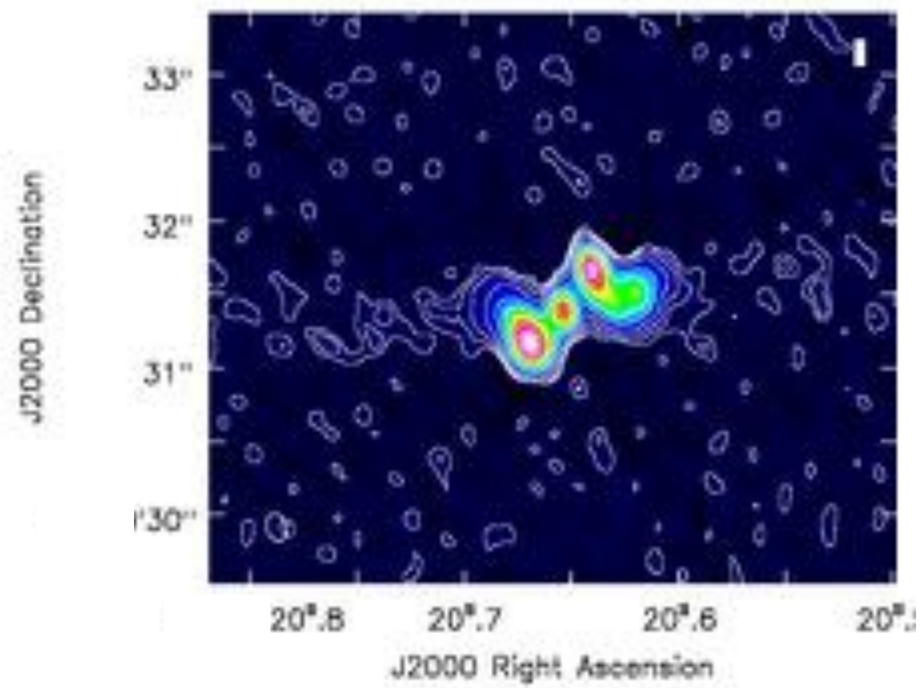
Archival data J1203

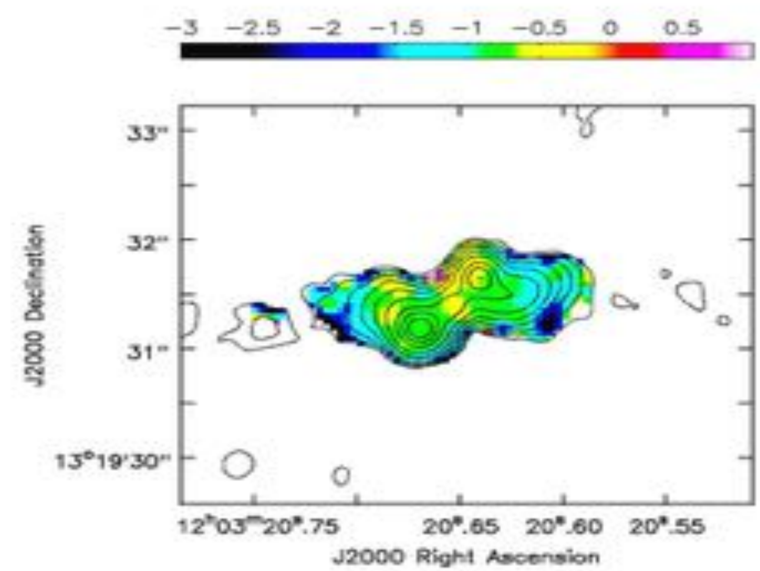
8.5 GHz images:



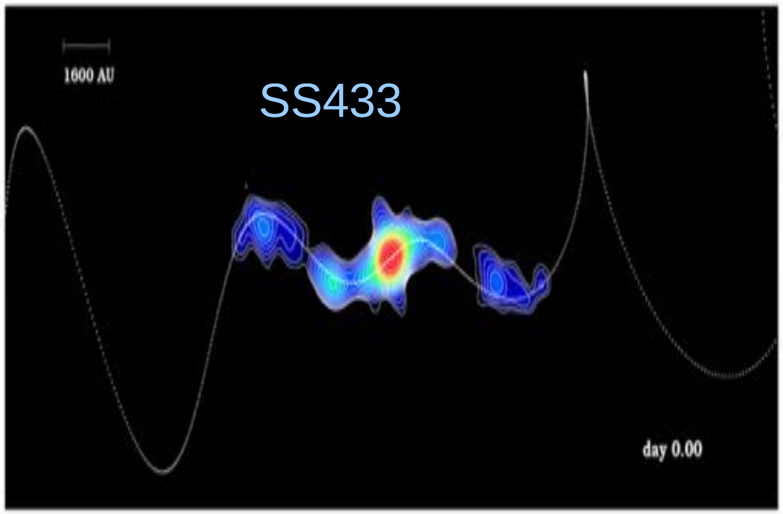


11.5 GHz images

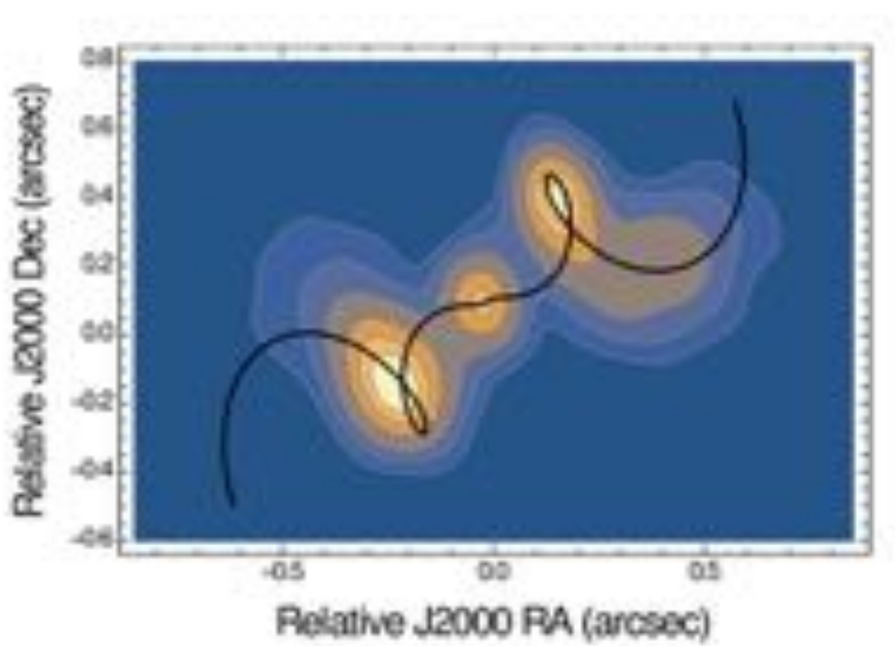




Modeling the S-shaped structure using jet precession



CREDIT: A. Mioduszewski et al., NRAO/AUI/NSF



We have modeled the S-shaped radio structure using the Hjellming & Johnston (1981) jet precession model. The model parameters are:

- Inclination angle (i)= $52^{0} \pm 5^{0}$
- Half opening angle (ψ) = $21^{0} \pm 2^{0}$
- Jet advance velocity= 0.023c
- Period = 10^{5} years
- Rotation angle (χ) = $33^{0} \pm 3^{0}$

Estimates of Lifetimes

- The lifetime of electrons from equipartition condition is $t \sim 2.1\times10^5$ yrs.
- We have calculated the age via spectral ageing analysis (Myers & Spangler 1985).
- Using 6-15 GHz spectral index map, age is $t > 1.3\times 10^5$ yrs.
- Using the jet extent and electron lifetime, the jet advance speed is $\beta = 0.023$.
- This matches the speed in the precession model.

What causes the precession in Radio Sources?

(i) Binary black holes orbiting each other producing precessing radio jets.
(ii) Warped accretion disks.
(iii) Instabilities in the radio jets (this may not always produce symmetric radio jets.

(i) We have calculated BH mass using M- σ relation.

- Velocity dispersion σ we have calculated using SDSS spectra and pPXF. It is 189 km/sec.

- The esimated mass is $(1.56 \pm 0.26) \times 10^8\ M_\odot$

- We have estimated the mass ratio using keplerian circular orbit.
-
- We have calcuated the separation using Begelman(1980).
  $P_{prec} \sim 600\ r_{16}^{5/2} (M/m)\ M_8^{-3/2}$ yr
- We have calcuated the separation to be ~0.02 pc.

Tilted accretion disk of a sinlge AGN

- Though binary models are interesting, a single AGN model can also explain the helical jet morphology.
- Lu (1990) suggested that a tilted accretion disk can also produce jet precession.
- There are few examples: 1946+708.
- We have used the period-luminosity relation from LU (1990).
- The calculated precession period is $\sim 10^5 - 10^9$ yrs.
- This timescale has large uncertainity but our jet precession model time esimate of $\sim 10^5$ yrs that was obtained precession model falls within this time range.

Origin of Double-peaked [O III] line

- The double peaked [O III] lines could be due to two SMBHs.
- we used the velocity separation Δv = 292 km s^{-1} of the [O III] emission lines.
- The calculated separation for M = 10^8 $M_\odot$ is ~ 8 pc.
- A precession period of 4.6 × 10^{11} yrs which is more than the Hubble time.
- So in the precession model it is not possible that a close binary is the origin of the double peaked emission lines.
- There is a dual system in which the precession has been induced during a close pass; in that case we cannot rule out the possibility that the DPAGN is due to two AGN.
- There is only a single AGN in which case the jet-ISM interaction is the probable origin of the double-peaked emission lines.

Detecting the dual/binary AGN in 2MASXJ1203

- Binary AGN at the separation of 0.02 pc: the separation is 18 microarcseconds in the sky, we cannot resolve the second AGN with current ground-based VLBI telescopes.
- A dual AGN system where a close pass of the secondary SMBH in the past has given rise to the jet precssion.
- A single AGN with a tilted accretion disk.
- Future higher resolution observations may help us if the SMBHs are at separation lying between $40 \leqslant d \leqslant 100$ pc.
- The second AGN does not have sufficient radio flux density.

Rubinur K et al.(2016), MNRAS accepted

Summary and Conclusion

- We observed 8 DPAGN with the EVLA at 6GHz. We have found 2 single compact cores, 4 extended cores and two dual core galaxies.
- We have done the follow-up observations for five objects at 15 GHz.
- **Results for J1203**
  - Our EVLA high resolution radio observations show that it has a S-shaped core-jet structure with core size 110 pc and jets that extend out to 3 kpc radius.
  - Our jet precession model gives a jet advance velocity 0.023c and precession period of 10^5 years:this matches the source lifetime estimated via spectral aging.
  - The presence of S-shaped precessing radio jets in 2MASXJ1203 can be due to binary/dual SMBH or a single SMBH with tilted accretion disk.
  - Double-peaked emission lines also can be due to binary/dual AGN or NLR kinematics of a single AGN.
  - While the binary/dual SMBH scenario is supported by several suggestions, we are unable to rule out other possibilities with the present data.

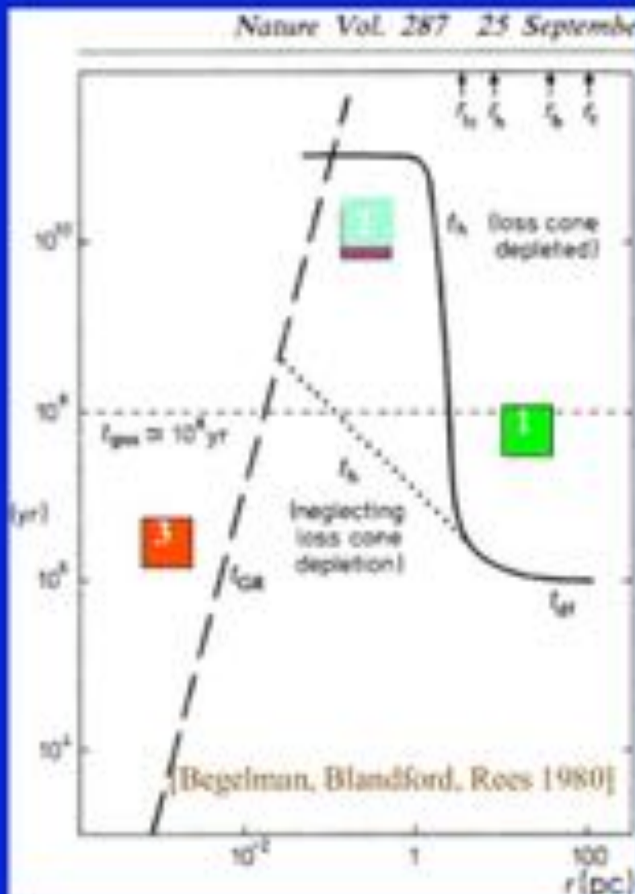
EXTRA SLIDES

Classification of AGN pairs

In the literature AGN pairs are loosely classified in the following way based on projected separation :

- *Dual AGN:*
- with SMBH separations of 100 pc -10 kpc.
- Most AGN pairs belong to this class.

- *Binary AGN:*
- with separations < 100 pc.
- They are often gravitationally bound SMBHs. Such systems are rare.



the two BHs evolve in 3 stages:

1: dynamical friction regime

in the early phase of merging of the two galaxies

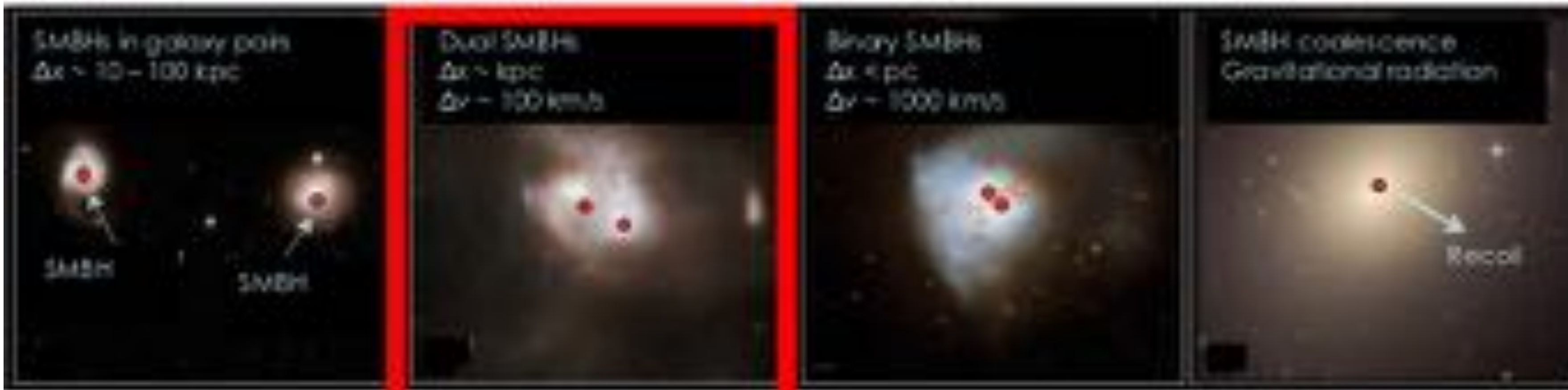
2: binary "hardening

the two SMBHs form a bound pair at separations of order 1 pc. Their orbit shrinks by interaction with gas/stars. Efficiency and timescale of shrinking are a field of active research; some binaries may stall for more than a Hubble time.

3: emission of Grav. Waves

at sub-pc separations, emission of GW leads to rapid orbital shrinkage and coalescence

Name	*z*	*Beam size*	*peak Flux in mJy*		*noise*	*total flux*	*Separation*		*Expected Morphology*
			Core 1	*Core 2*			″	*Kpc*	
2MASX J1617089+2226279	*0.065581*	*0.50″×0.37″*	*0.6*	*0.23*	1×10^{2}	*3.72*	*4.3*	*5.64*	*Dual core*
2MASX J1203206+1319316	*0.058423*	*0.42″×40″*	*15.26*	*12.07*	2.6×10^{2}	*337*	*0.54*	*0.748*	
2MASX J233604.04+000447.1	*0.032072*	*0.68″×0.38″*	*2.99*		2×10^{2}	*14.99*	–		*Extended Structure*
UGC 05353	*0.021088*	*0.55″×0.37″*	*3.5*		7×10^{2}	*31.97*	–		
2MASX J16441390+2528286	*0.055454*	*0.54″×0.37″*	*12.88*		3×10^{2}	*108*	–		
SDSS J23044283-0933454	*0.076531*	*0.66″×0.37″*	*2.1*		1×10^{1}	*9.8*	–		
2MASX J13490964+0404487	*0.079566*	*0.44″×038″*	*18.8*		3×10^{2}	*291*	–		*Single compact core*
2MASX J13245059+1758152	0.085935	0.41″×0.38″	3.8		1×10^{2}	57	–		



SMBHs in galaxy pairs

Thousands of confirmations

e.g., Hennawi et al. 2006, 2010; Myers et al. 2008; Shen et al. 2010; Liu et al. 2011; Koss et al. 2012; Ellison et al. 2013

Dual SMBHs

13 confirmations, many candidates

e.g., Barrows+, Bianchi+, Comerford+, Fabbiano+, Fu+, Ge+, Gerke+, Greene+, Hudson+, Komossa+, Koss+, Liu+, Mazzarella+, McGurk+, Rodriguez+, Rosario+, Shen+, Shields+, Smith+, Tingay+, Wang+

Binary SMBHs

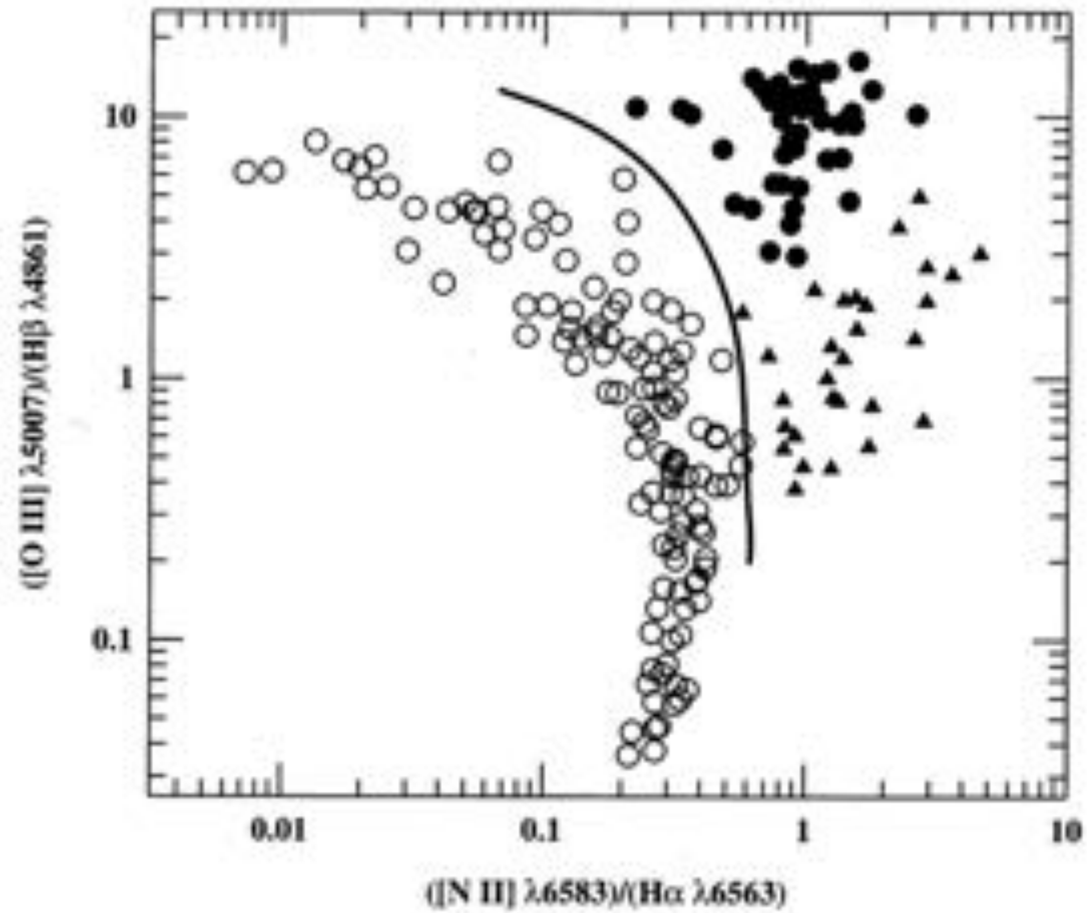
No confirmations yet, many candidates

e.g., Gaskell 1983, 1984; Valtonen et al. 2008; Bogdanovic et al. 2009; Boroson & Lauer 2009; Dotti et al. 2009; Decarli et al. 2010; Burke-Spolaor 2011; Tsalmantza et al. 2011; Eracleous et al. 2012; Ju et al. 2013; Shen et al. 2013

Recoiling SMBHs

No confirmations yet, several candidates

e.g., Komossa et al. 2008; Shields et al. 2009; Comerford et al. 2009; Civano et al. 2010, 2012



10
1
0.1
0.01
0.1
1
10
([O III] λ5007)/(Hβ λ4861)
([N II] λ6583)/(Hα λ6563)