Multi-wavelength studies of Zwicky's Nonet

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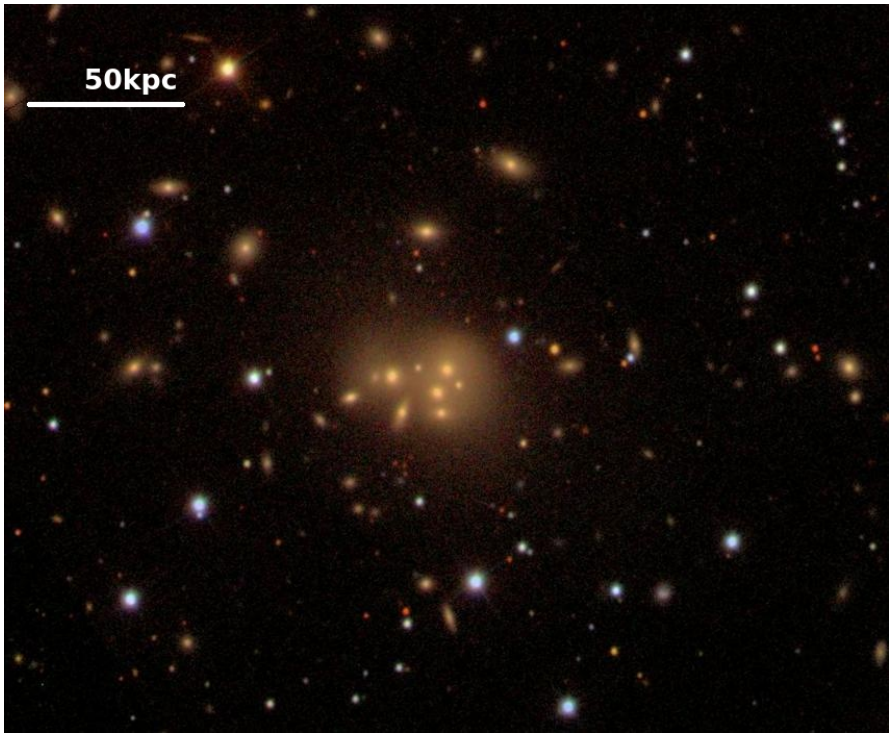
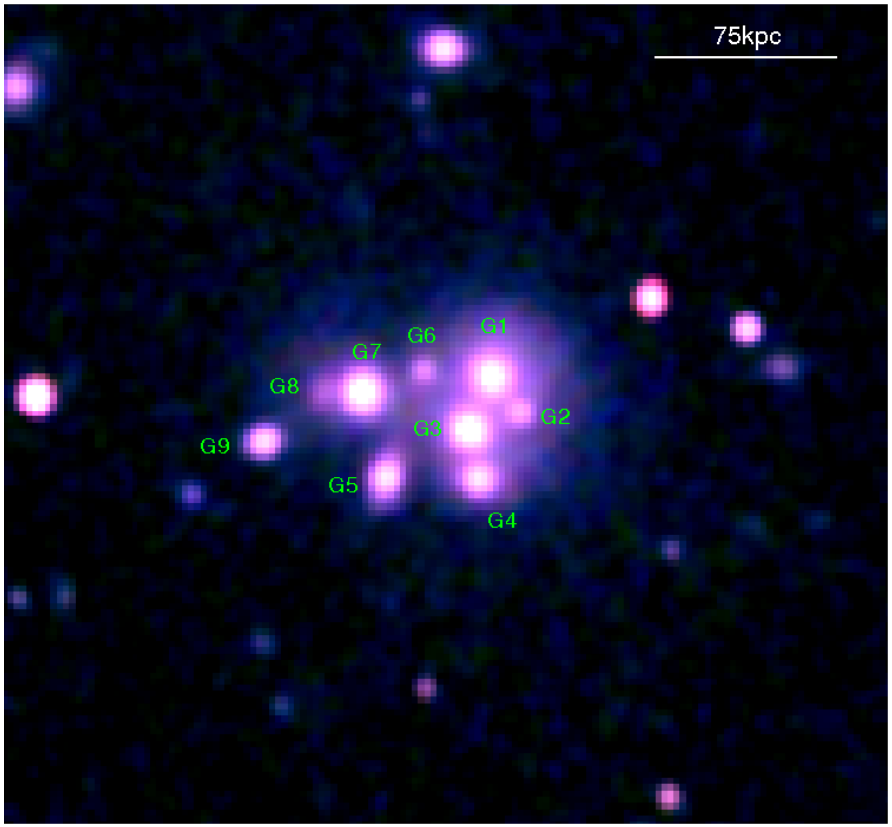
Zwicky's Nonet

- Abell 407 is a galaxy cluster at a redshift of 0.047, listed in the Abell catalogue of galaxy clusters . The optical image of the central region of this cluster from Sloan Digital Sky Survey (SDSS) shows a complex ensemble of at least nine galaxy like condensations within a region 1 arc min across ($\sim$ 50 kpc), embedded within a low surface brightness, diffuse stellar halo.



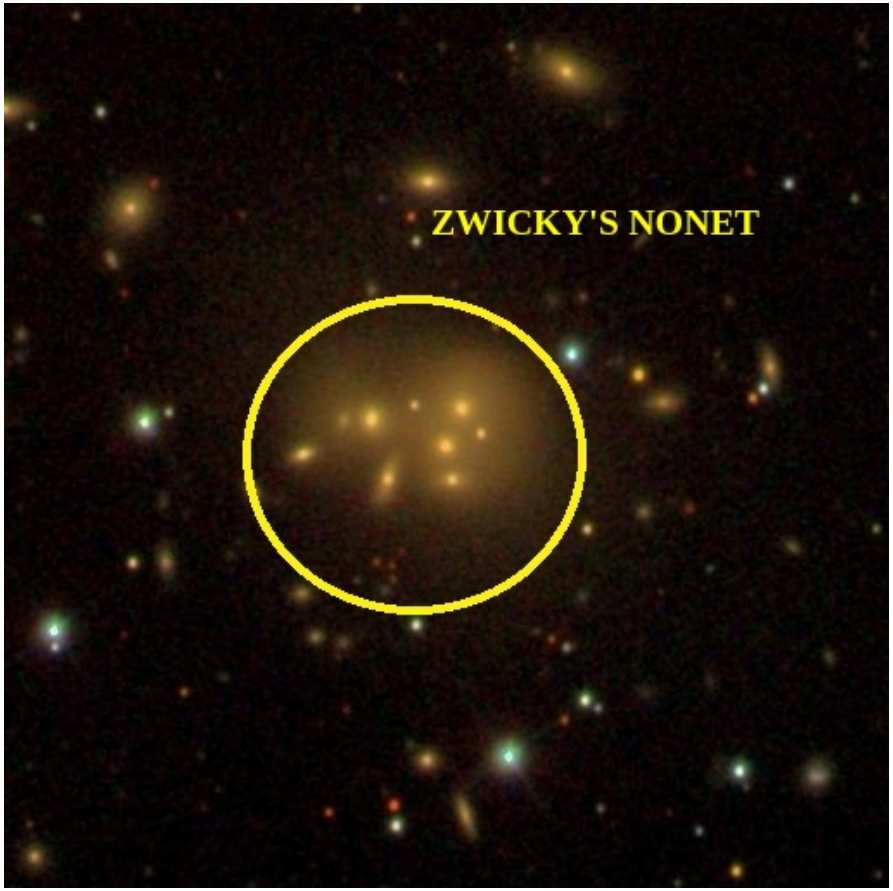
Zwicky's Nonet

- The central nine galaxies, embeded within an extensive, diffuse stellar halo have redshifts ranging from 0.046 to 0.049.
- Seven galaxy pairs in this region are separated by less than 10 kpc in projection.



Zwicky's nonet

- Fritz Zwicky in 1971 identified the central multiple nuclei system of A407, as a poor cluster V Zw 311. (z=0.047).
- Biju et al.(2017) proposed a name 'ZWICKY'S NONET' to this group of nine galaxies, honouring Fritz Zwicky, who discovered this galaxy group.
- Schneider and Gunn (1982) studied this galaxy group and proposed that this would result in the emergence of a cD like galaxy in about 2 billion years **(Schneider & Gunn,1982)..**

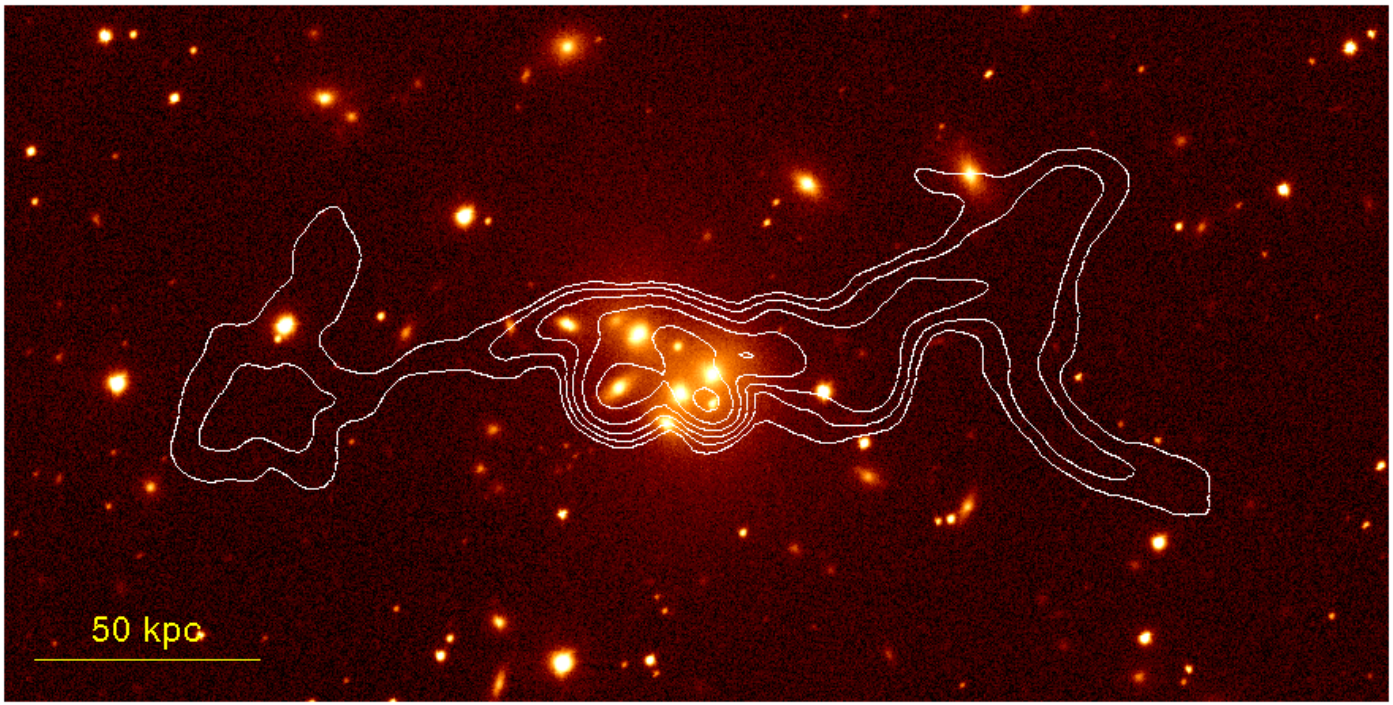


Radio Observations of Zwicky's nonet

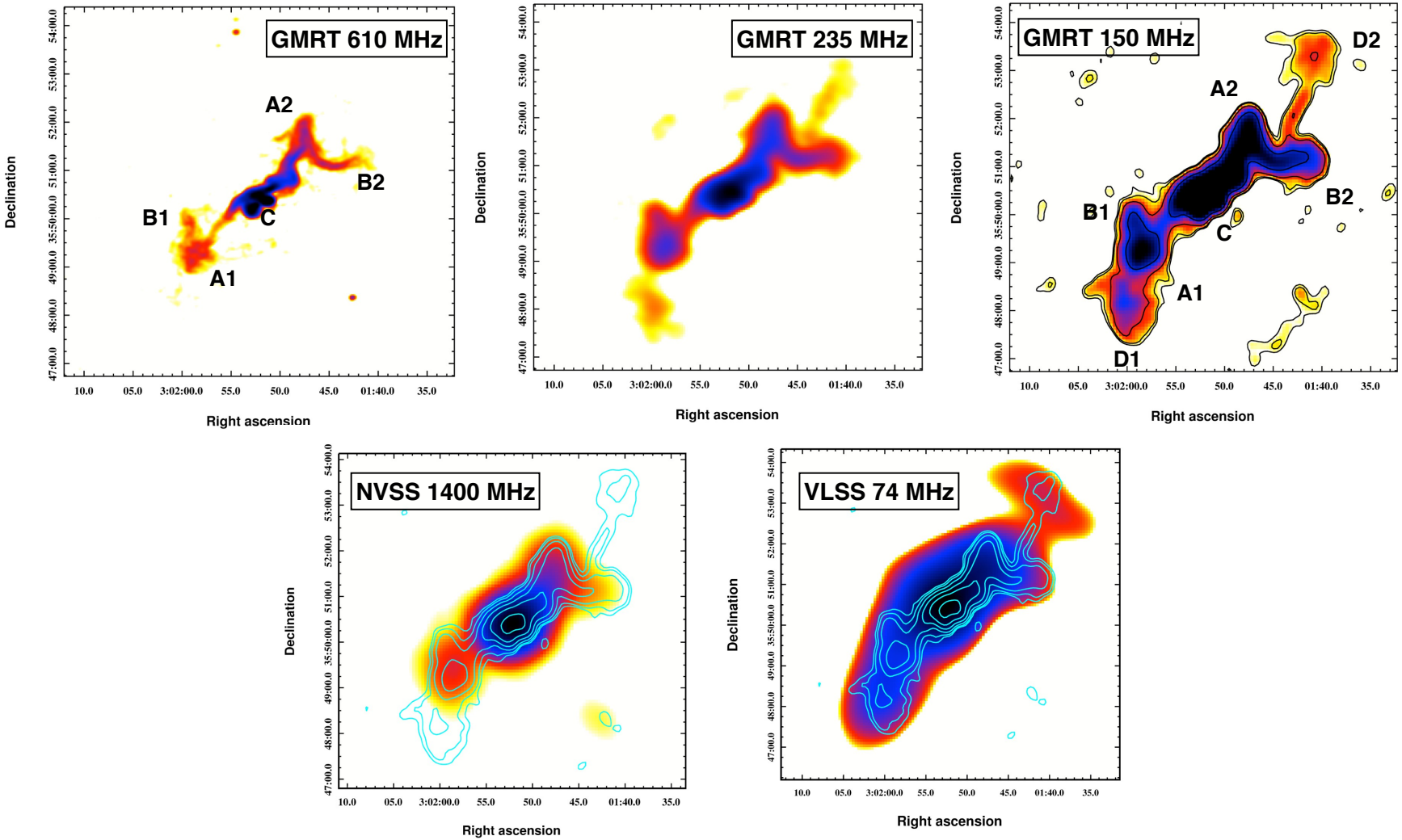
- We have observed the radio source 4C 35.06 hosted by the Zwicky's Nonet using GMRT at the following frequencies.
- 610MHz
- 235 MHz and
- 150MHz

Radio Observations of Zwicky's nonet

- GMRT 610 MHz radio contours of 4C 35.06 is plotted over the Optical i-band SDSS image of A407 cluster. The 610 MHz radio image of 4C 35.06 is having 5 arcsec^2 resolution.
- The 610 MHz radio image shows a peculiar helical morphology.
- It as a prime target for studying astrophysical processes related to AGNs and black holes in dense merging groups.



Results: Radio observations

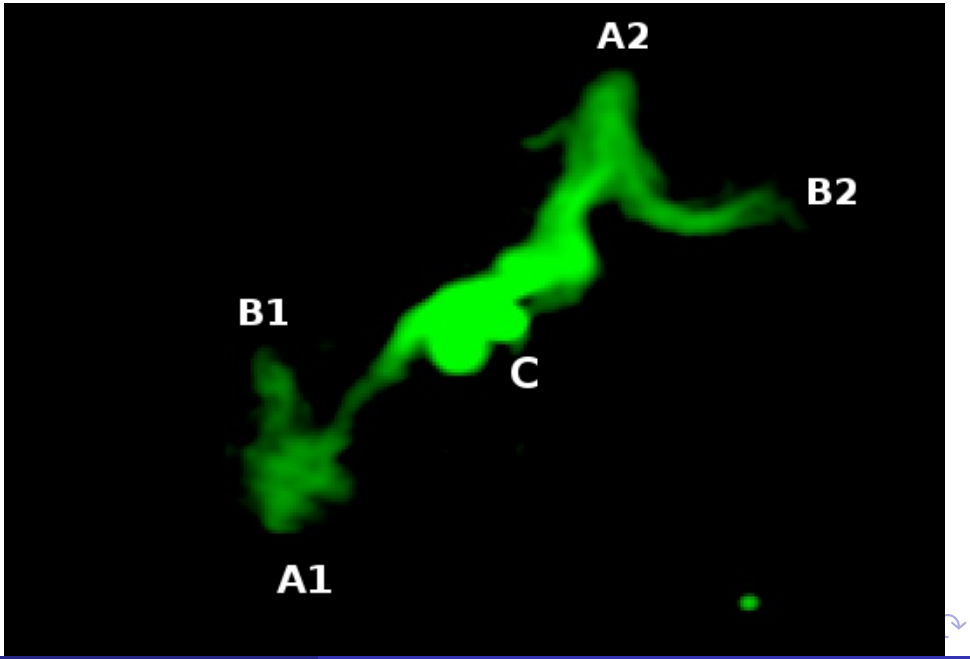


Results: Radio observations

- The linear size varies from $\sim$ $230kpc$ at 610 MHz to $\sim$ $400kpc$ at 150 MHz, suggesting extended emissions at lower frequencies.
- The flux densities are 1.7Jy at 610MHz, 4.7Jy at 235MHz and 6.0Jy at 150MHz.

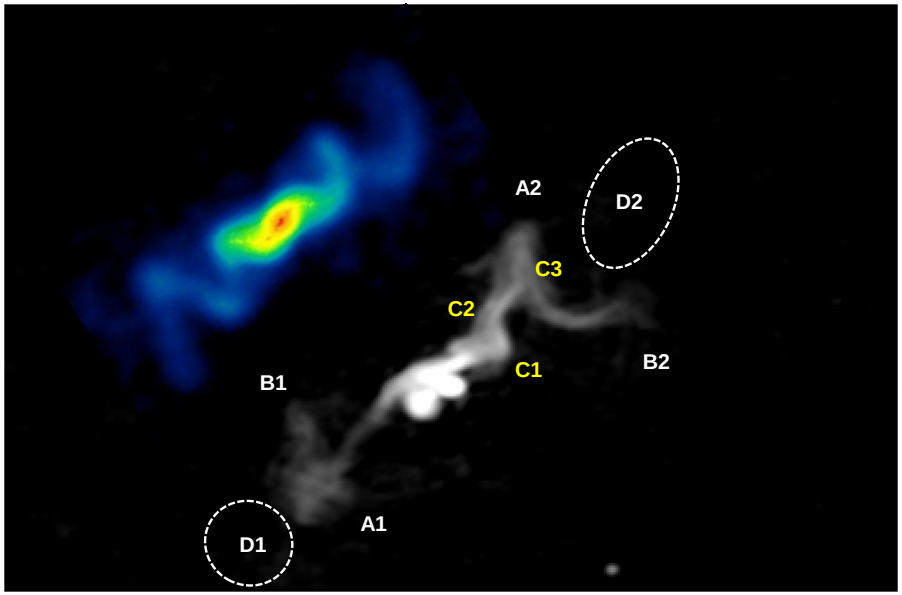
Results:Jet Precession

- Here the bipolar jet twists helically, inversion symmetric fashion, on either sides of the core C at the points marked A1 and A2.
- The N-W arm of the jet is observed to be more brighter, bending in to a prominent loop/arc from A2 to the point B2.
- Similar feature from A1 to B1 is seen in S-E arm as well, but relatively fainter and diffused compared to north western counterpart.
- This difference appears to be due to projection effects making western loop more prominent on the sky plane.Eastern loop possibly be oriented more along the line of sight away from the observer.



Results: Jet Precession

- The large scale jet structure in 4C 35.06 is analogous to that of SS 433, if we ignore the kinks (C1, C2 and C3) for the time being.
- The loop portions A2 to B2 and A1 to B1 are suggestive of the cork-screw pattern as a result of the continuous change of the jet axis due to the possible precessing motion of jet-ejection-nozzle coupled to the accretion disk.
- Also no flat spectrum terminal hot spots are found in the jet extremities, which is another indication for the continuous shifting of the jet direction.



Results:Jet Precession

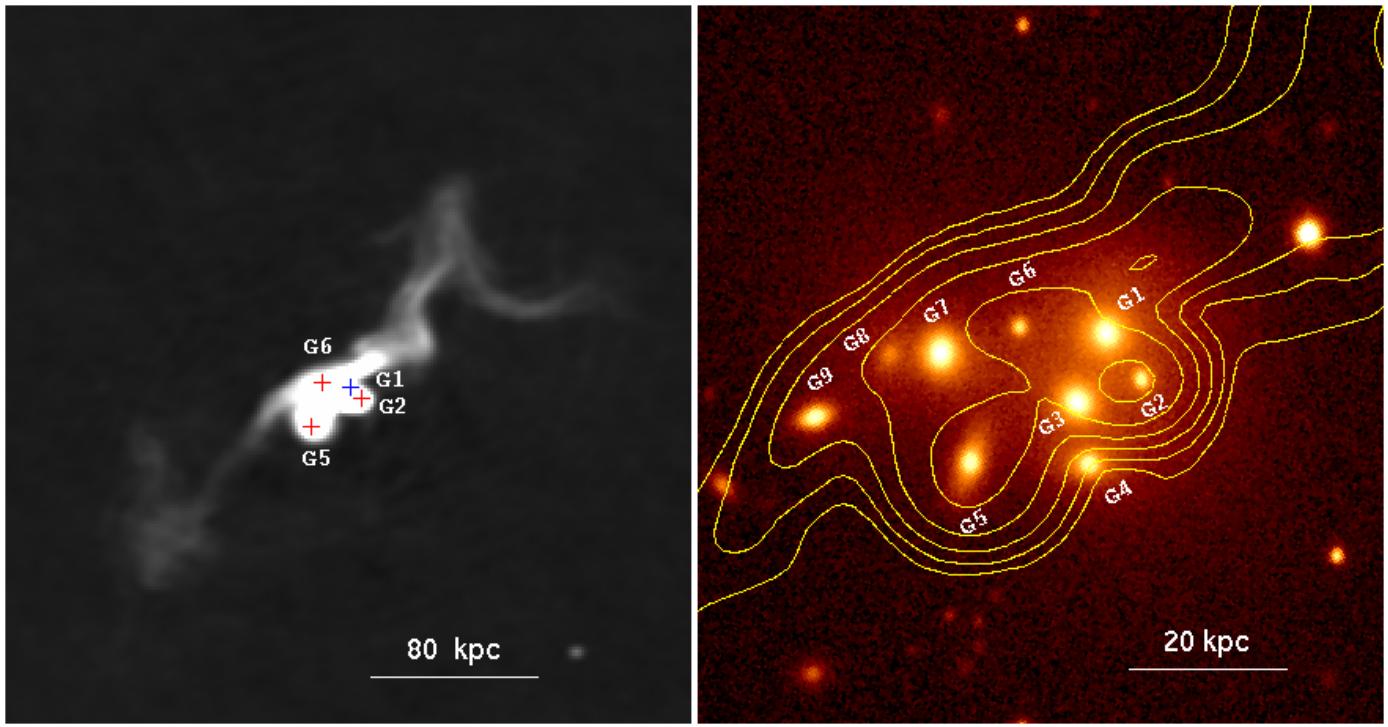
- Two possible mechanisms for Jet precession (a) Binary black hole model **(Begelman et al.1980,Tateyama & Kinham 2004)**, and (b) Lense- Thirring effect **(Bardeen & Peterson, 1975;Liu & Melia,2002)**.
- In the binary black hole model, The accretion disk of the AGN can be precessed by the torque exerted by the companion black hole. This precession of the accretion disk will lead to jet precession .
- Here the closeness of the galactic members and the rotationally symmetric helically modulated large scale jet structure together suggests this site ideal for the search of a binary supermassive black hole system **(Deane et al.2014; Begelman et al. 1980)**.

Results: Jet Precession

- The lense-Thirring effect comes in to play when the spin angular momentum of the blackhole is misaligned with the angular momentum of the accretion disk.
- We have estimated the precession time scale of the jet system **(Hongsu Kim & Yangwan.,2015)** for a black hole of mass $10^8 M_\odot$, with different values of specific angular momentum 'a' and Bardeen peterson radius r_{BP}.
- Bardeen peterson radius (r_{BP}) to be 10^2 *to* 10^3 (Mutiplication Factor 'F') times the schwarzschild radius R_s . **(Bardeen & peterson,1975,Scheuer & Feiler,1996;Shan-Jie Qian et al.,2014).**
- The precession time scales obtained are $\sim 10^5 years$ (with 'a'=0.1 and $F = 10^3$) and $\sim 10^8 years$ (with 'a'=0.1 and $F = 10^4$).
- The precession time scale matches with radiative age of the relic plasma ($\sim 10^8 years$) only at very low 'a' (~ 0.1) and high r_{BP} ($\sim 10^4 r_s$).

Results:Core of the radio source

- The radio peaks falls on the galaxies G2,G5 and G6.
- Here only one galaxy,G6 is aligned with the jet axis, which is a fainter member of the group.
- G6 appears as hosting the radio jets.

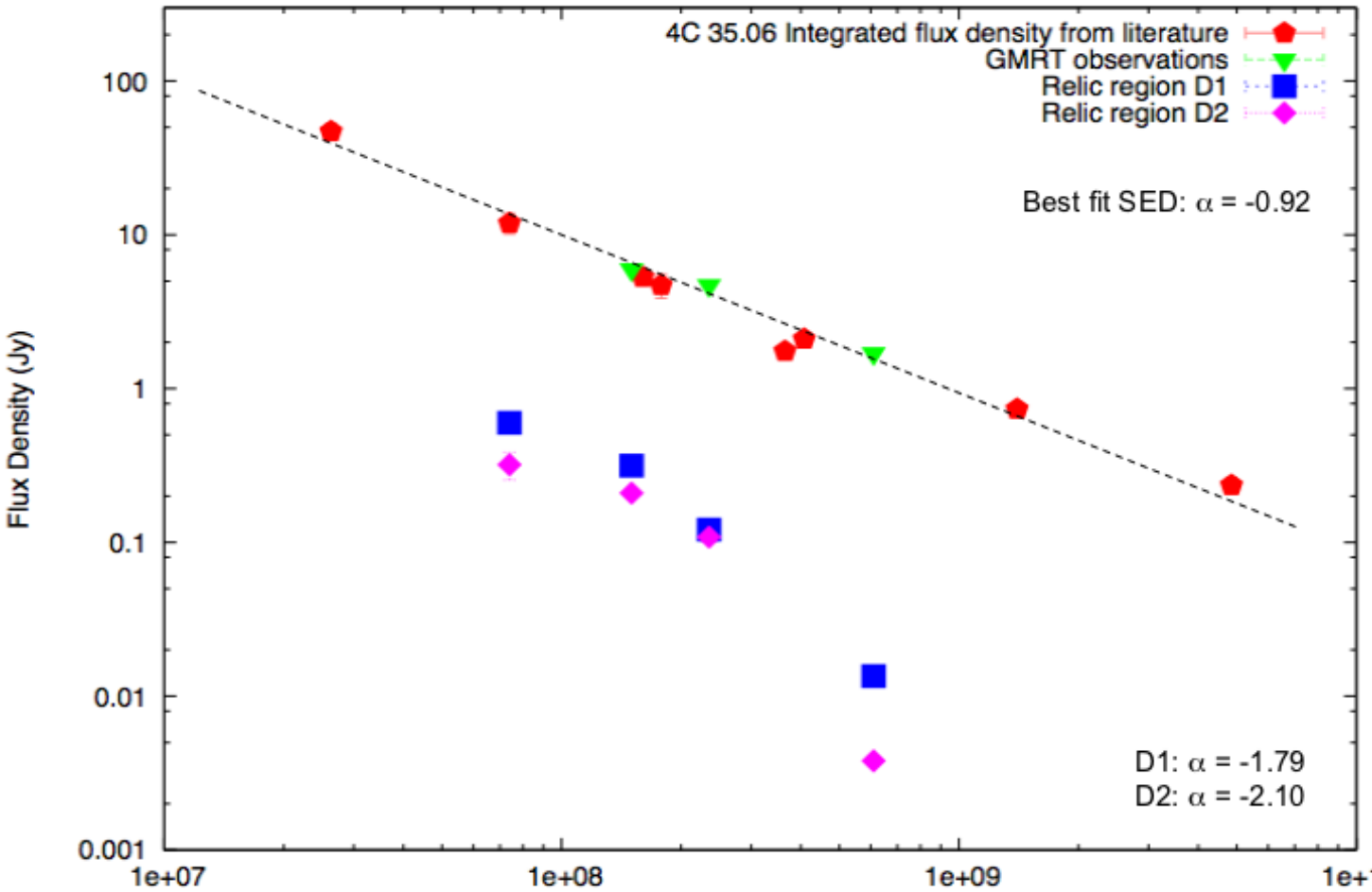


Results:Core of the radio source

- The Spectroscopic analysis gives a velocity dispersion of 143 kms^{-1} for G6, which yielded a black hole mass of $(0.52) \times 10^8 M_\odot$.
- But it is a possibility that this now faint galaxy has been stripped off the majority of its outer halo stars in multiple tidal encounters while still retaining a massive black hole and a dense stellar core near the centre.
- This is possibly also reflected in even smaller black hole mass of $(0.15 \pm 0.07) \times 10^8 M_\odot$ derived from its K-band magnitude $M_K = -21.16$

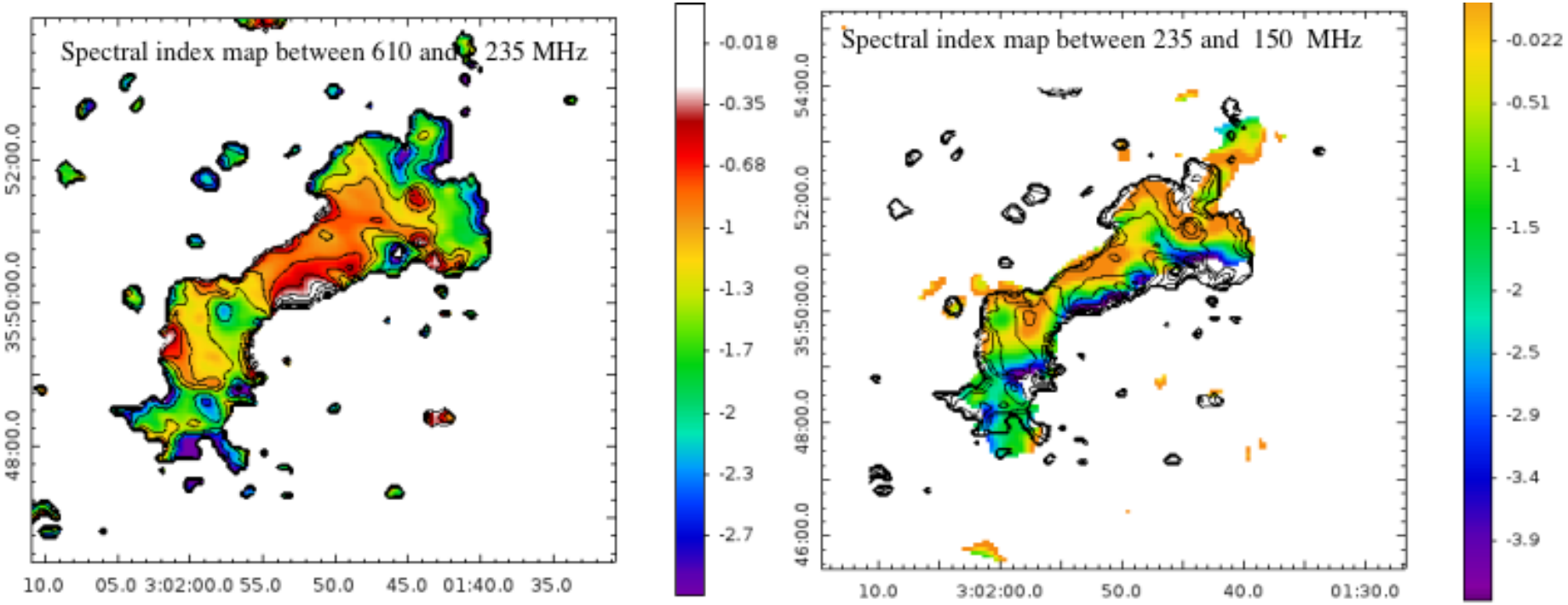
Results:Integrated spectra

- The integrated spectra shows a steep spectral index of -0.92 from 4.9 GHz down to 26 MHz. The spectral indices for the diffuse outer regions D1 is -1.79 and for D2 is -2.10 (ultra-steep).



Results:Spectral index map

- Left panel: spectral index map between 610MHz and 235 MHz; Right panel: spectral index between 235MHz and 150 MHz.
- The outermost regions show very steep spectral index (~ -2.5)

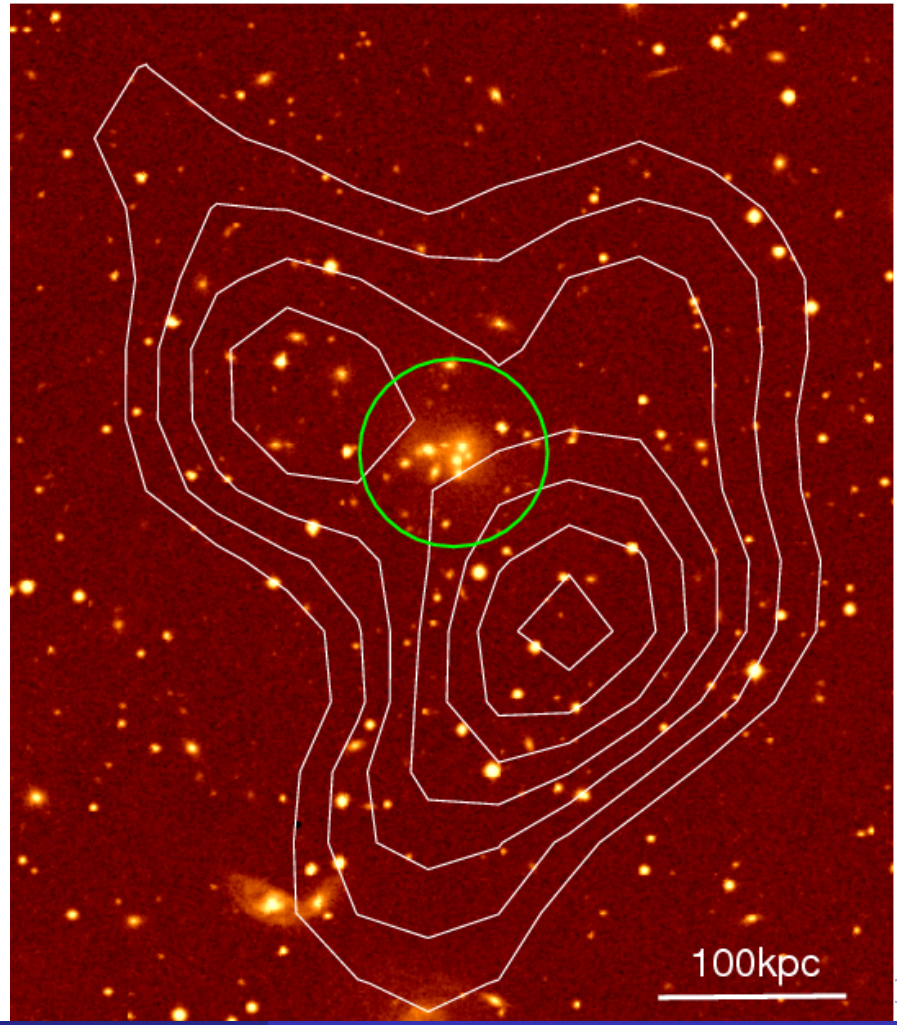


Results:spectral Index studies

- Spectral index studies conveys information about the energy gain and loss processes in the emission regions of the source.
- The extremely steep spectral nature of both D1 and D2 regions suggests that the radio emission originates from an ageing (relic) plasma subjected to strong energy losses.
- The central region of spectral index map shows flat spectrum, possibly due to superposition of emission from a few radio emitting galaxies.
- The spectral index became steeper on moving away from the center, upto the outer most extremities of the jet.
- This indicates that there is no fresh injection of accelerated particles in the relic regions, and hence the extreme steepness of the spectra therein.

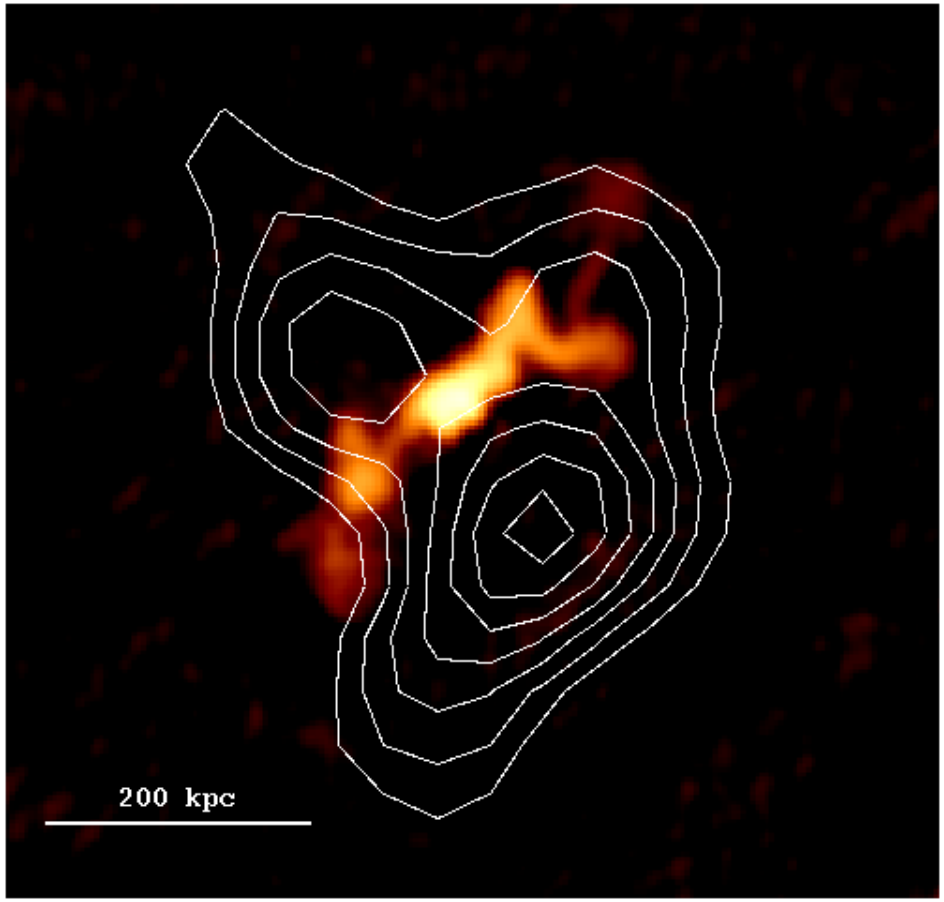
Zwicky's nonet: X-ray detcetion

- This is detected in the Rosat All Sky Survey (RASS), using the Position Sensitive Proportional Counter (PSPC) with an X-ray Luminosity of $3.167 \times 10^{43} ergss^{-1}$ in the 0.1-2.4 keV band(Bauer et al. 2000).
- In dynamically active clusters and merging clusters, there is a significant offset between the X-ray centroid and the position of BCG (Rykoff 2008).
- Mann & Ebling(2012) found that in very extreme cases of acive mergers the offset between X-ray peak and BCGs are more than 42



Results:Zwicky's nonet: X-ray detcetion

- The radio jets and lobes can influence the dynamical state of a system. In radio sources, the X-ray surface brightness along the jets and lobes are found to be very small.
- This suggests that the radio jets and lobes are capable of uplifting and displacing the thermal gas from the jet flow direction. (Carilli, 1994).
- Here the energetic jet system of 4C 35.06 has possibly affected the ambient X-ray medium by uplifting and displacing the gas along the mean jet flow



Optical spectroscopic Observations of Zwicky's Nonet.

- We have taken the spectra of the 5 members of the Zwicky's Nonet in grism 7 & grism 8 using IGO covering a wavelength range from 3700 to 8500.
- The spectra of the 3 faint members are taken using 200 inch Palomar Hale telescope.

Results: Optical spectroscopic observations.

- There is no AGN signatures or star forming activity in the optical spectra of these central galaxies.
- The spectra of all the eight galaxies resemble that of passive, early type red ellipticals.
- The small Hα luminosity shows that possible AGN in the system are of low-luminosity active galactic nuclei (LLAGN/LINER).

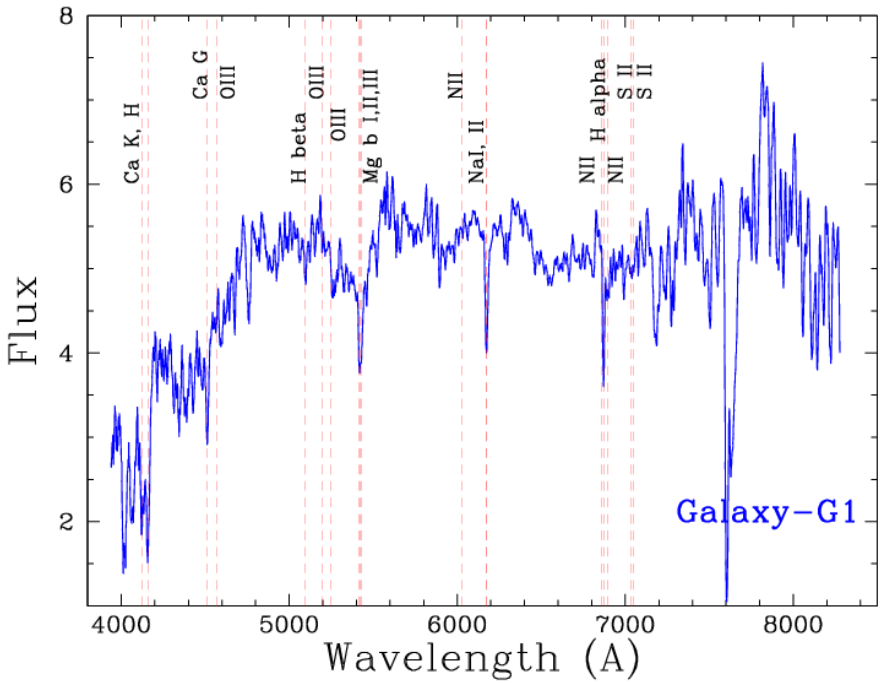


Figure: The spectrum of galaxy G1 taken from IUCAA Girawaly Observatory (IGO).

Results: Optical spectroscopic observations.

- Optical emission lines are found to be absent in many AGN showing radio emission and large scale radio jets.
- Also in many FRI radio sources in galaxy clusters are hosted by galaxies showing very weak or no optical emission lines .
- The galaxy G6 which can be the most possible AGN host is also showing any emission lines.

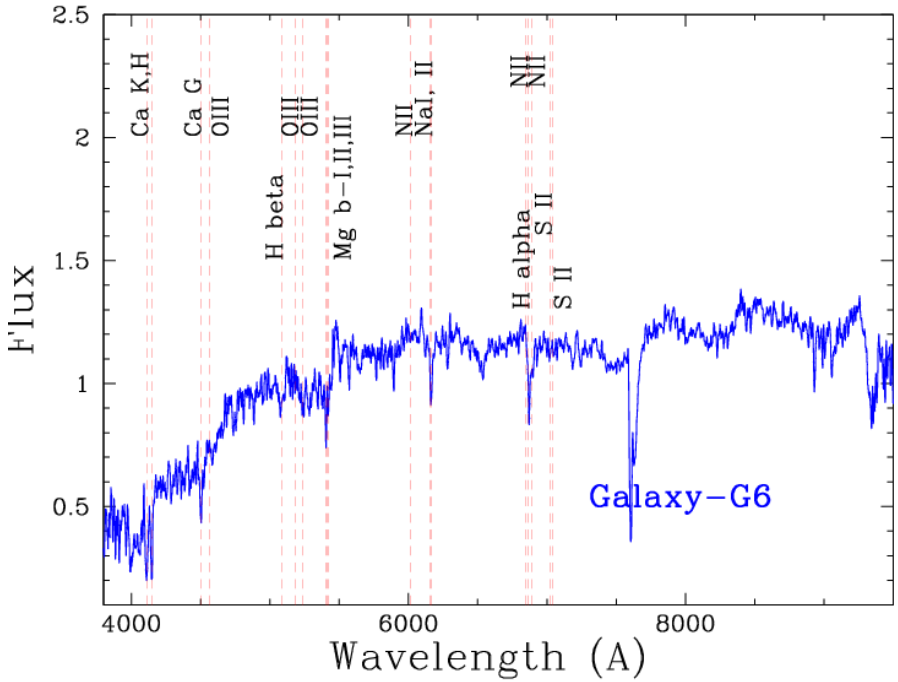
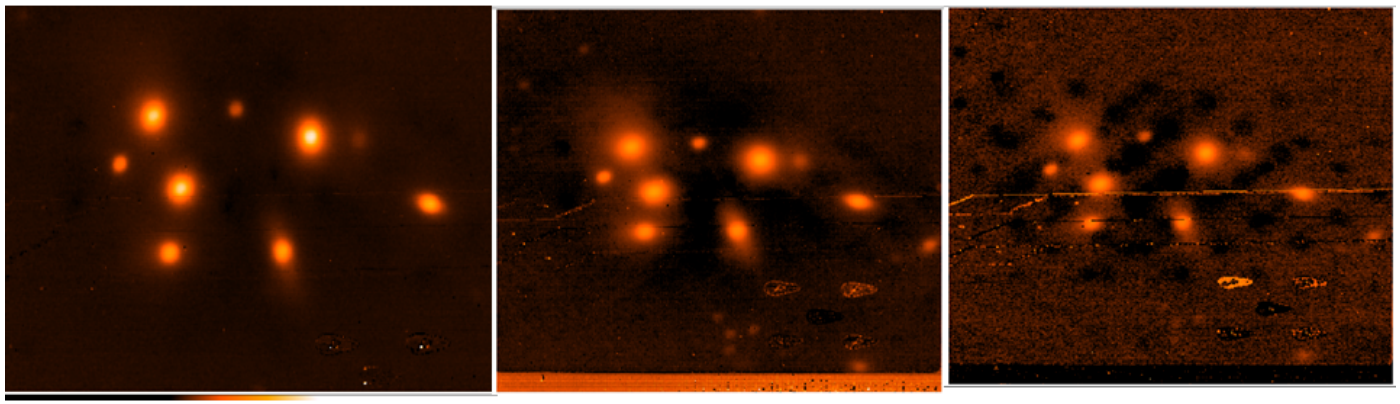


Figure: The spectrum of galaxy G6, the possible AGN host, taken from 200 inch Palomar Hale Telescope.

Devasthal Optical Telescope (DOT) observations

- Zwicky's nonet is imaged with DOT at IR bands J, H and K with $\approx$ 45 minutes exposure in each band.
- The analysis is in progress and the images in the three bands are shown below. Sagar Sethi (Project student, IUCAA) is currently working on this Data.



Images in J, H and K bands.

Summary

- The helical morphology is an indication of large scale precession which may be due to a binary black hole system or due to Lens-Thirring effect.
- It is an ideal case for studying the formation and evolution of SMBHs in cD galaxies.
- The extremely steep spectrum at the (α = -1.7 to -2.1) relic radio plasma (spectral age of 80$-$210 My),suggests that these radio emissions are from older plasma.
- Such AGNs in ultra steep spectrum relic systems are very rare and form an interesting population for understanding the life-cycle of releativistic jets.

Collaborators

- Joydeep Bagchi (IUCAA,Pune, India)
- Joe Jacob (Newman College,Kerala,India)
- Pratik Dabhade (IUCAA,Pune,India)
- Ishwara Chandra C.H. (NCRA,Pune,India)
- Sagar Sethi,(Project Student,IUCAA, India)
- Santosh Joshi (ARIES, India)
- M. Pandey-Pommier (Centre de Recherche Astrophysique de Lyon-Observatoire de Lyon, France)
- Sunil Kumar P (Govt. College,Perinthalmanna,India)
- Sheelu Abraham (IUCAA,India)
- M. Vivek (University of Utah,USA)
- Ashish A. Mahabal (Caltech)
- S. G. Djorgovski (Caltech)


THANK YOU