# GMRT Observing Application

**CYCLE 15 DEADLINE: Monday, July 07, 2008**
INSTRUCTIONS: Each numbered item must have an entry or N/A or NA
SEND TO: GMRT Time Allocation Committee, NCRA–TIFR,
Post Bag 3, Ganeshkhind, Pune 411 007, INDIA
Email: gtac@ncra.tifr.res.in

Proposal Code:

Received:

**(1)** Date of preparing this application: 06 July 2008

**(2)** Title of Proposal: The enigmatic cluster CL0910+41- the connection between AGN activity and star formation



| (3) AUTHORS† | INSTITUT ION | Will come to GMRT? | Email (needed for PI & Co-PIs) | Nationality * |
|---|---|---|---|---|
| RAYCHAUDHURY SOMAK | U. Birmingham, UK | Yes | somak@star.sr.bham.ac.uk | India |
| Hoekstra Henk | U. Victoria, Canada | | hoekstra@uvic.ca | |
| Bildfell Chris | U. Victoria, Canada | | bildfell@uvic.ca | |
| Mahdavi Andisheh | U. Victoria, Canada | | amahdavi@uvic.ca | |
| Giacintucci Simona | Harvard-Smithsonian CfA, USA | | sgiacint@head.cfa.harvard.edu | |
| Babul Arif | U. Victoria, Canada | | babul@uvic.ca | |
| Athreya Ramana | NCRA-TIFR, Pune, India | Yes | rathreya@ncra.tifr.res.in | India |



† Please write the PI's name in CAPITAL LETTERS.

* Nationality is mandatory to obtain official clearance, only for non-Indian nationals coming for observations.

**(4)** Related previous GMRT proposal number(s): N/A


**(5)** Contact author Address: Somak Raychaudhury, School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom Telephone: +44–121–427 3965
Fax: +44–121–427
Email: somak@star.sr.bham.ac.uk


**(6)** If this proposal is intended to support a Ph.D. project, please mention the **name** of the student, the anticipated **year** of completion of the Ph.D. and also include a brief **outline** of the project in the Scientific Justification. N/A

**(7)** Scientific Category:

○ astrometry, geodesy & techniques, ○ solar, ○ propagation, ○ planetary, ○ stellar, ○ pulsar ○ ISM, ○ galactic center, ○ galactic structure & dynamics (HI), ○ normal galaxies, ⊗ active galaxies, ○ cosmology

| | | 21 cm | 50 cm | 90 cm | 128 cm | 200 cm | dual (50/128) cm | Total |
|---|---|---|---|---|---|---|---|---|
| (8) | Wavebands | 21 cm | 50 cm | 90 cm | 128 cm | 200 cm | dual (50/128) cm | Total |
| (9) | Time requested (hrs) | 0 | 0 | 8 | 0 | 0 | 12 | 20 |

**(10)** Type of Observation: (check all that apply) ⊗ imaging, ○ point source, ⊗ continuum, ○ solar, ○ spectroscopy, ○ pulsar, ○ phased array, ○ Other __________

**(11)** ABSTRACT (Please type within this space only.)


The galaxy cluster CL0910+41 at $z = 0.44$ has a cooling flow of $1000\,M_\odot$ yr$^{-1}$, one of the most IR-luminous galaxies at its centre, a type II quasar at its core shrouded by warm dust, very high star formation (40 $M_\odot$ yr$^{-1}$), and a classic double-lobed radio structure at its core. The coexistence of these phenomena challenge current paradigms concerning the quenching of star formation by AGN activity, and the fuelling of AGN. We request GMRT observations at 240, 320 and 610 Mhz to derive a spatially resolved spectral index map, to find the age for the radio source and jets, and find its relation to the ongoing star formation, to address important issues in the mechanism of AGN feedback.

**(12)** Will PI/ Co-PI be present for observations? ⊗ Yes ◯ No  Data reduction at? ⊗ Home ◯ Other xxxxxx

**(13)** Help required: ⊗ None ◯ Consultation ◯ Friend (extensive help)

**(14)**

| Spectroscopy Only: | line 1 | line 2 | line 3 | line 4 |
|---|---|---|---|---|
| Transition (HI, OH, etc) | ——— | ——— | ——— | ——— |
| Rest Frequency (MHz) | ——— | ——— | ——— | ——— |
| Velocity (km/s) | ——— | ——— | ——— | ——— |
| Observing frequency (MHz) | ——— | ——— | ——— | ——— |
| Frequency Resolution (kHz/channel) | ——— | ——— | ——— | ——— |
| Rms noise (mJy/bm, nat. weight., 1 hr) | ——— | ——— | ——— | ——— |
| Rms noise (K, nat. weight., 1 hr) | ——— | ——— | ——— | ——— |

**(15)** Number of sources 1 (If more than 10 please attach a list together with LST range(s). If more than 30 sources give only selection criteria and LST range(s).)

| **(16)** Name | Epoch: 1950◯ 2000 ⊗ RA Dec hh mm ± xx.x∘ | GMRT array† | Freq. (MHz) | Band-width (MHz) | Flux Density line (mJy‡) | Flux Density cont. (mJy) | Max. ang. size (′) | Required rms (mJy/beam) | Time$^{\beta}$ requested (hrs) | LST* range (hrs) |
|---|---|---|---|---|---|---|---|---|---|---|
| CL09104+4109 | 09 13 45.9 +40 56 27 | F | 610/240 | 16 | | | | 0.1 | 8 | 0400-1400 |
| CL09104+4109 | 09 13 45.9 +40 56 27 | F | 320 | 32 | | | | 0.1 | 8 | 0400-1400 |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | | | | | | | | | |

† Please indicate your preference for the GMRT Array configuration as per the following possibilities:
F : All antennas available. Nxx: Only xx antennas required (eg. VLBI, pulsar test/ monitoring)
A00: Arm antennas only A01: Arm antennas only with upto 4 antennas from the Central Square
C00: Central square only C01: Central square + 1$^{st}$ antenna in each arm (for Phased Array)

‡ Peak flux density. ß including overheads.

* Please take help from www.gmrt.ncra.tifr.res.in/gmrt_hpage/Users/Help/sys/time.html

Notes to the table (if any):

**(17)** Dates preferably avoided: `Night time observation is requested (see proposal).`

**(18)** Special requirements of hardware, software, or operating procedures, etc:

- 1 side band (16 MHz) ◯ or, 2 side bands (32 MHz) ⊗
- Is integration time less than 8 seconds required for extended periods? ◯
- Specify expected disk space requirement for the project (if more than 10 GBytes):
- Non-standard Frequency ◯
- Short spacing critical ◯
- Frequency switching * ◯
- Correlator - Full Polar * ◯
- Correlator - High resolution (256 channels) ◯
- Phased array required ◯
- If pulsar, specify pulsar backend required:
  ————————————————

  * on experimental basis

**(19) IMPORTANT: Please mark in one of the two boxes below: [This is a mandatory field ].**

☐ The proposers have not been allotted time in GMRT before.

⊞ A brief status report (not exceeding 150 words) on each previous proposal, and any preprint/ reprint. based on these GMRT observations is attached

**(20)** Please attach a self-contained **Scientific Justification** not exceeding 1000 words. (Preprints or reprints will be ignored, unless reporting previous GMRT observations). When your proposal is scheduled, the contents of the cover sheets become public information (Any supporting pages are for refereeing purpose only).

# The enigmatic cluster CL0910+41- the connection between AGN activity and star formation

In the cores of rich clusters of galaxies, the cooling time for the hot X–ray emitting intracluster medium can be substantially less than the Hubble time, yet from high-resolution X-ray observations it is clear that the gas does not cool indefinitely inwards. The fate of the cooling gas, and the possible involvement of additional heating (*feedback*) to compensate for the observed radiative losses and to regulate the cooling, remains the subject of an extensive debate. One of the most promising sources of feedback is the active galactic nucleus (AGN) harboured in the central dominant galaxy in these systems (McNamara & Nulsen 2007, and references therein). Evidence of strong interactions between the radio and thermal plasma can be found in the detection of X–ray disturbances in the hot gas, such as cavities, edges and filaments, but the mechanism of the energy transfer from the radio source to the surrounding thermal gas (e.g., shocks, gravity waves, turbulence) is still unclear.

The rich cluster CL0910+41 at a redshift of $z = 0.44$ is a fascinating system where a lot of these interesting phenomena seem to coexist. At face value, it is a standard rich cluster with a pretty impressive cooling flow of 1000 $M_\odot$ yr$^{-1}$ within the central 200 kpc (Fabian & Crawford, 1995), where the cooling time is $< 10^{10}$ yr. Yet, at its core, the brightest cluster galaxy (BCG), is one of the most unusual objects. It is one of the most infrared-luminous galaxies (ULIRGs) known, and at its core lies the closest Type II quasar to us, the dust-shrouded IRAS P09104+4109 (e.g., Hines et al., 1999), with a highly polarized bipolar refelction nebula surrounding it. The dust obscuring this QSO is warm (T>50 K) - in fact the contribution of cold dust to its bolometric luminosity is <3% (Deane & Trentham, 2001). Clearly this is evidence of heating by the central AGN.

What makes this galaxy even more fascinating is that from the presence of molecular gas, and from optical spectra, it is now known that the nucleus is surrounded by a starburst region, which is currently forming stars at a very high rate (40 $M_\odot$ yr$^{-1}$), over a scale of 25 kpc. This is obvious from the very unusual filamentary structure seen around the BCG in the HST/WFPC2 image (see Fig 1, left), and the fact that the core of the galaxy is unusually blue for a BCG (Fig. 1, right).

As if this were not enough, the BCG harbours a classic double-lobed radio structure (see Fig. 2), with linear jets reaching far beyond the star-forming region, seemingly aligned with the hint of a cavity (or deficiency of hot gas) seen in the recent Chandra X-ray image of the intracluster gas surrounding the central hard and bright shrouded AGN (also Fig. 2).

CL0910+41 offers us a unique opportunity to explore the mechanics of AGN feedback. We have assembled a team who have expertise in dealing with an multi-wavelength ensemble of data, comprising of HST and ground-based optical data (to be used for weak-lensing), far-infrared and X-ray observations, which, together with the proposed GMRT observations, will address the following issues.

By fitting a spectral model, we will estimate the total radio energy output of the AGN, and find whether the luminosity of the dusty nucleus of the BCG derive its energy from the starburst, or from the AGN.

From the three proposed frequencies and the existing VLA 1.4 GHz data, we will construct a spatially resolved spectral index map, which we will use to derive an age for the radio source and jets, using a technique similar to that employed by us in Giacintucci et al. (2008) based on GMRT data (see also Fig. 3). Based on the jet's age, we will estimate the duration of the AGN feedback. If indeed the feedback is found to be long-lived, this will challenge some of the principal current models for AGN feedback. For example, in one popular model (Hernquist & Springel, 2003), as the AGN turns on, the gas is driven out of the galaxy which quenches star formation. Clearly, this is not happening here- there is a high rate of current star formation, and an overwhelming quantity of dust.

Star formation is not common in the cores of $z = 0$ clusters, but an increasing number of star-forming BCGs are being found (e.g., Bildfell et al., 2008), more so at higher redshift. Perhaps a more realistic model might involve infalling gas from a controlled cooling flow, forming stars as well as beginning to feed the AGN, which in turn begins to quench the star formation. If this is so, there should be a definite lag between the AGN activity and star formation. From optical spectroscopy, we will estimate the age of the current star formation. From the age of the jets, we will find the duration of the current radio outburst, which will help help to assess the validity of such models involving the relation between AGN activity and star formation.

### 0.0.1 Technical Justification:

We request for a total of 20 hours: 8 hours at 325 MHz and 12 hours at 235/610 MHz joint observation, including calibration time. The angular resolution obtained by employing the entire array will be needed to map the jet to its largest extent. In order to minimize the RFI, we ask to observe our targets at 235 MHz and 325 MHz during local nighttime.

*We need all three frequencies, together with the existing VLA 1.4 GHz C-array observation, to map the spectral index and estimate the radio energy output.* We have shown in our previous work for example, in Abell 3562 (Giacintucci

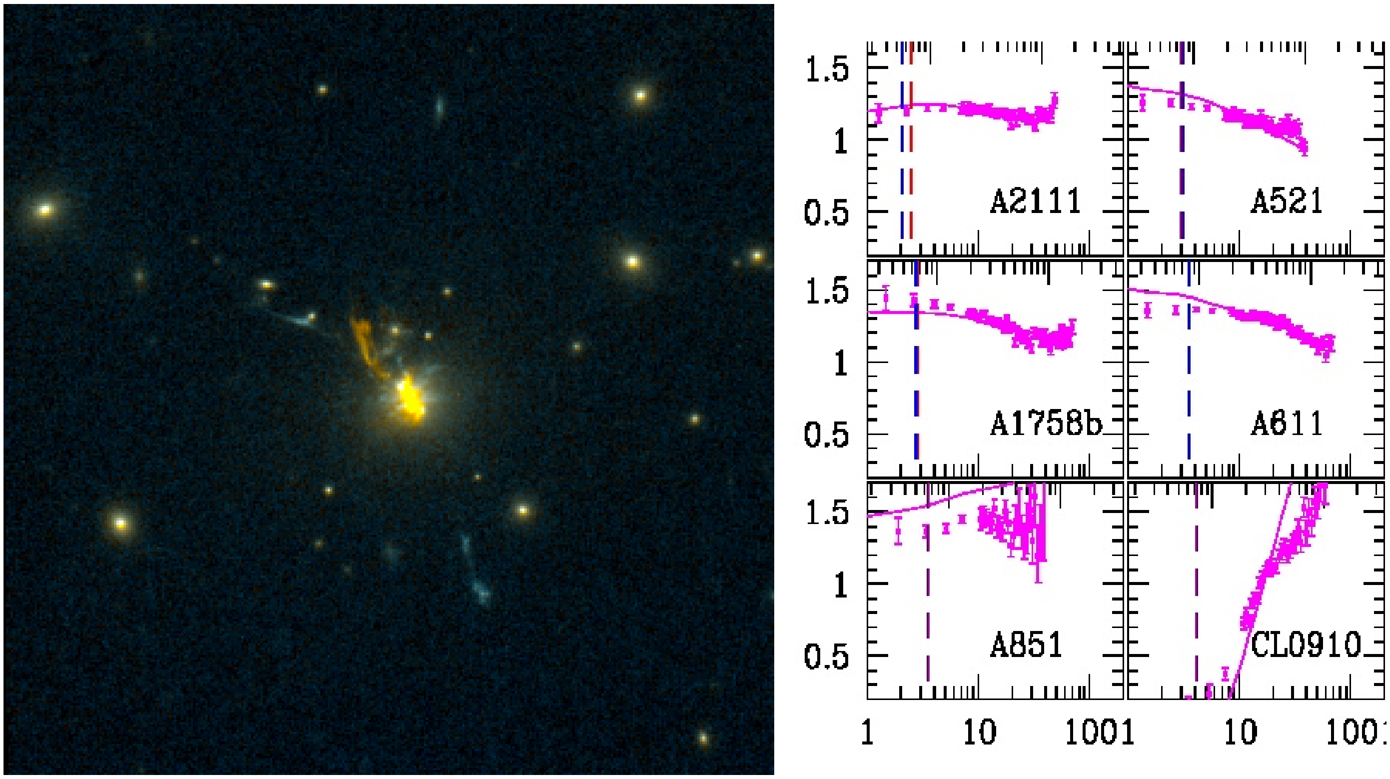


Figure 1: **Left:** HST/WFPC2 image of the cluster CL0910+41- this image was constructed using the images taken with the broadband filters F814W and F622W (unpublished). **Right:** The $g-r$ colour profile for the BCG from CFHT MegaCam images for a few clusters in the Canadian cluster comaprison project (Bildfell et al., 2008). Note how blue the core of the BCG of CL0910+41 is compared to other typical clusters. The $y$-axis is $g-r$ colour, and $x$-axis is distance from the centre in kpc ($H_0 = 70$).

et al., 2005) and AWM04 (Giacintucci et al., 2008), that due to the change in spectral slope below 1 GHz, at least two frequencies are needed in this region to properly estimate the spectral index.

Based on our experience with previous projects carried out with the GMRT at these frequencies (08TVa01, 10SGa01, 12SGa01), the indicated time request should allow us to reach a sensitivity of the order of 0.1 mJy $b^{-1}$ at all three frequencies with the integration time requested. Based on the VLA observations (Hines & Wills, 1993). the flux densities of the major features on the jet and lobe are between 2–6 mJy at 1.4 GHz, extending to >30 arcsec. At our frequencies of observation, we will hopefully be able to map the source to beyond this extent, with the 0.1 mJy $b^{-1}$ sensitivity at each frequency, and thus produce the spectral index map required.

We have also inspected 1 square degree NVSS field centered on each target, and found that no strong radio source ($> 1\ Jy$) is present in the field. Therefore we should not suffer from significant dynamic range limitation.

### 0.0.2 Status report on earlier proposals

**Continuum observations:** These have been very successful. PI Raychaudhury, and Co-I Giacintucci and Athreya have collaborated on several GMRT observations involving radio haloes and AGN feedback in groups and clusters. From 10SGa01, 12SGa01 and 13SGa01, multifrequency observations of AGN in groups, we have truly spectacular results- the first paper has been published (Giacintucci et al., 2008), and two others are close to submission. Results are being presented in two talks (Raychaudhury, Giacintucci) at the *Radio galaxies in the Chandra Era* meeting in Boston, MA in July 2008. Related 14SGa01 will be observed in August. 09Src02, a 3-frequency observation of 3C278 has been fully reduced (Co-I Kraft, Kantharia), and is being combined with the recently obtained XMM-Newton observation to produce a paper for ApJ. **Line observations:** 21 cm observations of XI groups 09Src01 and 12Src01 have been reduced and formed a chapter of Chandreyee Sengupta's (RRI) thesis- this is being written up for publication. 10Src01 was an ambitious project for 21cm observations of dark galaxy candidates (Co-I: Minchin, Davies)- this unfortunately produced no detection, and we are attempting to write a paper highlighting the significance of upper limits.

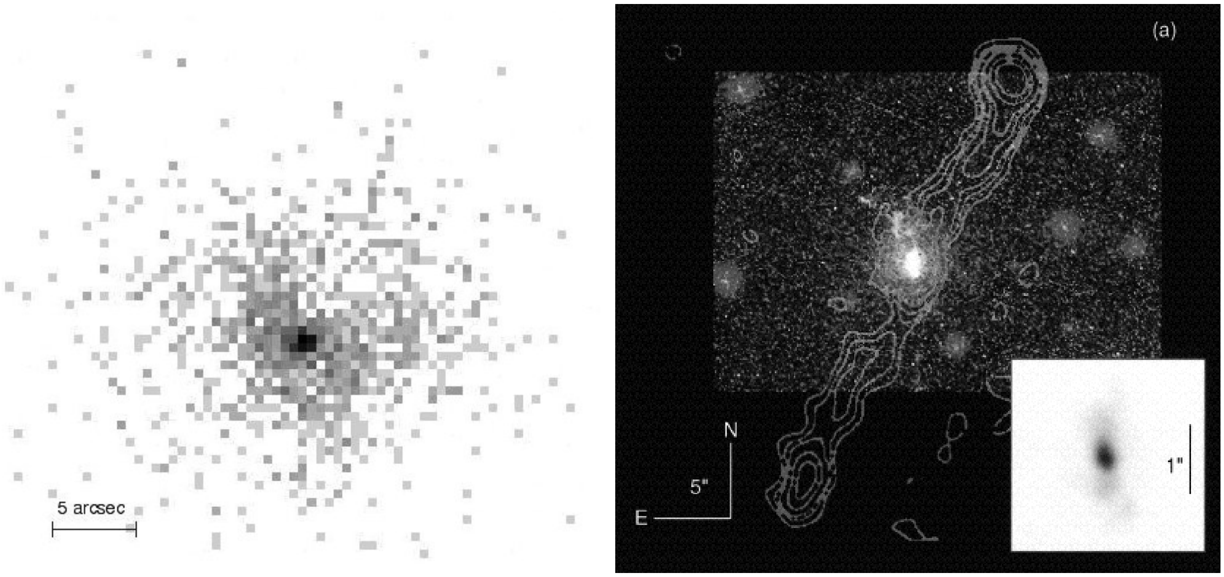


Figure 2: **Left:** The Chandra ACIS-S3 image X-ray (0.5-8 keV) image of the cluster CL0910+41 (Iwasawa et al., 2005). This relatively shallow (10 ks) exposure shows the presence of a wide cavity to the NW of the nucleus. Various filamentary structures associated with star formation are obvious. **Right:** The VLA 21 cm C-array image from Hines & Wills (1993), superposed on the Keck K-band image (inset is an HST WFPC2 cut-out) of the central BCG (Hines et al., 1999). THis shows a a classic core and double-lobed structure, with linear jets or bridges that line up nicely with the cavity seen in the Chandra image.

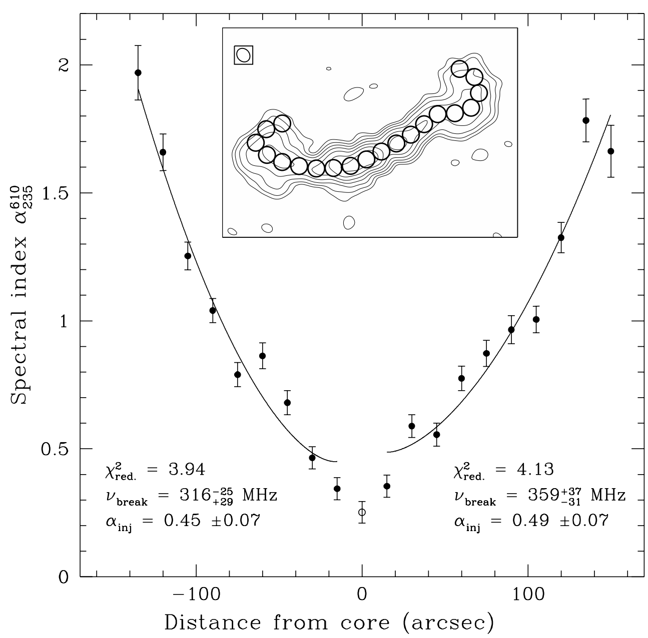


Figure 3: Figure to iluustrate our technique of finding the age of synchrotron emiiting electrons along a jet. The spectral energy distribution of GMRT observations at 235, 320 and 610 MHz of 4C+24.36, in the core of the poor cluster AWM4 (Giacintucci et al., 2008), helps us fit a radiative model, and thus find the age of the jet and the total energy of the outburst. We will use the same analysis in this work.

## References

Bildfell, C., Hoekstra, H., Babul, A., & Mahdavi, A. 2008, arXiv:0802.2712 Resurrecting the Red from the Dead: Optical Properties of BCGs in X-ray Luminous Clusters

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Fabian, A. C., & Crawford, C. S. 1995, MNRAS, 274, L63

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