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The COLA Project

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Abstract. The primary goal of the COLA (Compact Objects Low-power AGN) program is to determine the relationship between one facet of AGN activity, the compact radio core, and the circumnuclear region of the host galaxy by comparison of the multi-wavelength properties of a sample of AGN with compact radio cores to a sample of AGN without compact cores and a sample of galaxies without AGN.

In this poster we present an overview of the COLA project and discuss the selection criteria we have adopted to ensure that our samples are as independent as possible of such selection effects as source orientation and distance. We also present the global properties of the COLA galaxies and discuss the important differences which are already emerging between the 3 galaxy sub-samples.

1. Introduction

One of the more intriguing questions confronting astronomers today is why some galaxies possess active nuclei and others do not. Recent observations have shown that many of the host galaxies of active galactic nuclei (AGN) also exhibit circumnuclear phenomena such as starburst activity, inner rings, or bars. It is not known whether these signs of activity are related to the mechanisms for fuelling an AGN, are triggered by the AGN or are entirely unrelated to the presence of an AGN. The primary goal of the COLA (Compact Objects Low-power AGN) program is to determine the relationship between one facet of AGN activity, the compact radio core, and the circumnuclear region of the host galaxy by comparison of the multi-wavelength properties of a sample of AGN with compact radio cores to a sample of AGN without compact cores and a matched sample of galaxies without AGN.

In particular, the circumnuclear regions of three galaxy groups will be examined for evidence of fuelling (or fuelling supression) and the relative prevalence of nuclear structures such as bars or rings. The internal kinematic properties of their gas and the spatial distribution of emission mechanisms such as photoionisation and shock-excitation, e.g. ionisation cones, will also be investigated using emission-line imaging and optical spectroscopy. Finally we will aim to establish what differences, if any, exist between the AGN with compact radio cores and those without and whether their radio structure at pc-and kpc-scales is aligned or associated with any optical structures.

2. Sample selection

So far, investigations into the relationship between the occurrence of AGN and possible fuelling mechanisms have been compromised by the difficulties associated with defining an un-biased sample of AGN and a matching non-AGN comparison sample. To avoid Malmquist and other distance-dependent biases we selected a large initial sample of galaxies which consisted of all 217 objects in the IRAS catalogue with velocities in the range 3500-7000 km/s, $S_{60} > 4$ Jy and $|b| > 10^o$. From this initial sample of galaxies the following sub-samples will be selected:
(1) the **core AGN sub-sample**, defined by the detection of a compact (<0.05 arcsec) radio core >1mJy at 13-cm from VLBI snapshot observations;
(2) the **"non-core" AGN sub-sample**, consisting of galaxies classified as AGN using optical spectroscopic diagnostics but without compact radio cores;
(3) the **non-AGN sub-sample**, matched to the core and non-core AGN samples using orientation-independent measures, such as total HI + CO mass and I-band luminosity.

These criteria were used because a large dusty torus is believed to be present in all AGN, obscuring our view of the nucleus along certain lines of sight. Selecting AGN on the basis of their IR-UV emission can therefore introduce an orientation bias. Additionally, it is important for this study that the AGN selected are sufficiently strong to influence the circumnuclear regions of the host galaxy but galaxies with the optical spectral signature of an AGN can also contain a considerable amount of starburst activity. Conversely an AGN may also be also obscured by dust at optical wavelengths. The detection of a high brightness temperature ($T > 10^5$ K) compact radio core is a strong indication of AGN activity (Norris et al. 1990), and since the effect of dust is negligible at radio wavelengths, it is orientation independent. AGN with such compact radio cores exhibit a radio excess on the radio-FIR correlation (Roy et al. 1998) which, since the FIR emission is believed to be due to starformation activity in the galaxy disk, indicates that the AGN rather than the starburst dominates, at least at radio wavelengths. AGN with detectable compact cores should therefore be sufficiently powerful to influence the circumnuclear regions of the host galaxy.

3. Observations of the Southern Sample

3.1. Observations

The initial sample has been divided into Northern (dec<0; 110 sources) and Southern samples (dec<0; 107 sources) with observations of the Northern sample being undertaken by the USA-based astronomers. In the Southern hemisphere the following observations have been made:

- Low resolution radio observations on the ATCA at 4.8GHz, 2.5GHz and 1.38GHz to measure the total radio flux of the galaxies. At 4.8GHz 104 galaxies were detected at 5σ;
- I-Band observations of the whole Southern sample during 1997-1998 on the MSSSO 40" telescope;
- CO spectroscopic observations of 86 galaxies on SEST between 1998 and 2000. Of the remaining galaxies, CO measurements are available in the literature for 16 objects and 5 have yet to be observed.

These observations will enable us to determine the global properties of the whole sample and hence match the control galaxy samples to the AGN samples.

In order to classify the galaxies as "Core AGN", "non-Core AGN" or "non-active/starburst" galaxies, we have made the following observations of the Southern sample:

- VLBI snapshot observations obtained bteween 1998 and 2000 of 91 galaxies using the ATCA - Tidbinbilla (resolution 0.05", detection limit >1.5mJy) baseline and 13 galaxies using the ATCA-Parkes baseline (resolution 0.1", detection limit >1.5mJy). Compact cores were detected in 6 objects, all with fluxes >3mJy and angular diameters =<0.05";
- Optical spectroscopic observations of $\sim$90 objects obtained with the 2.3m MSSSO telescope, and emission-line diagnostics, i.e. BPT diagrams (e.g.Veilleux & Osterbrock, 1987), used to classify the excitation mechanisms as AGN or starburst dominated.

4. Results

The global properties of the Southern COLA sample have now been measured and we are in the process of selecting our three samples. Although we have yet to embark on the detailed study of the circumnuclear properties of the galaxies, several interesting characteristics of the COLA sample have already emerged.

4.1. Radio-FIR correlation

Most galaxies exhibit radio emission which is correlated with their far-infrared emission. This correlation is well-known and extends over several orders of magnitude from "normal" spirals (e.g. Helou, Soifer & Rowan-Robinson 1985; Wunderlich, Klien & Wielebinski 1987) to Seyfert galaxies. It is believed to be due to starformation activity in the disk of the galaxy with the FIR-emission attributed to thermal emission from dust heated by the stars while the non-thermal radio emission, generally coincident with optical indicators of star-formation activity, is probably generated from supernovae acclerating cosmic ray electrons. The radio-FIR correlation is known to break down for those AGN with compact ($20 \sim 200$ pc) radio cores, i.e some radio-quiet AGN and all radio-loud AGN (e.g. Impey & Gregorini 1993 and Roy et al. 1998), as they exhibit a radio excess.

As expected the COLA galaxies display a strong linear correlation between the radio and FIR luminosity at all wavelengths (Fig 1). However, those galaxies in which we detect compact cores (Fig 1; filled circles) depart significantly from the correlation, exhibiting a radio luminosity of between 0.3 to 30 times greater than would be expected from the star formation activity of a "non-active" galaxy at the same FIR luminosity. Following Helou et al. (1985), we define the quantity, $< q >$, the median FIR/Radio ratio, $q = log(S_{FIR}/S_{4.8GHz})$. For the galaxies in which we do not detect compact cores $< q > = 2.85 \pm 0.19$ whereas for those galaxies with compact cores $< q_{core} > = 2.276$. In fact none of the galaxies with compact cores lie within 1σ of $< q >$ (Fig. 1; solid lines), although one galaxy, IRAS 09375-6951, comes very close with a q=2.63. This result is formally significant at the 99.9% level using both the student - t test and the z test. The compact high-brightness-temperature radio emission is generally attributed to non-thermal synchrotron radiation from the core and radio jets. It is probably this nuclear component of radio emission which disturbs the FIR-radio correlation in Seyferts (e.g. Sanders & Mirabel 1985; Roy et al. 1998) and Baum et al. (1993) have found that subtraction of the inner 1 kpc of radio emission from Seyferts returned them to the FIR-radio correlation.

To investigate whether this is the case with the COLA "core" galaxies their VLBI core luminosity was subtracted from their 2.5GHz total luminosity as measured by the ATCA. Five out of six on the COLA galaxies still exhibit a significant radio excess, whereas the sixth galaxy, IRAS 09375-6951, moves to within 1σ of the median q value. These results indicate that the radio excess is not entirely accounted for by subtraction of the core luminosity and thus the radio structures associated with the central nucleus extend further than the 0.05 arcsec ($15 \sim 20$pc at these redshifts) resolution of the ATCA-Tidbinbilla baseline.

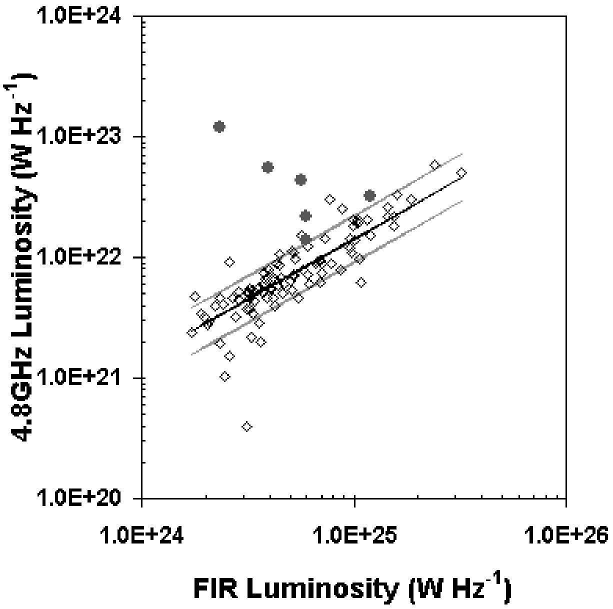

Fig. 1. Plot showing the total radio luminosity at 4.8GHz of the galaxies versus the FIR luminosity, calaculated from the IRAS flux at 60μm and 100μm following Helou et al. (1985). The open diamonds represent those galaxies in which we do not detect a compact core with the ATCA-Tidbinbilla array, the filled circles represent those galaxies in which a compact core $> 3mJy$ was detected. The central black line represents the median value of $q = log(S_{FIR}/S_{4.8GHz})$ for the galaxies in which compact cores were not detected. The lines either side represent values of $q = 1\sigma$ from the median.

4.2. Optical Spectroscopic Classification

Currently we have completed the classification of ~50% of the southern COLA sample using emission line diagnostics (e.g. Veilleux & Osterbrock 1987). 32% are classified as AGN (17 out of 53), 55% as HII or starburst galaxies (29 out of 53) and 13% have an ambigious classification, exhibiting HII or starburst -like ratios in some lines and AGN-like ratios in others.

Five of the six galaxies with compact radio cores exhibit strong, unambiguous AGN-like emission line ratios (Fig 2; filled circles). The one exception is again IRAS 09375 - 6951 which lies close to, but on the starburst side of, the HII/AGN partition (Fig. 2; filled diamond). Compact radio cores were not detected in the majority (12/17) of galaxies classified optically as AGN (Fig. 2 open circles). Only two of these sources exhibit a significant ($> 1\sigma$) radio excess while the remainder exhibit FIR to radio ratios which lie close to the median value. These results imply that if emission from the AGN dominates at radio wavelengths it tends to do so at optical wavelengths, whereas an AGN may dominate the optical spectrum without emitting a radio excess. They are described in more detail in Corbett et al. (2000a).

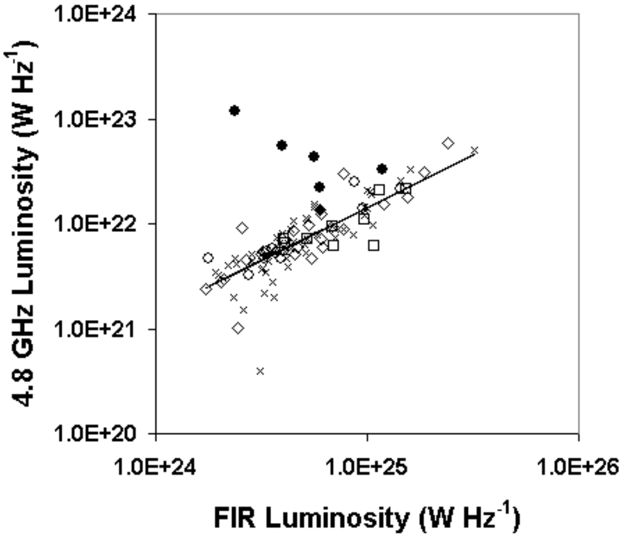

Fig. 2. Plot as before with the following symbols: circles represent galaxies classified optically as AGN, diamonds those classified starburst or HII regions, squares those with an ambigous optical classification and, finally, crosses represent galaxies yet to be classified optically. For all galaxy classes, a filled symbol indicates that it has a compact radio core and an open symbol that no core has been detected $> 3mJy$. All galaxies in which compact cores have been detected have been classified optically.Some of this data has been taken from Kewley et al. 2001

4.3. I-Band observations

No strong correlation was found between the I-Band luminosity and either the radio or FIR luminosity, indicating that the I-Band luminosity is dominated by the older stellar population rather than starburst activity (Brown 1999). The I-Band luminosity can therefore be used to "normalise" the luminosities for selection of the comparison sub-sample. Initial investigations using the I-Band images indicate that the galaxies with radio cores are not universally interacting, merging or disturbed (Brown 1999). However, these are very preliminary results, based on examination of the images by eye and a more detailed study would be needed to obtain statistically significant results.

5. Discussion

At this stage of the COLA project, we must establish whether the compact cores detected in the COLA galaxies are indeed AGN. The compact cores detected are all > 3mJy and the galaxies exhibit a significant radio excess relative to their FIR luminosity. Five of the galaxies with compact cores also exhibit strong AGN-like emission line characteristics with the one exception being IRAS 09375-6951. This galaxy also exhibits the smallest radio excess but the luminosity of its compact core is comparable to those of the other galaxies. We therefore conclude that at least five of the galaxies in which we detect compact cores are indeed AGN while the classification of IRAS 09375-6951 is ambiguous.

However, the question is then: what is the sixth galaxy, IRAS 09375-6951? This object could either contain an AGN which is obscured at optical wavelengths or a complex of supernovae remnants (e.g. M82; Unger et al. 1984). Observations by Kewley et al. (2000) of a sample of 61 IRAS galaxies have revealed compact radio cores (< 0.1" in diameter) in 37% of galaxies classified as starburst from optical spectroscopic observations and 80% of the galaxies classified optically as AGN. They find that the radio luminosity distribution of the compact cores is bimodal with the compact cores in the starburst galaxies tending to be less luminous ($\sim< 10^4 L_{solar}$) than those detected in the AGN. They attribute this to the compact cores in the starburst galaxies being complexes of supernovae remnants (e.g. M82, Arp 220; Smith et al. 1998) rather than obscured AGN. The compact core in IRAS 09375- 6951 has a luminosty of $\sim 10^{4.3} L_{solar}$ which would tend to place it among the AGN rather than the starburst galaxies but the fact that it is optically classified as a border-line HII or starburst galaxy combined with its relatively small radio excess points towards it being a supernovae complex candidate.

Two sets of observations may shed light on this matter. The first would be high resolution VLBI imaging of the core. This would have the potential to resolve out the individual radio supernovae if they are present. Alternatively it is possible that dust is obscuring an AGN or a relatively strong starburst component is diluting the AGN line emission characteristics. Emission line imaging may reveal whether this may be the case, either by allowing us to obtain spatially resolved BPT diagrams, perhaps revealing AGN-like emission in the central regions, or enabling us to map dust extinction across the cetral regions using the Blamer decrement thus providing information on whether the central regions are heavily obscured.

6. Conclusions and future work

We have obtained multi-wavelength observations of the 107 galaxies which make up the Southern half of the COLA galaxy sample. We have also obtained VLBI snapshot observations of 104 galaxies with 0.05" - 0.1" resolution and detected compact cores in 6 galaxies. We find that while the majority of the COLA galaxies follow the FIR-radio correlation, all the galaxies in which compact cores were detected exhibit a significant radio excess of between 0.3 to 30 times the radio flux predicted from the FIR emission.

We have obtained optical spectroscopy of approximately half the Southern COLA sample. Five of the galaxies with compact cores are classified AGN from their emission line ratios whereas the sixth galaxy is classified as a borderline starburst galaxy. We therefore conclude that the compact cores in five of the galaxies are AGN whereas the classification of the sixth galaxy is ambiguous.

We are now in a position to select the COLA galaxy sub-samples for further study of their circumnuclear regions using high resolution ATCA, VLBI (for the "core AGN" sample) and NIR observations combined with optical spectroscopic and emission line imaging. These observations will enable us to investigate the internal kinematic properties of their gas and the spatial distribution of emission mechanisms such as photoionisation and shock-excitation, e.g. ionisation cones. We also aim to establish whether their radio structure at pc-and kpc- scales is aligned or associated with any optical structures.

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