RADIO AGNS AMONG LUMINOUS INFRARED GALAXIES

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Abstract. An analysis of radio and FIR emission in over 1500 IRAS selected galaxies produces a good linear correlation between radio and FIR luminosity, indicating that star formation in normal field galaxies dominates the infrared luminosity in the local volume. Galaxies with clear radio-excess (defined as having at least 5 times larger radio flux over expected from FIR) are identified as hosting a radio AGN, and they account for only about 1% of the whole sample. This fraction increases to 10% among the more luminous galaxies with $L_{1.4GHz} \geq 10^{23}$ W Hz^{-1} (equivalently $L_{60\mu m} \geq 10^{11} L_{\odot}$), however. The characteristic mid-IR excess of a Seyfert nucleus is ubiquitously present among the radio-excess objects, suggesting that mid-IR excess is a robust tracer of an AGN despite the high mid-IR opacity. We conclude that about 30% of the luminous infrared galaxies ($L_{60\mu m} \geq 10^{11} L_{\odot}$) host an AGN based on the mid-IR excess, and about 40% of the mid-IR excess AGNs also host a radio AGN.

A VLA imaging survey of a distance limited sample of IR luminous galaxies has revealed the presence of 100 kpc scale giant radio plumes in 3 out of 9 cases (Mrk 231, Mrk 273, NGC 6240). Their large spatial extent, energetics, and presence of a powerful AGN in each case suggests that an AGN is the power source. Such plumes are not detected in other ultraluminous infrared galaxies which lack clear evidence for an AGN, such as Arp 220.

1. Introduction

One of the important unanswered questions concerning the luminous infrared galaxy phenomenon (thus the central question in this Workshop) is whether the large luminosity observed is powered by a starburst or by an AGN. Determining the nature of the power source is not a trivial task since the luminosity arises from the heavily obscured nuclear region (see contributions by Scoville et al. and Downes et al. in this volume). Clear evidence for an AGN, either hard X-ray emission (Nakagawa et al. in this volume) or a VLBI source with high surface brightness ($> 10^7$ K; Smith et al. 1998), has been detected in some cases, but proving that these active nuclei produce the bulk of the luminosity is a more demanding task.

To "see" through the obscuring clouds, we utilize two optically thin tracers, far-infrared (FIR) and radio continuum, and the well known correlation between them (see Condon 1992 and references therein). Presence of radio AGN and their statistical frequency among a large sample of field galaxies are determined using the IRAS and NVSS (New VLA Sky Survey, Condon et al. 1998) databases. Not all AGNs will produce detectable radio continuum emission, but the detected radio AGNs should serve as a good lower limit. The utility of radio-FIR correlation for identification of an AGN is also tested by comparing the result with the determination using mid-IR excess (de Grijp et al. 1985).

Our VLA imaging survey of a distance limited sample of IR luminous galaxies has revealed the presence of 100 kpc scale giant radio continuum plumes in 3 out of 9 cases (Mrk 231, Mrk 273, NGC 6240). Their large spatial extent is similar to the giant radio lobes/jets in powerful radio galaxies such as Cygnus-A (e.g. Carilli et al. 1998), and the presence of powerful AGN in each of three galaxies suggests an AGN as a power source. Therefore we analyze the physical properties of the observed radio plumes and examine the possibility that such radio plumes may be a sign post of an energetically important AGN.

2. Radio-FIR Correlation

The well known linear correlation between radio and FIR luminosity is interpreted as a direct relationship between star formation and cosmic-ray production (see Harwit & Pacini 1975, de Jong et al. 1985, Helou et al. 1985, Condon 1992). The plot of 1.4 GHz radio luminosity vs. 60 μm FIR luminosity for our IRAS flux limited complete sample of over 1500 galaxies (Fig. 1a) shows a linear correlation spanning over 5 decades in luminosity (see Yun et al. 1999 for the details of sample selection and analysis). The overwhelming majority of the galaxies with $L_{60\mu m}$ between $10^{9-11.5} L_\odot$ closely obey the linear relation. (The observed fluxes also shows a linear

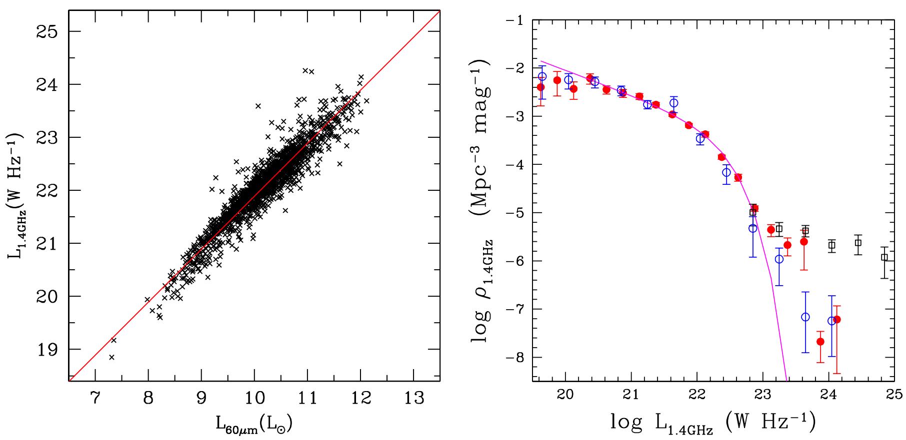

Figure 1. (left) Plot of 1.4 GHz radio luminosity versus IRAS 60 μm luminosity for the 1531 IRAS selected galaxies. The solid line is the linear relation with a unit slope, representing the well known radio-FIR correlation. (right) Plot of the 1.4 GHz radio luminosity function derived from the 1531 IRAS selected galaxies. Filled circles representing the IRAS galaxy sample agree very well with the luminosity function derived for the late type field galaxies by Condon (1989; open circles) while the AGNs ("monsters"; empty squares) are nearly entirely absent in our IRAS galaxy sample. The solid curve is the best fit Schecter luminosity function for the sources with $L_{1.4GHz} \leq 10^{23}$ W Hz^{-1} only.

relation spanning three orders of magnitude.) The derived luminosity function (Fig. 1b) shows that normal late type galaxies studied by Condon (1989) account for over 90% of the IRAS galaxy sample while the AGNs ("monsters") are nearly entirely absent in our IRAS selected sample.

3. Radio AGNs and their Frequency

Identification of any non-linearity in the radio-FIR correlation and "radio-excess" objects may be more easily performed by examining the "q" parameter (Condon et al. 1991),

$$q \equiv log[\frac{FIR}{3.75 \times 10^{12} \mathrm{W\ m^{-2}}}] - log[\frac{S_{1.4GHz}}{\mathrm{W\ m^{-2} Hz^{-1}}}]$$

The mean q value for the entire sample is 2.34, which is in excellent agreement with q values typically found in other star forming galaxies. In fact, 99% of galaxies in our IRAS sample are within a factor five of this mean value.

We classify as AGNs those objects having more than five times the expected radio luminosity from the linear radio-FIR correlation (i.e. $q \leq 1.64$). These account for only about 1% of our IRAS galaxy sample. This fraction increases to 11% among the high luminosity galaxies with $L_{1.4GHz} \geq$

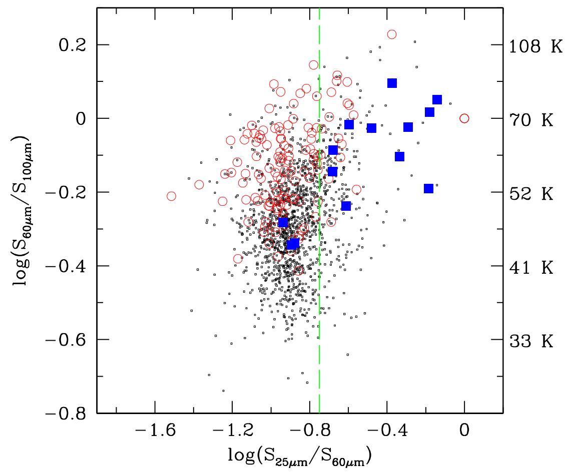

Figure 2. IRAS color-color diagram for the IRAS galaxy sample. Corresponding dust temperature is shown along the right hand side. Sources with $L_{1.4GHz} \geq 10^{23}$ W Hz^{-1} are plotted as empty circles while the lower luminosity sources are plotted as small dots. The filled squares represent the luminous "radio-excess" objects (radio AGNs). The radio AGNs nearly exclusively appear to the right of the dotted line marking the mid-IR excess characteristic of Seyfert galaxies (de Grijp et al. 1985). Therefore the mid-IR excess appears to be a robust tracer of an AGN even among these extremely dusty galaxies (Yun et al. 1999).

10^{23}W Hz^{-1} (equivalently $L_{60\mu m} \geq 10^{11} L_\odot$) and are thus more common among the high luminosity systems. Nearly all of them also show Seyfert-like mid-IR excess (see Fig. 2), and this mid-IR excess appears to be a robust tracer of energetic AGN even thought the high opacity inferred (e.g. Goldader et al. 1995, Lutz et al. 1998) may be capable of hiding such activities. The mid-IR excess objects account for 27% of the IR luminous galaxies ($L_{60\mu m} \geq 10^{11} L_\odot$), and 11 of 29 (38%) of these are radio AGNs.

4. Giant Radio Plumes among IR Galaxies

During the imaging survey of atomic hydrogen and 1.4 GHz radio continuum (Hibbard & Yun 1996, 1999), we have detected 100 kpc scale giant radio plumes in three (Mrk 231, Mrk 273, NGC 6240; Fig. 3) out of nine (33%) galaxies in our distance limited sample with $L_{IR} \geq 3 \times 10^{11} L_\odot$. They are well aligned with the rotation axis of the nuclear molecular gas complexes (Bryant & Scoville 1996, Bryant 1997, Downes & Solomon 1998), and this result suggests that the ages of these radio plumes are comparable to the time scale for the nuclear molecular gas disk, $\leq 10^8$ years. These edge-brightened features are also visible in the NVSS images, and high degree of polarization (20-50%) suggests a coherent magnetic structure. Radio plume sizes are between 75 to 230 kpc long, comparable to the jets/lobes

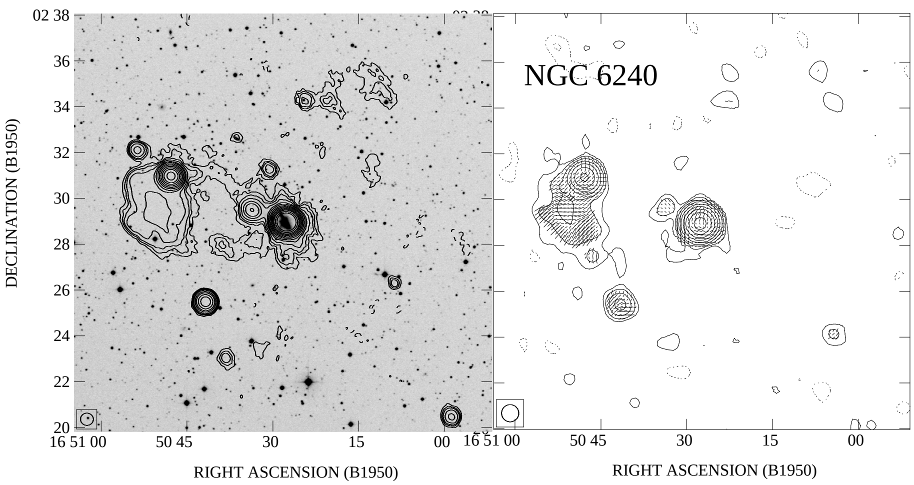

Figure 3. Giant radio plumes detected in NGC 6240 at 1.4 GHz using the VLA (left panel). These edge-brightened structures are also seen in the NVSS images (right panel), revealing high (20-50%) degree of polarization. It is possible that these extended radio features are unrelated and projected foreground or background objects, but the faint continuous emission connecting back to the optical galaxy as well as their alignment with the optical and X-ray emission lobes are strong evidence tying them to the activity in NGC 6240. In general, these radio plumes are well aligned with the spin axis of the nuclear molecular disks and the superwind flow, suggesting that they are directly related to the ongoing luminous activity in the central kpc region. The projected extent of the lobes are about 150 kpc long, comparable to the size of the radio jets/lobes in radio galaxies such as Cygnus A and much larger than those of the starburst driven superwind traced in X-ray or optical emission lines ($\leq$50 kpc).

in powerful radio galaxies and much larger than the extents of the nuclear superwind ($\leq$50 kpc; Heckman et al. 1990). Given their large sizes (l), the ages of the plumes are also large, $5\times10^7(\frac{l}{100\ kpc})(\frac{v}{2000\ km/s})^{-1}$ yrs. The low expansion speed ($v < 1000\ km/s$) associated with superwind phenomenon poses a difficulty relating them to the nuclear starburst.

The derived radio luminosity between 10 MHz and 100 GHz is $(0.6 \sim 3.6) \times 10^{40}$ ergs s^{-1}. This is comparable to the radio luminosity of the nuclear starburst. In comparison, the radio luminosity of nuclear superwind, Seyfert radio bubbles, and jets/lobes in radio galaxies are typically 10^{37-38}, 10^{38-39}, and 10^{40-45} ergs s^{-1}, respectively (Baum et al. 1993, Zirbel & Baum 1995, Colbert et al. 1996). Therefore, the observed radio luminosity is more consistent with activities powered by an AGN.

Minimum energy magnetic field for the radio plumes ranges between 0.6 and 1.8 μG, and the corresponding total energy is about 10^{57} ergs (see Miley 1980). If there is equipartition between magnetic field and relativistic particles, the particle density in the radio plumes is $n = 1.2\times10^{-6}[\frac{B}{1\mu G}]^2[\frac{v_A}{2000km/s}]^{-2}$ cm^{-3}. In comparison, the internal magnetic field and total energy stored in the radio lobes of Cygnus A is about 50-300 μG and $> 10^{59}$ erg, and $n = 10^{-4}$ cm^{-3} (Carilli et al. 1998). Highly ordered magnetic field aligned along the outer envelope (electric vector perpendicular to the outer curvature) can be inferred from the highly polarized emission (Fig. 3b), suggesting a bubble-like structure or a poorly collimated wind plowing into the external medium.

The radio luminosity associated with the giant radio plumes is much smaller than the bolometric (IR) luminosity or the kinetic luminosity in the superwind ($L_{plume}/L_{IR} \sim 10^{-5}$, $L_{plume}/L_{kin} \sim 10^{-2}$; see Heckman et al 1990 and references therein). Therefore, both AGN and starburst origin are energetically plausible. The advantage of an AGN/jet model is that the energy flux can be channeled, resulting in much smaller energy and momentum loss and thus enabling the particles to reach a greater distance in given amount of time. Nevertheless, a wind-driven bubble may be able to reach 100 kpc radius in 10^8 years if the bubble can enter the low density intergalactic medium and expand with relatively little loss of energy and momentum. All three galaxies with giant radio plumes host powerful AGNs (hard X-ray or radio VLBI sources) while other luminous IR galaxies without any evidence for an AGN (e.g. Arp 220) do not have a giant radio plume. These giant plumes may still be present but at a fainter level in all cases, and we are currently pursuing more sensitive observations to address if they are unique sign posts of galaxies hosting a powerful AGN.

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