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THE HOT AND COLD INTERSTELLAR MATTER OF EARLY TYPE GALAXIES AND THEIR RADIO EMISSION

Dong-Woo Kim and Giuseppina Fabbiano
Harvard-Smithsonian Center for Astrophysics

Over the last few years, the knowledge of the interstellar matter (ISM) of early type galaxies has increased dramatically. Many early type galaxies are now known to have ISM in three different phases: cold (HI, dust and molecular material), warm (ionized) and hot (X-ray emitting) gas. Early type galaxies have smaller masses of cold ISM (10^7 – 10^8 $M_\odot$; Jura *et al.* 1987) than later type spiral galaxies, while they have far more hot gas (10^9 – 10^{10} $M_\odot$; Forman *et al.* 1985, Canizares *et al.* 1987). In order to understand the relationship between the different phases of the ISM and the role of the ISM in fueling radio continuum sources and star formation, ~~we have~~ compared observational data from a wide range of wavelengths.

The Cold and Hot Interstellar Matter

The far infrared luminosity and mass of HI gas are correlated, although with considerable scatter, suggesting that the far infrared emission is due to dust in the ISM, and not to nuclear activity (see Jura 1986 and Kim 1988). The observational uncertainties are sometimes quite significant, particularly for the HI observations. There are also a few *intrinsic* reasons for the observed scatter: The dust temperature varies with the distance from the center and also varies from one galaxy to another because of different radiation sources; In some galaxies, a large fraction of the cold ISM may be in the form of molecular material; Also there may be an environmental dependence of the amount of HI gas. Nevertheless, a correlation between these two quantities is suggested by the enhanced far infrared detection rate in the HI sample (see Table 1). This result is confirmed using the method of Schmitt (1985) which uses the information in the upper limits (see Fabbiano *et al.* 1989 for applications of this method). The use of this test insures us against a distance bias in our results. The test showed that the HI masses and far infrared luminosities are correlated (the correlation coefficient is $0.76^{+0.05}_{-0.04}$, where the uncertainties are at 1σ). The dust lanes seen in optical imaging observations are a direct evidence of the presence of dust, and indeed the far infrared detection rate in the dust lane galaxies are as high as those in the HI sample (Table 1, see also Veron-Cetty and Veron 1988).

The next question is: Is there a correlation between cold and hot gas? Figure 1 shows a plot of far infrared luminosities against X-ray luminosities. No correlation (or anticorrelation) is found by the Schmitt analysis. For the less luminous galaxies the far infrared luminosity does appear to increase as the X-ray luminosity increases. However, for the X-ray bright galaxies the far infrared luminosity does not increase correspondingly. These are believed to contain hot gas because of the excess X-ray emission over what is expected by stellar X-ray sources (see Canizares *et al.* 1987; Fabbiano 1989).

If the cold and hot gas have the same origin, namely from mass losses of late type evolved stars, one would expect a correlation between the two different phases of ISM. If the cold gas results from cooling flows in the X-ray emitting hot gas, one would also expect a correlation. On the other hand, if the infrared emitting dust was destroyed by interacting with the hot gas, one may expect an anti-correlation. In our sample, there is neither a correlation nor an anti-correlation. A possible explanation is an external origin of cold ISM. This idea is supported by the decoupled gas and stellar kinematics in many well studied galaxies like NGC 1052 (van Gorkom *et al.* 1985). However, one can not exclude an internal origin, because some isolated early type galaxies, for which therefore no apparent nearby source of cold gas exists, have fairly regular gas kinematics (e.g., Kim *et al.* 1988).

Star formation, Nuclear Activity and Radio emission

Walsh *et al.* (1989) compared the far infrared and the non-thermal radio continuum emission. They showed that about half of the SO galaxies have infrared and radio continuum fluxes consistent with the relationship between these two quantities found in spiral galaxies (e.g., Wunderlich *et al.* 1987), suggesting that at least some SO galaxies are currently forming stars. They also found that the ellipticals with significant far infrared emission are more likely to have intense radio emission possible connected with nuclear activity than those without and that therefore cold gas is responsible for fueling the radio source. More recently, Fabbiano *et al.* (1989) showed that X-ray and radio luminosities are correlated. This suggests a connection between the hot gas and nuclear radio sources perhaps through accreting cooling flows fueling a central black hole. Because far infrared and X-ray emission are not correlated, as discussed above, the conclusion of these two studies are in apparent contradiction. To address this problem, we have re-examined the far infrared, X-ray and radio continuum correlations.

Recent VLA surveys by Wrobel and Heeschen (1989) and Fabbiano *et al.* (1989) are used for radio continuum data. These high sensitivity surveys (detection limit ~ 0.1 mJy) made it possible to study radio faint sources which may not be dominated by the nuclear radio emission. As an example of traditional single dish surveys, Dressel and Condon's (1977) Arecibo surveys are also used. Figure 2 shows the comparison between far infrared and radio emission (a: luminosity vs luminosity, b: flux vs flux). Three lines are drawn in the figures to illustrate the location of spiral galaxies in this plane (see Walsh *et al.* 1989). These are not the best fit to the data of spiral galaxies but just lines with a unit slope.

There seem to be three different populations of early type galaxies (see also Walsh *et al.* 1989; Bally and Thronson 1989). About 1/3 of galaxies (mostly S0) are within the line boundaries, hence are consistent with the relationship followed by spirals. This relationship is most likely due to star formation although the star formation rates in these galaxies are smaller than those in spirals. Another half of galaxies (mostly E) are above the lines with excess radio emission for a given far infrared emission. The excess radio continuum emission is related to nuclear activity (for example, active radio galaxies such as M87, NGC 1399). The excess radio emission is not correlated with the far infrared emission. There may be a third population of early type galaxies which have significant far infrared emission but do not have radio emission. This group of galaxies may only produce low mass stars or they may not produce any stars at all.

If the excess radio emission is related to the hot gas in the sense that cooling flows onto the center are the fuel for the central radio source (Fabbiano *et al.* 1989), then it is expected that the galaxies which have hot gas should fall in the region above the linear relationship in the L_{FIR}–L_{radio} plane. Figure 3 shows the results for the galaxies observed in X-rays (Canizares *et al.* 1987). The galaxies with excess X-ray emission above that expected from accreting X-ray binaries (see Fabbiano ***et al.*** 1989) are marked by filled circles and the others are marked by stars. In this diagram, the two groups of galaxies with large X-ray halos (hot gas) and with little or no halos are well segregated, suggesting that the presence of hot gas is important for the fueling of nuclear radio sources.

Table 1
Far Infrared Detection Rates[a]

	#	12μm	25μm	60μm	100μm
Total	1153	256(22%)	217(18%)	530(45%)	561(48%)
HI sample[b]					
	321	98(30%)	71(22%)	176(54%)	179(55%)
detection	89	36(40%)	35(39%)	74(83%)	72(80%)
upper limit	232	62(26%)	36(15%)	102(43%)	107(46%)
Dust lane galaxies					
	68	30(44%)	26(38%)	49(72%)	53(78%)

a. Far infrared data are from Knapp ***et al.*** (1989).
b. HI data are from Knapp ***et al.*** (1985) and Wardle and Knapp (1986).

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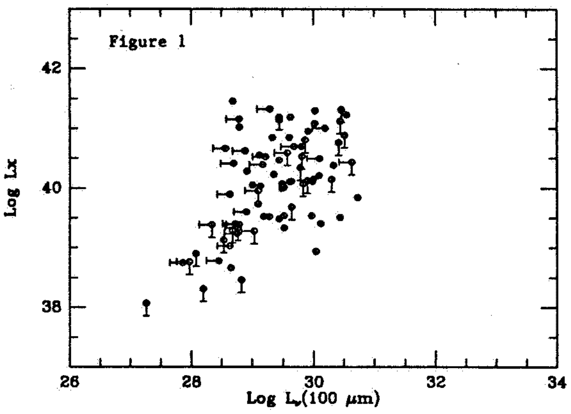

Figure 1. 100 μm luminosity vs X-ray luminosity for early type galaxies. Filled circles are detections and open circles are upper limits with bars indicating the limiting directions.

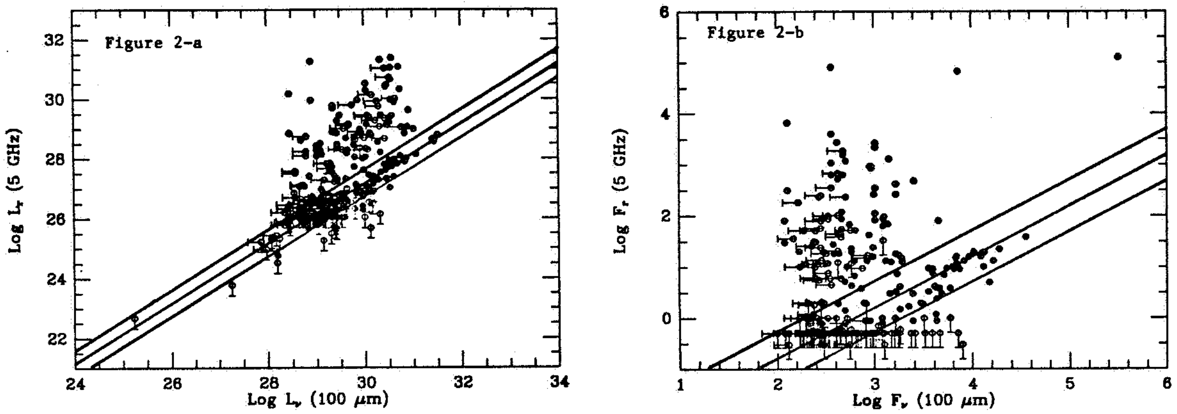

Figure 2. 100 μm luminosity vs 5 GHz radio continuum luminosity (a). The same but flux vs flux in (b). The symbols are the same as in Figure 1. The three lines indicate the location of spiral galaxies in this diagram.

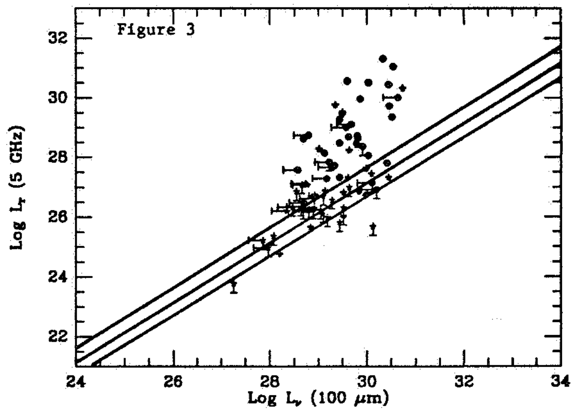

Figure 3. Same as Figure 2-a. Only galaxies with X-ray data are plotted. Filled circles are the galaxies with excess X-ray emission over that expected from stellar components and stars are those without the excess X-ray emission.