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THE ROLE OF STARBURSTS IN LUMINOUS INFRARED GALAXIES

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RESUMEN

Estudios multifrecuencia de galaxias con formación estelar, AGNs y galaxias altamente luminosas en el infrarrojo son presentados en este artículo. Estos estudios incluyen observaciones milimétricas con la antena IRAM y en rayos X con el satélite *ROSAT*. Modelos del flujo infrarrojo y radio emitido por regiones de formación estelar compactas son considerados. Las relaciones L_{FIR}/L_{5GHz}, $L_X/L_{H\alpha}$, L_X/L_{5GHz}, y L_{IR}/M_{H_2} son presentadas y discutidas. Los resultados de estos estudios indican que la formación estelar es la fuente de energía dominante en galaxias altamente luminosas en el infrarrojo.

ABSTRACT

Multifrequency studies of nearby pure starburst galaxies, AGNs with circumnuclear starbursts and more distant luminous infrared galaxies are presented. These studies include CO milimeter (IRAM) and X-ray (*ROSAT*/HRI) observations, as well as models of the radio and far-infrared flux emitted by compact starbursts. Several luminosity ratios like the L_{FIR}/L_{5GHz}, the $L_X/L_{H\alpha}$, the L_X/L_{5GHz}, and the L_{IR}/M_{H_2} are presented and discussed. The results indicate that star formation is the dominant energy source in luminous infrared galaxies.

Key words: **GALAXIES: ACTIVE — GALAXIES: NUCLEI — GALAXIES: STARBURST — STARS: FORMATION**

1. INTRODUCTION

Luminous infrared galaxies ($\log L_{FIR} > 11 L_\odot$; LIRG hereafter) are key targets to study (1) the causal relation between galaxy interactions and enhanced circumnuclear and/or nuclear star formation, and (2) the hypothesized evolution of nuclear starbursts into a massive central black-hole.

There is empirical evidence that an Active Galactic Nucleus (AGN) and starbursts may coexist in LIRGs. On the one hand, the detection in some LIRGs of VLBI compact, high brightness temperature radio cores (Lonsdale, Smith & Lonsdale 1993), and of polarized broad emission lines (Hines & Wills 1993; Hines et al. 1995) suggest the presence of a dust-enshrouded AGN. On the other hand, detection of diffuse extended radio emission (Condon et al. 1991), extended bubbles and winds with velocities of ~ 1000 km s^{-1} (Heckman, Armus, & Miley 1990), and H II-like optical emission line ratios in 50% of LIRGs (Veilleux et al. 1995) indicates the presence of nuclear and circumnuclear starbursts.

The coexistence of an AGN and circumnuclear star-forming regions is a well known phenomenon among nearby active galaxies. Prototypes of active galaxies having a circumnuclear star-forming ring ($\sim$0.5 to 3 kpc in size) and a central AGN include galaxies NGC 3504 (LINER), NGC 1068 (Seyfert 2), NGC 1097 (LINER/Seyfert 1), and NGC 7469 (Seyfert 1). High spatial resolution multifrequency studies of these nearby composite AGN plus star-forming galaxies allow to investigate the relative AGN and starburst contribution to the energy output as a function of wavelength and luminosity.

One fundamental question that still remains open is that of the dominant energy source in LIRGs. Luminous infrared galaxies are in general at distances of 100 Mpc and in most cases observations do not have enough spatial resolution to measure separately the energy output of the AGN and starburst. In addition, the large amount of dust and molecular gas hinder our view of the nuclear and circumnuclear regions of LIRGs allowing to only have a partial information.

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A direct multifrequency comparison of the measured properties of spatially resolved nearby composite AGN plus starburst galaxies with that of more distant LIRGs, gives a unique way of inferring what the dominant energy source in LIRGs is.

2. THE FAR-INFRARED – RADIO LUMINOSITY RELATION IN ACTIVE GALAXIES AND LIRGS

The far-infrared (FIR) – radio luminosity relation in active galaxies was first investigated by Sopp & Alexander (1991). These authors found that QSOs follow a FIR – radio relation similar to that of spirals, starburst galaxies, and luminous infrared galaxies (LIRG), suggesting the presence of star-forming regions in the QSO host galaxies.

Following the suggestion by Sopp & Alexander, the origin and scatter of the FIR – radio luminosity relation in active galaxies has been investigated (Colina & Pérez-Olea 1995) considering the scenario of a nuclear starburst where bright radio supernovae are created (Colina & Pérez-Olea 1992; Pérez-Olea & Colina 1995). Pure starbursts, modeled by a continuous star formation process lasting for, at least, 15 million years, cover the $6.6 \leq \log(L_{FIR}/L_{5GHz}) \leq 5.3$ range. Star formation processes characterized by different IMF slopes and mass limits do not greatly affect the value of the L_{FIR}/L_{5GHz} ratio. The major effect is due to the fraction of energy absorbed and re-emitted by dust.

According to this star-formation scenario, pure starbursts are able to reproduce the L_{FIR}/L_{5GHz} ratio observed in a large fraction of radio quiet active galaxies (RQAG) including starbursts, Seyferts, LIRG, and QSOs. However, pure starbursts cannot explain the FIR – radio relation observed in RQAG characterized by $\log(L_{FIR}/L_{5GHz})$ in the 4.5 to 5.3 range. For these RQAG, the contribution of a radio loud active galactic nucleus (AGN), dominating the radio emission output, is required.

The $\log(L_{FIR}/L_{5GHz})$ value ($\sim$5.9) measured in LIRG is consistent with the predictions of star-formation models characterized by a Salpeter IMF and upper mass limit in the 30 to 60 $M_{\odot}$ range (Colina & Pérez-Olea 1995). Even in those LIRG where a VLBI compact radio core has been detected (Lonsdale et al. 1993), the energy output of the AGN would account to only 10% – 20% of the total infrared, i.e., bolometric, luminosity (Pérez-Olea & Colina in preparation).

3. THE X-RAY EMISSION IN ACTIVE GALAXIES AND LIRGS

For a given bolometric luminosity, LIRGs are weak X-ray sources with hard X-ray fluxes two to three orders of magnitudes lower than those of bright Seyferts and QSOs (Rieke 1988). The origin of the X-ray emission in LIRG is still unclear. The presence of large amounts of dust and molecular gas suggest that the extinction along the line of sight is sufficiently high to block the X-rays coming directly from the nucleus. However, the existence of an intrinsically X-ray weak AGN and/or the contribution from circumnuclear star-forming regions can also be alternatives.

Recent *ROSAT* HRI observations of composite AGN plus circumnuclear star-forming galaxies have been complemented with similar observations of nearby starbursts, Seyferts and LIRGs. The soft X-ray fluxes have been combined with published radio continuum and Hα flux measurements to study the $L_X/L_{H\alpha}$ and L_X/L_{5GHz} ratios in pure starburst, Seyferts and composite AGN plus circumnuclear star-forming galaxies (Pérez-Olea & Colina 1996).

In composite AGNs plus circumnuclear star-forming galaxies, the contribution of the star-forming regions to the integrated X-ray luminosity decreases from $\sim$ 20% (NGC 1097) to $\sim$ 4% (NGC 7469) as the X-ray luminosity increases towards the high luminosity end ($L_X \sim 10^{43}$ erg s^{-1}).

The weak X-ray sources detected in LIRG (Arp220, NGC 3690 or Mrk 231) are characterized by X-ray to Hα and X-ray to radio luminosity ratios $L_X/L_{H\alpha} \sim 0.05$ and $L_X/L_{5GHz} \sim 20$, respectively. These values are consistent with the ratios measured in nearly edge-on nearby starburst galaxies like M82 and NGC 253, but are about 100 times smaller than those of composite AGN plus circumnuclear star-forming galaxies like NGC 1097 and NGC 7469 (see Pérez-Olea & Colina 1996 for details).

On the other hand, recent near-infrared integral field spectroscopy of the ultraluminous infrared galaxy Mrk 231 (Krabbe et al. 1996) indicate that the nucleus of this galaxy should be transparent at 2 μm and also in hard X-rays. A recent *ROSAT* PSPC soft x-ray spectrum of Mrk 231 supports this conclusion (Rigopoulou, Lawrence, & Rowan-Robinson 1996). These authors measure an hydrogen column density of only 2.8×10^{20} cm^{-2} equivalent to a visual extinction of $A_V \sim 0.15$ magnitudes. These results could suggest that Mrk 231 harbors a X-ray quiet AGN but the soft X-ray emission could also come from unobscured circumnuclear star-forming regions.

In summary, the X-ray emission measured in LIRG is consistent with being originated in relatively unobscured circumnuclear star-forming regions although the presence of an unobscured X-ray quiet QSO-type nucleus should also be considered.

4. THE L_{IR}/M_{H_2} RATIO IN ACTIVE GALAXIES AND LIRGS

The L_{IR}/M_{H_2} ratio gives a measure of the star formation efficiency in star-forming galaxies. In composite AGN plus circumnuclear star-forming galaxies, the contribution of the AGN to the luminosity affect the measured L_{IR}/M_{H_2} value. For a given molecular gas mass (M_{H_2}), the L_{IR}/M_{H_2} value will be larger than the average value measured in pure nuclear starburst galaxies, if the molecular gas is mostly associated with the starburst. IRAM CO observations of nearby pure circumnuclear starbursts and composite AGN plus circumnuclear star-forming galaxies have been combined with published interferometric CO observations of more distant LIRGs in an attempt to measure the L_{IR}/M_{H_2} ratio in different types of active galaxies and evaluate the contribution of the AGN to the luminosity in LIRGs (Planesas, Colina, & Pérez-Olea 1996).

The average L_{IR}/M_{H_2} value for pure starbursts is 23 $L_\odot$ $M_\odot^{-1}$. In composite AGN plus circumnuclear star-forming rings, the L_{IR}/M_{H_2} value increases from 35 to 50 $L_\odot$ $M_\odot^{-1}$ as a function of the bolometric luminosity (NGC 1097: 35 $L_\odot$ $M_\odot^{-1}$; NGC 1068: 42 $L_\odot$ $M_\odot^{-1}$; NGC 7469: 50 $L_\odot$ $M_\odot^{-1}$) while LIRGs have L_{IR}/M_{H_2} values in the 10 – 100 $L_\odot$ $M_\odot^{-1}$) range. If LIRGs are composite AGN plus circumnuclear star-forming galaxies, the relative contribution of the AGN and starburst to the overall luminosity changes from galaxy to galaxy, and the starburst is still in general the dominant energy source (see Planesas et al. 1996 for details).

5. SUMMARY

Luminous infrared galaxies ($\log L_{FIR} > 11 L_\odot$) should be understood as the distant analogs of nearby composite AGN plus nuclear/circumnuclear starburst galaxies where (1) starbursts are the dominant energy source, (2) AGNs could exist but in general account for 10% to 20% of the energy output, and (3) AGNs will in general not be a Seyfert 1 or QSO.

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