Astronomy with Millimeter and Submillimeter Wave Interferometry
ASP Conference Series, Vol. 59, 1994
M. Ishiguro and Wm. J. Welch (eds.)

IRAS GALAXIES

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ABSTRACT

Approximately thirty of the luminous infrared galaxies highlighted by the IRAS survey have now been mapped at high resolution using the millimeter arrays. In virtually all cases, extremely high gas concentrations are found in their nuclei ($\leq$2 kpc) and in several cases, the gas mass fraction is extremely high (25-100%). Optical and near infrared imaging of the most luminous infrared galaxies shows significant distortions, double nuclei, and/or tidal tails indicating that these galaxies have probably undergone a recent galactic interaction. The dense molecular gas probably plays a pivotal role in the evolution of such dynamically disturbed systems: being dissipative the gas readily sinks to the central regions where it may fuel a nuclear starburst and possibly build up and fuel a central active galactic nucleus. In this picture, the IRAS galaxies may be crudely characterized by three parameters: the initial mass of ISM in the progenitor galaxies, the time since the interaction, and the fraction of the total luminosity attributed to young stars versus an active nucleus. In this scenario, systems such as the antennae (NGC 4038/39) may represent the early stages of a merger before the gas has been deposited in the nucleus; Arp 220 the phase in which a large nuclear gas concentration is presently fueling a starburst/AGN, and NGC 1068 the later phase in which much of the central gas concentration has been consumed and the residual gas exists in a circumnuclear ring or arms.

1. LUMINOUS IRAS GALAXIES

The interstellar gas is probably the principle medium of rapid galactic evolution inasmuch as the gas responds dissipatively to dynamical disturbances and is the fuel for forming new populations of stars. In a disturbed system, the interstellar dust is well mixed with the young stars, and the bulk of the luminosity emerges at far infrared wavelengths. The IRAS survey thus provided a unique and fairly complete census of such rapidly evolving galaxies in the local universe at z<0.1.

Several ground based follow-up studies of the bright infrared galaxies have been done. The IRAS bright galaxy survey (Soifer et al. 1987) which includes all IRAS galaxies with the 60μm flux exceeding 5 Jy included 238 objects in the northern hemisphere at $|b| > 20°$. Virtually all of the luminous infrared galaxies in the sample are extraordinarily rich in molecular gas with H_2 masses in the range $2-50\times10^9 M_\odot$ (Sanders, Scoville & Soifer 1991) - - 1-20 times that of the Milky Way. And although the luminous ($10^{11}-10^{12}L_\odot$) and ultraluminous ($\geq 10^{12}L_\odot$) IRAS galaxies all have large masses of molecular gas, the gas contents are less elevated than the luminosities, relative to those of normal galaxies like the Milky Way. It is therefore clear that such objects are not simply scaled up, more massive versions of normal galaxies but that they represent a new, probably transitory, phase in the evolution of galaxies. For a galaxy in which the bulk of the luminosity is provided by stars, the ratio L_{IR}/M_{H_2} is a qualitative indicator of the cycling time of the interstellar medium into the stars. For the Milky Way this ratio is $4L_\odot/M_\odot$ (Scoville & Good 1989) and the cycling time for the ISM is $1 - 3 \times 10^9$ years. For the most luminous IRAS galaxies, the ratio of the luminosity to the ISM mass is as much as 10-50 times that of the Milky Way and the implied cycling times are correspondingly smaller. Similarly short time scales for the luminous IRAS galaxies are also implied by the fact that at the very highest luminosities most appear to be in the process of merging for which the time scale is $\sim 2 \times 10^8$ years (Carico et al. 1990).

In view of the fact that the infrared luminous galaxies are the dominant population in the local universe (z<0.1) at luminosities $> 3 \times 10^{11} L_\odot$ (in fact outnumbering optically selected quasars by 2:1, Soifer et al. 1987), it is believed that studies of these galaxies may lead to an understanding of the most energetic AGNs. Both the quasar and nuclear starburst activities may be fueled by gas from the interstellar medium and constraints on the quantity, spatial distribution, properties, and kinematics of the gas will be critical to understanding both the starbursts and AGNs. Millimeter interferometry offers a unique opportunity to study the molecular gas at the resolution required to link optical and infrared observations of the starbursts and AGNs.

Major questions posed by the luminous infrared galaxies are: 1) the role of large-scale galactic dynamics in determining the ISM distribution, 2) whether the high luminosity is generated by a high efficiency, short duration, starburst, or due to star formation with an initial mass function strongly biased towards high mass stars, 3) whether there exist central non-thermal energy sources contributing significantly to the luminosity, and 4) the relationship of the luminous infrared galaxies to AGNs and QSOs.

2. MILLIMETER-WAVE INTERFEROMETRY

Approximately 30 high luminosity galaxies have now been imaged with interferometers in the 2.6 mm CO line. In Table 1, the observational results are summarized for eighteen systems observed with the Owens Valley interferometer (cf. Scoville et al. 1991). Ten galaxies, some of which are in the Owens Valley sample, have also been observed using Nobeyama array (Okumura et al. 1991) and two Seyfert galaxies have been observed using BIMA (Meixner et al. 1990). The spatial resolutions of these maps are 2-7″, a factor of 10 better than is possible with a single dish observations.

The galaxies listed in Table 1 span the luminosity range $2 \times 10^{10} - 3 \times 10^{12} L_\odot$ ($\lambda = 8 - 1000\mu$m) and the masses of molecular gas in the nuclear sources are $10^9 - 4 \times 10^{10} M_\odot$ [assuming a Galactic CO-to-H_2 conversion factor: 3×10^{20} cm^{-2} (K km s^{-1})$^{-1}$)]. They all have infrared luminosity-to-molecular gas ratios significantly exceeding that of the Milky Way. It is also clear from Table 1 that the H_2 gas is very concentrated - - in many cases, the size of the CO emitting region is ≤ 1 kpc in radius. Below, we describe in detail the results for Arp 220,

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Table 1. OVRO Observations of High Luminosity IRAS Galaxies

Object	$<cz>$ km s^{-1}	D Mpc	Radius ″ (kpc)	L_{IR} $10^{11}L_\odot$	Nuclear M_{H_2} $10^9M_\odot$	M_{H_2}/M_{dyn}	CO Morphology
Mrk 231[1]	12660	174	<3.5 (2.9)	34.7	36.0		100% nuclear source
IRAS 17208-0014[2]	12850	171	<1.5 (1.2)	27.0	56.0		100% nuclear source
Arp 220[10]	5452	77	1 (0.3)	15.5	16.3	0.90	70% nuclear source
VII Zw 31[1]	16245	221	2.5 (2.7)	8.7	29.4		60% nuclear source
IRAS 10173+0828[2]	14680	196	3.5 (3.3)	6.0	9.0		40% nuclear source
NGC 6240[3]	7285	101	3.5 (1.7)	6.6	11.2	0.77	interacting pair
IC 694 (Arp 299)[4]	3030	42	1.3 (0.3)	4.1	3.6		triple source
VV114[1]	6028	78	2.5 (0.9)	4.2	10.0		double source
NGC1614[1]	4847	62	2 (0.6)	4.0	6.0		30% nuclear source
Arp 55[5]	11957	163	4 (3.2)	3.9	17.3	0.6	double source
NGC 1068[6]	1137	18	1.5 (0.13)	1.5	4.5		ring+nuclear source
NGC 7469 (Arp 298)[5]	4963	66	2.5 (0.8)	2.6	7.4	0.7	30% nuclear source
ZW 049.057[2]	3900	52	1.5 (0.4)	1.7	4.0		40% nuclear source
NGC 828[5]	5359	72	2.5 (0.9)	2.1	11.8	0.31	interacting pair
NGC 2146[7]	838	21	4/13 (0.4)	1.2	4		
NGC 520 (Arp 157)[8]	2261	29	2.5 (0.4)	0.6	3.2		interacting pair
NGC 3079[5]	1137	24	3/7 (0.3)	0.7	5	0.2	
NGC 4038/39 (Arp 244)[9]	1550	21	3.5 (0.4)	0.2	0.8		triple source

REFERENCES: (1) Scoville et al. 1989; (2) Planesas, Mirabel, & Sanders 1991; (3) Wang, Scoville, & Sanders 1991; (4) Sargent, & Scoville 1991; (5) Sanders et al. 1988a; (6) Planesas, Scoville, & Myers 1991; (7) Young, Claussen, & Scoville 1988; (8) Young et al. 1988; (9) Stanford et al. 1990; (10) Scoville et al. 1991.

NGC 3079 and NGC 1068 - - examples which illustrate some of the rich variety which is seen.

ARP 220

Arp 220 has an infrared luminosity at $\lambda = 8 - 1000\mu m$ of $1.5 \times 10^{12} L_\odot$, exceeding that in the visual by nearly 2 orders of magnitude and placing it in the luminosity regime of quasars. At optical wavelengths, the galaxy appears approximately spherical with a central dust lane and tidal tails extending up to 70 kpc away (Sanders et al. 1988). Single dish measurements show the CO emission spanning 900 km s^{-1} and the derived H_2 mass is $3.5 \times 10^{10} M_\odot$, approximately a factor of 15 greater than that of the Galaxy (Solomon, Radford, and Downes 1990).

In Figure I, the interferometric maps at 2″ resolution (750 pc) are shown from a recent Owens Valley study (Scoville et al. 1991). The continuum (mostly dust emission) and CO emission are shown in the upper panels as a function of displacement coordinates from the cm-wave radio continuum peak (Norris 1988). Both the CO and 110 GHz continuum peak are within 0.5″ of the western component of the nucleus seen in high resolution near infrared and radio maps (eg. Graham et al. 1990). In addition to the compact nuclear source, an extended CO emission component can be seen in maps with smaller velocity ranges. In the lower panels of Figure I, the emission is shown for velocity windows (ΔV = 104 km s^{-1}), centered at 5330 and 5642 km s^{-1}. The low level contours of CO emission are clearly extended along a NE-SW direction, parallel to the

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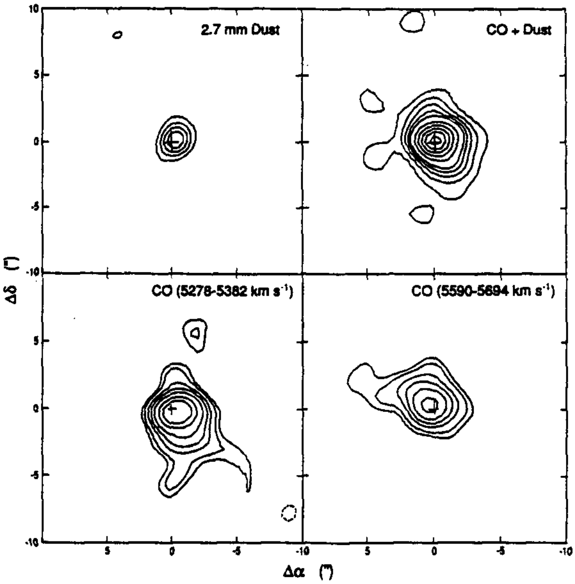

FIGURE I The $\lambda = 2.7$ mm dust emission and integrated CO emission are shown in the upper panels as a function of displacement coordinates from the centimeter-wave non-thermal radio peak in Arp 220. In the lower panels, the CO emission at 5278-5382 and 5590-5694 km s^{-1} are shown. The synthesized beam is $1.9 \times 2.1''$ (PA= 96°, Scoville et al 1990).

dust lane.

The CO emission can be separated into two components: a core $1.4 \times 1.9''$ and an extended component $7 \times 15''$ (deconvolved sizes). The former contains 2/3 of the flux detected by the interferometer; the latter contains the remaining 1/3. The H_2 masses in the core and extended components are $1.8 \times 10^{10} M_\odot$ respectively. The mean diameter of the core component ($\sim 1.7''$) corresponds to a radius of 315 pc and the H_2 density, smoothed out over the volume is 2900 cm^{-3}. The dynamical mass for the core is similar to the gas mass (H_2+He) there.

In Figure I (lower panels), a velocity gradient in both the core and extended components may be seen - the lower velocity emission displaced SW the higher velocity emission NE. A similar gradient is seen in HCN (Radford et al. 1991). The direction of this velocity gradient is parallel to the major axes (PA=52-63°) of the two CO emission components and the dust lane seen in the optical. Thus, the molecular gas has partially relaxed to a disk-like configuration with angular momentum playing a significant role in the gas distribution, probably inhibiting further collapse towards the center. The upper limit to the emission measure of ionized gas derived from the 3 mm continuum permits only $1.4 \times 10^{11} L_\odot$ for a population of only O5 stars. If a starburst is to account for the total luminosity, its duration must exceed 10^8 yr or the IMF must be deficient at $\geq 30 M_\odot$ (Scoville et al. 1991).

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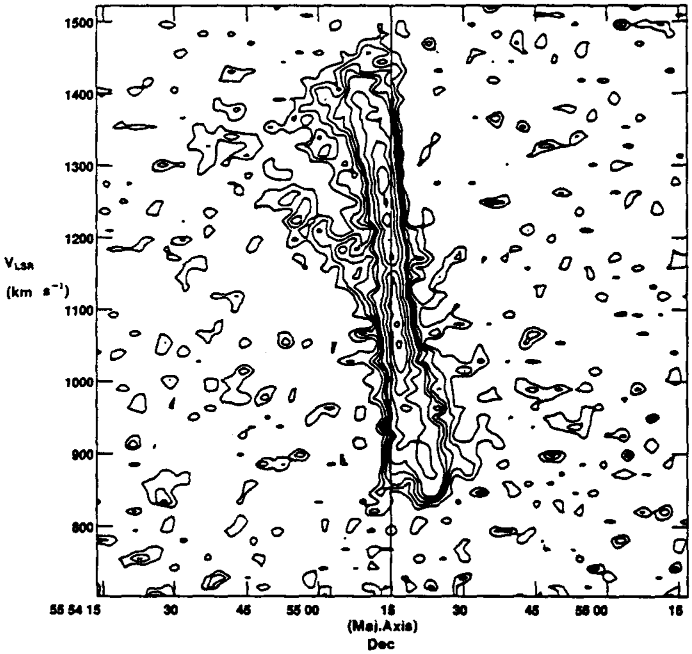

FIGURE II CO spatial-velocity map for the disk of NGC 3079 at 3.8″ resolution (Sofue & Irwin 1992).

NGC 3079

NGC 3079 is an edge-on spiral galaxy exhibiting radio lobes emerging from its nucleus and a high concentration of molecular gas within the central 1 kpc. Although the radio lobes may originate from accretion onto a compact object (Irwin & Seaquist 1988), the minor axis also exhibits strong Hα emission in a bubble morphology perhaps generated by a nuclear starburst as in M82. The galaxy has recently been studied at high resolution (3.8″ corresponding to 280 pc) in CO (Sofue & Irwin 1992) with the Nobeyama array. The spatial - velocity map (Figure II) reveals a rapidly rotating core within the central 3″ (200 pc, eg. the emission which can be seen at $\delta = 55°55'15''$, $v_{LSR} = 850$ km s^{-1}). The mass of gas contained in this component is approximately $1.5 \times 10^9 M_\odot$ and the ratio of the gas mass to the deduced dynamical mass is approximately 50%. Also evident in Figure 2 is a component which Sofue & Irwin interpret as a ring at radii $3 - 10''$ containing approximately $10^{10} M_\odot$ of molecular gas. This feature produces the two peaks at approximately 1050 and 1250 km s^{-1} in Figure II. A similar gas mass fraction is deduced for this component. Recently Tilanus & Veilleux (1992) have mapped the CO and HCN emission at 2.6 and 3.6″ resolution using the Owens Valley array and find a strong gradient in the ratio of HCN to CO with the HCN more centrally concentrated in the core source. Thus, it appears that the volume densities of the molecular clouds are considerably higher at small radii since the critical density for collisional excitation of HCN is approximately a factor of 30 larger than that of CO.

Sofue & Irwin (1992) also investigated the relationship of the molecular gas

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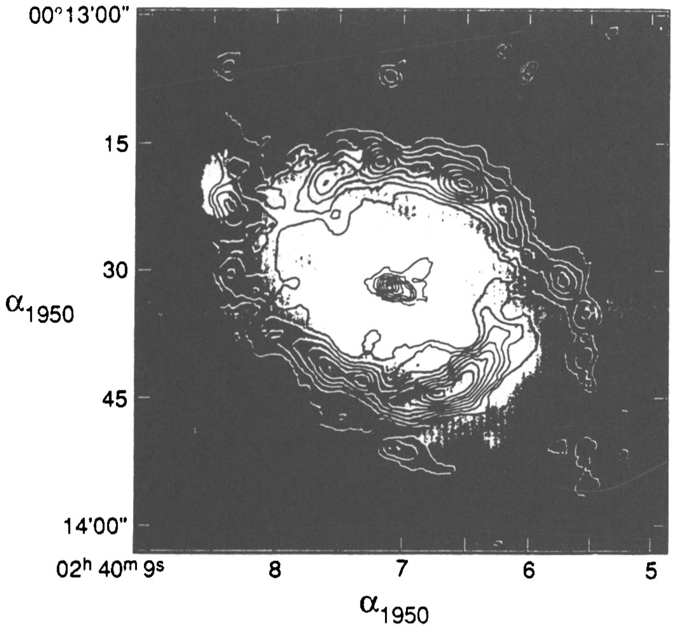

FIGURE III Map of the integrated CO emission in NGC 1068 overlaid on an optional image of the inner region of the galaxy. The synthesized beam size is 2.9″ (Planesas, Scoville & Myers 1991).

to the extended radio lobes. A modest distortion of the CO contours can be seen along the minor axis at the position of the radio "jet". This feature is evident in Figure II as the inclined CO emission feature extending to lower δ and higher velocities. They suggest that the nuclear jet is focused along the minor axis by the surrounding molecular gas.

NGC 1068

The total bolometric luminosity of NGC 1068, $3 \times 10^{11} L_\odot$, is almost equally divided between an extended inner disk of radius 1.5 kpc and a central point-like AGN source (<30 pc). Although, the AGN exhibits a Seyfert II spectrum, optical spectral - polarimetry (Antonucci & Miller 1985) reveals polarized broad emission lines suggesting an obscured Seyfert I nucleus. Radio continuum maps show a triple source with jet-like morphology on arcsecond scales. In continuum mapping at 2.2μm, a stellar bar extends $\sim$ 30″ across the inner disk at PA=48°(Scoville et al. 1988). Figure III shows a map of the CO emission at 2.9″ resolution obtained using the Owens Valley array (Planesas, Scoville, & Myers 1991). The dominant CO features are two spiral arms with the biggest complexes at the start of these arms near the ends of the 2μm bar. The arm 38 complexes have masses $10^7 - 10^8 M_\odot$. Also evident in Figure III is a CO emission region coincident with a nucleus of the galaxy for which Planesas et al. (1991) deduce a mass of $6 \times 10^7 M_\odot$. This gas (and associated dust) may hide the

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Seyfert I nucleus. NGC 1068 has also been mapped with the Nobeyama array at resolution $4.2 \times 5.2''$ (Kaneko et al. 1992). The CO emission seen by them shows a reasonable correspondence with that in Figure III with the exception that they see an additional feature extending from the arm on the southeast into the nucleus and they do not see the nuclear component. Additional observations to verify the reality of these features are needed. The former doesn't correspond to any obvious features seen in the optical or at 2μm. It is interesting to note that the molecular gas and young stars in NGC 3310 (Kikumoto et al 1992) exhibit similar distributions to those NGC 1068.

3. SUMMARY

In most of the infrared galaxies large concentrations of molecular gas are found in the nuclei but not always right on the nucleus (eg. NGC 1068). The ratios of infrared luminosity to molecular mass indicate high rates of energy production, implying relatively short bursts ($\leq 2 \times 10^8$ years) of starburst activity if the luminosity is generated by young stars.

There exist three basic models proposed to account for the high luminosities of these galaxies: the kinetic energy liberated during the collision of the interstellar media in merging galaxies (Harwit et al. 1986), nuclear starbursts (eg. Joseph, Wright, and Wade 1984), and a dust embedded active nucleus (eg. Sanders et al. 1988). The kinetic energy model runs into the severe problem that the observed luminosity in the most energetic systems can be sustained only $\sim 10^6$ years. Starburst models have two flavors - the formation of stars with higher efficiency per unit mass of interstellar gas or with an initial mass function more heavily weighted towards high mass stars than in the Milky Way. In the Galaxy, it has been suggested that high mass star formation is triggered by the expansion of HII regions or supernova shells (eg. Elmegreen and Lada 1977) or by cloud-cloud collisions (Scoville, Sanders, & Clemens 1986). It is also possible that the starburst and AGN scenarios are related. Norman & Scoville (1988) suggest that the formation of a dense young stellar cluster at the nucleus can naturally lead to the buildup of a massive black hole if the potential well is sufficiently deep to trap stellar mass loss material.

ACKNOWLEDGMENTS

This research is supported in part by NSF Grant AST 9016404.

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DISCUSSION

Y. Taniguchi Comment: Nick has presented a good correlation between the surface gas density and the star formation efficiency(L_{FIR}/M_{H2}) for the IRAS galaxies in which the molecular gas is highly concentrated in the nuclear regions. I would like to extend this analysis for starburst nuclei and relatively normal spiral galaxies. As a result, I find that there exists the general correlation between the above quantities for the IRAS, the starburst, and the relatively normal galaxies. Note, however, that the L_{FIR}/M_{H2} ratio apparently increases as the starburst proceeds. This evolutionary effect shows the opposite sence of the correlation. If we treat the observational data properly, the diagram found by Nick is highly useful to study the star formation histories for various kinds of galaxies.

R.S. Booth We have been observing a sample of southern interacting galaxies. I find that many do not show CO. Can you comment? Can you comment, also, on the relation between CO and interaction states?

N. Scoville The interacting galaxies with low CO luminosity could be systems in which the progenitors were gas-poor galaxies or they could be systems which were gas-rich but they are at a later state of merger evolution and they have exhausted their gas supply. I would guess that your systems are in the former class since I think it would be difficult to use up the gas with a very high efficiency.

S. Ishizuki What is the origin of the energy of luminous IR-galaxies. Is it starburst, or AGN? What produces the high energy production rate per unit mass of molecular gas.

N. Scoville It is certainly reasonable to believe that most of the molecular gas-rich IRAS galaxies are undergoing starbusts. The question to me is which ones have AGNs and what fraction of the luminosity comes from the AGN. At present we don't have a good handle in this issue but I believe that the potential does exist in near infrared spectroscopy (eg. Si VI at 1.9 μm) to at least say if there is an AGN. Determining what fraction of the luminosity is from the AGN versus the starburst is much more difficult.

R. Ekers Many speakers have shown images of the centimeter radio continuum emission which is often well correlated with regions of high IR & molecular emission. Much of the centimeter radio emission is non-thermal indicating the presence of high magnetic fields and cosmic ray density. Why are these two physically important constituents generally being ignored in the star burst scenario being discussed?

N. Scoville They are not being ignored (see response to Z. Wang's question).

Z. Wang This is an additional comment following Ron Ekers' comments. It is true that both magnetic field and cosmic rays are often neglected in the analysis of IRAS bright galaxies. However, the extremely good correlation between the FIR flux density and radio continuum flux density (excluding AGNs) may suggest that the variation due to magnetic field / cosmic rays may not be as important as you mentioned.

N. Scoville In the second hypothesis which I dismissed (H_2 cloud compressed in starburst galaxies by an high pressure intercloud medium), this pressure is provided by cosmic rays and the hot intercloud medium energized by young stars and supernovas.

K.Y. Lo
1) Comment: Related to your mentioning of the possible connection between CO and radio continuum in NGC3079, the poster paper by R. Plante et al on the nucleus of NGC4258, a similarly anomalous galaxy with unusual radio continuum jet and arms, shows spatial and kinematic evidence for interaction between the jet and the molecular gas.
2) From the millimeter interferometric observation of the interacting galaxies, do you have any direct evidence to support your suggestion that cloud collisions lead to starbursts?

N. Scoville The H_2 2μm emission could arise from cloud-cloud collisions but this emission could also arise in other ways.

S.K. Okumura Does your correlation diagram (Σ_{co} vs. L_{IR}/M_{H_2}) show the evolution of merging galaxies to AGN?

N. Scoville No.

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