HIDROGENO ATOMICO Y EMISION DE OH EN GALAXIAS INFRARROJAS SUPERLUMINOSAS

ATOMIC HYDROGEN AND OH EMISSION IN LUMINOUS INFRARED GALAXIES

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RESUMEN: En las galaxias luminosas en el infrarrojo encontramos eficiencias de formación de nubes moleculares y estrellas masivas, mucho más mayores que en galaxias normales. Las observaciones de hidrógeno atómico en absorción y del radical oxhidril en emisión, revelan la existencia de movimientos altamente turbulentos en las regiones centrales de las galaxias infrarrojas superluminosas. Discrepancias estadísticas entre las velocidades ópticas y de radio, sugieren que las nubes donde se originan las líneas de emisión ópticas se expanden a partir del núcleo. Las galaxias infrarrojas ultraluminosas consumen su gas en períodos de tiempo cortos comparados con la vida de una galaxia y representan una fase breve de transición hacia sistemas casi totalmente desprovistos de gas interestelar.

ABSTRACT: Luminous infrared galaxies have enhanced efficiencies of molecular cloud formation, and star

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formation, relative to normal galaxies with comparable total amounts of interstellar gas. The HI absorption and OH megamaser emission reveal high turbulent, non-circular motions in the nuclear regions of ultraluminous infrared galaxies. Outflow motions of the optical line-emitting nebulae are suggested by a statistical blueshift of the optical velocities relative to the radio velocities. Ultraluminous infrared galaxies are rapidly consuming their interstellar gas and represent a transient phase toward early type systems.

I. INTRODUCTION

One of the most important results from the IRAS survey was the discovery of extragalactic objects with total luminosities dominated by far-infrared emission. In some remarkable instances, more than 95% of the radiated flux is in the far-infrared, with luminosities greater than 10^{12} solar luminosities. These objects have the optical appearence of advanced mergers, and their study may provide clues for the understanding of the origin of early type galaxies, active nuclei, and quasars.

We first review the overall content of interstellar gas in the Luminous Sample ($L_{FIR} > 2 \times 10^{10}\ L_{o}$) of IRAS galaxies with $Z < 0.1$ (Soifer et al., 1987). The data base on the interstellar gas that we use for the analysis comes from two homogeneous surveys, one made in the 21 cm line of atomic hydrogen using the Arecibo telescope (Mirabel and Sanders, 1987a), the other in the 2.6 mm line of CO made at Kitt Peak (Sanders and Mirabel, 1985; Sanders et al., 1986). Since the data on the interstellar gas is only from two large and homogeneous surveys, the relations between the HI, H_2, and far-infrared flux, derived in the present study, are subject to the same systematic errors in all the objects of the sample.

In the second part, we point out some relevant properties of the strong maser emission in the OH main lines observed in ultraluminous infrared galaxies. The OH maser signals, as well as the HI absorption, can be used to study the kinematics of the interstellar gas in the nuclear regions of ultraluminous infrared galaxies.

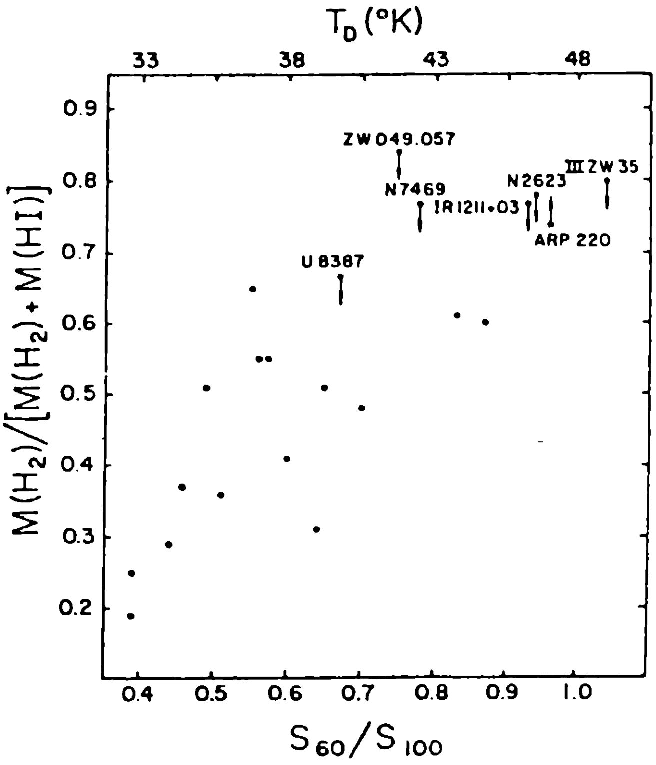

Figure 1: Fraction of molecular gas versus the 60 to 100 microns flux ratios for 23 galaxies observed in our HI and CO surveys.

2. THE EFFICIENCIES OF MOLECULAR CLOUD AND STAR FORMATION

One of the most striking results from the Arecibo 21 cm survey of HI in luminous IRAS galaxies is the frequent presence of broad absorption. Among the 90 galaxies surveyed at Arecibo we find 15 spectra with HI absorption. The absorption signals may be as broad as several hundred km/s, up to 1000 km/s. They are indicative of highly turbulent, non-circular motions of the gas along the line of sight to the nuclear radio source. Although the column densities of the absorbing HI may be as large as 10^{21} to 10^{22} atoms/cm^2 if T_s = 100 K, they correspond to masses that are smaller than 3 x 10^8 M_O.

Among the galaxies surveyed at Arecibo, there are 23 galaxies with total CO luminosities determined from single spectra. These galaxies are at redshifts larger than 4000 km/s, and are unresolved by both, the 21 cm Arecibo beam and the 2.6 mm beam of the 12-m telescope of NRAO. The H_2 masses were computed from the CO luminosities using the relation found by Sanders, Solomon and Scoville (1984).

In Figure 1 is plotted the fraction of molecular gas to total interstellar gas versus the 60 to 100 microns flux ratio. For six galaxies with HI absorption we can only estimate lower limits for the HI mass since the absorption arising in front of the nuclear radio continuum flux may neutralize the detection of atomic hydrogen emission. On the contrary, for Arp 220 a limiting mass of 4.6 x 10^9 M_O of atomic hydrogen has been found from more detailed observations by Mirabel (1982) using Arecibo, and by Baan et al. (1987) using the VLA. Therefore, for this galaxy we determine a lower limit of the $M(H_2)/[M(HI)+M(H_2)]$ ratio. Several galaxies in Figure 1 have overall fractions of molecular gas that are larger than 50% the total mass content of interstellar gas. For instance, in Arp 220 more than 74% of the interstellar gas is in molecular form, since in this ultraluminous far-infrared galaxy is found less atomic hydrogen than in the Milky Way galaxy. In our Galaxy, fractions of molecular to atomic gas greater than 50% are only found in the inner regions, at galactocentric distances smaller than 4 kpc.

Figure 1 shows that the efficiency of molecular cloud formation per unit mass of interstellar gas, and the mean temperature of the interstellar dust are correlated. This correlation is expected a priori, since a high efficiency of molecular cloud formation is a condition for the formation of stars that warm up the surrounding dust.

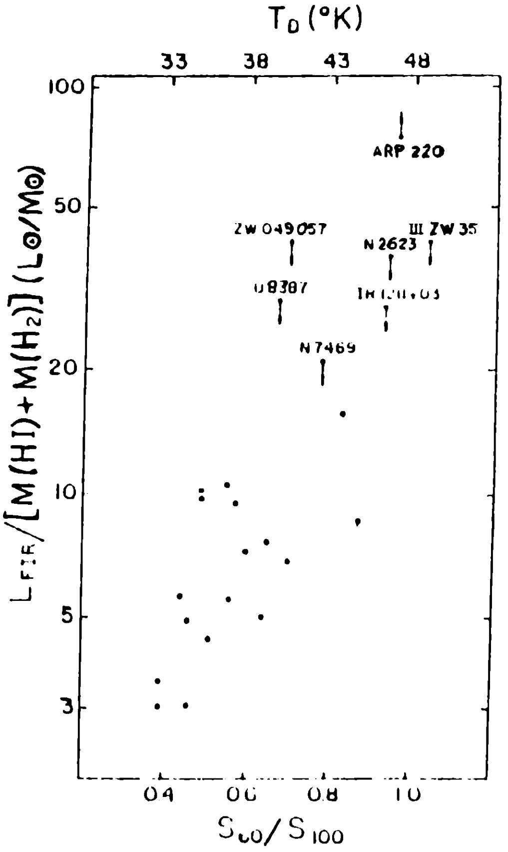

Figure 2: Current rate of star formation per unit mass of total interstellar gas versus the 60 to 100 microns flux ratios.

In Figure 2 are plotted the ratios of the far-infrared luminosities to total mass of interstellar gas versus the 60 to 100 microns flux ratios. If the far-infrared flux is thermal radiation from dust heated by stellar radiation, the quantities on the vertical coordinate provide a measure of the current rate of star formation per unit mass of interstellar gas. The correlation shown in Figure 2 is also expected a priori, since a high rate of star formation is a condition to warm up the dust. Although most of the galaxies in Figure 2 have masses of interstellar gas that are within a factor of three of the total mass of interstellar gas in the Milky Way, they have rates of star formation that are between 2 and 100 times higher than in our Galaxy. Arp 220 has a rate of star formation per unit mass of interstellar gas that is about 50 times that found in our Galaxy although its total gas content is comparable within a factor of two to that of the Milky Way.

The higher $L_{FIR}/ [M(HI)+M(H_2)]$ ratio implies that the total star formation in galaxies is determined by: (i) the total amount of interstellar gas, and (ii) an efficiency of star formation per unit of mass of interstellar gas. This efficiency of star formation is a variable that depends on the disturbances introduced in the internal large scale dynamics of individual galaxies during galaxy-galaxy interactions. All galaxies with $L_{FIR}/ M(HI)+M(H_2)$ ratios larger than 10 are colliding galaxies in a state of advanced fusion. Since the rates of star formation per unit mass of interstellar gas observed in the warm galaxies represented in Figure 2 imply that their interstellar gas will be depleted in less than 10^7 years, they must be rapidly transforming into early type galaxies.

3. COMPARISON BETWEEN THE RADIO AND OPTICAL SYSTEMIC VELOCITIES

A striking finding from our Arecibo survey of the atomic hydrogen in luminous IRAS galaxies is a clear preponderance for the HI to be redshifted relative to the optical systemic velocities. In Figure 3 are represented histograms of the velocity differences between the HI, CO and optical redshifts. The velocities of the HI (emission or absorption) are the midpoint heliocentric velocities at 20% fractional level of the peak signals (emission or absorption). The optical systemic velocities were taken in order of priority from the Center for Astrophysics Survey (Huchra et al., 1983), or the Palomar survey conducted by the IRAS group at Caltech. When no redshift was measured in the former surveys, the optical redshift is the unweighted mean of the optical redshifts catalogued by Palumbo et al. (1983).

In Figure 3a is shown a histogram of the V_{HIABS} - V_{OPT} difference for the 15 galaxies of our sample with HI absorption spectra. This difference is positive for 14 galaxies, and negative only for one galaxy. The mean value is +130 km/s. Figure 3b shows a histogram of the V_{HI} - V_{OPT} difference for the 33 galaxies with $L_{FIR} > 10^{11}$ L_{o} and HI measured at Arecibo in absorption and/or emission. The mean value of this difference is +78 km/s. The trend for the HI systemic velocities to be greater than the optical is not a consequence of systemic errors in the HI velocities. Among the 33 galaxies represented in the histogram of Figure 3b there are 15 galaxies with CO detections. A comparison of the HI and CO redshifts for these 15 galaxies is shown in

Figure 3c. Since the mean difference $V_{HI} - V_{CO}$ is only -9 km/s, we conclude that no significant trend is found between the HI and CO data.

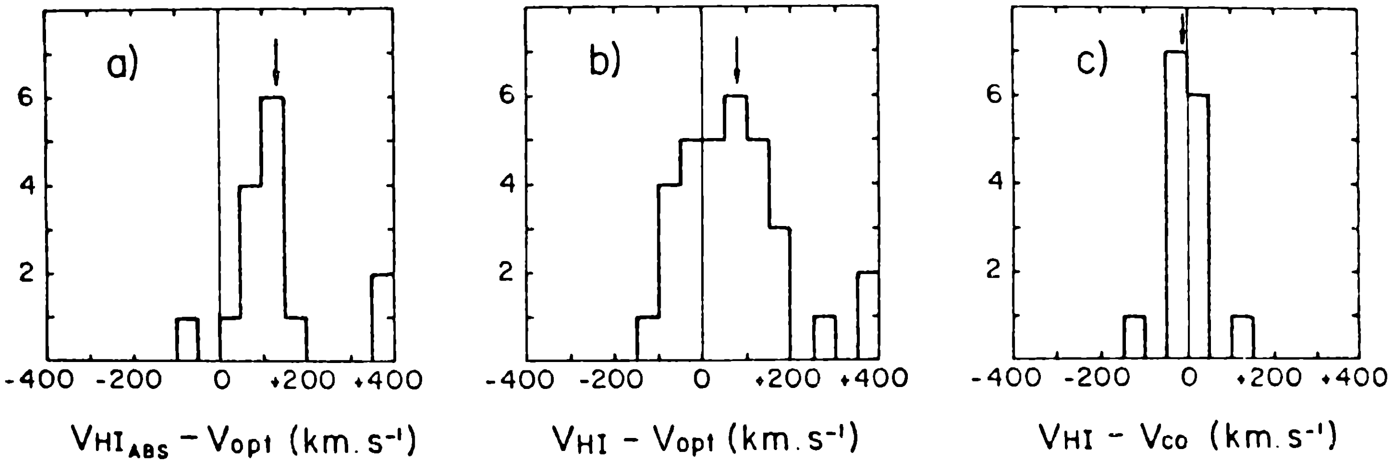

Figure 3: a) Histogram of the difference between the HI absorption and optical velocities for 15 galaxies. b) As Fig. 3a but for HI absorption and/or emission of 33 galaxies with $L_{FIR} > 10^{11}$ L_0. c) Histogram of the differences between the HI and CO redshifts for 15 galaxies with $L_{FIR} > 10^{11}$ L_0.

We favor a real difference between the radio and optical redshifts, due to the outward motion of the optical gas, in the central regions of these galaxies. The optical systemic velocities of these galaxies are often determined from narrow emission lines using low dispersion spectra. If the outwardly moving line-emitting gas is mixed with dust, the attenuation of optical emission from the far side leads to an optical redshift below systemic. The statistical blueshift of the optical relative to the radio systemic velocities, as well as the individual instances of blue wings in the narrow emission lines observed by Heckman et al. (1987), are indications for mass outflows presumably driven by the high rates of supernovae explosions occuring in the nuclei of luminous infrared galaxies. We point out that similar statistical trends have been found in Seyfert galaxies by Mirabel and Wilson (1984), and in quasars by Hutchings et al. (1987).

4. OH MEGAMASERS IN LUMINOUS FAR INFRARED GALAXIES

Extragalactic OH emission with luminosities over six orders of magnitude greater than the most luminous galactic maser have been detected so far in a total of 15 galaxies. The detections have been made by researchers using large radiotelescopes at Nancay (Bottinelli et al. 1987; Kazes et al. 1987), Jodrell Bank (Staveley-Smith et al. 1987), Parkes (Norris et al. 1987), Green Bank (Baan et al. 1985), and Arecibo (Baan et al. 1982; Mirabel and Sanders 1987b). The megamasers are detected in luminous ($L_{FIR} > 2 \times 10^{11}$) and warm ($S_{60}/S_{100} > 0.70$) far infrared galaxies with relative strong radio continuum emission coming from the nuclei.

As an example, in Figure 4 are shown the OH, HI, and CO spectra of the luminous infrared galaxy IIIZW035. The 1667 MHz line extends over 760 km/s at the 3 sigma level, and the isotropic luminosity of this 1667 emission is 527 L_o. Velocity broad OH maser emission with widths of up to 1000 km/s, and luminosities in the 1667 MHz line of up to 1800 L_o have been found in luminous IRAS galaxies. The main lines are not circularly polarized, and the ratio of the 1667 to 1665 peak emissions tend to be higher than the LTE ratio.

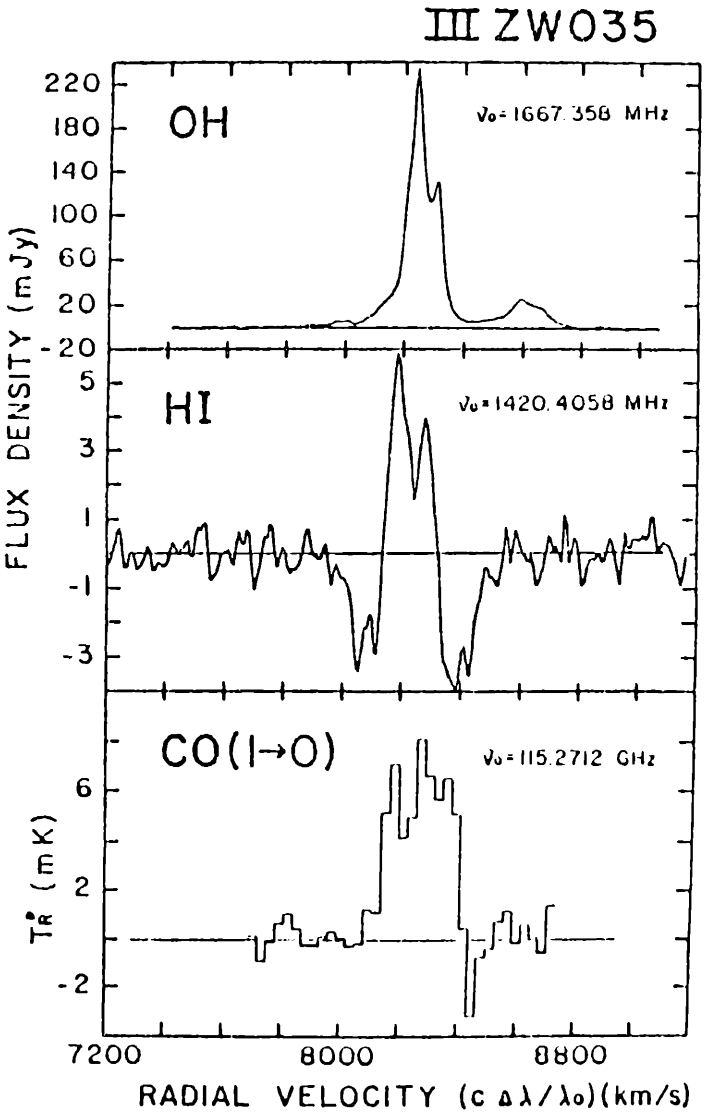

Figure 4: The OH, HI and CO spectra for the galaxy IIIZW035. The velocity scale for the OH profile refers to the 1667 line. The 1665 line is displaced by 351 km/s toward the right.

There are indications that the OH megamasers originate in physical processes that differ from those that occur in the most commonly studied galactic OH masers. The extragalactic OH megamasers are likely to arise in extended regions of low density gas. The optical depth of the interstellar gas between 30 and 120 microns is low, and the OH could be inverted by the far-infrared radiation over large distances, allowing masers to arise in large volumes of space. The velocity widths of the OH megamasers and the absence of circular polarization in the OH emission lines are indications that they are coming from extended regions.

In Figure 5 are plotted the ratios of the 1667 to 1665 fluxes versus the ratios of the 1667 peak flux to 60 microns flux, for all megamasers reported so far in the literature. There seems to be a correlation between the pumping efficiency of the infrared photons and the 1667 to 1665 MHz flux ratio. IIIZW035 and IRAS 1017+08 are the megamasers with the highest infrared pumping efficiencies, which are at least 5 times larger than in any other megamaser. The peak flux ratios between the two OH main lines in these galaxies are 9.1 and 14.6 respectively.

The extraordinary strength of megamasers suggests the possibility of their use for studies of topical interest in astrophysics. First, they can be used to probe the Universe in earlier epochs, when galaxies more commmonly underwent episodes of intense star formation. Using the Arecibo telescope, a megamaser as the one shown in Figure 4 could be detected at a redshift of 0.5. In fact, using the Nancay radiotelescope, Kazes et al. (1987) have recently detected a megamaser from a galaxy that is receding from the Sun at 22,000 km/s. The second potential use of megamasers is for high spatial resolution studies of the interstellar gas in the nuclear regions of luminous infrared galaxies.

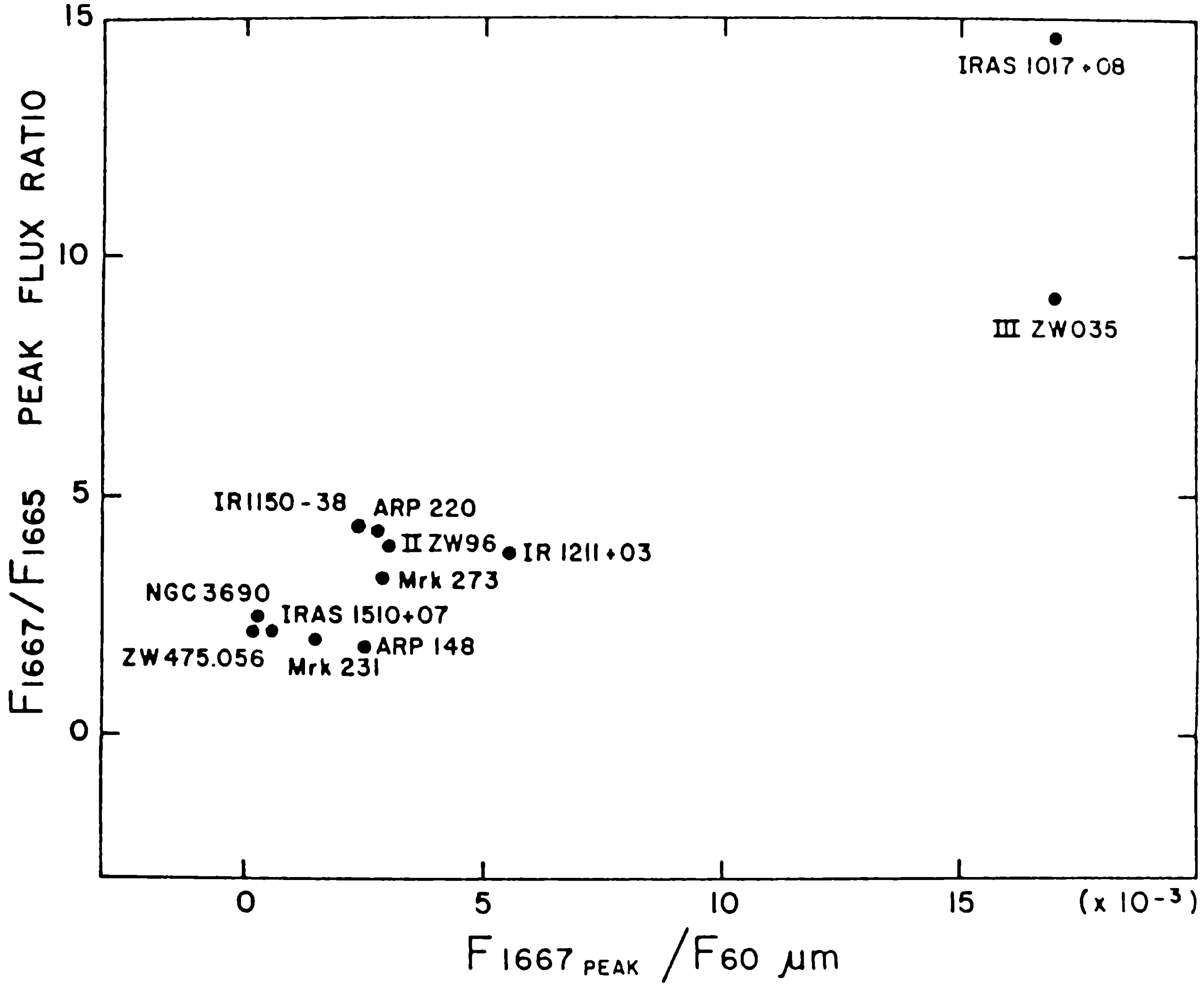

Figure 5: Peak flux ratios of the 1667 and 1665 MHz transitions of the OH versus the 1667 MHz peak flux to 60 microns flux ratio for all published megamasers.

The VLA observations of the OH emission and HI absorption in Arp 220 (Baan et al. 1984, 1987) show that all the OH emission and HI absorption comes from the inner 1 kpc. This result is consistent with the results obtained from interferometric observations of the CO (Sargent et al. 1987), and the near infrared (Becklin and Wynn-Williams, 1987).

4. CONCLUSIONS

The total amount of interstellar gas in most of the luminous infrared galaxies is within a factor of three the total amount of interstellar gas in the Milky Way galaxy. However, the star formation rate in those galaxies can be up to 100 times larger than in the Milky Way. This enhanced star formation rate per unit mass of interstellar gas is a consequence of an enhanced molecular cloud formation rate per unit mass of atomic gas. In several luminous infrared galaxies we find overall fractions of molecular gas that are comparable to the fractions of molecular gas found in the inner regions of our galaxy. The power of galaxies to form giant molecular clouds and massive stars seem to be a function of the disturbances produced in the large scale internal dynamics of the systems during galaxy-galaxy collisions. The star formation rates observed in ultraluminous infrared galaxies imply a rapid depletion of the overall content of interstellar gas, and a on-going conversion of these galaxies into early type systems.

In luminous infrared galaxies there is a clear preponderance for the optical velocities to be lower than the radio velocities. This trend is interpreted as an indirect, statistical evidence, of outflow motions of the optical emission line nebulae. Similar mass outflows seem to occur in Seyfert galaxies and quasars, since similar statistical trends between optical and radio velocities are found in these types of objects.

OH megamasers reside in the nuclei of luminous and warm infrared galaxies. Because of their remarkable luminosity, they could be used to probe the Universe at large redshifts, when galaxies more commonly underwent episodes of intense star formation. The high spatial resolution observations of the OH emission and HI absorption, show that in superluminous infrared galaxies large fractions of the interstellar gas with high turbulent motions are concentrated within the inner hundred parsecs.

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