Activity in galaxies

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In a long term project, we are investigating in various types of galaxies two fundamental quantities: the gas content M_{gas} and the luminosity L_{IR}. It is the main result of this study that the stage of activity can be well described by the ratio L_{IR}/M_{gas}, i.e. by the efficiency of producing luminosity out of a given gas reservoir.

Introduction

Most galaxies maintain their luminosity by the formation of stars – a process that normally proceeds rather quietly, for example, throughout the galactic disk in case of the Milky Way, but which can also appear as an explosive event, as in the center of an active galaxy, like M82. A few exotic objects, radio galaxies and quasars, possess an additional source of energy, probably an accreting black hole. Both star formation and black holes are fueled by the interstellar gas, and about ten years ago it was suggested that the ratio luminosity over gas mass, L/M_{gas} is linked to activity. For the Milky Way, a "normal" galaxy, this number is about 5, whereas significantly higher values are observed in active systems. In order to put the proposition, that L/M_{gas} is an indicator of activity, on a firm footing one has to reliably determine the two fundamental quantities L and M_{gas} in various types of galaxies.

Luminosity and Gas Mass

A galaxy radiates not only in the optical region, but over the entire electromagnetic spectrum, from X–rays to radio waves. During the last two decades it became clear that many output a large fraction of their total luminosity in the infrared part of the spectrum. This is due to the fact that the stellar radiation is absorbed by interstellar dust and re-emitted at longer wavelengths. Even for the Milky Way, this fraction is one third and in some galaxies it exceeds 90%. Let us define the IR luminosity as the energy emitted per unit time between 12 μm and 1300 μm = 1.3 mm. The limits are somewhat arbitrary: The lower bound comes from the infrared satellite *IRAS*, which twelve years ago conducted an all-sky survey in four filters at 12, 25, 60 and 100 μm, and the upper bound of 1300 μm marks a convenient observing band. Measurements at other wavelengths are rare because, but for a few atmospheric windows around 400 and 800 μm, they cannot be done from the ground. The important point is that between 12 μm and 1300 μm radiation by dust is the dominant emission process.

The gas content of a galaxy consists of two major components. In one, hydrogen is atomic (HI) and can be detected by its hyperfine transition at 21 cm; in the other, it is molecular (H_2) and can usually not be seen directly. To detect a cloud of molecular hydrogen, one has to observe a tracer whose emission must, of course, be sufficiently strong. In practice, this may either be dust, which is well mixed with gas independent of whether hydrogen is atomic or molecular, or carbon monoxide, a robust and easily excitable molecule. Models for the chemical composition of the interstellar medium predict that CO is roughly coextensive with H_2. As far as the spatial distribution in a galaxy is concerned, the rule of thumb says that atomic gas (HI) prevails in the outer regions, whereas molecular gas (H_2) is concentrated towards its center. In the Milky Way, the total masses of HI and H_2 are about equal, each $\sim 3\ 10^9\ M_\odot$.

Dust emission

Interstellar dust follows Kirchhoff's law so that at any wavelength the emission coefficient κ_λ equals the absorption coefficient times the Planck function $B_\lambda(T_d)$ taken at the dust temperature. T_d Now in the far IR, the dust absorption coefficient falls quickly with wavelength, approximately $\kappa_\lambda \propto \lambda^{-2}$ so that for $\lambda > 50\ \mu m$ practically all interstellar clouds become optically thin. Consequently, the far IR flux S_λ observed from a galaxy at distance D is directly proportional to the dust mass M_d and related to it through

$$M_d = \frac{S_\lambda D^2}{\kappa_\lambda B_\lambda(T_d)} \qquad (1)$$

In the Milky Way, the amount of gas is about 150 times larger than of dust. Adopting this dust-to-gas mass ratio for other galaxies, one can infer from the above equation the total mass of interstellar matter, for convenience simply called the gas mass M_{gas}.

Emission from CO

Rotational levels of CO are mostly excited in collisions with hydrogen molecules and helium atoms. The lowest radiative transition from rotational level J=1 down to J=0 has a wavelength of 2.6 mm, the next higher from J=2 to J=1 is at 1.3 mm; the lines are simply denoted by (1–0) or (2–1). It takes a density of a few hundred particles per cm^3 to thermalize the J=1 level, i.e. to populate it close to the value of thermal equilibrium at the given kinetic gas temperature. For the J=2 level, the required density is an order of magnitude higher.

Suppose that we direct our telescope towards the core of a galactic cloud. The density there is usually high and the J=1 and J=2 level are both thermalized. Consequently, the (1–0) and (2–1) lines of CO have the same antenna temperature (this is a radio astronomical unit for intensity and is measured in K). Quite contrary to this, in a CO observation of a galaxy we see not only cloud cores, but all gas, also the diffuse cloud envelopes, and the (2–1) line may well be less excited than (1–0) and thus weaker.

When we integrate the intensity in the line over the full velocity range, this is graphically just the area under the line, and multiply by the square of the distance to the source, we obtain a quantity called CO luminosity, L_{CO}. It has been verified empirically to be proportional to the gas mass, at least, roughly:

$$M(H_2) = \beta L_{CO} \qquad (2)$$

The justification for this relation is a bit obscure and it is an important problem to find experimentally the factor, which has a different value for the (1–0) and (2–1) transition, and check whether indeed it is constant. In essence, when we use the CO luminosity for estimating the gas mass, we are dealing with a dynamical method. Measuring a CO line of a single molecular cloud, Eq.(2) holds when the cloud is in virial equilibrium, so that the line width is determined by the cloud mass, and the line temperature does not deviate much from a mean value. On the other hand, when we look at a galaxy, where we have many clouds in the telescope beam, the observed line is a linear superposition of many lines, each arising from one individual cloud. Therefore Eq.(2) stays in force, although the width of the line, now typically 200 km s^{-1}, is determined by the rotational velocity of the galaxy and thus by the mass of the stars, and not the gas. In the inner regions of galaxies, where hydrogen appears only in molecular form, we can thus measure the total gas mass after Eq.(2).

Observations

The bulk of dust in a galaxy is at rather low temperatures (20...40 K) and the spectral energy distribution has its maximum typically between 100 and 200 μm. Nevertheless, experience has shown that, when all technical aspects like telescopes, receivers or atmospheric transparency are included, a wavelength of 1300 μm is best suited for observing dust in galaxies.

The observations, we are talking about here, have been conducted at the SEST, the JCMT and the IRAM 30m telescope. For the measurement of the dust emission, we used ^{3}He cooled bolometers operating at 450, 800, and 1300μm. The observing technique is identical to that at near IR wavelengths, i.e. one performs differential ON–OFF measurements in order to suppress atmospheric fluctuations. A crucial aspect of these observations is the determination of the atmospheric transmission which, especially at submm wavelengths, is severely reduced by the water vapor of the atmosphere. For this purpose, one measures the emission of the sky (which does not only absorb, but also emits) at different elevations. The fluxes were calibrated on the planets Mars and Uranus. To account for the extent of the objects, we observed at several (up to seven) positions in the galaxy. At the SEST, the diffraction limited beam size at 1.3 mm is 24″. The beam separation was fixed at 70″; this ensured that the OFF beam was free of contamination from emission from the outer parts of the galaxies. Typical integration times were 30 minutes per position.

In addition, we also observed the lower rotational transitions of ^{12}CO at 1.3 and 2.6 mm. Here we could use highly sensitive, low noise SIS receivers available at the SEST and at the IRAM 30 m telescope. Integration times for a single spectrum ranged from one to three hours.

The Samples

From the compilation of Cataloged Galaxies and Quasars Observed in the IRAS Survey (Fullmer & Lonsdale 1989) we selected samples of normal spirals, active galaxies and radio-quiet quasars with the goal to determine their gas content M_{gas} and their IR luminosity L_{IR}. Normal spirals had to fulfill the condition that their flux density at 100 μm is larger than 10Jy and their optical diameter, D_{25}, smaller than 180″; in this way, we obtained 138 normal galaxies. Active galaxies were picked from the catalogs of Markarian et al. (1989), provided their 100 μm flux density is larger than 9Jy; this gave a sample of 49 active galaxies. The radio-quiet quasars were taken from Neugebauer et al. (1986); all objects with observations at 3 or 4 IRAS bands were selected, which amounted to a sample of 29 quasars.

Because of the relative faintness of the objects, we have not yet investigated all of them in detail. Nevertheless, we already now have a statistically meaningful number of galaxies, where we have data on the 1.3 mm dust emission and the CO (2–1) and (1–0) lines. As we have used different telescopes, we can also compare dust and CO observations made with identical beam sizes.

Results

In the following, we list some results from our comparative study. Tedious as observational work is, they have been presented in a dozen papers spread over almost ten years. For those interested, details and further references may be found in Chini et al. (1995 a,b).

7.1 Normal Spirals – The spatial distribution of dust was investigated by mapping the galaxies at different mm/submm wavelengths. It turned out that the distribution of dust is comparable to the optical extent of the sources. By contrast, the CO emission is much more concentrated towards the central region ($r \leq 2.5$kpc). Analyzing the spectral energy distribution between 12 and 1300 μm, we find that the region from 100 to 1300 μm is dominated by cold dust of $T_d = 15 \pm 5$ K which contains the bulk of mass. At shorter wavelengths, dust of higher temperatures ($T_d \geq 50$ K) is required, but its contribution to the total dust mass is negligible.

Using Eq.(1) to convert the 1.3 mm dust emission into a gas mass, and integrating the energy distribution from 12 to 1300 μm to derive the IR luminosity, we find a ratio $L_{IR}/M_{gas} = 5 \pm 2$. Our galaxies range in gas mass from $2 \cdot 10^9$ to $6 \cdot 10^{10} M_\odot$ and in IR luminosity from $6 \cdot 10^9$ to $3 \cdot 10^{11} L_\odot$.

7.2 Active Galaxies – Whereas in normal galaxies star formation and thus the luminosity are spread across the disc, activity is a property of the nucleus. Therefore, the spatial distribution of dust in Markarian galaxies is – by contrast with normal spirals – strongly peaked towards the nucleus; the same holds for the CO emission. Also the spectral energy distribution is different in the sense that a single dust component of 33 ± 5 K is sufficient to describe the data between 60 and 1300 μm. At shorter wavelengths, dust hotter than 100K is responsible for the emission. Applying Eq.(1) again yields a ratio $L_I/M_{gas} = 92 \pm 53$, which is about 20 times higher than for normal spirals. The gas masses in this sample are in the range $5 \cdot 10^7 \leq M_{gas} \leq 8 \cdot 10^{10} M_\odot$ and for the IR luminosities $5 \cdot 10^9 \leq L_{IR} \leq 3 \cdot 10^{12} L_\odot$.

7.3 Quasars – Quasars certainly belong to the most active objects in the universe. Most of them are radio-quiet. The energy distributions of these objects resemble those of active galaxies. For a long time they were interpreted as originating from (non–thermal) synchrotron radiation. During the last few years, however, it turned out that the FIR/mm emission is also due to dust heated to about 40 K. Therefore, one can use again the 1.3mm dust emission to determine the gas content in these objects. We found that the gas mass in radio-quiet quasars is comparable to that in active galaxies, but the ratio L_{IR}/M_{gas} is larger, approximately 550.

Discussion

We want to discuss two aspects of our study. One concerns the accuracy and reliability of gas mass determinations, the other the stage of activity of normal spirals, Mkn galaxies and quasars.

8.1 Mass Determinations – The methods for determining the gas mass, described in Section 3 and 4, are not totally on safe ground, particularly when applied to external galaxies. We have indicated the uncertainties with respect to the CO luminosity; for the interpretation of dust emission, the weak point lies in the poor knowledge of the mass absorption coefficient κ_{1300}. To estimate the errors of the two methods, we compare the resulting gas masses. We do this by plotting in Fig.1 the ratio of two purely observational quantities: CO luminosity L_{CO} and 1300 μm-luminosity $L_{1300} = S_{1300} D^2$. We can write this ratio in the following way

$$\frac{L_{1300}}{L_{CO}} = \frac{M_{dust}}{M(H_2)} \cdot \beta \cdot \kappa_{1300} \cdot B_{1300}(T_d) \quad (3)$$

i.e. as the product of the dust–to–gas ratio , the conversion factor β in Eq.(2), the absorption coefficient κ_{1300} per gram of dust, and the Planck function. The dust temperature T_d is determined independently by submm and IRAS observations. The data of Fig.1 refer to a subset of normal spirals where we have observed the central dust emission and the CO (2–1) line with the same beam.

The scatter in Fig.1 is surprisingly small and might even be entirely attributed to observational errors considering the uncertainties of about 20% associated with the dust and CO observations. Fig.1 therefore implies first that, provided we can calibrate the conversion of L_{1300} and L_{CO} into gas mass, both methods give the same result and should therefore be quite accurate. Second, the fundamental quantities R, β and κ – or at least their product times the Planck function – do not vary much from one galaxy to another. The last point becomes even more interesting when we realize that κ_{1300} is probably more or less constant because of the common origin of dust (old stars, supernovae) and the insensitivity to grain size at this wavelength.

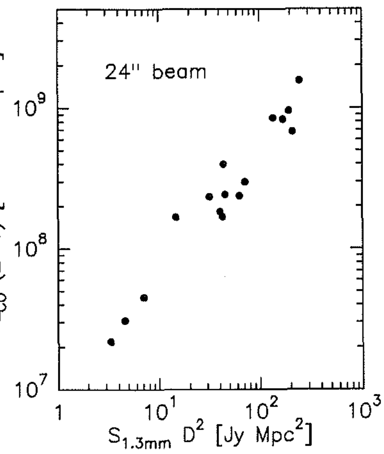

Figure 1: *The CO (2–1) luminosity L_{CO} vs. the luminosity at 1300μm L_{1300} for a sample of non-active spirals observed at SEST.*

8.2 The Stage of Activity – In Fig.2 we summarize the results concerning the ratio L_{IR}/M_{gas} for three classes of objects. We see that the luminosity itself is not an indicator of activity. For example, at luminosities from 10^{11} to $10^{12} L_\odot$, an extragalactic object may be a normal or an active galaxy or even a quasar. Put differently, out of a given gas mass one can produce significantly diverging luminosities. It is the efficiency of converting gas into luminosity, i.e. the quantity L_{IR}/M_{gas}, that determines the level of activity. Non-active galaxies are characterized by rather low values, of order 5. Active galaxies produce 20 times more luminosity out of the same reservoir of gas. The various L/M ratios reflect the vehemence of this process, extending from quiet star formation in galactic discs over explosive star bursts in galactic nuclei to quasars at the upper end of this sequence.

The high ratio L_{IR}/M_{gas} in Mkn galaxies may be explained within the framework of star formation by a combination of two effects. Either the star formation rate is enhanced compared to normal galaxies, i.e. more gas is transformed annually into stars (in the Milky Way $5 M_\odot yr^{-1}$), or the initial mass function (IMF) is biased towards massive stars of high luminosity. (The IMF describes the relation between the number of stars formed simultaneously in a certain volume and their mass.)

Undoubtedly, the star formation rate is high in active galaxies. To produce a steady luminosity of $10^{10} L_\odot$ with a normal IMF, one needs to convert $1 M_\odot$ of gas per year into stars. Therefore, activity has to end after at most 10^8 years when all gas has been used up. It is a time limited phenomenon that occurs once or repeatedly in the nuclei of normal galaxies.

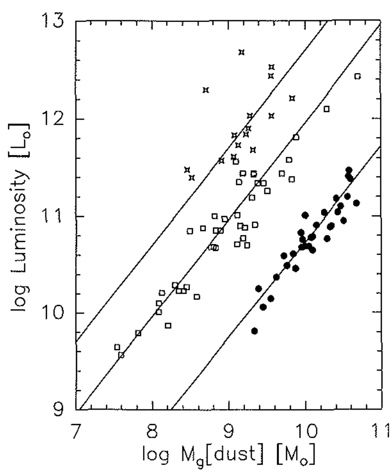

Figure 2: *IR luminosity L_{IR} vs. the gas mass M_{gas} for non-active spirals (•), active Mkn galaxies □ and radio-quiet quasars (⋆). The straight lines represent the loci of equal L_{IR}/M_{gas} with average values of 5 (normal), 100 (active) and 550 (QSO), in solar units.*

Most of their lifetime galaxies are located in the "non-active strip" of Fig.2, while occasionally they are excited to activity. The question arises what causes the transition from the quiet to the active phase. It has become clear that interaction and merging of galaxies and the subsequent transfer of gas into the nucleus plays an important role. The precise triggering mechanism is still debated. Our model computations show that under most conditions a gas-rich nucleus is intrinsically unstable towards star formation and a series of bursts (not just one) seems inevitable (Tutukov & Krügel 1995). They are based on the idea that the gas in the nucleus is supported against collapse by turbulent motions. As the turbulent energy is dissipated, the gas contracts and above some critical gas density star formation occurs. The following supernova explosions can replenish the turbulent energy so that the gas expands again. This cycle is repeated. If, for some reason, the turbulent energy of the gas is not sufficiently replenished by supernova explosions, gravity will pull the gas inwards and a catastrophic collapse towards a supermassive object ensues. This idea links star formation in galactic nuclei to quasars.

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Discovery of the first extra-galactic SiO maser, and the quest for more

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Red Supergiants (RSG) and stars at the tip of the Asymptotic Giant Branch (AGB) experience phases of heavy mass loss, which can reach values as high as $10^{-4} M_\odot$/yr. The physical conditions in the cool and dense circumstellar envelope (CE) allow dust to form: these stars may even be the main contributors of dust to the interstellar medium. Radiation pressure on the dust grains combined with collisional coupling between the dust and the gas drives the expelled matter away from the star.

The inner part of the CE is free of dust. How the matter is transferred from