THE MID-INFRARED PROPERTIES OF SPIRAL GALAXIES

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Abstract

We present the results of our study of 69 nearby spiral galaxies observed in the Mid-Infrared (MIR) at 6.75 and 15 μm with ISOCAM, the camera on-board ISO. We use these images to investigate the spatial distribution of the infrared emission as well as the relation between the infrared colors and the star formation activity in normal galaxies. We show that at ISOCAM's resolution, the nuclear regions of spiral galaxies are the only one where star formation is able to produce a significant color enhancement. In the disks of spiral galaxy, we evidence a strong correlation between the MIR brightness and the star formation rate, identical at both MIR wavelengths. We then use ISOCAM capacity to disentangle nuclear from disk emission to comment on the relation between star formation and FIR emission in normal galaxies, and present the implication this work will have in the FIRST era.

Key words: Galaxies: spiral – Stars: formation – Infrared: continuum – dust, extinction – Missions: ISO

1. Introduction

Although nearby normal spiral galaxies may not have the attractive power of their high-redshift newly-formed counterparts, they offer the invaluable advantage that the amount of data at high spatial and spectral resolution that can be gathered on them at a multitude of wavelengths will simply never be surpassed by high-redshift studies. Therefore, even if the rates of star formation are not comparable, nearby galaxies offer the opportunity to study in details the interplay between massive stars and the ISM, the relative spatial distribution of the different phases of the ISM, the abundances of these phases, and so on. Considering that these elements also play a crucial part in the appearance of high-redshift objects, one immediately realizes the potential benefits of studies of normal nearby objects.

It is with these considerations in mind that a number of programs were designed to be performed with ISOCAM. The general idea behind these programs was to map the galaxies at 6.75 and 15 μm, assuming that these wavelengths would sample dust in two different regimes. Indeed, most dust models (e.g. Désert et al. 1990) indicated that two components could emit in the MIR band, the now well-known PAH one which shows up as a series of large infrared bands, with a concentration of them in the ISOCAM 6.75 μm filter, that dominates the emission in cirrus clouds, and a still less constrained very small grain component, emitting a featureless continuum in the 10-60 μm range. It was thus assumed that maps in the 15 μm filter would emphasize regions of star formation when compared to the 6.75 μm maps. As is now realized (e.g. Contursi et al. 1997, Dale et al. 1999, 2000), the behavior of the MIR spectral energy distribution (SED) of normal galaxies is more complex than this simple picture.

All results presented here can be found, in a much more complete form in Roussel et al. 2001a, b, and c.

2. The sample

Galaxies used in this study come from five different ISOCAM programs. We first merge the results from three ISOCAM guaranteed time programs:

- The CAMBARRE program (PI C. Bonoli) was targeted at nearby barred galaxies.
- The VIRGO program (PI J. Lequeux) observed ∼100 spirals in the Virgo cluster (Boselli et al. 1998).
- The CAMSPIR program (PI L. Vigroux) mapped a few large spirals of special interest (M 51, M 83, M 101, NGC 1365, NGC 4736, 6744).

We have then added galaxies taken from the ISO archive, selected to avoid objects with non-stellar activities or strong signs of interactions. These supplementary galaxies come from the programs:

- SF_GLX (PI G. Helou) is the US guaranteed time program on star formation in galaxies (Dale et al. 2000).
- IRGAL (PI T. Onaka) is a prepraratory program for the japanes mission IRIS.

All the observations consist in raster maps in the 6.75 and 15 μm broad-band filters (LW2 and LW3), taken with a pixel field of view of 3 to 6″. Eventhough part of the sample has already been published, all data were re-reduced to get a homogenous sample. Details on the data reduction process as well as maps of the galaxies can be found in Roussel et al. (2001c).

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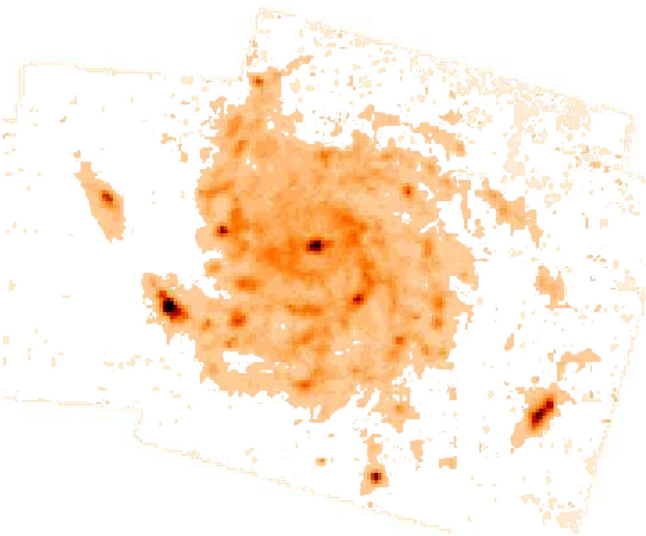

Figure 1. A 15 μm map of M 101, obtained with ISOCAM. The map shows beautifully the spiral arm structure, the external giant HII regions, which in this case, do show up as MIR color enhancements, the very small MIR nuclear condensation and some hints of a barred structure.

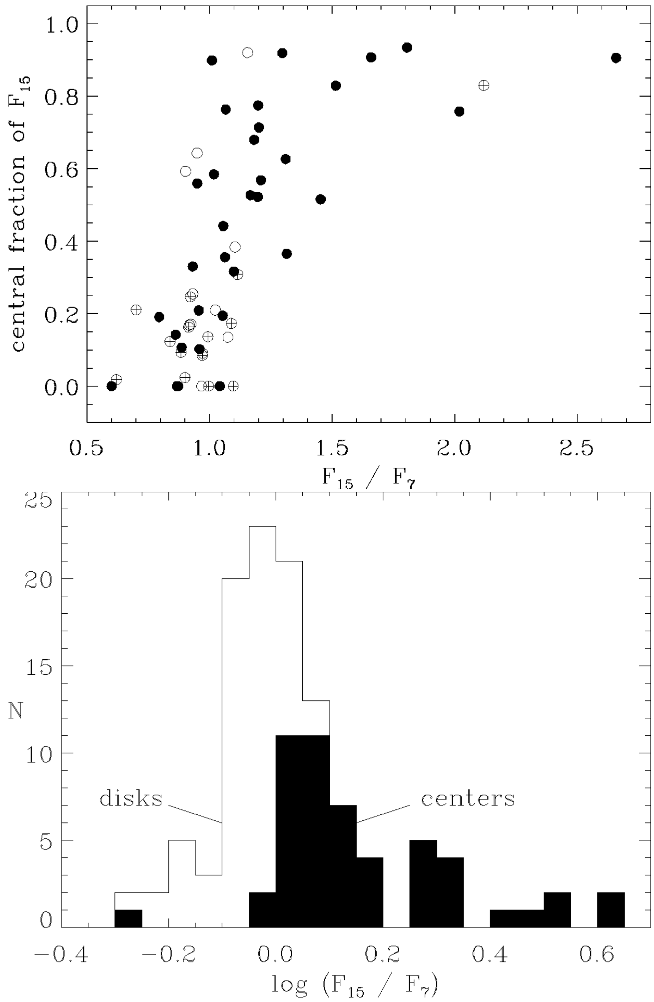

Figure 2. (a-top) The relation between the flux concentration at 15 μm and the MIR color: large MIR colors occur only in galaxies with extremely large flux concentrations. (b-bottom) Histograms of the MIR color distribution for the disks and central regions. The disk distribution is quite narrow and centered approximately around 1, while the central region colors show a much larger spread extending to very large values.

3. MIR morphologies and global colors

As mentionned in Roussel et al. (2001c), a first surprise is that the 6.75 and 15 μm morphologies are very similar. So much in fact that it is generally impossible to tell one wavelength from the other based simply on the images. Furthermore, the spiral structure is always very prominent in the galaxies and inspection of several MIR maps show that they bear striking resemblence with Hα or UV maps (see e.g. the FUV map of M 101 in Waller et al. 1997, or the comparison of Hα and 15 μm maps of M 51 in Sauvage et al. 1996).

In fact, the aspect in which MIR maps of galaxies drastically depart from what was already known at other wavelengths is in the importance of the nuclear regions. All our maps show a nuclear condensation, which is not necessarily coincident with the galaxy's bulge, of varying importance. In Fig. 1 the nuclear condensation is very small (it represents only 2% of the 15 μm flux), but in NGC 1672 it amounts to 58% of the flux, and up to 80% in NGC 7552 (see Roussel et al. 2001b and c for the method used to define the central regions, and the flux concentration fractions for the whole sample).

The central regions can not only make an important contribution to the total flux emitted by the galaxy, but they can also drastically modify its mid-infrared color, defined as $F_{15\mu m}/F_{6.75\mu m}$. As shown in Fig. 2a, it is only those galaxies with a large 15 μm flux concentration ($\geq$ 80%) that can show a significant color excess. Otherwise, most galaxies show a very similar color of $\sim$1. Furthermore, the histogram of disk and central region colors shown in Fig. 2b indicates, as expected, that the color change is strictly related to what is happening in the central regions: over our whole sample, the distribution of MIR colors in disk is clustered quite narrowly around 1 while the distribution for the central regions shows an important tail extending toward larger colors.

4. Enhanced star formation in galactic nuclei

Since the central regions of our galaxies are those that show the most variability from one galaxy to another, we have studied them in more details. In Fig. 3 we show the behavior of the 6.75 μm surface brightness and of the MIR color as a function of the molecular gas average surface density in the central regions of our galaxies (see Roussel et al. 2001b for details on the compilation of the H_2 data). As expected, given that the MIR dust emission comes from the interstellar medium, Fig. 3a shows that the MIR

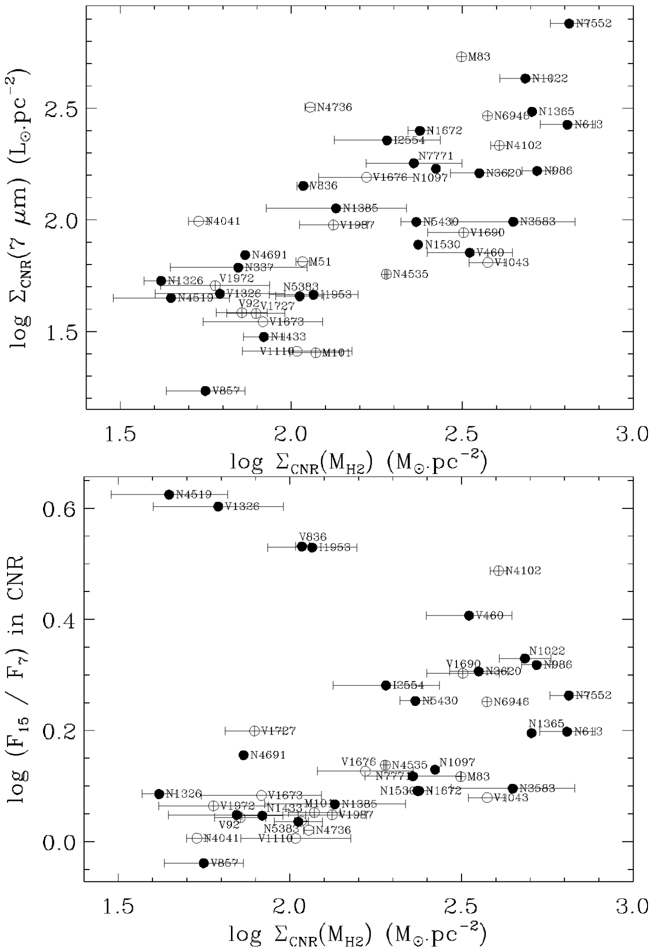

Figure 3. (a-top) The 6.75 μm surface brightness as a function of the average H_2 surface density in the central region. As can be expected, both are correlated, reflecting the fact that the MIR emission arises in the interstellar gas. (b-bottom) The MIR color as a function of the average H_2 surface density in the central region. Here again a correlation is present, which we interpret as due to enhanced star formation in the nuclei. However, at the top of the trend, the H_2 surface density drops while the color still increases.

surface brightness and H_2 surface density are correlated. More interesting is Fig. 3b where we see that the MIR color is also correlated with the H_2 surface density. If the Schmidt law applies here then a consistent explanation is that the trend is due to increasingly enhanced episodes of star formation occuring in the central regions of galaxies.

Evenmore interesting are the 4 galaxies with the largest nuclear color that completely depart from the trend. We do not think that this departure is due to an underestimation of their central molecular content (see Roussel et al. 2001b) and rather, we propose that in these galaxies the star formation episode is caught at a stage where is has consumed or dispersed most of the accumulated gas. Dust is depleted too but, given the presence of a large number of massive stars, it can still reach very high MIR colors.

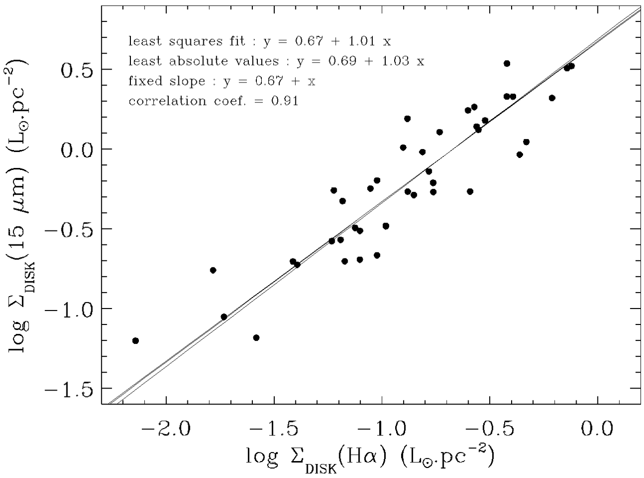

Figure 4. The correlation of the size-normalized Hα and 15 μm fluxes. The correlation is very good (correlation coefficient 0.91) and linear.

5. Star formation in galactic disks

Now that we have examined the status of the nuclear regions, let us turn to the properties of the disk. Since we have seen earlier on that the disk colors are constant and around 1, the 6.75 and 15 μm flux are interchangeable. We have compiled Hα flux for 46 galaxies of our sample (see details in Roussel et al. 2001a). Fig. 4 shows the relation between the size-normalized[1] Hα and 15 μm fluxes. The correlation is quite tight and extremely linear. This implies that in the disk of spiral galaxies, and for the regime of star formation that is encountered there, the MIR can be used as a reliable star formation indicator. The fact that the 6.75 and 15 μm flux show the same correlation with Hα indicates that the ideas exposed in the introduction regarding the behavior of these two bands were too simplistic. In the disk of galaxies, the MIR emission is dominated by the dust component that emits the infrared bands, and the increase of the star formation rate simply changes the level of this emission, but does not affect its SED.

With this in mind, we finally turn to the far-infrared (FIR). Indeed there has been a large debate as to whether the FIR fluxes collected by IRAS can be use to reliably infer the state of star formation in galaxies (see Kennicutt 1998 for a review of the issue). The information we have collected on our sample can help shed some light on this matter. In Fig. 5 we show the relation between the size-normalized FIR and 15 μm fluxes. As can be seen, the relation is extremely tight, which implies that the origin of the emissions, both in terms of dust component and of spatial distribution, have to be strongly coupled. Does our result in Fig. 4 implies that the FIR emission should be as good a star formation tracer as the MIR one? We

[1] Meaning that to get rid of size effects, the fluxes are normalized by the square of the optical diameter of the galaxy.

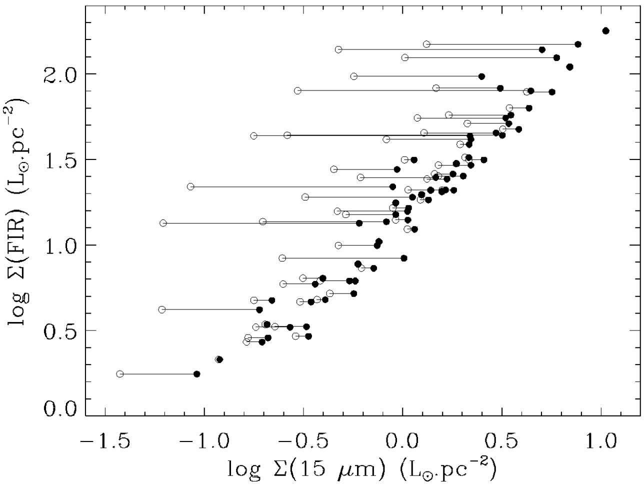

Figure 5. The correlation of the size-normalized FIR and 15 μm fluxes (filled circles). The correlation is extremely tight, implying that the two dust emissions have to come from related sites, however we have also plotted the corrections implied if one wants to consider only the disk fluxes (open circles). These can only be measured at 15 μm due to the poor IRAS resolution. However they show that it is quite likely that for a number of galaxies, the FIR fluxes are also dominated by a central region.

do not think so. One has to remember that Fig. 4 relates to disk fluxes while in Fig. 5 we plot the total flux, as the separation is impossible to do in the FIR for lack of adequate resolution. We have indicated on Fig. 5 the disk-only 15 μm flux. As one can see, the corrections can be extremely large. Thus in a number of galaxies, the IR fluxes will come mostly from the central regions, in which case our correlation no longer apply.

As a test we have checked that the FIR-Hα correlation is non-linear for our complete sample, a well-known fact that was used to indicate that the FIR fluxes do not measure accurately the star formation rate (see e.g. Sauvage & Thuan 1992), while, if we restrict ourselves to those galaxies where the disk dominates the 15 μm emission, the FIR-Hα correlation is linear. Although this remains to be demonstrated by high resolution FIR studies, this is a sign that in the disks the FIR emission could be used as a star formation tracer as well. This is however of little practical use since it is generally impossible to decouple the disk and nuclear emission component in the IRAS data. With FIRST however, such a decoupling will be possible for a large number of objects.

6. CONCLUSION

Our study of a sample of 69 nearby galaxies has revealed, among other properties not discussed in this short paper, the following facts:

- At the resolution of ISOCAM, the MIR color of the disk of spiral galaxies is quite constant and around 1 from one galaxy to the other, a color which is also that of the quiescent ISM in our galaxy.
- Only the central regions of galaxies can show significant color enhancement.
- the fraction of the total MIR flux that originates in the central region is very variable from a few percent to a dominant (i.e. $> 80\%$) contribution.
- The MIR color changes that occur in the central regions of galaxies can be interpreted as the sign of increasingly enhanced episodes of star formation. Our data also suggest that these episodes can consume/scatter the interstellar gas more rapidly than galactic dynamics is able to channel it toward the central regions.
- In the disk of spiral galaxies, both the 6.75 and 15 μm fluxes are well correlated with the Hα flux. This indicates that the MIR emission can be used as a star formation tracer in the disk of galaxies and also that the MIR emission of the disk of spiral galaxies is dominated by the dust component that is also responsible for the infrared bands.
- Finally we postulate that the reason why the FIR flux provides an unreliable estimate of the star formation rate in galaxies is because we cannot separate in the IRAS data the disk component, which should be a good tracer of star formation, from the nuclear component whose behavior with respect to star formation is less constrained.

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