ISOCAM OBSERVATIONS OF GALAXIES

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ABSTRACT

The current results of our ISOCAM Guaranteed Time observations of nearby galaxies demonstrate the wide variety of physical conditions and components that are present in mid infrared wavelengths. In the disks of normal galaxies, where the emission is dominated by the aromatic carbon particles, the mid-IR emission at 6 μm and 15 μm provides a useful star formation indicator, while the same is not true when the mid infrared emission is dominated by central HII regions, as in starburst galaxies. Early type galaxies show a variety of characteristics, from mostly photospheric emission to various degrees of dust emission, while some ellipticals are clearly dominated by strong non-thermal radio sources in the mid infrared. ISOCAM imaging spectroscopy provide strong and unique constraints on the nature of the infrared sources associated with luminous infrared galaxies.

Key words: ISO; IR astronomy; IR dust emission, galaxies.

1. INTRODUCTION

Observations of galaxies had been confined for a very long period of time to the visible and radio domains. Stellar content is probed by the galaxy emission in the visible, while the interstellar matter, HI or molecules are probed by emission in the radio domain. IRAS then brought to the fore the importance of the infrared (IR) domain in understanding the energy budget of galaxies. The infrared flux of galaxies is dominated by the radiation from dust heated by the interstellar radiation field. The shape of a galactic spectral energy distribution is determined by the fraction of the interstellar radiation field which is absorbed by the dust and radiated in the infrared, assuming a fixed dust composition and grain size distribution. IRAS observations have shown that the fraction of the interstellar radiation field which is absorbed by dust can be very large, ranging from 10% to almost 100% (Soifer et al. 1987). Therefore, observations at visible wavelengths alone cannot be used to determine the bolometric luminosity of a galaxy since they do not provide information about the absorbed energy that is emitted in the IR. The discovery of galaxies with luminosities 100 times larger in the infrared than in the visible was a major outcome of IRAS (Soifer et al, 1984). However, the lack of spatial resolution of IRAS has limited investigations to the integrated properties of galaxies, with the exception of the Magellanic Clouds, which were among the few galaxies that were well resolved by IRAS (Schwering 1989; Schwering & Israel 1989; Sauvage et al 1990). IRAS infrared color-color diagrams demonstrated that galaxies fall in a well defined sequence which has been interpreted in terms of different proportions of star forming regions, diffuse interstellar matter and active nucleus emissions (Helou 1986, Rowan-Robinson & Crawford 1989). The adequate separation of the various star forming complexes from the diffuse interstellar medium was difficult, if not impossible, before ISOCAM (Cesarsky et al. 1996a), which provided a spatial resolution of 6 arcsec, 20 times higher than IRAS, corresponding to a linear size of a few 100 pc in nearby galaxies.

About 50 nearby galaxies, spanning a wide range of morphological types, luminosities and activity levels, have been completely imaged in various ISOCAM Guaranteed Time programs. Most of the observations were done with the two main ISOCAM filters: LW2, from 6 to 8 μm and LW3, from 12 to 17 μm. The limiting surface brightness of most of these maps is 2 μJy arcsec^{-2} with a spatial resolution of 6 arcsec. The brightest galaxies have also been observed with the Circular Variable Filter (CVF) from 5 to 16.5 μm with spectral resolution of R=35. The limiting surface brightness of most of these CVF scans is 100 μJy arcsec^{-2}. The LW2 wavelength domain can be dominated by the emission of the Unidentified Infrared Bands (UIBs), at 6.2, 7.7, and 8.6 μm, carriers of which are proposed to be particles with an aromatic hydrocarbon component and stochastically heated to high temperatures (for example, PAHs: Léger & Puget 1984; Allamandola et al. 1989; coal grains: Papoular et al. 1991). Emission from hot very small carbon grains (VSGs; Desert et al. 1990) is responsible for the underlying continuum that is often present in the LW3 filters, but there can also be a significant contribution from a pseudo continuum and a wide band at 12.7 μm, which seems to be due to the same carriers which are responsible for the UIBs at shorter wavelengths.

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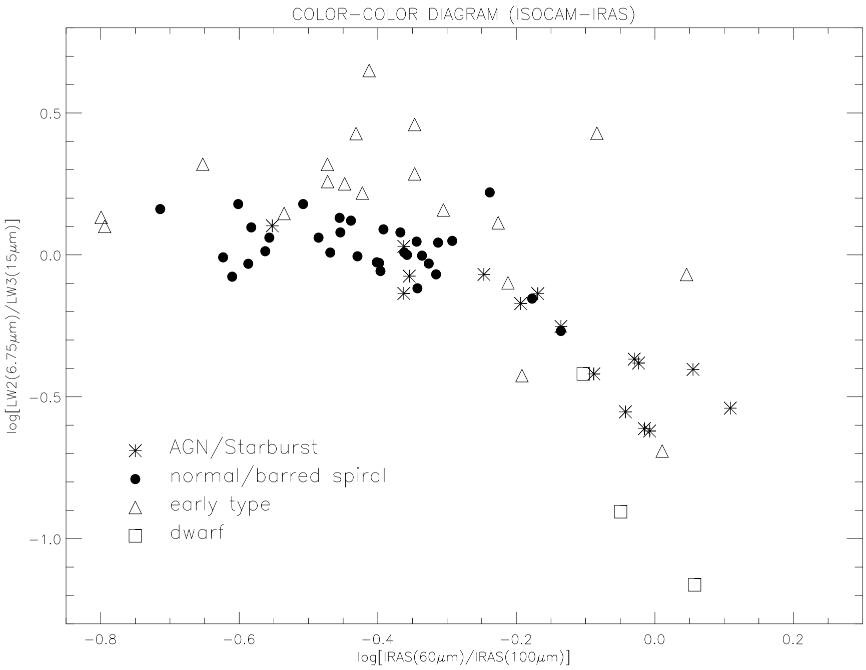

Figure 1. ISOCAM color-IRAS color diagram for galaxies in our program. The programs are separated into active galaxies, barred and normal galaxies, early-type galaxies and dwarf galaxies. Note the turn over for IRAS 60/100 flux ratios > 0.5, in the domain occupied predominately by the AGN/starbursts and dwarf galaxies. The can be explained by the destruction of the UIBs (LW2 band) in the intense radiation field, as the emission from very small hot grains (LW3) increases.

2. OBSERVATIONS OF NORMAL SPIRAL GALAXIES

From our program of normal galaxies, we find that throughout the galaxies, the mid infrared integrated colors of normal galaxies are relatively constant, with a LW2/LW3 flux ratio of the order of 1 with a large dispersion. In a LW2/LW3 flux density ratio versus IRAS 60μm/100μm flux density ratio, the sequence defined by our sample of normal galaxies is flat for galaxies with IRAS 60/100 ratios below 0.5 and decreases for the most active galaxies (Figure 1).

This result, first obtained by Helou (these proceedings) on a sample of galaxies selected to cover the whole range of IRAS colors, is confirmed for our larger sample. Early type galaxies do not follow the main trend, while blue compact dwarf galaxies are located in the region populated by the most active starburst galaxies and AGNs. Observations of Galactic nebulae (e.g. Cesarsky et al, 1996b) have shown that LW2/LW3 flux density ratios of the order of 1 are typical in the neutral interstellar medium and in photodissociation regions (PDRs), where the 2 filters at 7 and 14 μm are dominated by the aromatic bands and pseudo continuum. This ratio is much lower (<0.5) in the HII regions, where the carriers of the aromatic bands are destroyed and the 14 μm emission is dominated by the strong continuum due to hot VSGs. The mid IR colors of normal and mildly active galaxies demonstrate that their mid IR flux is dominated by the neutral ISM and PDRs. A detailed analysis of a sample of nearby spiral galaxies has shown that the emission from galaxies is dominated in the mid IR by PDRs with only a minor contribution from the neutral ISM which never represents more than 30% of the total emission at 7 μm (Roussel et al. 1999). The 7 μm maps of two well-known spiral galaxies, M51 and M83, are good illustrations of the importance of PDR emission in the disk of spiral galaxies (Figure 2).

The spiral arms are the most prominent features in these maps. At the resolution of ISOCAM, there is a good correlation between the spiral arms as seen in H_α, and the spiral arms discernible by the 7 μm emission. Color maps of 7μm/14μm flux density ratios show very small variations around the mean value of 1 observed for the disk as a whole. Since in the core of HII regions this ratio is much smaller than 1, this means that the mid IR emission is dominated by PDRs, and not the HII regions themselves. These results hold only in the disks of normal spirals. There are two noticeable exceptions to this rule. In the most active regions where strong starbursts are present, the 7μm/14 μm flux density ratios decrease below 0.5 (Figure 1). In these cases, the mid IR emission is dominated by ionized regions with strong contributions from hot VSGs. On the other hand, in low star formation galaxies like M31, (Cesarsky et al., these proceedings) the 7 μm emission does not coincide with the star formation complexes, mainly due to extinction effects. It follows, instead, the neutral gas distribution and traces the gas density.

The tight correlation between star formation complexes and mid IR emission in the disks of spiral galaxies indicates that the mid IR emission should be a good star formation efficiency indicator. Cer-

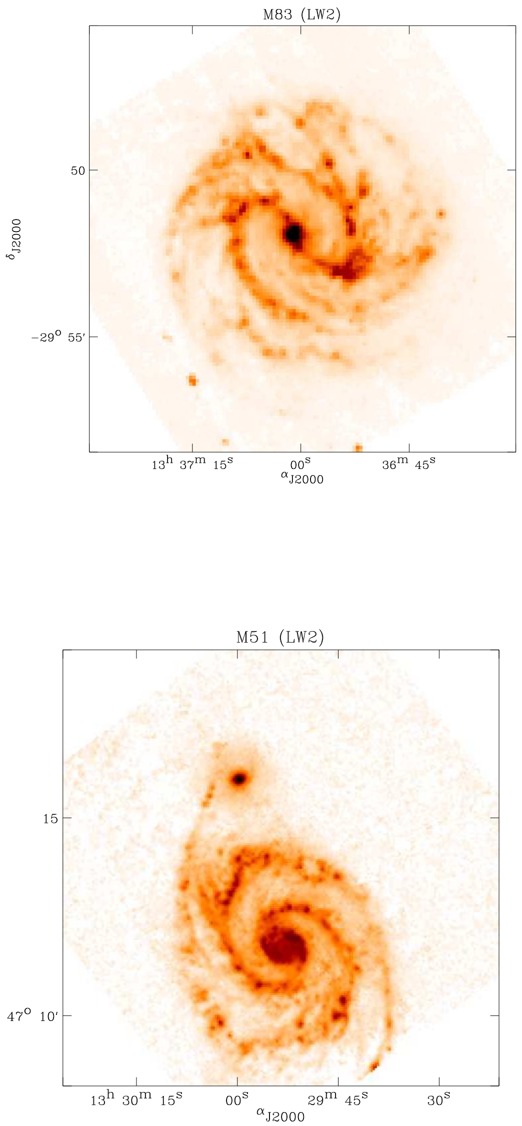

Figure 2. ISOCAM 7 μm images of M83 (upper) and M51(lower) using 6" pixel field of view

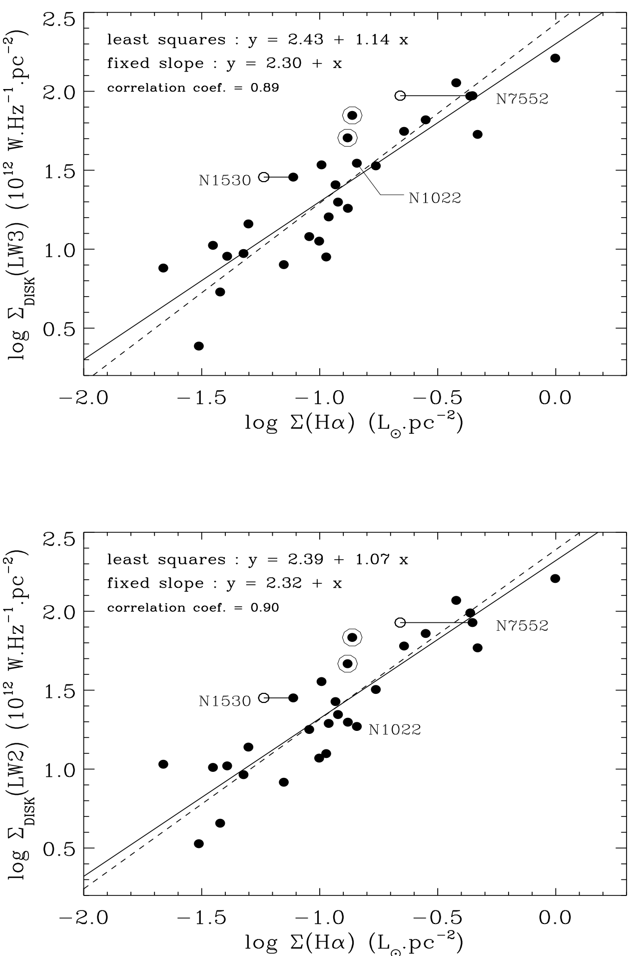

Figure 3. Relationship between surface brightnesses averaged over the whole disk of Hα and : (upper) LW3 (12 to 18 μm) ; (lower) LW2 (5 to 8.5 μm). The dashed line is the best least squares fit and the linear correlation is shown as the solid lines.

tainly, mid IR emission is less prone to absorption than Hα or Hβ. However, the conversion mechanism between the amount of young stars formed and the 15 μm flux densities is less straightforward than for hydrogen recombination lines. The Hα energy can be computed with a simple set of parameters such as density and ionizing photon fluxes, while mid IR calculations require a detailed model of dust composition and radiation transfer. Such a model does not exist at the level which is needed to derive a star formation rate from mid infrared fluxes in galaxies. But, a calibration of mid infrared fluxes can be performed using other well established indicators. Roussel et al, (1999) have shown that, in the disks of spiral galaxies, a good correlation exists between mid IR fluxes, at 7 and 15 μm and Hα (Figure 3).

This correlation holds when the total emission remains dominated by PDRs, which is the case as long as the star formation rate integrated over the disk remains < 0.1 M$_\odot$ yr^{-1} kpc^{-2}. At larger star formation rates, this relationship does not hold since the mid IR emission is dominated by the central HII regions where Hα is strongly absorbed. This is the case in central regions of barred galaxies where a high star formation rate is induced by gas mass transfer along the bar (Martinet & Friedlich 1998), or in interacting galaxies which have experienced a strong starburst due to shocks in the colliding gaseous disks (Vigroux et al. 1996). The mid IR luminosity of spiral galaxies is a combination of the luminosity of the disk and the central regions. The ratio of the central region luminosity over the disk luminosity ranges from a few percent in normal spirals to a factor 2 or more in early type barred spirals or AGN. The integrated mid IR luminosity cannot be used to derive star formation rates without knowing what the relative fractions of the disks and central regions are.

The integrated mid IR luminosity of galaxies is tightly correlated with the IRAS far infrared (FIR) luminosity (Figure 4) (Roussel et al. 1999). In recent years, the FIR luminosity has been proposed to be a reliable indicator of star formation (Devereux & Young, 1990), despite the fact that the relationship between SFR and FIR luminosity is not linear (Lonsdale & Helou, 1987, Sauvage and Thuan, 1992). The ISOCAM observations confirm that the integrated FIR luminosity is not a good indicator of star formation in normal or mildly active galaxies, since it is proportional to the integrated mid IR luminosity which, itself, is not a good star formation indicator. However, the reason for the non linearity is not the relative variation of a diffuse component and star forming complexes. It is rather due to the variation of the bright hot central regions with respect to the cold disks. FIR luminosity can be used as a good star formation indicator only in strong starburst galaxies, as has been done in the past, but not in normal or mildly active galaxies, where two mechanisms of infrared emission exist, disks where the emission is dominated by the PDRs and central regions where it is dominated by the hot continuum of grains. The long standing interpretation of the IRAS color-color diagram as due to the variation of a cold cirrus like component with respect to active star forming complexes (Helou, 1986), is no longer valid in light of ISOCAM results. The relevant parameters are the proportion of star formation in the disk and in the central regions. It is only at wavelengths longer than 100 μm that the coldest cirrus like component can take a major role in the integrated light of a galaxy.

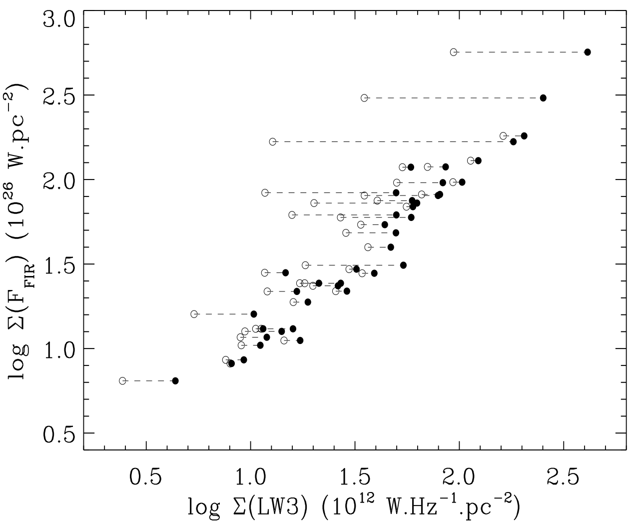

Figure 4. Proportionality between far-infrared and mid-infrared surface brightnesses. Far-IR fluxes are a combination of 60 and 100 μm IRAS fluxes as defined in Helou et al. 1988. Filled circles represent total fluxes and empty circles show the effect of taking into account only bare disks (this was possible only for LW3, since galaxies are not resolved by IRAS). The best least-squares fit gives a slope of 1.04 ($^{+0.14}_{-0.12}$ at a 3 σ confidence level) with a correlation coefficient of 0.97. The relationship with LW2 fluxes is very similar.

3. OBSERVATIONS OF EARLY-TYPE GALAXIES

IRAS has shown that up to 50% of early type galaxies can have a significant infrared emission (Knapp et al. 1989; 1992; Jura et al, 1996). This emission has been attributed to dust released by stellar winds of metal rich stars and heated by the strong interstellar radiation fields prevailing in the core of elliptical galaxies. However, some of these galaxies have strong 10 μm emission excess, the origin of which was still a matter of debate. Some authors attributed this MIR excess to photosphere emission of AGB stars (Jura et al. 1987; Knapp et al. 1992), some others to the presence of interstellar hot dust (Sauvage and Thuan, 1994). The distribution and origin of the mid infrared emission in early-type galaxies has been difficult to ascertain with IRAS data, due to the lack of spatial resolution. To address this question, we have observed a sample of 20 nearby early type galaxies spanning a large range of properties, regular ellipticals, dusty ellipticals and radio sources (Madden et al., these proceedings). The galaxies were observed through three filters, LW1 at 4.5 μm, LW2 at 7 μm and LW3 at 15 μm. The central cores were observed with the 3 arcsec lens at 7 and 15μm, and the complete galaxies at 6 arcsec with the 4.5, 7, and 15 μm filters. The results of this sample are not reconcilable with a single explanation; instead they demonstrate a wide variety of behavior in the mid IR. Stellar photospheric emission dominates the mid IR in normal ellipticals, such as NGC 1399 and NGC 2300 and, more surprisingly, also in the HI rich star forming S0 galaxies NGC 5102. These galaxies which have progressively less dust lie above the relatively flat slope of the disk galaxies in the color-color diagram of Figure 1. Low level residual dust may also be present in these galaxies, as suggested by the spectrum of NGC 1399, which also hints of a silicate emission feature. Strong 7 μm emission is found in the dusty galaxies of our sample like NGC 5266, NGC 5363 and NGC 5866, enhanced well above the 4.5 and 15 μm emission - an unambiguous signature of the presence of the aromatic bands which are ubiquitous in the photodissociation regions in Galactic sources and other galaxies. The presence of UIBs is also demonstrated by a CVF spectrum obtained toward NGC 5173 where the 11.3 microns band is detected (M.Sauvage, private communication). However, the band structure may be different from that observed in spiral galaxy disks where the 7 μm to 15 μm flux density ratio is always less than 1, in contrast to most of the ellipticals in our sample. This may be due to a difference in excitation mechanism: if UV photons, usually attributed to the heating of the carriers of the UIBs in spiral galaxies, prove to be insufficient in exciting these particles in early-type galaxies, visible photons may well be the excitation agents. Finally, some other sources have mid infrared colors which cannot be interpreted without a non-thermal continuum, as in the case of strong radio sources such as M87, Abell 426 and NGC3928.

4. INTERACTING GALAXIES

Since IRAS, interacting galaxies are known to have very large infrared emission (Soifer et al, 1984, 1987). In the most extremes cases, the Ultra Luminous Infrared Galaxies (ULIRG), almost 100% of the galaxy energy is emitted in the far infrared with a flux density peak between 60 and 100μm. IRAS observations were limited to integrated fluxes in four bands which did not provide sufficient constraints to determine the origin of the infrared emission. The two mechanisms which have been proposed are emission due to starbursts (e.g. Joseph & Wright 1985) or that due to dust shrouded active galactic nuclei (e.g. Sanders et al. 1988). Several ground-based observations have shown that most AGNs are surrounded by starburst regions, such as in NGC 1068, for example (Telesco et al, 1988; Condon et al. 1991; Downes & Solomon, 1998), yet the origin of the large IR emission of these galaxies remains a source of discussion. ISO provided the first opportunity to perform detailed studies of these galaxies offering spatial resolution with ISOCAM, and spectral resolution with SWS and LWS adequate to provide constraints on the different models. Spectral diagnostics have been obtained by Genzel et al., (1998) to separate the AGN from the starburst region. They are based on emission line flux ratios of ions, like NeII, NeIII and NeV, which provide a measure of the hardness of the ionizing photon energy spectrum, combined with the intensity of aromatic bands. These bands are absent in AGN, but dominate the mid IR emission in starburst regions. However, the spatial resolution of SWS (20 x 40 arcsec^2), and LWS (3 arcmin diameter) were not sufficient to resolve the regions which are at the origin of the infrared emission. ISOCAM, with its CVF mode, also provides a unique tool to survey the origin of this infrared emission.

Interactions between two large spiral galaxies can be observed at different stages: from weakly interacting systems like the Antennae Galaxies (NGC 4038/4039), to almost totally merged systems, like Arp 220. In the Antennae, the interaction has created the conditions for intense star formation in the region where the two disks overlap. Cold dust (Evans et al. 1998), molecular gas (Stanford et al. 1990) and CII emission (Fischer et al. 1996; Nikola et al. 1998) all peak in the overlap region. The overlap region radiates 50% of the total 15$\,\mu$m flux density of the whole system (Vigroux et al, 1996). The structure of the overlap regions in the mid infrared is very similar to the complex patches observed in radio continuum (Hummel & van der Hulst 1986). The brightest of these mid IR sources, which is not very conspicuous at optical wavelengths, radiates about 15% of the total 15$\,\mu$m flux density of the two galaxy system (Mirabel et al, 1998). All these observations demonstrate that, in this interacting system, most of the star formation takes place in the overlap region, and not in the two nuclei of the parent galaxies. A similar result has been observed in the more advanced merging system, Arp 299. In this case, the structure is even more complex than in the Antennae (Gallais et al. this volume). Two bright infrared knots dominate the mid infrared emission. But, if the west knot coincides with one of the galaxy nuclei as seen in J band, the east IR knot is displaced by 500 pc with respect to the other nucleus. The spectra of the different knots of Arp 299 can be interpreted in view of a starburst origin with varying degrees of intensity and extinction. In contrast, the mid IR spectrum of the interacting pair IRAS 19254-7245 is dominated by only one of the two nuclei, which hides a dusty AGN (Laurent et al. these proceedings). These interacting galaxies have complex structures, with starburst regions not necessarily coincident with galactic nuclei and dusty AGNs. The large beam of the two ISO spectrographs encompass a complex structure of knots with different infrared spectral energy distributions. The modeling of these observations in term of physical conditions, electron temperatures, densities, radiation flux, etc. is hampered by the complexity of the geometry of the emitting region given the SWS and LWS beam sizes. Despite its poor spectral resolution, ISOCAM CVF observations provides strong constraints on the nature of the infrared sources associated with luminous infrared galaxies (Laurent et al., these proceedings).

Radio galaxies are thought to be giant elliptical galaxies powered by accretion of interstellar matter onto a supermassive black hole. Interactions with gas rich galaxies may feed them with cold interstellar matter, but a major problem is to understand how the fueling gas finds its way from typical galactic radii of several kiloparsecs down to a few parsecs from the center, and at the rates required to power the AGN. Bar structures have been proposed in theoretical models but prove to be very difficult to observe. Centaurus A may serve as a template to investigate these questions (Mirabel et al, 1999, and references therein). Figure 5 shows the 7$\,\mu$m ISOCAM image and the 20 cm radio contours (Condon et al. 1996), overlaid on an optical image of Centaurus A. The 7 μm emission from dust reveals a bisymmetric structure of 5$'$ ($\sim$5 kpc for a distance of 3.5 Mpc) in total length. In contrast to the optical dark lanes which show a wide and somewhat chaotic distribution, the structure of the mid-infrared emission is remarkably thin, smooth and bisymmetric. The central structure corresponds to a bar 3 kpc long rotating as a solid body. This gaseous disk and its associated bar are thought to be the result of the capture of a gas rich galaxy, the gas of which settled into a disk. As the disk lies in a plane which is not aligned with the main axis of the galaxy, it is subject to a large torque (Barnes & Hernquist 1992), forcing it to warp. However, the low temperature of the gas make this disk self-gravitating and stable. A bar can develop over a few rotation period. The CVF spectra shows two main components: a central active nucleus surrounded by starburst complexes found in the central regions of the bar. These ISOCAM observations provide the first direct evidence for the mechanism which transport the material toward the central region and ultimately, to the central active nucleus.

5. CONCLUSIONS

ISOCAM observations are helping to elucidate the nature of the mid-IR emission of nearby galaxies. In doing so, we see that ISOCAM can probe the large variety of physical phenomena present in galaxies at mid infrared wavelengths, something that was motivated by IRAS, yet was not possible to constrain until ISO. Yet, despite the power that we now possess in the mid infrared to understand the physical phenomena prevailing in galaxies, one of the critical links in the picture remains the absence of comparable high spatial resolution in the far infrared. This

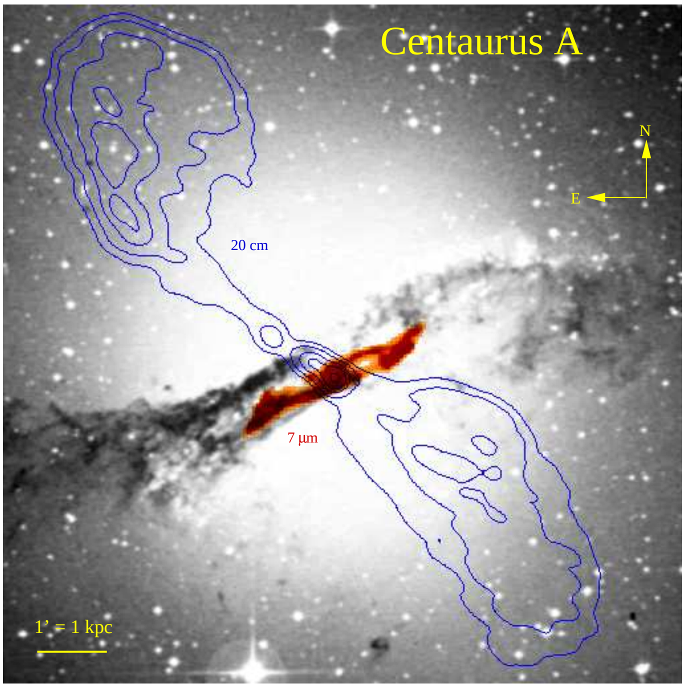

Figure 5. ISOCAM 7µm image (red) and 20 cm continuum contours (Condon et al. 1996) superposed on an optical image of Centaurus A (Mirabel et al. 1998).

aspect will await future missions which will provide far infrared measurements at the same spatial resolution as the ISOCAM maps in the mid-IR. As incentive for future missions, it should be noted that the interpretation of the emission mechanisms in nearby galaxies would have been misunderstood without the information obtained with the spectral imaging capability provided by the ISOCAM CVF. Unfortunately, such a mode does not exist in the SIRTF payload. In this respect, the interpretation of SIRTF observations will have to rely on ISOCAM CVF results for interpretation. Space-borne imaging spectroscopy will be achievable in the FIR on FIRST with the SPIRE and PACS instruments. SPIRE is based on an imaging FTS with a field of view of 2.5 x 2.5 arcmin^2 and a pixel field of view of 18 arcsec, while the grating spectrometer, PACS, will have a field of view of 1 x 1 arcmin^2 and 9 arcsec pixels. Thus SPIRE and PACS together will complement the ISOCAM observations in the far infrared.

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