# THE MID-INFRARED SPECTRA OF INTERACTING GALAXIES: FROM ISO TO SIRTF

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ABSTRACT

We present mid-infrared (5–16$\mu m$) images and spectra of a sequence of interacting galaxies, observed by ISOCAM. The galaxies were selected as being at progressive stages in the time evolution of a merging event, following what is known as Toomre's "merger sequence", and having no detected contribution from an active galactic nucleus (AGN) in their mid-infrared spectrum. To trace the intensity of the global star formation in those galaxies, we use the ratio of the 15$\mu m$ to 7$\mu m$ flux. Our analysis indicates that this ratio increases from $\sim 1$ to $\sim 5$ as galaxies move from the pre-starburst to the merging/starburst phase only to decrease to $\sim 1$ again in the post-starburst phase of the evolved merger remnants. Moreover, we find that the variation of this ratio is well correlated with the one of the IRAS 25$\mu m$/12$\mu m$ and 60$\mu m$/100$\mu m$ flux ratios. The potential to test and improve upon these results using the Infrared Spectrograph (IRS) on board SIRTF is discussed.

Key words: ISO – infrared: galaxies – galaxies: nuclei – galaxies: starburst

## 1. INTRODUCTION

One of the major steps in the understanding of galaxy evolution was the realization that tails and bridges are the result of galaxy interactions (Toomre & Toomre 1972). It was also proposed by Toomre (1977) to use the morphology of the observed tidal features and the separation between the galaxies in order to create a "merging sequence" of 11 peculiar NGC galaxies, also found in the Arp atlas. Ever since, improvements in numerical modeling of the stellar and gaseous component in galaxies have clearly demonstrated that galaxy interactions cause large scale instabilities in the galactic disks leading to the formation of transient bars which drive the gas into the center of the galaxies (Barnes & Hernquist 1992). Furthermore, numerous multi-wavelength studies of those systems (see Hibbard 1995; Schweizer 1998 and references therein) have been performed in effort to better understand phenomena such as starburst and AGN activity, as well as mass transfers and morphological transformations associated with interacting galaxies. One of the major quests in those studies remained the identification of observational characteristics which could be used as alternatives of assigning an "age" to the event of the interaction (i.e. Schweizer & Seitzer 1992). The discovery by IRAS of the class of luminous IR galaxies which harbor of obscured massive starbursts (Soifer et al. 1986) and the revelation later on that they are also interacting/merging systems (Sanders et al. 1988), attracted further attention to this problem (see Sanders & Mirabel 1996 for a review).

In this paper we examine the global star formation activity in a sample of interacting galaxies as it becomes evident in the mid-infrared via the heating of the dust.

## 2. THE SAMPLE

The galaxies of our sample were part of the ISOCAM (Cesarsky et al. 1996) active galaxy proposal CAMACTIV (P.I. F. Mirabel). The galaxies were observed in the spectro-imaging mode with the Circular Variable Filter (CVF) or, for weaker sources, in the raster mode with broad band filters. Information on the whole CAMACTIC sample as well as on the observational techniques can be found in Laurent (1999) and Laurent et al. (1999). The standard data reduction procedures pertinent to ISOCAM data were followed resulting in a photometric accuracy of 20%.

The galaxies were selected with an *apriori knowledge* of their stage of interaction and also based on the fact that the AGN contribution is negligible in the mid-infrared (Laurent et al. 1999). They form an evolution sequence from galaxies in early stages of interaction: NGC4676, NGC 3263, and NGC 520; to galaxies approaching a merger stage: NGC3256, NGC6240 and Arp220; and finally to the classified late merger remnants: NGC7252 and NGC3921. The selection process and details on the galaxies are beyond the scope of this paper and will be presented in Charmandaris et al. (2000).

## 3. DISCUSSION

### 3.1. The ISO results

In Figures 1 and 2 we present mid-infrared images and integrated spectra of the galaxies in our sample. All galaxies show evidence of star formation activity as it's indicated by the presence of the Unidentified Infrared Bands (UIBs)

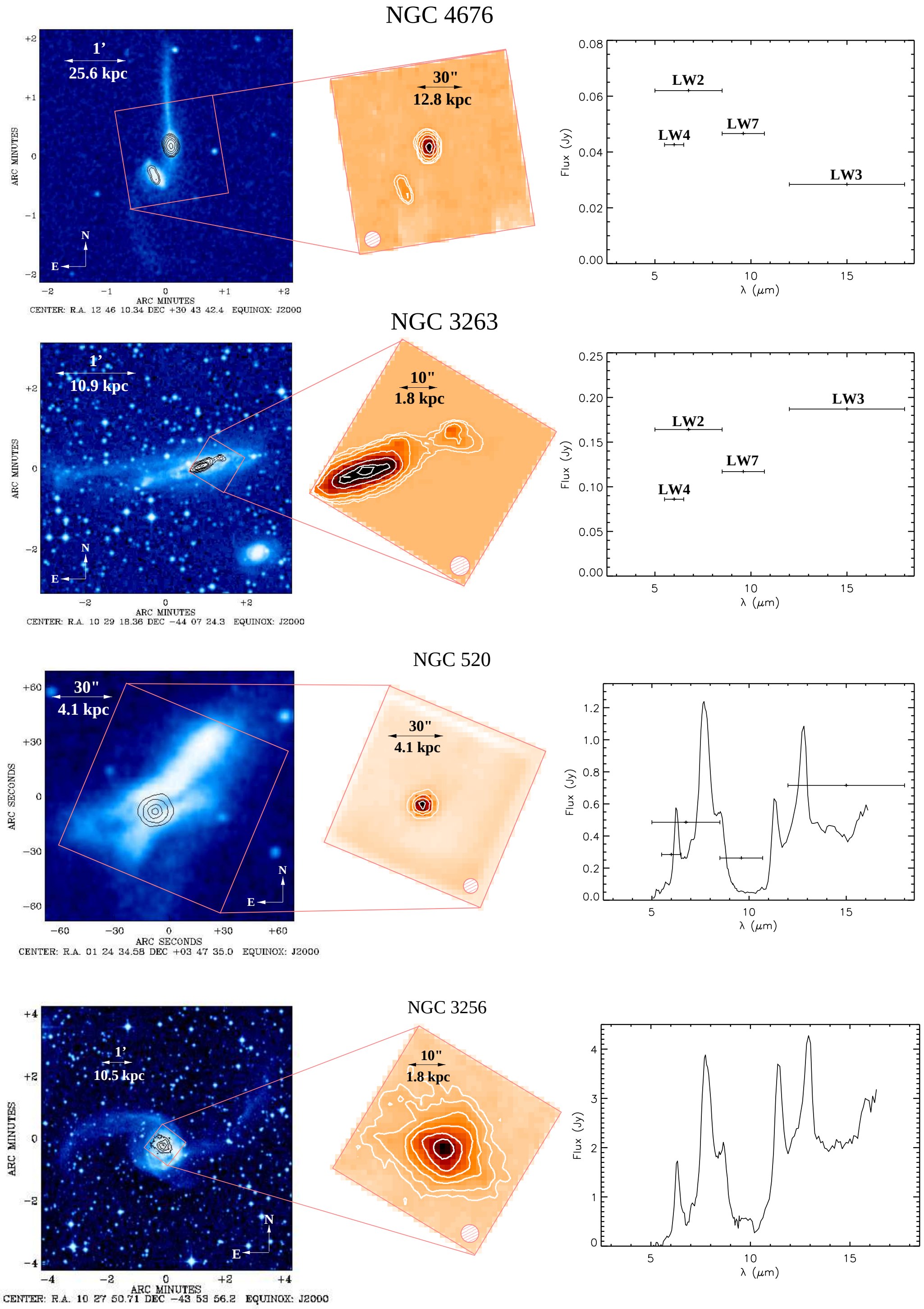


*Figure 1. In this figure we present four of the eight galaxies of our sample found in increasing stages of interaction. From NGC 4676 at the top to NGC 3256 at the bottom. For each galaxy we include an optical DSS image on the left, marked with the box imaged by ISOCAM, a 7μm image in the middle and the mid-infrared spectrum of the galaxy on the right. Note how the flux beyond 10μm progressively increases comparing to the strength of the UIB features. The horizontal bars indicate the width of several of the broad band filters used in the observations. NGC 4676 and NGC 3632 as well as NGC 3921 (see Fig. 2) were observed only in broad band filter mode.*

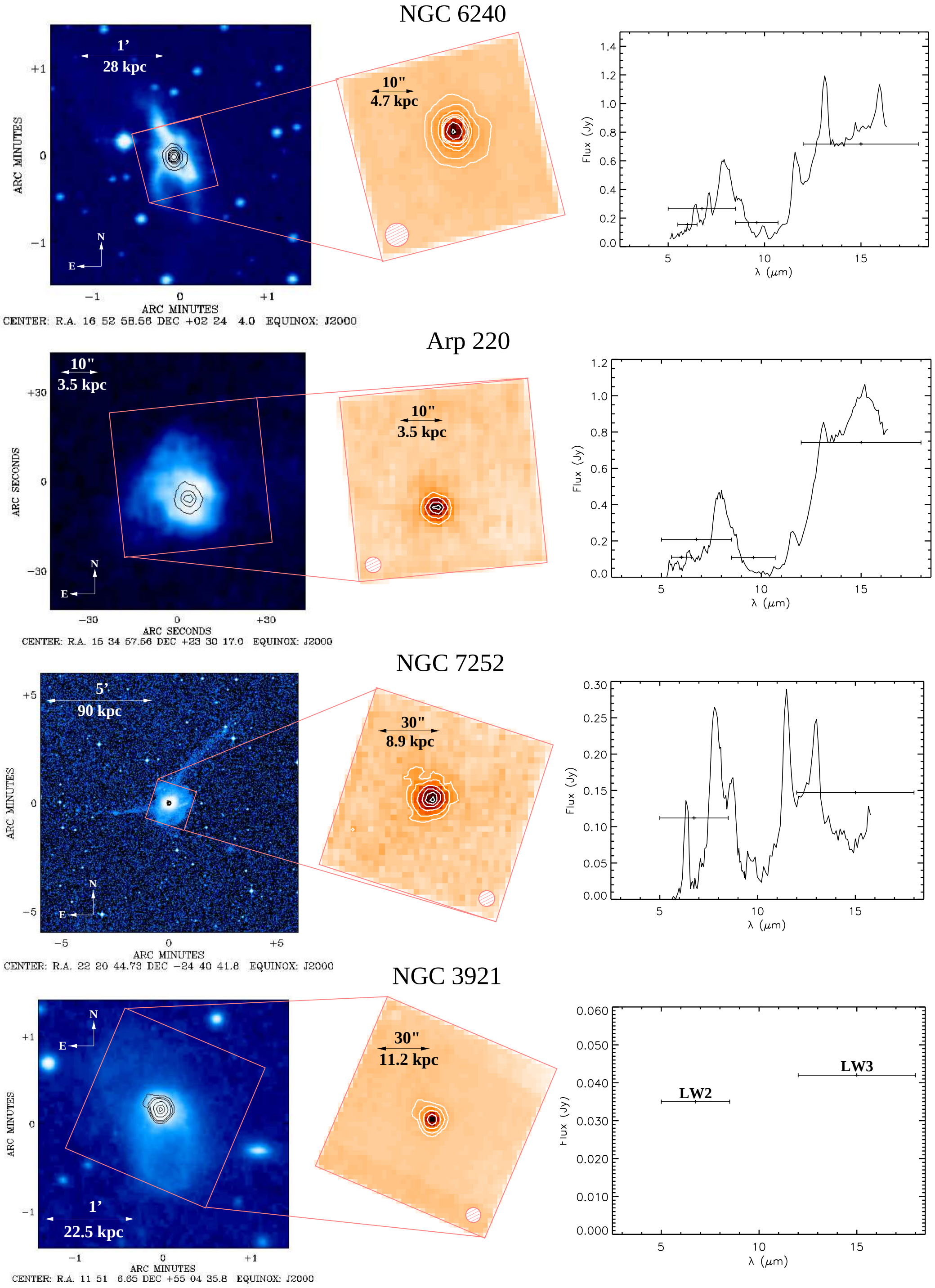


*Figure 2. Same as in Fig. 1 for the remaining four galaxies. The mid-infrared continuum reaches its peak emission in Arp220 and progressively decreases in NGC7252 and NGC3921. The solid circle in the mid-infrared 7μm images indicates the FWHM of the point spread function.*

in their spectra (Léger & Puget 1984). Two trends became apparent from those figures:

As we move from early stage interactions to mergers the continuum at 12-16 $\mu$m is rising very steeply. This continuum is attributed to Very Small Grains (VSGs) with radius less than 10 nm (Désert et al. 1990), and is prominent in regions actively forming stars. It reaches its peak in

NGC6240 and Arp220, which host massive starbursts, and progressively becomes flatter in post-starburst systems.

The fraction of the mid-infrared flux associated with the UIB features decreases when we reach the starburst phase. This can be easily seen by observing the strength of the 7.7$\mu$m feature. This could be due to the fact that in massive starbursts one has numerous young stars and their associated HII regions. As a result the filling factor of the photodissociation regions where UIBs form would decrease as well as the corresponding UIB emission.

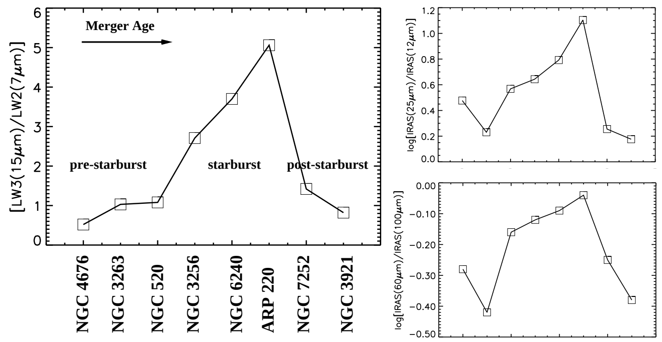


*Figure 3. A comparison of the variation of the ISOCAM LW3/LW2 flux ratio along the merging sequence, with the well known IRAS flux ratios. Note how well the ISOCAM starburst diagnostic follows the evolution of the star forming activity/merger age of the sequence. One may effectively consider the LW3/LW2 ratio as a tracer of the location of FIR peak of the bolometric luminosity. The IRAS 12$\mu$m and 25$\mu$m fluxes, corrected for the extent of the galaxies, have been kindly provided by D.B. Sanders (Univ. Hawaii).*

One can attempt to quantify this phenomenon by observing the variation of the global mid-infrared colors of the galaxies. We present the flux ratio the total broad band LW3(12-18$\mu m$)/LW2(5-8.5$\mu m$) for our galaxies in Figure 3. This has been proposed as an indicator of the fraction of the VSG continuum to the UIB feature emission and it is close to 1 for quiescent star formation (Boselli et al. 1998). As we clearly see this ratio presents a monotonic variation with the intensity of the star formation activity in the galaxies.

We can also examine how the IRAS colors vary across the same sequence of galaxies. Of particular interest is the IRAS60$\mu m$/IRAS100$\mu m$ ratio since this indicates the location of the peak of the spectral energy distribution. The correlation of the ISOCAM LW3/LW2 diagnostic ratio with the IRAS colors is apparent. The only discrepant point is NGC4676, but this can be understood since one of the galaxies has an old stellar population which can contribute to the mid-infrared emission (Hibbard 1995).

This result suggests that *even though the bolometric luminosity of interacting luminous infrared galaxies is found at $\lambda \geq 40\mu m$, the study of the mid-infrared spectral energy distribution can be used to trace the location of the far-infrared peak.* Moreover, the higher spatial resolution one can achieve in the mid-infrared (Soifer et al. 2000) would further facilitate the identification of the most active regions in the galaxies (ie. Mirabel et al. 1998)

## 3.2. The SIRTF/IRS contribution

Strong absorption by dust can distort the apparent morphology of interacting galaxies, hiding the main heating source and revealing to us only reprocessed radiation. Consequently, ISO estimates of the absorption using measurements of line strengths (Lutz et al. 1996) may be biased towards lower limits. The use of the depth of the 9.6$\mu$m silicate absorption feature could be an alternative, but as seen in Arp220 this feature can often be nearly saturated and the underlying continuum is poorly determined.

IRS, the infrared spectrograph (Houck et al. 2000) on board SIRTF, with a spectral coverage from 5.3 to 40 $\mu$m will enable to address this issue. Improved estimates on the absorption could be obtained using the depth of both silicate absorption bands (at 9.6 and 18 $\mu$m) and the shape of the mid-infrared continuum (Dudley & Wynn-Williams 1997). Moreover, the superb sensitivity and good spatial and spectral resolution of IRS will allow us to further expand the diagnostic of Fig.3 in fainter more distant systems.

## REFERENCES

Barnes J.E., Hernquist L.E., 1992, ARA&A 30, 705
Boselli A., Lequeux J., Sauvage M., et al., 1998, A&A 335, 53
Cesarsky C., Abergel A., Agnese P., et al., 1996, A&A 315, L32
Charmandaris, V., Laurent, O., Mirabel, I.F., et al., 2000, (in preparation)
Désert, F.-X, Boulanger, F., Puget, J.L., 1990, A&A, 237, 215
Dudley C.C., Wynn-Williams C.G., 1997, ApJ 488, 720
Houck J., van Cleve J., Brandl B., et al., 2000, this volume
Hibbard J., 1995, Ph.D. Thesis, Columbia Univ.
Laurent O., 1999, Ph.D. Thesis, Univ. Paris XI
Laurent, O., Mirabel, I.F., Charmandaris, V., et al., 1999, A&A. (submitted)
Léger A., Puget J.L., 1984, A&A 137, L5
Lutz D., Genzel R., Sternberg A., et al., 1996, A&A 315, 137
Mirabel I.F., Vigroux L., Charmandaris V., et al., 1998, A&A 333, L1
Sanders D.B., Mirabel, I.F. 1996, ARA&A 34, 749
Sanders D.B., Soifer B.T., Elias J.H. et al. 1988, ApJ 325, 74
Schweizer, F. 1998, in "Galaxies: Interactions and Induced Star Formation", Saas-Fee Advanced Course 26, 105
Schweizer F., Seitzer P., 1992, AJ 104, 1039
Soifer B.T., Sanders D.B., Neugebauer G., et al., 1986, ApJ 303, L41
Soifer B.T., Neugebauer G., Matthews, K., et al., 2000, AJ 119, 509
Toomre A., 1977, in "The Evolution of Galaxies and Stellar Population", eds. B.M. Tinsley & R.B. Larson, 401
Toomre A., Toomre J., 1972, ApJ 405, 142