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Detection of the 3.3 μm feature in two starburst galaxies

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Abstract. This paper reports the detection of the 3.3 μm emission feature in the centre of two external galaxies: IC 694 (interacting with NGC 3690) and NGC 4194 (a merger). This feature has been previously detected in various galactic and extragalactic objects and is thought to be due to very small grains or large molecules that probably belong to the Polycyclic Aromatic Hydrocarbon (PAH) family. Its presence, as well as the IRAS colours, strongly suggest that these galaxies are dominated by starbursts rather than active nuclei. From published data and the present observations, we study the brightness of the feature in different galaxies. A simple model of radiative transfer shows that the 3.3 μm feature brightness of a given galaxy allows the determination of the unreddened surface brightness of the galaxy stellar content. In galaxies with relatively large extinction, the 3.3 μm feature (and the other PAH related features) is therefore a useful spatial indicator of star-formation activity in their centres.

Key words: galaxies: general – individual: NGC3690 – IC 694 – NGC4194 – irregular – Interstellar medium: dust

1. Introduction

An important goal of extragalactic astrophysics is to understand the nature and spatial extension of sources of energy in galaxies. Optical astronomy has provided a great deal of information at high resolution (~1″) on the stellar distribution but, because of obscuration by dust, has failed to quantitatively assert the regions of recent star formation. On the other hand, far infrared (FIR) astronomy has yielded important results on the global energetics of galaxies, specially after the *Infrared Astronomical Satellite* (IRAS) mission. However, the resolution at FIR wavelengths is only a few arcminutes at present. By contrast, ground-based near infrared (NIR) studies provide resolutions comparable to optical ones and suffer less from obscuration than the optical ones. In this context we specifically study here the use of an unambiguous emission feature at 3.3 μm. In Sect. 2, we report the detection of this feature in two galaxies that show signs of strong activity thought to be due to a starburst. We briefly discuss in Sect. 3 the origin of the feature in the two galaxies and in Sect. 4 we show how its brightness can be related to the unreddened surface brightness of stars, an essential parameter for galaxies.

2. Observations and results

The two galaxies IC 694 (forming, with NGC 3690, the closely interacting system Arp 299 ≡ Markarian 171) and NGC 4194 were observed during the night of 1987 May 3, using the 3 m Infrared Telescope Facility (IRTF). The instrument used in the L atmospheric window (3.1–3.8 μm) was the new Cooled Grating Array Spectrometer (CGAS: Tokunaga, Smith and Irwin, 1987) with 32 InSb detectors. It has an entrance aperture of 2.7 arcsec diameter and, with the 'A' grating (75 lines per mm), gives a resolution of $\lambda/\Delta\lambda \simeq 180$ at 3.3 μm. The total spectral coverage was ~ 0.6 μm with no dead space and no overlap between adjacent pixels. Pixel 13 measurement has been eliminated because it consistently yielded erratic results. Sky subtraction was achieved by chopping in declination by 120″ (well outside the main body of the galaxies), every three seconds of integration. The star used for flux calibration, HD 129653, $\alpha = 14$h 40mn 38s, $\delta = 37°00'07''$, $L = 6.9$ (Elias et al., 1982), was observed within 0.1 of the airmass of the two galaxies. Wavelength calibration was achieved via emission lines of an Argon lamp. The total integration time (including chopping) was only 8 mn for IC 694 and 10 mn for NGC 4194, as rapidly rising bad weather prevented us from observing them longer.

Figures 1 and 2 show the reduced spectra of the two galaxies. The vertical bars represent the statistical uncertainty of each mean value (1 σ). They seem to be larger than the relative pixel-to-pixel flux variations (the atmospheric transparency may have varied during the integration). The only feature present in this small spectral range is the 3.290 μm emission feature (Tokunaga and Young, 1980) detected at a redshift in agreement with the velocity of the galaxy. The data are given in Table 1.

The telescope was quickly centered on the brightest optical spot of the two galaxies and the positions were subsequently reconstructed by reference to nearby bright stars with an accuracy estimated to 3 arcsec. The position for IC 694 is within 3″ of

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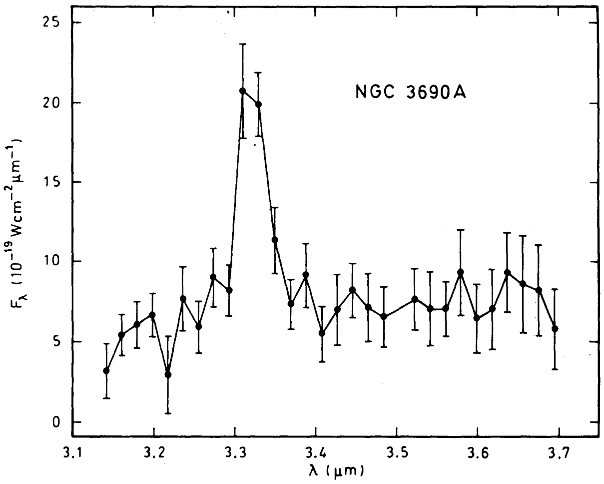

Fig. 1. Spectrum of IC 694. Pixel 13 (3.50 µm) has been removed (see text)

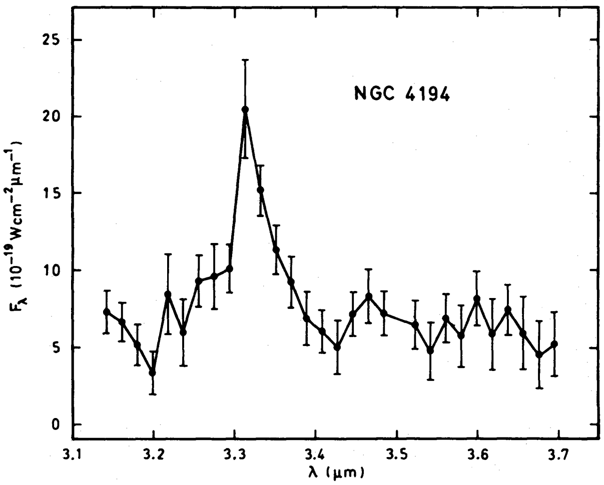

Fig. 2. Spectrum of NGC 4194. Pixel 13 (3.50 µm) has been removed (see text)

Table 1. Summary of observations

	NGC 3690A	NGC 4194
Observed position	= IC 694	
$\alpha(1950)$	11h 25mn 44.3s	12h 11mn 41.1s
$\delta(1950)$	+58° 50′ 20.9″	+54° 48′ 16.8″
Velocities[a] (km s^{-1})	3160	2500
3.3. µm feature parameters		
$W_{3.3}$ (µm)	0.059 ± 0.012	0.036 ± 0.020
$P_{3.3}$ (10^{-16} W/m^2)[b]	5.0 ± 0.9	3.4 ± 1.0
IRAS fluxes[c]		
F_4 (100 µm, in Jy)	109.7	25.2
F_1/F_4	0.034	0.034
F_2/F_4	0.197	0.174
F_3/F_4	0.96	0.89

[a] Optical velocities by de Vaucouleurs et al. (1976)

[b] Power emitted in the feature, the continuum emission being subtracted.

[c] From the point-source catalog (2nd version) (see IRAS Explanatory Supplement 1985)

the radio centre (Source, A, Gehrz et al., 1983) and the position of NGC 4194 is within 10 arcsec of Dressel and Condon's (1982) position.

The 3.3 µm feature cannot be mistaken with the atmospheric methane absorption line at 3.2 µm because the emission feature is easily seen in the raw spectra before division by the calibration star, which indeed showed the methane absorption line. However, because the equivalent width of the methane line varied (from 6 10^{-3} µm to 9 10^{-3} µm) in different spectra of the calibration star, the uncertainties on the equivalent width $W_{3.3}$ and the power emitted $P_{3.3}$ in the feature may be slightly larger than in Table 1.

3. Interpretation

The 3.3 µm emission feature is usually associated with the family of so-called "unidentified features" which contains also features at 6.2, 7.7, 8.6 and 11.3 µm. These features, always associated with dust emission at longer wavelengths, are observed together in a variety of interstellar environments (see e.g. Aitken, 1981, and reference therein). By studying reflection nebulae, Sellgren (1984) pointed out that the likely emission mechanism was the cooling of very small dust grains that are transiently heated to high temperature after absorption of single UV or visible photon. A tentative identification of the feature carriers was subsequently made by Léger and Puget (1984) and Allamandola et al. (1985) with Polycyclic Aromatic Hydrocarbon (PAH) molecules which have vibration modes at the precise wavelengths of the features. We adopt thereafter this identification, though the interpretation of our results does not depend on the exact nature but only on the very small size of the feature carriers.

Concerning the PAH features in external galaxies, several observations (particularly Aitken and Roche 1985, and references therein, and Moorwood 1986) have separated galaxies according to the presence or not of the PAH features in their nuclei. Désert and Dennefeld (1988) studied the relation between the IRAS properties of galaxies and the presence or not of the PAH features and conclude that the absence of PAH features in the center of a galaxy is always associated with the presence of an active galactic nucleus (AGN). This relation was quantified in two criteria: when the IRAS 12-to-100 µm flux ratio F_1/F_4 (the fluxes being expressed in Jy) is lower than 0.05 and/or when the 25-to-100 µm flux ratio F_2/F_4 is less than 0.4 F_3/F_4-0.08, then the 3.3 µm feature and the other related PAH features are likely to be present and the influence of any active nucleus is negligible. For IC 694 (alias NGC 3690A) and NGC 4194, the detection of the 3.3 µm PAH feature and the IRAS colors (Table 1) are in agreement with the two criteria given by Désert and Dennefeld (1988). Hence, it is very likely that the energetics of these two galaxies is dominated by stellar radiation.

In the case of IC 694, the interpretation of the spatial distribution of the emission in the nucleus is somewhat complicated by its intricated nature. In the visible (Arp, 1966), two main components can be distinguished in Arp 299: IC 694 to the NE and NGC 3690 to the SW, separated by 40 arcsec. Near-infrared mapping of the system (Telesco et al., 1985) reveals two main sources, A and B, identified with the nuclei of the two galaxies. These two sources are offset from the visual centroids of the galaxies, but coincide with the two main components at both 10 μm and 20 cm (Gehrz et al., 1983). Several other components (C, d, e . . .) are seen in radio and IR but have a smaller contribution to the total fluxes. As the boundary between the two galaxies is not well defined, it has become of common use to designate the whole system under the name of NGC 3690 with IC 694 = NGC 3690A, but we keep here the original names for clarity. Most of the emission in visible, IR and radio can readily be explained by strong episodes of star formation, the one in IC 694 being older than the others. However, the flat spectrum of the unresolved radio source in this A component is an indication that the starburst is of a different nature than elsewhere in the NGC 3690 system (Gehrz et al., 1983). Our detection of the 3.3 μm feature supports the starburst hypothesis, as do the IRAS fluxes of the whole galaxy with the above mentioned relations. The IRAS position is centered on the component *A*, thus indicating that a large fraction of the infrared flux is coming from there. Although our observed position was within 3″ of the radio position *A*, a detailed mapping, which we could not even attempt due to the weather conditions, of the NGC 3690 system would be very valuable to improve our knowledge of the starbursts. Our observations, however, together with the IRAS colours, strongly suggest that the energetics of IC 694 is dominated by a starburst and that the contribution of an active nucleus, which was believed to be dominant on the basis of a large ratio of IR luminosity to H_2 mass (Sargent et al., 1987) is negligible.

The situation is less complicated in NGC 4194 which is considered as a typical example of a merger of two galaxies (Joseph and Wright, 1985). The optical spectra show emission lines typical of H II regions (Balzano, 1983) without obvious indications of a Seyfert nature (Feldman et al., 1982). The radio emission is mainly concentrated in a nuclear source less than 1″ in diameter, but some extended components are found outside (Hummel et al., 1984). Ground-based 10 μm observations (Joseph and Wright, 1985) as well as the far IR IRAS fluxes indicate very large infrared luminosities which are best interpreted as due to large star formation rates. This is entirely confirmed by our detection of the 3.3 μm feature.

The two galaxies IC 694 and NGC 4194 have a very large luminosity (respectively 27 and $4\,10^{10}\,L_\odot$). The detection of the 3.3 μm feature is thus an indication, following Désert and Dennefeld (1988), that an AGN, if there is any, does not play a dominant role in these two extreme galaxies. The differentiation between starburst and AGN is often spectroscopically difficult for such objects in the visible because they generally suffer from large extinctions (see below). The 3.3 μm feature, being in a spectral domain where the extinction is low, if not negligible, is therefore a quantitative tool to measure the intensity of the starburst, as will be shown in the next section.

4. The 3.3 μm feature surface brightness

We propose to show that the 3.3 μm feature can be used to derive the total stellar energy output before it is obscured by interstellar dust. For that purpose, we discuss first a simple model of radiation transfer in a galaxy. Then, we compare it with the data available on the 3.3 μm emission in external galaxies.

The main hypothesis of the model is that the 3.3 μm feature carriers are coextensive with the absorbing dust of the galaxy. Then, because of the emission mechanism of very small grains, the ratio of the number of emitted 3.3 μm photons to the number of absorbed UV and visible photons does *not* depend on the distance to the emitting star. On the contrary, for big grains, the ratio of the emission at a particular wavelength to the absorption is temperature dependent, hence varies with the distance to the illuminating source. Such effects have been observed in reflection nebulae by Sellgren (1984) and Castelaz et al. (1987). After being emitted by stars, the UV and visible photons either escape the galaxy or are absorbed by interstellar dust. A given fraction of these absorbed photons will be absorbed by the feature carriers (assumed to be in constant proportion to the total dust) and the 3.3 μm emitted photons will be proportional to this fraction. Altogether, the 3.3 μm feature intensity is proportional to the light absorbed by the galaxy (or by the part of the galaxy which is observed). Hence, for galaxies which are relatively obscured (A_V of at least one magnitude), the feature can be a good tracer of the light produced by stars hidden in the galaxies. The spatial resolution that can be achieved in the feature provides information on the localisation of strong energy sources in galaxies, especially star-forming regions.

More quantitatively, we can apply a model developed by Puget, et al. (1985) (see also Désert and Boulanger, 1988) that deals with the emission of PAHs in the interstellar medium, using the prototype PAH coronene, dehydrogenated by a factor 10. The luminosity of PAHs per hydrogen atom when embedded in the solar neighbourhood interstellar radiation field (ISRF e.g. Mathis et al., 1983) is:

$$L_{\rm PAH}/N_{\rm H} = 1.15\,10^{-7}\ {\rm W\,m^{-2}}/(10^{20}\ {\rm H\,cm^{-2}}). \tag{4.1}$$

In a different radiation field this luminosity can be scaled with the respective energy density of the ISRF. The ratio of PAH luminosity to the total dust luminosity $L_{\rm dust}$, which is also the total power absorbed by dust is:

$$L_{\rm PAH}/L_{\rm dust} = 0.18, \tag{4.2}$$

and is proportional to the abundance of PAHs which is here taken as 4% of the total dust mass. The ratio of 3.3 μm feature emission to the PAH emission is given by:

$$L_{3.3}/L_{\rm PAH} = 4.0\,10^{-3}. \tag{4.3}$$

These numbers are in agreement with the UV efficiency, defined as the ratio of the number of IR photons emitted at 3.3 μm to the number of UV photons absorbed, of about 0.02 observed in the Orion Nebula (Sellgren, 1981) and two reflection nebulae (Sellgren et al., 1985). The parameters of the dust model having been scaled to observations, the uncertainties in the quoted numbers should not be larger than 50%, unless the assumptions are changed. Our main assumption in the above model is that the abundance of PAHs relative to the total dust composition does not vary in the galaxies (global metallic abundances are allowed to vary in the following). In the Galaxy, some regions observed by IRAS show a deficit of 12 μm emission relative to longer wavelengths that can be interpreted either 1) as presence of extinction at 12 μm as for example in the HD 147889 region studied by Ryter, Puget and Pérault (1987), or 2) as an under-abundance of PAHs, due to some destruction mechanisms as in σ Sco (Ryter et al., 1987) or ζ Per (Boulanger et al., 1988). Although it is true that PAH's can be destroyed inside H II regions, the energetics of H II regions is dominated in the IR by their interaction with the *surrounding* molecular material (Leisawitz and Hauser, 1988) which contains PAH's: HII regions globally show strong NIR emission features altogether (e.g. Hefele and Hölzle, 1980; Sellgren, 1981). Finally, a large part of the sky has a quite uniform 12-to-100 μm ratio between 0.3 and 0.5 (Boulanger and Pérault, 1988) that is also observed in external galaxies which justified our hypothesis (Eq. 4.2).

Defining ***f*** as the fraction of photons (averaged over the UV and visible frequencies) emitted by stars and escaping a galaxy, formulae (4.2) and (4.3) give the relationship between the 3.3 μm feature surface brightness $\sigma_{3.3}$ and the unreddened stellar luminosity per galaxy unit area l_s:

$$4\pi\sigma_{3.3}=(1-f)(L_{3.3}/L_{\rm PAH})(L_{\rm PAH}/L_{\rm dust})l_s=7.2\;10^{-4}(1-f)l_s \tag{4.4a}$$

or, with appropriate units,

$$\sigma_{3.3}=2.3\;10^{-7}(1-f)(l_s/10^4\,L_\odot\,{\rm pc}^{-2})\,{\rm W\,m^{-2}\,sr^{-1}}. \tag{4.4b}$$

The quantities $\sigma_{3.3}$ and l_s have been chosen instead of fluxes because they are distance independent. In formulae (4.4)a,b, we neglect the reddening at 3.3 μm (for the Galaxy A_V/A_L (3.4 μm) $=17$, Rieke and Lebofsky, 1985). Only in some exceptional cases like Arp220 or NGC4418 is there some evidence that this hypothesis fails. For obscured galaxies, as soon as on average $A_V\simeq 2$, the fraction ***f*** is negligible ($f\ll 1$) and formula (4.4) allows a *direct* computation of l_s although in a *model-dependent* way. As opposed to the optical lines like Hα, Hβ which can measure only the "skin" activity of galaxies, the 3.3 μm feature (as well as the other PAH features) is a deep probe of the stellar brightness inside galaxies.

In order to show a first application of this model, a list of galaxies with published measurements of the 3.3 μm feature is presented in Table 2, which includes the relatively large sample of galaxies observed by Moorwood (1986). Using the beam diameter ***b*** of each measurements, the 3.3 μm feature brightness $\sigma_{3.3}$, which is an average of the brightness inside the beam, has been estimated from the published figure of the spectrum for each galaxy. The linear radius ***r*** of the observed region (corresponding to half the diameter ***b***) has also been calculated using $H_0=75$ km s^{-1} Mpc^{-1}. Table 2 summarizes the galaxy parameters along with the references of the 3.3 μm observations. Figure 3 shows the dependence of 3.3 μm feature surface brightness $\sigma_{3.3}$ with the distance ***r***. There is global tendency for a decrease of the 3.3 μm brightness when the distance increases, in roughly $\sigma_{3.3}\propto r^{-0.5}$. This therefore suggests that the UV production, thus the star formation activity, is decreasing outwards. Indeed, for individual galaxies where observations with different beams have been made (NGC 253, M 82, NGC 7552 and He2-10), the brightness $\sigma_{3.3}$ decreases when the beam diameter increases, except for NGC 4945, where infrared extinction might play a role. M 82 and IC 694 are on the upper envelope of the galaxies location in Fig. 3, denoting a large stellar activity on a large scale.

Conversely, we can take the available optical data and use our model to predict what is the expected 3.3 μm surface brightness. If we take a maximum surface brightness for a galaxy disk component of 19.9 mag$_B$/arcsec^2 in its center (see e.g. Kent, 1985), and convert it with formula (4.4b), by taking $\lambda\,F_\lambda$ (B band) as the bolometric luminosity ($l_s=430\,L_\odot\,{\rm pc}^{-2}$) and $f=0$, we obtain $\sigma_{3.3}\simeq 1.0\;10^{-8}$ Wm^{-2} sr^{-1}, that is a factor of 100 below the typical value in our sample. Even if some of these galaxies are irregular and/or interacting, therefore atypical, it is likely that a large part of the discrepancy is due to obscuration of the visible light. In the specific case of NGC 4194 where the total central surface brightness has been measured (Kent, 1984): 18 mag$_B$/arcsec^2 (average on a 2″.7 beam), it is 44 times less than the unreddened blue stellar surface brightness deduced from formula 4.4 i.e. there are at least 4 magnitudes of extinction at the center of NGC 4194 in the B band.

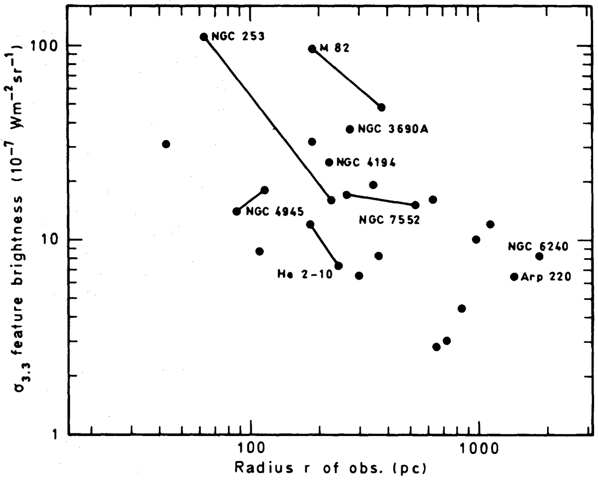

Fig. 3. Dependence of the 3.3 μm feature average surface brightness $\sigma_{3.3}$ with the radius r of the observed region in different galaxies. Multiple observations of the same galaxies with different beams have been connected. They show that the emission is different from a point-source emission because the slopes of the lines are less than 2. Uncertainties in the brightness can be found in the original papers but are usually less than 30%

Finally, using the same dust model as before, which assumes that the 12 μm IRAS flux of galaxies (continuum plus features) is produced by the same population of PAHs as the one producing the 3.3 μm feature, the following relationship holds between the flux in the 3.3 μm feature and the nominal 12 μm flux in the IRAS band (taking into account the IRAS detector's response):

$$F_\nu(12\,\mu m)=6.1(F_{3.3}/10^{-14}\,{\rm W\,m^{-2}})\,{\rm Jy}. \tag{4.5}$$

For example, this relation is in agreement with observations at 3.3 μm and 12 μm (see Table 2 and IRAS point-source catalog) of M 82. We can therefore use the ground-based observations at 3.3 μm of a given galaxy to predict its 12 μm flux within the same, usually small, beam. A comparison with the 12 μm IRAS flux, observed within a much broader beam (0.76 × 4.6 arcmin), reveals therefore the extension of the emission. For example, returning to the two present detections, the fluxes at 12 μm predicted from the 3.3 μm feature, in a beam of 2.7 arcseconds, are 0.31 and 0.21 Jy in NGC 3690A and NGC 4194 respectively. A comparison with the IRAS 12 μm fluxes for these galaxies (3.71 and 0.86 Jy respectively) shows therefore clearly the latter comes from a region much more extended than 2″.7. Table 2 gives, for each galaxy, the ratio of the predicted 12 μ small beam flux F_{1p} (through formula 4.5 and the 3.3 μm measurement) to the observed IRAS flux F_1 (0.76 × 4″.6). We note that, in this sample, most galaxies are extended relative to ground-based measurements, except for NGC 5757, Arp 220, NGC 6240, and NGC 7582, where the ratio F_{1p}/F_1 saturates near unity, therefore revealing a centrally concentrated emission. The fact that this ratio hardly exceeds unity (within the

Table 2. Data on the 3.28 μm feature in external galaxies

	Name	IRAS name	$F_{3.3}$ 10^{-20} W/cm^2	Beam arcsec	$\sigma_{3.3}$ 10^{-7} W/m^2/sr	Vel. km s^{-1}	r pc	F_{1p}/F_1	$L_{\rm FIR}$ 10^{10} $L_\odot$	Ref. 3.3 Obs.
1	NGC 253	00450−2533	111	7.5	110	259	62.9	0.33	1.4	3
2	NGC 253	00450−2533	214	27	16	259	226	0.64	1.4	3
3	NGC 1365	03317−3618	8.5	7.5	8.2	1502	364	0.16	5.4	3
4	NGC 1614	04315−0840	12	7.5	12	4643	1128	0.53	18	3
5	NGC 1808	05059−3734	33.6	7.5	32	769	186	0.50	1.6	3
6	HE2-10	08341−2614	12	7.5	12	750	182	0.67	0.35	3
7	HE2-10	08341−2614	13.5	10	7.3	750	243	0.75	0.35	3
8	NGC 3034	09517+6954	400	15	96	388	188	0.46	4.4	5
9	NGC 3034	09517+6954	800	30	48	388	377	0.92	4.4	5
10	NGC 3256	10257−4338	16.4	7.5	16	2595	630	0.31	17	3
11	NGC 3690A	11257+5850	5.0	2.7	37	3155	276	0.08	27	6
12	NGC 4194	12116+5448	3.4	2.7	25	2528	221	0.24	3.8	6
13	NGC 4945	13025−4911	14	7.5	14	356	86.5	0.23	1.5	3
14	NGC 4945	13025−4911	33.8	10	18	356	115	0.57	1.5	3
15	NGC 5236	13341−2936	16	10	8.7	337	109	0.21	0.38	2, 3
16	CIRCINUS	14092−6506	32	7.5	31	176	42.8	0.11	0.21	3
17	NGC 5757	14449−1852	8.2	10	4.4	2600	842	1.04	1.4	3
18	IC 4553	15327+2340	7.6	8	6.4	5541	1436	1.01	83	4
19	NGC 6240	16504+0228	9.7	8	8.2	7116	1844	1.04	31	4
20	NGC 7172	21591−3206	2.9	7.5	2.8	2698	655	0.38	1.4	3
21	NGC 7469	23007+0836	6.3	5.9	10	5102	975	0.30	19	1
22	NGC 7552	23134−4251	8	5	17	1636	265	0.16	5.4	3
23	NGC 7552	23134−4251	28	10	15	1636	530	0.57	5.4	3
24	NGC 7582	23156−4238	20	7.5	19	1427	346	0.90	2.8	3
25	NGC 7714	23336+0152	3.2	7.5	3	2980	724	0.39	2.5	3

References for the 3.3 μm feature observations are: (1) Cutri et al. (1984); (2) Lee et al. (1982); (3) Moorwood (1986); (4) Rieke et al. (1985); (5) Willner et al. (1977); (6) this work. Velocities are from de Vaucouleurs et al. (1976). The far-infrared luminosity $L_{\rm FIR}$ is deduced from the formula given in the "Cataloged galaxies and quasars observed with IRAS survey" (1985) and from IRAS data taken from the second version of the point-source catalog ($H_0 = 75$ km/s/Mpc).

uncertainties of about 20%) strongly supports the validity of formula (4.5), at least for the limited sample of Table 2.

The method presented here allows a computation of the stellar energy output of a galaxy before obscuration (Eq. 4.4). It is a global method, which treats the dust emission from different regions of the interstellar medium on an equal footing. The interpretation is similar to the one given by Jones and Rodriguez-Espinosa (1984) for M 82, but it is not restricted to H II regions only (Le Van and Price, 1987). This method is therefore usable on a wider scale than Brackett line measurements and also easier to operate than Br α observations. Furthermore, the 3.3 μm feature being ascribed to a specific component of dust, measurements of its intensity give a direct insight into the energetics of galaxies, contrary to broad-band NIR measurements whose interpretation requires a mixture of several components of stars and dust.

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