INFRARED EMISSION OF NORMAL GALAXIES FROM 3 TO 12 μm

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ABSTRACT

We report infrared spectra over wavelength ranges from 2.5 to 5 μm and from 6 to 11.6 μm on a sample of 45 disk galaxies whose bolometric luminosities are derived predominately from stellar sources. The vast majority of the sample spectra look "alike" and can be modelled by a set of emission features (EFs or UIR bands) including those at 6.2, 7.7, 8.6 and 11.3 μm and their associated emission plateaux, superposed on a low-level continuum that possibly extends to and mixes with a photospheric continuum at near-infrared (IR) wavelengths. These continua, which dominate the near-IR part of the spectrum, and the EFs, which dominate the mid-IR part, contribute about equally to the total spectral energy between 3 and 12 μm that in turn carries a luminosity equivalent to about 10% to 40% of the far-IR luminosity for a normal galaxy. From the most quiescent to the most active galaxies in the sample, we found (i) little systematic trend in the relative strengths of the mid-IR features, except for the 11.3 μm feature that could be depressed relative to the other features by up to a factor of 2 or so; and (ii) the ratio of the EF flux to the far-IR flux drops by about 60% on average.

Key words: infrared: lines and bands; ISM: general.

1. INTRODUCTION

The wavelength range of 3 to 12 μm contains a number of important spectral signatures from the ISM, including the so called UIR bands or broad emission features (hereafter EFs) centered around 3.3, 6.2, 7.7, 8.6 and 11.3 μm (Gillett, Forrest & Merrill 1973) and a possible near-infrared continuum (Sellgren 1984; Bernard et al. 1994). Spectra over various parts of this wavelength range have been obtained on a few dozens of infrared bright galaxies using ground-based observations or IRAS (e.g., Roche et al. 1991). But high-S/N spectra were not available before ISO on more normal galaxies. Such data are needed in order to characterize the mid-IR emission of galaxies in an unbiased way.

With its unprecedented sensitivity and continuous wavelength coverage, ISO made it possible for the first time to study spectroscopically in the mid-IR a large number of normal galaxies. As part of the ISO Key Project on Normal Galaxies (Helou et al. 1996), we obtained low-resolution spectra over 2.5 to 12 μm for a sample of 45 galaxies. By covering a broad range of parameters such as optical luminosity, the shape of the far-infrared (FIR) dust continuum emission, the FIR-to-blue luminosity ratio and the optical morphology, the sample was selected to represent the population of normal, star-forming galaxies in the local universe. In this short report, we concentrate on characterizing the observed mid-IR spectra and a few correlations of the EF strengths with galactic parameters at other wavelengths.

2. SPECTRA

The spectra were taken in the PHT-S spectroscopic mode of ISOPHOT (Lemke et al. 1996) whose two 64-element detector arrays cover respectively the wavelength ranges of 2.5 to 4.9 μm with 0.04 μm per element (or pixel), and of 5.9 to 11.7 μm with 0.1 μm per pixel. The aperture size is $24'' \times 24''$ per pixel. We used a chopping mode with sky positions placed at 150 arcsec on either side of each galaxy position. The final sky-subtracted spectra were derived from the Edited Raw Data using the PHOT Interactive Analysis (PIA, Version 7) in a standard way, but with the flux scale determined by a detector responsivity derived directly from calibration observations of standard stars in a similar chopping mode (Acosta-Pulida private communication). ISOCAM imaging data in the LW2 filter (centered at 6.7 μm; Cesarsky et al. 1996a) are available from Silbermann et al. (1996) on 2/3 of our sample galaxies. The flux scales of these two independent data sets agree with each other within $\sim 20\%$ over the wavelength range of LW2. The CAM images also show that the PHT-S aperture contains, on average, about half of the total mid-IR luminosity of a galaxy.

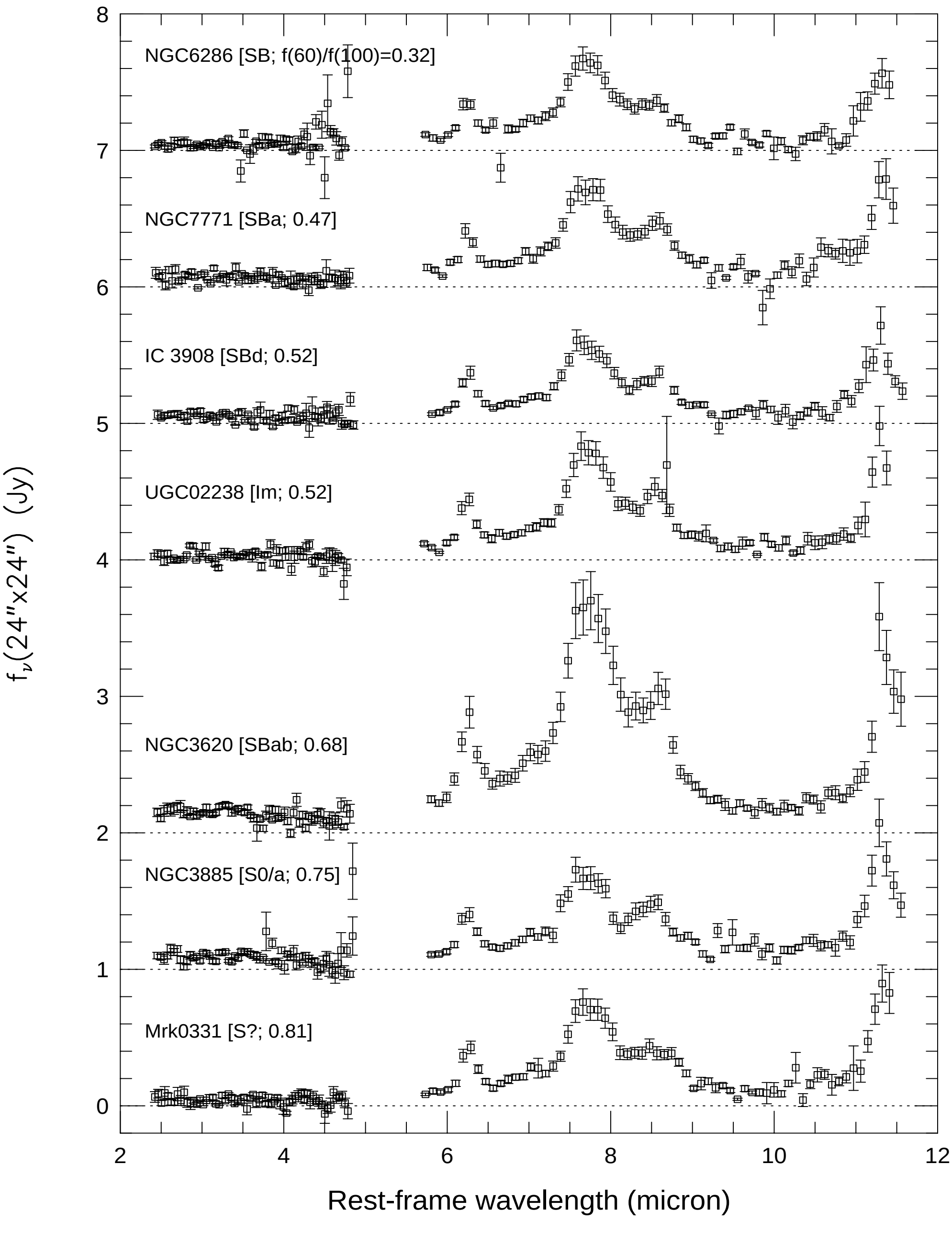

Figure 1. *PHT-S spectra of 7 sample galaxies. The ordinate is the flux density within the PHT-S aperture and the abscissa is the rest-frame wavelength. Each spectrum has been vertically shifted by a constant shown by the corresponding dotted line. For each galaxy, its optical morphological type and IRAS 60μm-to-100μm flux density ratio are indicated next to the galaxy name.*

The vast majority of the sample galaxies look "alike" over this wavelength range. Figure 1 displays 7 sky-subtracted, rest-frame spectra representative of the majority of galaxies in the sample. The spectra can be characterized by a set of broad EFs with relative intensities similar to those of Type-A spectra of Galactic sources (e.g., Geballe 1997), superposed on a possible low-level continuum that can be visually identified in most individual spectra at near-IR wavelengths away from those bright EFs. The wavelength dependence of this continuum seems to be significantly shallower than the power law of $f_\nu \propto \lambda^{-2.5}$ which describes the long-wavelength tail of stellar photospheres as observed in a number of elliptical galaxies (e.g., Boselli et al. 1998), suggesting a possible non-stellar continuum that could become brighter than the photospheric continuum at wavelengths longer than about $4\,\mu$m. We defer a quantitative analysis of this continuum till the flux calibration at these wavelengths is better understood. To estimate roughly the energetics of the EFs and the underlying continuum, we approximate the combined (stellar and non-stellar) continuum by a power-law function fitted to the sections of the spectrum in the rest frame between 3.5 and $5\,\mu$m and between 9.5 and $10.5\,\mu$m. On average, the fitted continuum contributes to about 50% of the total spectral energy between 3 and $12\,\mu$m.

The overall spectral similarity among galaxies of quite different optical and FIR properties implies either (i) the carriers of the mid-IR emission are not in thermal equilibrium, or (ii) the emission arises only from the part of the ISM under a *certain narrow* range of physical conditions if (i) is not true. Spectra of the EFs similar to those in Figure 1 have been seen toward various Galactic sources, suggesting that (i) should be the correct explanation here.

3. MID-IR EMISSION FEATURES

We consider here only the brightest EFs in mid-IR that are unambiguously detected in individual spectra. The $3.3\,\mu$m feature and other weak features that show up clearly only when we average over a number of sample spectra are analyzed elsewhere.

In order to compare our results later on with those of sources of other types (e.g., AGNs and HII regions) where a strong mid-IR continuum may be present, we derived a continuum-subtracted flux for each EF using the continuum fit defined above. The flux of the $6.2\,\mu$m feature, EF(6.2), is a spectral integration from 6 to $6.6\,\mu$m in wavelength, EF(7.7) from 7.2 to $8.2\,\mu$m, EF(8.6) from 8.2 to $9.2\,\mu$m, and EF(11.3) is twice the flux integrated from 10.9 to $11.3\,\mu$m. Note that these fluxes only include part of the emission plateau between 6 and $9\,\mu$m. Taking into account the full extent of this plateau as well as the $12.7\,\mu$m feature and its associated plateau (see Boulanger et al. 1996; Cesarsky et al. 1996b), the total flux would be roughly 1.25 times the combined EF fluxes defined here.

Using these fluxes, we show various relative feature strengths in Figure 2 as functions of $f(60)/f(100)$, IRAS 60μm-to-100μm flux density ratio; and in Figure 3 as functions of $\log(L_{\rm FIR}/L_{\rm B})$, the FIR-to-blue luminosity ratio. L_{FIR}, as defined in Helou et al. (1988), approximates the total dust emission between 42 and $122\,\mu$m. In these figures, we use only the 36 brightest sample galaxies with a heliocentric redshift below 0.03. The filled circles in the figures are the subset of 22 galaxies for which a PHT-S aperture correction has been derived from the CAM imaging data at $6.7\,\mu$m and is less than 75%. In spite of the large ranges in both $f(60)/f(100)$ and L_{FIR}/L_B that our sample covers, the relative strengths among EF(6.2), EF(7.7) and EF(8.6) remain largely unchanged. Relative to these 3 features, the strength of EF(11.3) however decreases by a factor of ~ 2 from quiescent galaxies [i.e., f(60)/f(100) $\sim$ 0.3 or $L_{\rm FIR}/L_{\rm B} \sim 1$] to galaxies of somewhat starburst characteristics [i.e., f(60)/f(100) $\sim$ 0.8 or $L_{\rm FIR}/L_{\rm B} > 30$]. If the EFs arise from the so-called polycyclic aromatic hydrocarbon mole-

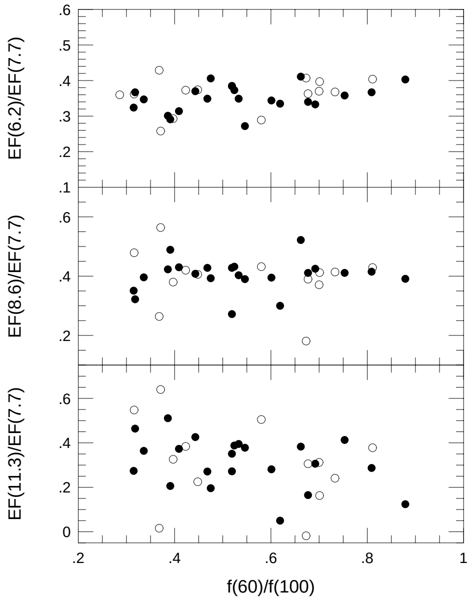

Figure 2. Plots of the relative strengths between the brightest mid-IR EFs as a function of IRAS 60μm-to-100μm flux density ratio for the 36 brightest sample galaxies at heliocentric heliocentric redshifts below 0.03. The filled circles are for the subset of 22 galaxies for which a PHT-S aperture correction is available and is less than 75%.

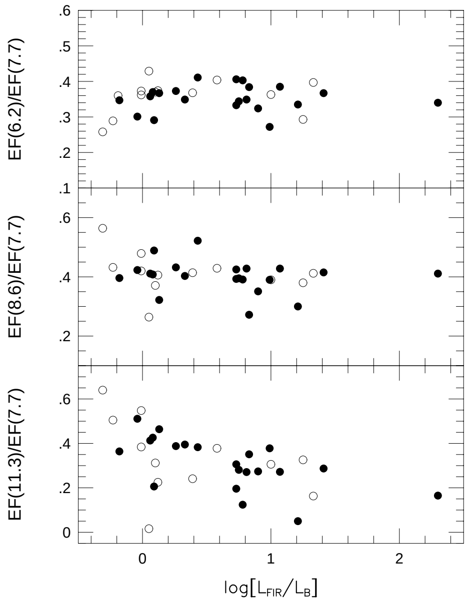

Figure 3. The same as Figure 2, but with the abscissa being the FIR-to-blue luminosity ratio.

cules (PAHs; Léger & Puget 1984; Allamandola, Tielens, & Barker 1985) and the observed variation of EF(11.3)/EF(7.7) arises from a changing percentage of ionized PAHs (cf. Langhoff 1996), it is then surprising to see that EF(6.2)/EF(7.7) remains roughly constant over the entire sample (see, for example, Lu 1998).

Figures 4 and 5 show that the ratio of the combined flux of the 4 mid-IR EFs to that of the FIR emission from dust grains of much larger sizes decreases as f(60)/f(100) or L_{FIR}/L_B increases. In these plots, we show only those 22 galaxies with an available PHT-S aperture correction that is less than 75%. For star-forming galaxies, an increase in f(60)/f(100) or L_{FIR}/L_B is usually attributed to an increasing contribution to the total dust emission from the warm dust in star-forming regions. Therefore, these trends could be a result of the EF carriers being preferentially destroyed in HII regions, a phenomenon that has been known in our own Galaxy (e.g., Helou, Ryter, & Soifer 1991). Also note that the flux ratio of EFs/FIR could become only a few percent for starburst galaxies, a factor that needs to be taken into account when one plans to use the mid-IR features to determine the redshifts of distant, FIR-selected galaxies.

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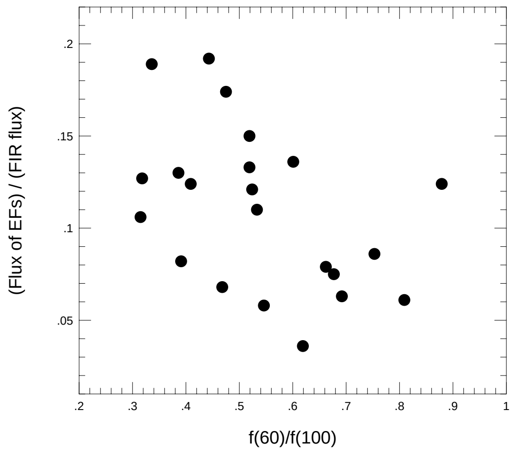

Figure 4. The ratio of the combined flux of the four mid-IR features to the FIR flux is plotted as a function of IRAS 60μm-to-100μm flux density ratio for the 22 sample galaxies for which a PHT-S aperture correction is available from CAM imaging data at 6.7μm and is less than 75%.

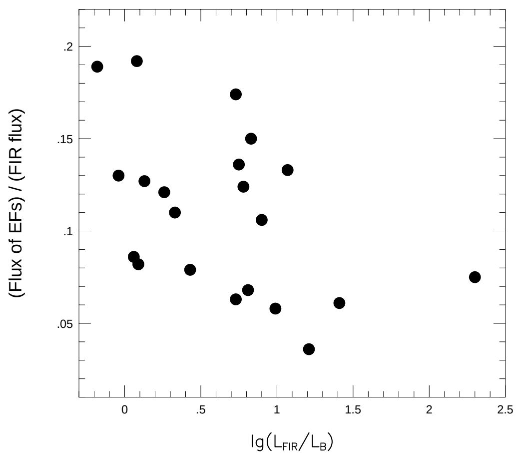

Figure 5. The same as Figure 4, but with the abscissa being the FIR-to-blue luminosity ratio.