MID-INFRARED GALAXY MORPHOLOGY ALONG THE HUBBLE SEQUENCE

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ABSTRACT

The mid-infrared emission from 18 nearby galaxies were imaged with the Infrared Array Camera (IRAC) on the Spitzer Space Telescope, sampling the spatial distributions of the reddening-free stellar photospheric emission and the warm dust in the interstellar medium. These two components provide a new framework for galaxy morphology classification in which the presence of spiral arms and their emission strength relative to the starlight can be measured directly and with high contrast. Four mid-infrared classification methods are explored, three of which are based on quantitative global parameters (colors and bulge-to-disk ratio) that are similar to those used in the past for optical studies; in this limited sample, all correlate well with traditional B-band classification. We suggest reasons why infrared classification may be superior to optical classification.

Subject headings: dust, extinction — galaxies: fundamental parameters — galaxies: structure — infrared: galaxies — ISM: lines and bands — stars: formation

1. INTRODUCTION

The morphological classification scheme introduced by Hubble (1926, 1936), based on blue-light images, has been modified periodically over the years (e.g., Sandage 1961; de Vaucouleurs 1959; Kormendy 1979; Buta 1995) but remains a fundamental method by which astronomers continue to sort and compare galaxies. From a contemporary viewpoint, the scheme is useful because it closely follows the fundamental distinction between galaxies with and without significant amounts of interstellar matter. Within each major class (spirals and irregulars on the one hand, ellipticals and lenticulars on the other), the subclass reflects the history of each galaxy, although the details are still a topic of active study. Furthermore, within the spiral-irregular branch, subclass is closely correlated with the number and luminosity of young stars relative to old stars.

Hubble morphological classification is essentially a visual exercise that is sometimes assigned a numerical index (such as the T index in the Third Reference Catalogue of Bright Galaxies; de Vaucouleurs et al. 1991, hereafter RC3) in order to facilitate comparisons with various quantitative global parameters. Despite the essentially qualitative process, there is general agreement among many human classifiers (Naim et al. 1995).

Different classification schemes have been developed over the years, such as spectral (absorption vs. emission line; Morgan & Mayall 1957; Bromley et al. 1998), ultraviolet (Marcum et al. 2001), and near-infrared (Jarrett 2000; Block & Puerari 1999). Detailed comparisons have also been made between the optical classifications and various global galaxy parameters, such as: color (blue vs. red; Buta et al. 1994; de Vaucouleurs 1960); light distribution via the bulge-to-disk ratio (van den Bergh 1976), concentration index (Okamura et al. 1984; Abraham et al. 1994), and galaxy asymmetry (Abraham et al. 1996); and trained neural network schemes (Odewahn et al. 1996). These various methods often show good correspondence among them (Roberts & Haynes 1994), but there are significant and systematic differences among at least some (Connolly et al. 1995; Kochanek et al. 2000). So far, no alternate scheme appears to be as directly tied to the composition and history of a galaxy as Hubble’s.

In this paper, we revisit the morphological classification scheme using images with resolutions and sensitivities similar to those used for traditional optical classifications—but at mid-infrared wavelengths. While some nearby galaxies could have been resolved by previous infrared space missions operating at these wavelengths, equal or better spatial resolution can also be obtained from the ground, the combined wide-field coverage and sensitive infrared imaging detectors of the Infrared Array Camera (IRAC) on the Spitzer Space Telescope permits us to explore an entirely new region of parameter space for imaging nearby galaxies. These images demonstrate a new approach to galaxy classification based on the properties of the galaxy interstellar medium relative to its starlight.

2. SAMPLE

The 16 galaxies presented here are a small but representative subset of a sample of about 100 scheduled to be observed. These galaxies were drawn from a complete sample from Ho et al. (1997) that contains nearly 500 galaxies in the northern sky at $B_T < 12.5$ mag. A subsample of approximately 100 galaxies was drawn from it under the constraints: (1) the galaxies should have small sizes (less than 7′′), so that they would fit in the instantaneous instrument field of view; and (2) the two-parameter space of luminosity and morphological type is fully spanned. The galaxies were randomly drawn within these constraints. Several low-surface-brightness galaxies were added to the subsample, as the parent sample was judged to be missing such galaxies. The sample will be more fully described in a future paper.

It is fortunate that the sample to date nearly fully spans the classical morphological sequence (Sa and Sab are missing). Two additional galaxies (NGC 3031 and NGC 300) were observed for Early Release Observations; the first one is in the parent sample, while the latter is southern and is not. Both observations are described elsewhere in this issue (Willner et al. 2004; Helou et al. 2004) and are only included in the color and bulge-to-disk ratio plots. We adopt the RC3 optical
classifications throughout this paper for comparison purposes, with the exception of NGC 5363; it is misclassified as l0?, but is most likely intended to be the type S0pec. We have adopted E/S0pec for it.

3. OBSERVATIONS

The data were taken with the IRAC (Fazio et al. 2004) on the Spitzer Space Telescope (Werner et al. 2004) during the first four IRAC campaigns of normal operations (2003 December–2004 March). Sixteen galaxies (Spitzer AOR 0004431104) were imaged, each using five exposures of either 12 or 30 s each on the source in all four detectors. The standard pipeline BCD (Basic Calibrated Data, ver. 8.9–9.5) products were used in the reductions. The first 5.8 μm image had an additional “first-frame delta sky dark” subtracted from it, which was based on an independent data set. The bias level for the 5.8 μm images was significantly variable such that the median value of the background plus bias (which was iteratively determined via a σ-clipping algorithm) had to be subtracted from each individual frame before mosaicing.

A mosaic of each target in each bandpass was made using custom software operating under the IRAF environment and using the WCSTOOLS package. Optical distortion was removed in the process, and the images were subpixelled to 0''86, which is a linear reduction by a factor of √2 in each dimension. A first-iteration mosaic was constructed using a median combination of the individual frames. Each separate BCD frame was then compared with the mosaic, and differences much larger than the amount expected from the known noise were assumed to be cosmic rays or other artifacts. Pixels affected were flagged as invalid, and the resulting cleaned frames were then combined into the final mosaic. The resulting 3.6 and 8 μm images are shown in Figure 1 (Plates 1 and 2). The 4.5 and 5.8 μm images look similar to 3.6 and 8.0 μm, respectively.

Quantitative data in this paper are given in instrumental magnitudes relative to Vega. The existing calibration of IRAC data is based on point-source observations (Fazio et al. 2004). Extended sources will have aperture corrections that are different from those for point sources, and the correct values are still unknown. In particular, for the elliptical galaxy NGC 777, which shows the least evidence for any dust emission, we assume a pure stellar spectrum matching that of an M0 III star. The classification is based simply on the visual appearance of Fomalhaut, except for 5.8 μm or, perhaps even better, on the visual appearance of nonstellar emission at 8 μm, as shown in Figure 1. The reason is easy to see: the dust emission tracks interstellar matter, which is predominantly resident in spiral arms. Arm/interarm contrast is significantly higher in 8 μm images than in visible images. While not directly shown here, we note that ultraviolet light also shows high contrast, but can be affected significantly by dust obscuration.

4. ANALYSIS

For each galaxy, the [3.6]−[4.5] color is nearly constant with radius and is consistent with stellar photosphere emission. Dust emission is likely to be important at longer wavelengths. The stellar emission was subtracted from the 5.8 and 8.0 μm images, using the 3.6 and 4.5 μm images suitably scaled to match the theoretical colors of M0 III stars: [3.6]−[4.5] = −0.15 mag, [4.5]−[5.8] = +0.11 mag, and [5.8]−[8.0] = +0.04 mag (M. Cohen & T. Megeath 2004, private communication). The resulting images are referred to as “nonstellar emission” and are shown in Figure 1.

Surface photometry was measured on the galaxies, using the IRAF task ELLIPSE and following the methodology of Phare (1999). The full fitting was done on the 3.6 μm image, then the flux at each isophote was measured for the other wavelengths using the isophotal shapes defined from the 3.6 μm image. Circular aperture magnitudes were also measured for each galaxy. Corrections for flux lost due to the point-spread function (PSF) were applied to the surface brightness and aperture magnitude profiles in the manner described in Phare (1999). One-dimensional models of J/K S0pec. We have adopted S0pec throughout this paper for comparison purposes, and the correct values are respectively.

Extended sources will have aperture corrections that are different from those for point sources, and the correct values are currently heavily dominated by the systematic effects of both the stellar calibration and the extended source calibration based on NGC 777 adopted here.

5. INFRARED GALAXY CLASSIFICATION

5.1. Morphology of the λ = 8.0 μm Emission

The classification is based simply on the visual appearance at 8 μm or, perhaps even better, on the visual appearance of nonstellar emission at 8 μm, as shown in Figure 1. The reason is easy to see: the dust emission tracks interstellar matter, which is predominantly resident in spiral arms. Arm/interarm contrast is significantly higher in 8 μm images than in visible images. While not directly shown here, we note that ultraviolet light also shows high contrast, but can be affected significantly by dust obscuration.

5.2. Infrared Colors of the Stellar Population

The IRAC color [3.6]−[4.5] varies systematically with galaxy morphological type, as shown in Figure 2. This is probably a population age effect: young A0 V stars have color of zero, an intermediate-age population matches the bluer color of a K0 III star (−0.06 mag), and an old stellar population matches the yet bluer colors for later type K2 III–M0 III stars of −0.14 to −0.15 mag. While this is a rather simplistic exploration of the intrinsic colors of the stellar population, it does highlight a general feature of the [3.6]−[4.5] color: that it becomes redder for galaxies of increasingly late types.

The amount by which the [3.6]−[4.5] color changes with galaxy type T is Δ(3.6−4.5)/ΔT ≈ 0.01 mag. This is similar to the slope for the optical color (V − R), but is significantly smaller than the slopes for other optical colors (U − B), (B − V), and (V − J) (Buta & Williams 1995). While this might imply that IR classification based on [3.6]−[4.5] is more prone to the effects of photometric errors, the optical colors are affected by the systematic error of internal reddening, and hence by inclination effects. For this reason, we argue that IR colors are more representative of the properties of the underlying stellar populations.

The near-IR color K_s−[3.6] shows significantly more scatter than the IRAC-only colors. Part of this is due to the larger
| Galaxy Name | Spitzer AOR Key | Type       | $T$ (km s$^{-1}$) | $r_{(K_{20})}$ (arcsec) | $b/a$ | $K_{36}$ (mag) | $K-\text{[3.6]}$ (mag) | $\text{[3.6]}-\text{[4.5]}$ (mag) | $\text{[3.6]}-\text{[8.0]}$ (mag) | $B/D$ | ± |
|------------|----------------|------------|-----------------|--------------------------|------|---------------|--------------------------|-------------------------------|-------------------------------|-------|---|
| NGC 777    | 0004431104     | E1, Sy2    | −5.0            | 4985                     | 51.1 | 0.840         | 8.508                    | 0.092                         | −0.165                       | 0.004 | 14.320 2.634 |
| NGC 5077   | 0004478976     | E3–4, LINER, Sy1.9 | −5.0 | 2817                     | 57.2 | 0.700         | 8.309                    | 0.106                         | −0.130                       | 0.062 | 13.848 10.153 |
| NGC 5813   | 0004490496     | E1–2       | −5.0            | 1972                     | 90.6 | 0.770         | 7.592                    | 0.079                         | −0.137                       | −0.016 | 0.875 0.114 |
| NGC 5363   | 0004484352     | E/S0pec[107] | −3.5           | 1139                     | 102.5 | 0.740         | 6.991                    | 0.084                         | −0.126                       | 0.521 | 4.745 1.879 |
| NGC 1023   | 0004432640     | SB(r)s0–    | −3.0            | 637                      | 181.0 | 0.380         | 6.318                    | −0.036                        | −0.143                       | −0.007 | 2.708 1.833 |
| NGC 4203   | 0004457216     | SAB0--; LINER | −3.0           | 1086                     | 77.3 | 0.940         | 7.517                    | 0.124                         | −0.101                       | 0.250 | 1.434 0.485 |
| NGC 5548   | 0004486656     | (R')SA(s)0/a, Sy1.5 | 0.0           | 5149                     | 26.3 | 0.940         | 9.547                    | 0.204                         | 0.546                         | 2.545 | 6.128 3.619 |
| NGC 6340   | 0004492012     | Sa(s)0/a, LINER | 0.0            | 1198                     | 51.4 | 0.940         | 8.506                    | 0.076                         | −0.114                       | 0.331 | 0.692 0.101 |
| NGC 3031   | 0006629120     | SA(s)ab, LINER, Sy1.8 | 2.0            | −34                      | 487.6 | 0.510         | 3.896                    | 0.285                         | −0.111                       | 1.124 | 0.570 0.076 |
| NGC 5746   | 0004489728     | SAB(r)sb? , sp | 3.0            | 1724                     | 162.2 | 0.260         | 6.934                    | −0.119                        | −0.102                       | 1.256 | 0.335 0.040 |
| NGC 3147   | 0004441856     | SA(rs)bc, Sy2 | 4.0            | 2820                     | 83.1 | 0.820         | 7.523                    | 0.319                         | −0.053                       | 2.451 | 0.511 0.064 |
| NGC 1961   | 0004435712     | SAB(rs)c, LINER | 5.0            | 3934                     | 78.6 | 0.670         | 7.952                    | 0.224                         | −0.077                       | 2.545 | 0.405 0.041 |
| NGC 5669   | 0004488960     | SAB(rs)cd   | 6.0            | 1385                     | 55.9 | 0.380         | 10.360                   | 0.549                         | −0.033                       | 2.664 | 0.341 0.189 |
| NGC 6689   | 0004494336     | SBcd        | 6.0            | 467                      | 38.1 | 0.580         | 10.336                   | −0.084                        | −0.045                       | 2.103 | 0.109 0.033 |
| NGC 300    | 0006069760     | Sa(s)d      | 7.0            | 144                      | 199.4 | 0.620         | 7.063                    | 0.371                         | −0.017                       | 2.079 | 0.007 0.003 |
| NGC 5668   | 0004488192     | Sa(s)d      | 7.0            | 1583                     | 16.2 | 1.000         | 11.781                   | 1.082                         | −0.047                       | 2.351 | 0.126 0.052 |
| NGC 5204   | 0004480512     | Sa(s)m, H n | 9.0            | 201                      | 42.1 | 0.680         | 10.117                   | 0.159                         | −0.015                       | 1.840 | 0.026 0.020 |
| NGC 1156   | 0004434176     | IB(s)m      | 10.0           | 375                      | 70.5 | 0.400         | 9.468                    | 0.129                         | −0.007                       | 2.192 | 0.025 0.009 |
Fig. 2.—Colors and bulge-to-disk ratios of the galaxies as a function of morphological type T. (a) The 2MASS-IRAC color $K_s-[3.6]$, evaluated at the $\mu_g = 20$ mag arcsec$^{-2}$ isophote. AGN-dominated NGC 5548 is plotted as an open symbol. (b) IRAC color $[3.6]-[4.5]$, evaluated at the same isophote. Early-type galaxies are blue in this color and match the colors expected for stars of type M0 III. Late-type galaxies are red in this color, matching the colors expected for K0 III through A0 V stars. The AGN-dominated NGC 5548 is off the plot at $[3.6]-[4.5] = +0.55$ mag. (c) Same for $[3.6]-[8.0]$. The nonstellar emission goes from near-zero contribution in the early-type galaxies to the dominant emission for the late-type galaxies. ([3.6]-[8.0] = 2.5 mag implies that the PAH emission is 10 times greater than the stellar emission.) (d) Bulge-to-disk ratio for the galaxies as measured in the IRAC 3.6 $\mu$m images. Emission in this bandpass is a direct tracer of the stellar mass distribution; hence, these bulge-to-disk ratios imply similar ratios in the stellar masses in each galaxy component. The bulge-to-disk ratio shows a strong decrease from early- to late-type galaxies. The plotted value for NGC 1156 ($T = 10$, type Im) is an upper limit; there is no evidence for a bulge component.

photic errors from the 2MASS measurements, which range from 0.02 to 0.11 mag. Another part of the large scatter may lie in imperfect matching of the isophotal aperture between 2MASS and IRAC.

5.3. Infrared Colors of the Nonstellar Emission

The IRAC color $[3.6]-[8.0]$ varies with galaxy type even more strongly than $[3.6]-[4.5]$ (Fig. 2). This is because the 8.0 $\mu$m filter is detecting the warm dust, which is probably emitting mostly via the PAH emission features at $\lambda = 7.7$ and 8.6 $\mu$m (Gillett et al. 1973). Galaxies of increasing morphological type T show increasing ratios of polycyclic aromatic hydrocarbon (PAH) emission at 8.0 $\mu$m to stellar mass at 3.6 $\mu$m; hence, this color becomes redder with T. The fraction of 8 $\mu$m light from nonstellar emission ranges from below 10% for the early-type galaxies to more than 90% for the late types.

5.4. Infrared Bulge-to-Disk Ratios

Since starlight at $\lambda = 3.6$ $\mu$m very nearly follows the Rayleigh-Jeans limit of blackbody emission for $T > 2000$ K, the colors of both early- and late-type stars are all nearly the same. There is virtually no dust extinction at this wavelength either, since any standard extinction law predicts only a few percent of the extinction compared to optical wavelengths. The 3.6 $\mu$m light therefore traces the stellar mass distribution free of dust obscuration effects.

The bulge-to-disk ratios for the galaxies progressively decrease with galaxy morphology type, demonstrating that there is an increasing stellar mass fraction in the disk component of the later type galaxies. Unlike optical wavelengths, this effect cannot be ascribed to the emission of a small number of luminous young stars, which have little total mass. Since the 3.6 $\mu$m light is virtually all stellar, the bulge-to-disk ratios we derive here will be similar to the $K$ band.

6. DISCUSSION OF INDIVIDUAL OBJECTS

Galaxy NGC 5548 has a powerful active galactic nucleus (AGN) of type Sy 1.5 in its nucleus, which appears very red relative to the starlight (Fig. 1). It has been studied extensively as part of the AGN Watch project (Peterson et al. 2002). No correction for the nuclear emission was done, hence the galaxy is plotted as an open symbol in Figure 2.

A number of other galaxies show much weaker evidence, via both spatially resolved point-source nuclei and reddening trends in $[3.6]-[4.5]$, for active nuclei (see Willner et al. 2004 for the case of M81). Spatial and spectral separation of AGNs will be the subject of a future contribution.

Lenticular early-type galaxies NGC 5363, 1023, and 4203 all show evidence of spatially resolved dust emission at 8.0 $\mu$m and are discussed in a companion paper (Pahre et al. 2004).

Nearly edge-on spiral NGC 5746 is classified by RC3 as SAB(rs)b/sp?, which reflects considerable uncertainty, due to its prominent dust lane. The IRAC images easily penetrate the obscuration and demonstrate that it is SB(r)ab, with the presence of a large inner ring and an apparent bar roughly perpendicular to the plane of the sky.

7. SUMMARY

IRAC images offer powerful new tools for studying both the stellar and interstellar components of nearby galaxies. Both the relative amounts of these components and their spatial distributions can be used to classify galaxies. Early indications from this limited sample are that such classifications correlate well with the traditional Hubble scheme. Three of four classification schemes suggested are strictly quantitative and therefore can be applied without personal biases; the fourth could probably be made quantitative through Fourier analysis techniques.

The principal advantages of a mid-IR classification scheme are as follows:

1. The mid-IR traces both interstellar matter and starlight without the effects of extinction.

2. The mid-IR dust emission, particularly the PAH feature at $\lambda = 7.7$ $\mu$m, is a clear tracer of the presence of interstellar matter. The emission shows high contrast against stellar emission at the same wavelength.

3. The colors of stellar photospheres in the mid-IR vary only a small amount with population age or mass function, and hence the stellar emission is a direct tracer of stellar mass. The bulge-to-disk ratios measured at 3.6 and 4.5 $\mu$m therefore sample the mass ratio of the stellar content, not a mixture of stellar content and recent massive star formation activity.

4. The stellar photospheric component is straightforward to model based on the 3.6 and 4.5 $\mu$m images, and hence it provides a simple framework for separating the stellar from the ISM emission at 5.8 and 8.0 $\mu$m.
The mid-IR emission is a more natural tracer of the underlying astrophysics that gives rise to the galaxy sequence, namely the star formation rate per unit stellar mass. Future work may include a quantitative investigation of the properties of galactic potentials, bars, and spiral arms. As Figure 1 demonstrates, such galaxy features can be imaged strikingly well at mid-IR wavelengths.

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| Type     | Name      | v   | LINER | Sy | 3.6 - 8.0 µm | 3.6 µm | 8.0 µm | Non-stellar |
|----------|-----------|-----|-------|----|--------------|--------|--------|-------------|
| E1       | NGC0777   | 4985|       |    | DSS          |        |        |             |
| E3-4     | NGC5077   | 2817| LINER | Sy1.9 |              |        |        |             |
| E1-2     | NGC5813   | 1972|       |    | DSS          |        |        |             |
| E/S0pec[I0?] | NGC5363 | 1139| LINER |    | DSS          |        |        |             |
| SB(rs)0- | NGC1023   | 637 |       |    | DSS          |        |        |             |
| SAB0-    | NGC4203   | 1086| LINER |    | DSS          |        |        |             |
| SA(s)0/a | NGC6340   | 1198| LINER |    | DSS          |        |        |             |
| (R')SA(s)0/a | NGC5548 | 5149| Sy1.5 |    | DSS          |        |        |             |

Fig. 1.—Images of the galaxies sorted by increasing morphological type $T$ (RC3). Blue Digitized Sky Survey images are provided for comparison. Each panel is $5' \times 5'$ in size. The IRAC color images are composed of 3.6 ("blue"), 4.5 ("green"), and 8.0 µm ("red"). The 8.0 µm "nonstellar" images have had the stellar light subtracted from them (see text). All IRAC images displayed in this figure use an identical square-root scaling and limits of 0–10 MJy sr$^{-1}$ (gray scale) or 0–5 MJy sr$^{-1}$ (color).
Fig. 1.—Continued

| Type  | Name  | V  |
|-------|-------|----|
| SAB(rs)b?_sp | NGC5746 | 1724 |
| SA(rs)bc | NGC3147 | 2820 |
| SAB(rs)c | NGC1961 | 3934 |
| SAB(rs)cd | NGC5669 | 1385 |
| SBcd | NGC6689 | 490 |
| SA(s)d | NGC5668 | 1583 |
| SA(s)m | NGC5204 | 201 |
| IB(s)m | NGC1156 | 375 |

Plate 2