THE MID-INFRARED TULLY–FISHER RELATION: SPITZER SURFACE PHOTOMETRY

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ABSTRACT

The availability of photometric imaging of several thousand galaxies with the Spitzer Space Telescope enables a mid-infrared calibration of the correlation between luminosity and rotation in spiral galaxies. The most important advantage of the new calibration in the 3.6 μm band, IRAC Channel 1, is photometric consistency across the entire sky. Additional advantages are minimal obscuration, observations of flux dominated by old stars, and sensitivity to low surface brightness levels due to favorable backgrounds. Roughly 3000 galaxies have been observed through Spitzer cycle 7 and images of these are available from the Spitzer archive. In cycle 8, a program called Cosmic Flows with Spitzer was initiated, which will increase the available sample of spiral galaxies with inclinations greater than 45° from face-on that are suitable for distance measurements by 1274. This paper describes procedures, based on the photometry package Archangel, that are being employed to analyze both the archival and new data in a uniform way. We give results for 235 galaxies, our calibrator sample for the Tully–Fisher relation. Galaxy magnitudes are determined with uncertainties held below 0.05 mag for normal spiral systems. A subsequent paper will describe the calibration of the [3.6] luminosity–rotation relation.

Key words: galaxies: distances and redshifts – galaxies: photometry – infrared: galaxies

Online-only material: color figures

1. INTRODUCTION

The cosmic microwave background temperature dipole (Fixsen et al. 1996) is usually interpreted as a motion of our Galaxy of over 600 km s⁻¹, but the considerable majority of the posited motion is developed on large scales with origins that are still poorly understood. Our overarching goal is to measure distances and, hence, parse departures from the mean Hubble expansion, on scales extending to 200 Mpc. We are gathering distance measurements from a multitude of methods and contributors within a program that we are calling Cosmic Flows (see the Appendix). Of particular importance to us are distances accrued from the correlation between the rotation rate of a galaxy and its luminosity, the Tully–Fisher relation (TFR; Tully & Fisher 1977). There are methodologies that provide distance estimates that are individually more accurate but an abiding advantage of the TFR is its applicability to a large fraction of all galaxies over a wide range of environments and distances. The prospect of utilizing the TFR to obtain distances to several tens of thousands of galaxies out to redshift z ~ 0.05 (∼200 Mpc) exists.

In the process of accumulating an appropriate data set of distance measurements, our Cosmic Flows Large Program on the 100 m Green Bank Telescope and complementary southern observations on the Parkes Telescope (Courtois et al. 2009, 2011b) provide us with quality rotation information from HI line profiles and the combination of our own and optical photometry from the literature (Courtois et al. 2011a) provide the other elements that permit a modern re-calibration of the TFR at an optical band (Tully & Courtois 2012). The data accumulated in support of this program, including the new material to be discussed in this paper, are made available at the Extragalactic Distance Database (EDD³; Tully et al. 2009).

It has long been appreciated that infrared photometry may offer advantages because of reduced extinction and because infrared flux arises in large part from old stars that should dominate the inventory of baryonic mass (Aaronson et al. 1979). K, band photometry from the Two Micron All Sky Survey has been used with the TFR (Karachentsev et al. 2002). However, a major concern with ground-based infrared observations is the high and variable sky foreground. Much of the flux from galaxies lies in extended components with surface brightnesses (SBs) that are well below the ground-based sky level. Flux at the extremities of galaxies is lost and very low surface brightness (LSB) galaxies are not even seen.

Observing from space removes the problem of high contamination from Earth’s atmosphere. We have initiated a sub-program that we call Cosmic Flows with Spitzer (CFS) with NASA’s Spitzer Space Telescope (Werner et al. 2004). Observations began in cycle 8, during the post-cryogenic period, to obtain wide-field images of galaxies with the Infrared Array Camera (IRAC) in Channel 1 (ch.1). The present paper describes our reduction and photometric analysis. We will discuss the steps for transformation from raw Spitzer post-basic calibrated data (PBCD) obtained from the Spitzer archive to the parameter needed for the TFR calibration: apparent [3.6] magnitudes. The photometry is carried out with a Spitzer-adapted version of Archangel (Schombert 2007; Schombert & Smith 2012). We will discuss the corrections to be made to the apparent magnitudes and conclude with a discussion of uncertainties. A subsequent paper will discuss the calibration of the TFR at 3.6 μm.

2. [3.6] BAND DATA

Once the cryogens were exhausted on the Spitzer Space Telescope, useful observations were restricted to IRAC ch.1 (centered at 3.55 μm which we round to 3.6 μm) and ch.2 (4.5 μm). For the purposes of measuring distances with the TFR the two channels are highly redundant. Given a choice with the availability of finite observing resources between more galaxies in one band versus fewer galaxies in two bands, we chose to observe more galaxies in one band. In our CFS program, we concentrate on IRAC ch.1 observations in the 3.6 μm window.

³ Accessed online at http://edd.ifa.hawaii.edu.
that give us magnitudes [3.6] in the AB system. This window provides observations with minimal dust extinction (Draine & Lee 1984) and exhibits a minimum of zodiacal background radiation (Ootsubo et al. 1998).

Figure 1 provides examples of the spectral energy distribution (SED) of spiral galaxies (Silva et al. 1998). The Spitzer [3.6] band lies on the Rayleigh–Jeans tail of the SED of normal populations of stars not yet strongly affected by the flux from warm dust that starts to become a factor at wavelengths longer than 4 μm. The discrete spectral features seen in the SED arise from polycyclic aromatic hydrocarbon (PAH) molecules (Tielens 2008). The highest frequency PAH at 3.3 μm is contained within the [3.6] bandpass. Meidt et al. (2012) have investigated the impact of various contributors to flux in the 3.6 μm window with six representative spiral galaxies observed with the Spitzer S4G program. They find that contributions from hot dust and PAHs together contribute 9% ± 4% of the global flux in the 3.6 μm band; intermediate-age asymptotic giant branch and red supergiant branch stars contribute 3% ± 2% of the global flux; and the rest, the great majority, is contributed by old stars, predominantly K and M giants. These non-stellar and young stellar contributions should only slightly degrade the correlation between old stars and mass in normal spirals.

Using Spitzer/IRAC ch.1, a point-spread function (PSF) with a mean FWHM of 1′.66 is sampled with 1′.2 pixels. The field of view is 5′.2, adequate to encompass most galaxies to beyond twice $d_{25}$, the diameter at a $B$ isophote of 25 mag arcsec$^{-2}$. Larger galaxies require mosaics. Integrations of the CPS program involve the combination of $8 \times 30$ s slightly dithered exposures for a total of 4 minutes per field. As will be discussed, these integrations provide images that probe somewhat fainter limits than most ground-based optical photometry programs and much fainter limits than ground-based infrared photometry programs. Spitzer SB levels reach 10 mag below typical ground-based infrared sky levels. No existing near-infrared ground survey achieves the accuracy obtained with the Spitzer Space Telescope. The outstanding advantages of space observations are background stability and all-sky consistency (Fazio et al. 2004).

Our cycle 8 post-cryogenic program CFS avoids repetition of earlier Spitzer observations. Archival information is used where available. Major contributions from earlier programs come from the Spitzer Infrared Nearby Galaxies Survey (SINGS; Dale et al. 2005, 2007), and the Local Volume Legacy survey (LVL; Dale et al. 2009), carried out during the cryogenic phase, as well as the Spitzer Survey of Stellar Structure in Galaxies (S4G; Sheth et al. 2010), and the Carnegie Hubble Program (CHP; Freedman et al. 2011), subsequently carried out during the post-cryogenic phase. Smaller programs undertaken during the cryogenic phase supply us with a few more fields. These data are available for public use at the Spitzer Heritage Archive (SHA) Web site.4 The variety of source programs introduces variations in the details of the acquisition. This particularly affects the total integrations, dithering procedures, and the extent of fields with reference to $d_{25}$. However, with all the data that will be considered, the fields are large enough and the exposure times are long enough that, at most, only a few percent of the light from a target is lost.

3. PHOTOMETRY

3.1. Surface Photometry

Large numbers of pixels complicate simple parameter extractions. A galaxy is spread over a large area of the sky. At some point, the outer pixels have more sky luminosity (zodiacal light and background contaminants) than galaxy luminosity. Setting the “sky” dominates the total magnitude error budget. An analysis of a large galaxy (extending across many pixels) requires surface photometry involving fits of isophotes and lines of constant luminosity. Isophotes are often set as ellipses (Milvang-Jensen & Jørgensen 1999). Our interest is spiral galaxies with types typically between Sa and Scd. A well-behaved spiral is approximated by an oblate spheroid that appears circular when viewed face-on and projects to an ellipse when viewed toward edge-on. Two-dimensional galaxy images described as elliptical isophotes can be summed in annuli to reduce to a one-dimensional description. Then, the one-dimensional profiles are fitted by various functions in order to extract the radial SB distribution, global structure or geometrical characteristics, spatial orientation, stellar populations, characteristics of dust, etc. To obtain apparent magnitudes, de Vaucouleurs (1977) introduced the growth curve, a plot of magnitude within a radius as a function of radius. With an adequate signal-to-noise ratio (S/N), the growth curve could be enough to place large apertures around galaxies and sum the total amount of light, minus the sky contribution. In practice, a galaxy luminosity distribution decreases toward larger radii so larger apertures catch more galaxy light but also introduce more sky noise. Some light is inevitably lost below the sky level. Isophotal intensities associated with the galaxy light at large radii are sensitive to the sky setting. Restriction to a smaller radius leads to underestimates of total light. The problem is that galaxies do not have discrete edges.

It is never possible to measure 100% of the light of a galaxy. Measurements are made to an isophotal level, dictated by telescope optics, the detector, exposure times, and sky brightness. Different authors measure magnitudes to different isophotal levels then often extrapolate to total magnitudes. Our interest is spiral galaxies. These galaxies characteristically decay exponentially in luminosity with radius. In an ideal case, the light contained within a specified isophotal level is a simple function of the disk’s central SB and the exponential decay scale length. To extrapolate in such a case, one can assume that the light at large radii falls off like an exponential disk with central

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4 http://irsa.ipac.caltech.edu/data/SPITZER/docs/spitzerdataarchives/
Figure 2. Output of the Archangel software showing the ratio of $b/a$ and the position angle in the two top panels and the fitted ellipses and masking in the two bottom panels for PGC41729 = NGC 4522.

(A color version of this figure is available in the online journal.)

SB and scale length characterized by a fit to the main body of the galaxy. The estimated contribution lost below the sky level can be added to what is observed to give an extrapolated magnitude (Tully et al. 1996).

3.2. Archangel

Schombert (2007) developed Archangel, a flexible tool for galaxy surface photometry built from a combination of FORTRAN and Python routines. Archangel performs procedures such as (1) masking of stars and flaps, (2) ellipse fitting at expanding radii from the galaxy center, (3) compression of two-dimensional information into one-dimensional SB and magnitude growth curves as a function of radius, and (4) extrapolation via fits to the magnitude growth curve at large radii involving rational functions (Schombert & Smith 2012). Position angles and ellipticities are freely determined at each radial step in the development of the growth curve. At large radii, noise dominates and position angle and ellipticity are frozen for the remaining outward steps in radius. The program provides flexibility in where these parameters become frozen and allows that they may be frozen at all radii. Total magnitudes, the most important product of this analysis, are found to be negligibly affected by position angle and ellipticity details at intermediate radii. Comparisons with alternative photometry are discussed in Section 5.1. See Figure 2 for an example of masking and ellipse fitting with Archangel.

To obtain magnitudes in the AB system from the archival PBCD, we use magnitude and VEGA/AB conversion parameters from the IRAC Instrument Handbook5 and from Caputi et al. (2006), respectively. At optical bands, it is common practice to quote magnitudes in the Vega photometric system, but when working in the mid-infrared, it is more useful to use the AB system. In instances where comparisons are made between the optical and mid-infrared, we use the following transformations (Frei & Gunn 1994):

$$B(\text{Vega}) = B(\text{AB}) + 0.163,$$

$$R_C(\text{Vega}) = R_C(\text{AB}) - 0.117,$$

$$I_C(\text{Vega}) = I_C(\text{AB}) - 0.342, \text{ and}$$

$$[3.6](\text{Vega}) = [3.6](\text{AB}) - 2.785.$$

A significant source of uncertainty arises from setting the sky level (see Section 5). In Archangel the sky is taken as the median of the sky boxes placed around the galaxy. This method gives realistic initial sky background estimates (Hall et al. 2012). If targets are modest in size, there is a reasonable control of the sky level. If the sky is set properly, then the magnitude growth curve should go asymptotically flat at large radii. One can also evaluate the sky setting by looking at the SB as a function of radius. SBs are not expected to flare or drop precipitously at the sky level, although such occurrences are not phenomenologically excluded (MacArthur et al. 2003; Erwin et al. 2008). Visual inspections of the magnitude growth curve and SB dependence with radius ensure an optimal sky setting. Fortunately, the sky values are low in the Spitzer data, even though we will show in the last section that this problem remains our major source of uncertainty.

In an analysis, an issue related to the sky problem is the matter of the terminal radius. A limit to the fitting process can be imposed by signal-to-noise considerations. Integration times

5 http://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/
permit us to reliably reach a radius $a_{26.5}$ at the isophotal level of 26.5 mag arcsec$^{-2}$ in the [3.6] band. We try to extend the ellipse fitting to $1.5a_{26.5}$ in the [3.6] band. A goal of the program is to ensure that the ellipse fitting extends to at least $1.1a_{26.5}$, with mosaics if necessary. This [3.6] band dimension is not available before the observation, so we rely on a substitution found to be comparable based on the $B$-band diameter $d_{25}$ requiring that the observed area extend to a radius of $1.5d_{25}$ (Sheth et al. 2010).

3.3. One-dimensional Fits and Parameter Extractions

The mean SB in mag arcsec$^{-2}$ in an annulus at radius $r_i$ depends on the mean flux in a pixel at that radius $F(r_i)$ and the mean sky flux in a pixel $S$:

$$
\mu(r_i) = -2.5\log\left(\frac{F(r_i) - S}{0.6}\right) + 21.585, \quad (1)
$$

where the constant in the denominator provides a conversion from pixels to arcseconds.

Archangel allows for a description of the run of SB with the radius as the sum of the disk and bulge components. Instead, we choose to restrict to disk fits only. With multiple component fits there are frequently trade-offs such that the overall fit may be satisfactory while the physical meanings of parameters are ambiguous. Usually the dominant radial SB characteristic of spiral galaxies is an exponential decay of projected luminosity with radius. Deviations are most frequently seen toward the center, where a bulge may become dominant. It is beyond the scope of this program to dissect galaxy images into detailed morphological components because such a dissection has a negligible effect on the product that most interests us: total magnitudes. We restrict fitting to a rough characterization of the exponential fall-off.

The radial run of SB in an exponential disk, $\mu_d(r)$, has a behavior described by an $e$-folding scale length, $\alpha$, and a central SB, $\mu_0$:

$$
\mu_d(r) = \mu_0 + 1.0857(r/\alpha). \quad (2)
$$

We determine the disk parameters with a fit over the range of radii from the half-light radius $a_e$ to the isophotal limit radius $a_{26.5}$. This range is modified if a visual inspection indicates the need. An example of an SB product is illustrated in Figure 3.

An example of a magnitude growth curve as a function of semimajor axis is shown in Figure 4. The light from each succeeding annulus contributes to the (negatively) increasing magnitude with increasing radius. If the sky value is properly set, then the growth curve will asymptotically flatten. Should the curve turn over, then it would be inferred that the sky level is set too high—flux from the galaxy is being attributed to the sky and being removed. Conversely, a sky value set too low causes flux from the sky to be attributed to the galaxy and the growth curve will fail to flatten.

The Spitzer photometry is sufficiently deep that the magnitude in the growth curve approaches the total magnitude of the galaxy. One way to extend to the total magnitude uses the procedure built into Archangel based on interpolations and extrapolations with rational functions. Such functions have a wide range in shape and have better interpolating properties than polynomial functions. They suit data where an asymptotic behavior is expected. The quadratic form/quadratic form, meaning a degree of two in both numerator and denominator is the simplest choice. The asymptotic magnitude is $c_1/c_2$ where $c_1$ and $c_2$ are the second-order coefficients of the numerator and denominator, respectively. However, rational functions are nonlinear. They can produce vertical asymptotes due to roots in the denominator that are to be ignored. Fit uncertainties are given by the standard
Table 1

|   | Extracted Photometry Parameters |
|---|---------------------------------|
| 1 | PGC                               | 41729 |
| 2 | Name                              | NGC 4522 |
| 3 | Date                              | 2007.02.14T14:46:36.378 |
| 4 | Exp                               | 240 |
| 5 | $a_{26.5}$                        | 181 |
| 6 | $[3.6]_{26.5}$                    | 11.98 |
| 7 | $[3.6]_{tot}$                     | 11.970 |
| 8 | $\sigma_m$                       | 0.003 |
| 9 | $[3.6]_{ext}$                     | 11.957 |
| 10 | $\mu_0$                          | 20.32 |
| 11 | $a$                               | 31.8 |
| 12 | $b/a$                             | 0.26 |
| 13 | $\sigma_{b/a}$                   | 0.01 |
| 14 | PA                                | 34 |
| 15 | $a_{50}$                          | 77 |
| 16 | $\mu_{50}$                       | 23.04 |
| 17 | $a_e$                             | 36 |
| 18 | $\mu_e$                          | 21.24 |
| 19 | $\langle \mu_e \rangle$          | 20.31 |
| 20 | $a_{20}$                          | 15 |
| 21 | $\mu_{20}$                        | 19.99 |
| 22 | $(\mu_{20})$                     | 19.53 |
| 23 | $C_{82}$                          | 5.2 |
| 24 | Ref/Link                          | SSOV |

Notes. (1) Principal Galaxies Catalog (PGC) number, (2) common name, (3) date of Spitzer observation, (4) nominal total integration, seconds (actual time collecting photons is somewhat less), (5) $a_{26.5}$: major axis radius at isophote 26.5 mag arcsec$^{-2}$, (6) $[3.6]_{26.5}$: AB magnitude within $a_{26.5}$, (7) $[3.6]_{tot}$: total AB magnitude from rational function asymptote, (8) $\sigma_m$: rms deviations, rational function fit, (9) $[3.6]_{ext}$: total AB magnitude by extrapolating flux beyond $a_{26.5}$ assuming continuity of exponential disk, (10) $\mu_0$: central disk surface brightness from inward extrapolation of disk fit, mag arcsec$^{-2}$, (11) $a$: exponential disk scale length, arcseconds, (12) $b/a$: ratio of minor to major axes, (13) $\sigma_{b/a}$: uncertainty in axial ratio, (14) P.A.: position angle of major axis, deg (15) $a_{50}$: major axis radius of annulus enclosing 80% of total light, arcseconds, (16) $\mu_{50}$: surface brightness at $a_{50}$, mag arcsec$^{-2}$, (17) $a_e$: "effective radius," major axis radius of annulus enclosing 50% of total light, arcsec, (18) $\mu_e$: surface brightness at $a_e$, mag arcsec$^{-2}$, (19) $\langle \mu_e \rangle$: average surface brightness within $a_e$, mag arcsec$^{-2}$, (20) $a_{20}$: major axis radius of annulus enclosing 20% of total light, arcseconds, (21) $\mu_{20}$: surface brightness at $a_{20}$, mag arcsec$^{-2}$, (22) $\langle \mu_{20} \rangle$: average surface brightness within $a_{20}$, mag arcsec$^{-2}$, (23) $C_{82}$: concentration index, $a_{80}/a_{20}$, (24) Spitzer program link.

4. CORRECTIONS

Corrected apparent magnitudes $[3.6]^{b,k,i,a}$ for Spitzer/IRAC ch.1 data are given by

$$[3.6]^{b,k,i,a} = [3.6] - A_{b}^{[3.6]} - A_{k}^{[3.6]} - A_{i}^{[3.6]} + A_{a}^{[3.6]}$$

with the apparent magnitude $[3.6]$ output from Archangel, galactic extinction correction $A_{b}^{[3.6]}$, internal extinction correction $A_{k}^{[3.6]}$, $k$-correction $A_{i}^{[3.6]}$, and the aperture correction $A_{a}^{[3.6]}$. We shall describe these terms in the following subsections.

4.1. Galactic Extinction Correction

Galactic extinction depends only on coordinate and observational wavelengths. The Infrared Science Archive provides an online tool at http://irsa.ipac.caltech.edu/applications/DUST/ with 100 $\mu$m cirrus maps (Schlegel et al. 1998) that supply us with differential reddenings, $E(B - V)$. We use the correction term given by Cardelli et al. (1989), accounting for a small shift to the centroid of the Spitzer passband:

$$A_{b}^{[3.6]} = R_{[3.6]} E(B - V)$$

with $R_{[3.6]} = 0.20$. Galactic extinction magnitude corrections at $[3.6]$ are only 9% compared to at $I_C$ and 4% of the corrections at $B$. Corrections at latitudes above 15$^\circ$ are almost always 0.05 mag or less, with uncertainties $\sim$0.01 mag.

4.2. Internal Extinction Correction

Internal extinction is usually the greatest concern. Fortunately, in the infrared such extinction is very small. Giovanelli et al. (1995, 1997) showed that there is a luminosity dependence on internal galaxy obscurations. Tully et al. (1998) confirmed and provided an alternative description of the effect. There is a subtle problem with this because absolute magnitudes are not known a priori, they are a product of the analysis. Tully et al. (1998) framed magnitude corrections in terms of a distance-independent surrogate, the line width parameter, $W_{mx}$. Accordingly, the internal extinction correction can be written as

$$A_{i}^{[3.6]} = \gamma_{[3.6]} \log(a/b),$$

where $\gamma_{[3.6]}$ is

$$\gamma_{[3.6]} = 0.10 + 0.19 \left(\log W_{mx} - 2.5\right)$$

if $W_{mx} > 94$ km s$^{-1}$ and $\gamma_{[3.6]} = 0$ otherwise. $W_{mx}$ is a measure of twice the maximum rotation rate of a galaxy derived

error of the estimate, SEE:

$$SEE = \left(\frac{1}{n} \sum_{i=1}^{n} (m(a_i)_{hit} - m(a_i)_{measured})^2\right)^{1/2}.$$

Given the growth curve as seen in Figure 4, it is straightforward to define the useful parameters $a_{20}$, $a_e$, and $a_{50}$ enclosing 20%, 50%, and 80% of the light, respectively. The associated magnitudes and semimajor radii are illustrated in Figures 2–4. Other products are the average SB within $a_e$ and $a_{20}$ and a concentration index of $C_{82} = a_{80}/a_{20}$. Table 1 gives the parameters that are extracted for the galaxy and used as an example in Figures 2–4 and illustrates what is seen in a single row in the Spitzer [3.6] Band Photometry catalog of the EDD.
from $W_{m50}$, the H1 profile width at 50% of the mean flux within the velocity range encompassing 90% of the total H1 flux (Courtois et al. 2009, 2011b). The measure includes a depopulation adjustment for the inclination $i$ (see the above references for the derivation of inclinations).

There is an advantage to this formulation of the internal extinction. If the inclination is underestimated, $\log(a/b)$ is underestimated, driving $A_i[3,6]$ lower, but then $W_{m50}$ is overestimated, which drives $f_{[3,6]}$, and hence $A_i[3,6]$, up. The two terms in $A_i[3,6]$ are affected in opposite directions. Regardless, internal absorption corrections are always small, rarely reaching 0.1 mag. Uncertainties in these corrections are less than 0.02 mag.

### 4.3. K-correction

The K-correction (Oke & Sandage 1968) is small at the redshifts we encounter. Huang et al. (2007) show a linear dependence of the K-correction with the redshift at 3.6 $\mu$m. This linear dependence is independent of the galaxy type at small redshifts at this position on the Rayleigh–Jeans tail of the SED of star light. We use the low-$z$ formulation by Huang et al. (2007):

$$A_k[3,6] = -2.27z,$$

with $z$ being the galaxy redshift. Uncertainties are at the level of 0.01 mag or less.

### Aperture Correction

The fourth and last adjustment is the aperture correction. Aperture corrections are required for extended source photometry with Spitzer (e.g., galaxies) because their absolute calibrations are tied to point sources with IRAC observations. There is extended emission from the point-spread function outer wings, and scattering of the diffuse emission across the focal plane that is captured by the extended source photometry but not by the calibrations of the point sources. Since the photometry is normalized to 12″, a correction must be applied for large apertures (Reach et al. 2005; IRAC Instrument Handbook). The following correction is recommended.\(^6\) For an effective aperture radius $r$ in arcseconds, the ch.1 IRAC extended source aperture correction is

$$f_{IRAC \text{true}} = f_{IRAC \text{measured}} \times (A e^{-r^2} + C)$$

where $A = 0.82$, $B = 0.37$, and $C = 0.91$. The extended source aperture correction in magnitudes is

$$A_e[3,6] = -2.5\log(A e^{-r^2} + C).$$

The average correction for galaxies of interest to our program is 0.10. The variations on this correction from source to source for our galaxies, which are typically larger than 1′, is 0.01 mag, and 10% relative uncertainties in the adjustment are negligible.

## 5. uncertainties

An extremely important virtue of the Spitzer [3,6] band photometry is the robustness of the luminosity measurements, which offer (1) uniformity across the sky, (2) inclusiveness of target light due to the sensitivity, and (3) small adjustments. There was a discussion of uncertainties associated with the adjustments in the last section and it can be summarized that as long as sources are not in extremely obscured regions of our Galaxy ($A_b < 1$), then the global uncertainty in adjustments is at the level of 0.03 mag or less, with the internal absorption within the sources dominant in the error budget. The IRAC handbook gives a 2%–3% error on the absolute flux calibration (excluding the aperture correction), but more importantly for this program, it claims that photometry is repeatable across the sky at the 1% level.

Among our parameters we determine the isophotal, “total,” and “extrapolated” magnitudes. The latter two both approximate the global magnitude—the “total” magnitude is from the rational function asymptote of the growth curve and the “extrapolated” magnitude is from the extension of the exponential disk fit beyond the radius of the isophotal magnitude. By construction, $[3,6]_{26.5}$ is fainter than $[3,6]_{\text{ext}}$ and should be fainter than $[3,6]_{\text{tot}}$. The average difference $([3,6]_{26.5} - [3,6]_{\text{ext}}) = 0.016$ mag corresponds to a typical disk fit of 6.2 exponential scale lengths at the 26.5 mag arcsec$^{-2}$ isophote. The typical uncertainty in this extrapolation is below 0.01 mag except if the target is of extremely low surface brightness. SB profiles of spirals can depart from a pure exponential at large radii, either with flares or truncations, because of the interplay between bulges and disks (Kent 1985). Yet because such a large fraction of the flux is captured by the deep Spitzer integrations, the differences between the measured isophotal and extrapolated magnitudes are so small as to leave little room for uncertainty in the extrapolation.

By comparison, $([3,6]_{26.5} - [3,6]_{\text{tot}}) = 0.007$ mag, that is, $[3,6]_{\text{tot}}$ is fainter than $[3,6]_{\text{ext}}$ by 0.009 mag on average. The rms scatter is 0.018 mag between these alternative measures. The differences are primarily due to a slight instability in the rational function fits. We give preference to the exponential disk extrapolations.

We turn to what is probably the largest source of error, the setting of the “sky” level. With observations in space at [3,6] band, this noise level is dominated by diffuse zodiacal light and discrete high-redshift galaxies. The discrete contaminants can be easily seen to very faint levels in regions beyond the galaxy. They are less easy to see and exclude if they are superimposed on the target galaxy. A major task before running a surface photometry analysis is the removal of contaminants like foreground stars and background galaxies. Our approach is not to be too aggressive with the removal of contaminants. We remove contaminants as best we can on the target and remove contaminants in the adjacent sky to the same level, leaving in place fainter sources since such sources must also be hidden within the galaxy.

It was described in the section on Archangel photometry that sky settings were established from the median of pixel fluxes in boxes placed around the galaxy and validated by the nature of the magnitude growth curve (it should go asymptotically flat) and the SB profiles (flares or cutoffs as noise dominance is approached are suspicious but not considered a conclusive sign of bad sky setting). In order to generate a quantitative test of the effects of sky variance, we have run the Spitzer-adapted Archangel on 235 galaxies our calibrator sample (defined in Tully & Courtois 2012). Our calibrator sample contains only a few LSB and irregular galaxies.

A first run gives us the sky value $S_0$ and its uncertainty. We run Archangel two more times with sky values of $S_0 \pm \sigma_{\text{sky}}$ respectively for each one of our selected galaxies. This gives us three extrapolated magnitudes which we call $[3,6]_0$, $[3,6]_+$, and $[3,6]_-$. Figures 5 and 6 show the variation of $([3,6]_0 - [3,6]_+) + [3,6]_-)/2$ as functions of type and apparent magnitude. These plots show the sensitivity to the choice of sky value and that this sensitivity becomes particularly acute

\(^6\) http://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/
Figure 5. Variation of magnitude uncertainty as a function of morphological type. The mean offset of 0.04 mag and rms scatter of 0.02 mag indicated by the solid red and dotted blue lines, respectively, exclude types Sd and later. Three cases with contamination from nearby bright objects are indicated by asterisks. The scatter is asymmetric about the mean since an absolute value difference from the fiducial value cannot be less than zero. (A color version of this figure is available in the online journal.)

Figure 6. Variation of magnitude uncertainty as a function of magnitude. Type Sd systems, here referred to as low surface brightness galaxies, are represented by squares while type Sdm–Sm–Im irregular galaxies are represented by triangles. The asterisks denote galaxies with a very bright object close to them. The mean offset and scatter lines have the same meaning as in the previous figure. (A color version of this figure is available in the online journal.)

Figure 7. Variation of magnitude uncertainty as a function of the sky value in MJy sr$^{-1}$. The squares represent low surface brightness galaxies while the triangles stand for irregular ones. Galaxies represented by asterisks are galaxies with a very bright object close to them. Sky uncertainties can be four times higher than normal without resulting in an abnormally high uncertainty in magnitude. (A color version of this figure is available in the online journal.)

indicates that the uncertainties do not strongly increase at fainter magnitudes.

Next, we test for uncertainties in magnitude due to the sky against the sky value itself, as well as against the isophotal semimajor axis in the [3.6] band $\alpha_{26.5}$, inclination from face-on, and apparent area defined as the area of the ellipse at $\alpha_{26.5}$ to see if any trends exist. The results in Figures 7 and 8 show no correlation. In Figure 7, we can see that the uncertainty in magnitude does not depend on the sky value. We checked for a dependence on sky uncertainty and find no correlation. These results suggest that the total and extrapolated apparent disk magnitudes are adequate (we do not show the plots for both magnitudes here as they are very similar). In any case, the highest sky values are relatively moderate ($<0.20$ MJy sr$^{-1}$). One can also notice that sky values and sky uncertainties are not correlated, evidently a reflection of the relative uniformity of background across dimensions of 5–10 arcmin. Structure in the background could be a worse problem when the sky setting is very low. Perhaps it is a surprise that the uncertainty is not proportional in the apparent galaxy area (Figure 8, bottom). The more pixels that are affected by setting a new sky, the more the magnitude might change. In any case, these tests indicate that magnitude uncertainties can be taken to be approximately constant for all normal spiral galaxies.

5.1. Comparisons with Alternative Analyses

Our Archangel analysis procedures can be compared with alternative reductions of Spitzer observations. Comparisons with magnitudes found by the projects SINGS (Muñoz-Mateos et al. 2009), S$^4$G (Sheth et al. 2010; K. Sheth et al. 2012, private communication), and CHP (Freedman et al. 2011; W. L. Freedman et al. 2012, private communication) show that our Cosmic Flows project is on the same magnitude scale as all these projects. In the case of CHP, we give special attention to this comparison because our two programs, CHP and CFS, have the common ambition of measuring galaxy distances. As we go forward, we want to understand to what degree the alternative photometry analyses are interchangeable. A comparison is given between the two sources in Figure 9. There is a slight tendency for CHP values to be brighter for the largest galaxies, with
Figure 8. Variation of magnitude uncertainty as a function of galaxy: (top) semimajor axis, (middle) inclination, and (bottom) apparent area. Squares, triangles, and asterisks represent low surface brightness, irregular, and possibly contaminated galaxies, respectively. There is no apparent correlation between magnitude uncertainty and the radius, inclination, or apparent area of a galaxy. (A color version of this figure is available in the online journal.)

essentially no difference faintward of \( [3.6] = 12 \). The most likely explanation for a difference with the bright, large galaxies is small differences in the way sky values are set. The rms scatter in the differences (six deviant points rejected) is ±0.052, which, if attributed equally, implies an uncertainty in an individual measurement of ±0.037 mag for each source.

Comparisons with other projects give comparable results. Typical zero-point differences are ±0.01 mag and rms uncertainties are ±0.04 to 0.05 mag. See a summary of the comparisons with other major programs in Table 2. These results provide an estimate of the internal errors of alternate fitting procedures with the same data. We recall that our two measures of magnitude agree at the level of 0.01 with a scatter of ±0.02.

In a summary of the errors, the dominant contributions are sky settings (0.04 mag), flux calibration (0.02 mag), and extinction (0.02 mag), leading to total uncertainties in magnitudes of ≈0.05 mag. The great interest of the Cosmic Flows program is to use the TFR to measure distances to galaxies. The typical scatter in the TFR is 0.4 mag and 20% in distance. With photometry errors after corrections held to 0.05 mag, the contribution to the distance error budget from photometry is minor.

6. CONCLUSIONS

Our photometric procedures for the semi-automated analysis of Spitzer/IRAC channel 1 data at 3.6 μm have been described. Galaxy surface photometry is carried out with the Archangel software (Schombert 2007; Schombert & Smith 2012) adapted for Spitzer data input. Material already is available for some 3000 galaxies from the Spitzer Heritage Archive and our CFS program will supply information for an additional 1274 galaxies. The 235 galaxies analyzed in the course of this paper will be
used in a subsequent paper for the calibration of the mid-infrared Tully–Fisher relation.

The final goal of our project is to measure distances, hence map peculiar velocities, across our local universe within 10,000 km s$^{-1}$ using the correlation between galaxy luminosities and their rotation rates. We have demonstrated the ability to use Spitzer Space Telescope mid-IR data to perform surface photometry with a relatively high accuracy. No correlation is found between magnitude uncertainties and other important galaxy parameters such as inclination, apparent area, or semimajor axis. We conclude that, after all corrections, the uncertainties on magnitudes are of the order ±0.05 for the regular spiral galaxies at the heart of our project. These uncertainties are small compared with the overall scatter in the TFR. LSB galaxies or very irregular ones require special attention but these classes of galaxies are not of principal interest to us.

For our purposes, the advantages of mid-infrared photometry from space include the minimization of both galactic and internal obscuration issues, very low backgrounds, and source fluxes dominated by old stellar populations that are good representatives of the baryonic mass. The most outstanding advantage, though, is the integrity and consistency of the photometry in all quadrants of the sky. The EDD contains H$\alpha$ profile information that provides useful line widths for over 11,000 galaxies. Ongoing Spitzer observations are providing the complementary photometric information required for a dense, detailed map of structure and motions in the near part of the universe.

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APPENDIX

COSMIC FLOWS PROGRAM OVERVIEW

Cosmic Flows may have as many arms as an octopus. At its core, it is a collaboration between H. Courtois and B. Tully to obtain accurate distances to galaxies. A major part of the program involves the exploitation of the TFR. Activities in this regard began with the accumulation of H$\alpha$ profiles for the necessary kinematic information within the Cosmic Flows Large Program using the U.S. National Radio Astronomy Green Bank Telescope (Courtois et al. 2009, 2011b) and the accumulation of optical photometry for the necessary magnitude and inclination information using the University of Hawaii 2.24 m telescope (Courtois et al. 2011a). The present extension embarks on complementing the optical photometry with mid-infrared photometry. The current paper describes analysis procedures developed within the core program but CFS embraces the larger team identified in the acknowledgement.

The next paper in this series will include most of the CFS team in a discussion of the TFR calibration with Spitzer photometry.

Near-, intermediate-, and far-TFR samples in the Cosmic Flows program were described by Courtois et al. (2011b). The “near” sample is intended to achieve dense coverage of a volume extending to 3300 km s$^{-1}$ with the inclusion of all galaxy types later than Sa that are brighter than $M_K = -21$, inclined greater than 45°, and not obscured, disrupted, or confused. The “intermediate” sample is drawn from flux and color limits applied to an IRAS redshift survey (Saunders et al. 2000). The flux limit at 60 μm is 0.6 Jy, the color criterion to separate normal spirals from active nuclei is a ratio of 100 μm to 60 μm flux greater than 1, there is a velocity cutoff at 6000 km s$^{-1}$, and there is the same inclination restriction as applies with the near sample. By contrast, the “far” sample is restricted to extreme edge-on systems drawn from Flat Galaxy catalogs (Karachentsev et al. 1999; Mitronova et al. 2004). Candidates in the sample that lie at declinations accessible to the Arecibo Telescope have velocities extending to 15,000 km s$^{-1}$. These are our well-defined samples. In addition, we derive distances to all other suitably observed galaxies. Generally, the information for the additional systems comes from archives. In all, presently good data are available for about 7500 appropriate galaxies.

A quite separate and active component of Cosmic Flows is a program with the Hubble Space Telescope to obtain tip of the red giant branch distances to nearby, spatially resolved galaxies (Makarov et al. 2006; Rizzi et al. 2007; Jacobs et al. 2009). Exquisite distances (5% accuracy) are available for approaching 300 galaxies within ~10 Mpc.

Distances for Cosmic Flows encompass measures by other methodologies discussed in the literature. Foremost among these are the Cepheid period–luminosity relation, surface brightness fluctuation, fundamental plane, and supernova Ia procedures. The diverse material is drawn together in the EDD (Tully et al. 2009). The EDD goes beyond the compilation of catalogs relevant to extragalactic distances to include redshift catalogs, which, with various levels of completion, describe the distribution of galaxies in the local universe, and group catalogs, which help identify entities where averaging over velocities or distances is reasonable. The first assembly of distances in this program (Tully et al. 2008) has now been given the name Cosmicflows-1. A core team is now involved in the assembly of Cosmicflows-2 (Tully & Courtois 2012; Courtois & Tully 2012b).

The holy grail of Cosmic Flows is the use of distances to determine peculiar velocities and, subsequently, mass fluctuations. Peculiar velocities are departures from the cosmic mean expansion and it is assumed that they arise due to density irregularities. The two regimes require separate attention. The high-density environments in and around collapsed halos are at the extreme of nonlinear dynamics. Within the collaboration we have developed numerical action methods that provide an optimal description of the distribution of mass affecting galaxies on curved orbits on first approach to an attractor (Shaya et al. 1995; Peebles et al. 2001, 2011). The other extreme is the regime of linear dynamics. A procedure we have used that is appropriate with redshift data sets of 10$^5$ or more objects is based on the action principle (Lavaux et al. 2010). However, the methodology that most interests us starts with Wiener filtering of the peculiar velocity field, resulting in descriptions of the density field, independent of the information provided by redshift surveys (Zaroubi et al. 1995; Courtois et al. 2012). The current density field can be mapped back to the initial conditions which
are the starting point for constrained simulations that attempt

approximate the observed universe with a computer model (Klypin et al. 2003; Gottloeber et al. 2010; Courtois & Tully 2012a).

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