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MID-INFRARED EMISSION FROM ELLIPTICAL GALAXIES: SENSITIVITY TO STELLAR AGE

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ABSTRACT

Mid-infrared observations (3.6 - 24μm) of normal giant elliptical galaxies with the *Spitzer* space telescope are consistent with pure populations of very old stars with no evidence of younger stars. Most of the stars in giant elliptical galaxies are old but the mean stellar age determined from Balmer absorption in optical spectra can appear much younger due to a small admixture of younger stars. The mean stellar age can also be determined from the spectral energy distribution in the mid-infrared which decreases with time relative to the optical emission and shifts to shorter wavelengths. The observed flux ratios $F_{8\mu m}/F_{3.6\mu m}$ and $F_{24\mu m}/F_{3.6\mu m}$ for elliptical galaxies with the oldest Balmer line ages are lower than predicted by recent models of single stellar populations. For ellipticals with the youngest Balmer line ages in our sample, 3-5 Gyrs, the flux ratios $F_{24\mu m}/F_{3.6\mu m}$ are identical to those of the oldest stars. When theoretical mid-IR spectra of old (12 Gyr) and young stellar populations are combined, errors in the $F_{24\mu m}/F_{3.6\mu m}$ observations are formally inconsistent with a mass fraction of young stars that exceeds $\sim 1\%$. This is less than the fraction of young stars expected in discussions of recent surveys of elliptical galaxies at higher redshifts. However, this inconsistancy between Balmer line ages and those inferred from mid-IR observations must be regarded as provisional until more accurate observations and theoretical spectra become available. Finally, there is no evidence to date that central disks or patches of dust commonly visible in optical images of elliptical galaxies contribute sensibly to the mid-IR spectrum.

Subject headings: galaxies: elliptical and lenticular; galaxies: ISM; infrared: galaxies; infrared: ISM

1. INTRODUCTION

The mid-infrared emission from elliptical galaxies is sensitive to their mean stellar age. As a single stellar population evolves, progressively less mass is lost from red giant stars with a corresponding decrease in mid-IR emission from photospheric and circumstellar dust (Bressan et al. 1998; Mouhcine 2002; Mouhcine & Lancon 2002; Piovan et al. 2003).

While the vast majority of stars in giant elliptical galaxies are thought to be very old, enhanced Balmer line absorption in many galaxies indicates the presence of a small subfraction of much younger stars (Gonzalez 1993; Worthey 1994; Tantalo et al. 1998; Trager et al. 2000a; Kuntschner et al. 2002). A $\sim 5\%$ population of young stars is consistent with the red colors of these galaxies and may result from past merging or internal star formation. This low level of star formation could occur from time to time in all ellipticals, or alternatively the young stars could be a relict of the earlier evolution of elliptical galaxies when star formation was stronger. Such a transition from blue star-forming galaxies to red ellipticals with very little star formation is required to understand the increasing total mass of red galaxies that have evolved at nearly constant color since redshift $z \sim 1$ (e.g. Gebhardt et al. 2003; Koo et al. 2005). To preserve the tightness of the color-magnitude relation among ellip-

ticals, this evolution-driven star formation must be quasi-continuous and avoid strong bursts, implying a broad range of stellar ages among the younger stars. Large star formation episodes due to mergers may nevertheless occur in a few galaxies.

Piovan et al. (2003) have predicted a strong evolution of the mid-infrared spectral energy distribution (SED) for a single stellar population. Mid-IR observations should in principle confirm the presence of the small "frosting" of younger stars in elliptical galaxies required to explain the Balmer line ages. Our previous attempt to do this using archival 15μm data from the *Infrared Space Telescope (ISO)* was somewhat indeterminate due to the large fraction in that sample of unrepresentative elliptical galaxies containing large masses of dust and cold gas. Nevertheless several normal ellipticals in that sample with Balmer line ages of 2–5 Gyrs showed no evidence of young stars at 15μm (Temi, Mathews & Brighenti 2005). We report here recent 3.6 to 24μm observations of a sample of more normal, recently archived elliptical galaxies observed with the *Spitzer Infrared Telescope* and with known Balmer line ages. We find, however, essentially no mid-IR evidence for younger stars and a significant mismatch with recent predictions of mid-IR SEDs.

2. OBSERVATIONS

Table 1 lists our sample of 9 bright, reasonably isolated elliptical galaxies from the the *Spitzer* Infrared Nearby Galaxies Survey (SINGS) legacy program and from time allocated to Guaranteed Time Observers (PI G. Fazio, program ID number: 69). A wide range of Balmer line stellar ages is represented. These data reach a noise level unprecedented in previous space observations, a few μJy in the IRAC channels and about 30μJy in the 24μm

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MIPS channel.

The data were taken with the Infrared Array Camera (IRAC) and the Multiband Imager Photometer (MIPS) (Fazio et al. 2004, Rieke et al. 2004). Full coverage imaging was obtained for all observations with additional sky coverage to properly evaluate the background emission. Details on the observing strategies, field coverage and integration times for the SINGS program are described by Kennicutt et al. (2003). For all nine galaxies data were recorded at four IRAC channels (3.6, 4.5, 5.8, 8μm) while the 24μm MIPS channel was available only for five galaxies in the selected sample.

We used the Basic Calibrated Data (BCD) products from the Spitzer Science pipeline (version 11.4) to construct mosaic images for all objects. Pipeline reduction and post-BCD processing using the MOPEX software package provide all necessary steps to process individual frames: dark subtraction, flat-fielding, mux-bleed correction, flux calibration, correction of focal plane geometrical distortion, and cosmic ray rejection.

We used the task ELLIPSE in the IRAF data reduction package to derive surface brightness profiles and to measure aperture photometry. Photometry of these extended sources was performed in each band by fitting surface brightness isophotes and also by measuring the fluxes in suitable circular apertures around the centers. A number of point sources were present in the final mosaiced images at all bands, with the vast majority evident in channel 1 and 2 (3.6 and 4.5 μm). These were identified by eye as foreground stars and other galaxy in the field and cross-checked using surveys at other wavelengths (Digital Sky Survey and 2MASS). They were then masked out before performing the isophotal fitting and surface photometry. The correction for the extended emission was applied to the fluxes as described in the Spitzer Observer's manual. The uncertainties on the final absolute calibration are estimated at 10% for the four IRAC channels and 15% for the 24μm data.

3. RESULTS

Figure 1 shows an overview of the observations from Table 1 arbitrarily normalized to the flux at 3.6μm and compared with the single population SEDs predicted by Piovan et al. (2003) for ages 3 and 12 Gyrs and for solar abundance. Most of the elliptical galaxies in our sample have very similar SEDs between 3.6 and 24μm, but the trend does not closely follow the predicted SED for either old or young populations. The most aberrant galaxy, NGC 1316, is no surprise since it is currently undergoing a spectacular merger with a gas and dust rich galaxy; we discuss the infrared emission from this galaxy in more detail in Temi et al. (2005). For the remaining E galaxies in Figure 1 the SEDs between 3.6 and 8μm are very similar to those of the dust-free elliptical galaxies in the *Spitzer* observations of Pahre et al. (2004). At 24μm NGC 4472 is slightly weaker relative to the 3.6μm flux than the other three normal ellipticals at this MIPS wavelength.

In Figure 2 we plot the flux ratios $F_{8\mu m}/F_{3.6\mu m}$ and $F_{24\mu m}/F_{3.6\mu m}$ against the mean stellar age found from the Balmer line index, which are accurate to within about 20-30%. The errors for the mid-IR fluxes are dominated not by observational signal to noise, but by calibration errors that are uncertain at the present time. The error

bars for the mid-IR ratios in Figure 2 are very conservatively estimated as follows: The positive (negative) error is found by increasing (decreasing) the numerator flux by 10% (15% for the 24 μm flux) and decreasing (increasing) the denominator flux by 10%. The solid lines in these plots are the predicted flux ratios for single stellar populations at the indicated age. Apart from NGC 1316, the highest point in both plots, the observed ratios are consistent with no evolution as indicated by the horizontal dotted lines; galaxies with radically different Balmer line ages show no variation in their mid-IR spectral shapes. Note however that the data points of the oldest ellipticals are offset below the predicted flux ratios.

About 50-70% of normal elliptical galaxies have small optically visible dusty clouds or disks in their cores (von Dokkum & Franx 1995; Lauer et al. 2005), and our *Spitzer* archival sample is typical in this regard (Table 1). Since IRAC and MIPS flux ratios measured with different apertures, $R_e/8$ and $R_e/2$, are not substantially different, we assume that emission from these central dust clouds is not influencing the flux ratios plotted in Figure 2. Nor is there any tendency for ellipticals without visible central dust (NGC 4649 and 6703) to have different mid-IR fluxes. These results are consistent with our discussion of the *ISO* sample (Temi et al. 2005) where we were unable to detect 15μm emission from the central dust clouds in elliptical galaxies. Finally, we note that the mid-IR surface brightness profiles for all galaxies observed in the *Spitzer* archival sample follow de Vaucouleurs profiles to a good approximation.

The mean Balmer line stellar age for the galaxies plotted in Figure 2 is assumed to be that of an old population skewed toward younger ages by a small admixture of younger populations. Suppose for simplicity that all the old stars have an age of 12 Gyrs and that the young stars have a single, much younger age. In this case there is a degeneracy between the fraction by mass f_{young} of the younger population and its age. The same mean Balmer line age corresponds either to a very small fraction of very young stars or a larger fraction of somewhat older stars (but still much less than 12 Gyrs). Using the Piovan et al. (2003) predictions as a guide, we plot in Figure 3 the mid-IR flux ratios expected for four small fractions f_{young} against the age of that population. The initial mass function (IMF) of the younger population is assumed to be no different than that of the 12 Gyrs old population, namely the Salpeter law. While the $F_{8\mu m}/F_{3.6\mu m}$ ratios are generally insensitive to small fractions of intermediate age ($\gtrsim$ 4 Gyr) stars, the predicted $F_{24\mu m}/F_{3.6\mu m}$ ratio can be used to effectively detect small fractions of very young (2-3 Gyr) stars. Although the three normal ellipticals in our sample with mean ages less than 5 Gyrs – NGC 584, 3923 and 6703 – have flux ratios $F_{8\mu m}/F_{3.6\mu m}$ and $F_{24\mu m}/F_{3.6\mu m}$ almost identical to those of the old galaxies, and therefore consistent with no young stars, the calibration errors still allow some nonzero contribution.

Suppose we ignore the offset in Figure 2 between observations and predicted flux ratios at ∼12 Gyrs and consider the sensitivity of the *Spitzer* observations to detect age variations within the errors of the $F_{8\mu m}/F_{3.6\mu m}$ and $F_{24\mu m}/F_{3.6\mu m}$ ratios. In both panels of Figure 3 we show two dotted horizontal lines separated by the height of typical error bars of our mid-IR observations normal-

ized to the ratios at 12 Gyrs predicted by Piovan et al. (2003). For example using the flux ratio evolution in the upper panel of Figure 3, the typical mid-IR flux errors in Figure 2 allow $F_{8\mu m}/F_{3.6\mu m}$ ratios approximately consistent with young populations with $f_{young} = 1, 3, 5$ and 10% and ages of $\sim 0.5, 1, 1.4$ and 2 Gyrs respectively, assuming 12 Gyrs for the old population. The estimated young population ages are the intersections of the upper dotted line with the curves of constant f_{young} in Figure 3. Clearly, the age of just the young stellar population must not exceed the Balmer line age which includes both old and young stars. It is reassuring that the mean ages of the younger stellar population in NGC 584, 6703 and 3923 that are consistent with the predicted mid-IR SEDs and observational errors are also less than the global mean age for these galaxies determined from the Balmer absorption lines.

However, applying this same procedure to the lower panel in Figure 3, the typical errors for the $F_{24\mu m}/F_{3.6\mu m}$ observations allow the presence of young stars with mass fractions $f_{young} = 1, 3, 5$ and 10% having ages of ~ 1.5, 2.5, 3.3 and 4.7 Gyrs respectively, assuming again that the remaining stars are 12 Gyrs old. Consequently, errors in the observed flux ratios $F_{24\mu m}/F_{3.6\mu m}$ for NGC 584 and 6703, with Balmer ages of 2.8 and 4.8 Gyrs respectively, allow single younger populations with ages that do not exceed the Balmer line ages if $f_{young} \lesssim 3\%$ and $f_{young} \lesssim 10\%$ respectively. It should be recognized that this requirement on the ages – that the age of the young stellar population in a binary population not exceed the mean combined Balmer age of both young and old stars – is a very conservative criterion for inconsistency.

For an alternative estimate for the age of the young population in these galaxies, we compare the age and mass fraction of the younger population from optical Hβ indices with the mid-IR values in Figure 3. The three youngest galaxies, NGC 584, 3923 and 6703, have Hβ indices of 2.1, 1.9 and 1.9 respectively (Thomas et al. 2005). Assuming an old population of 12 Gyrs, we determined the age and f_{young} for the young population for

H$\beta = 1.9$ and 2.1 using the interactive program at Guy Worthey's website (adopting Padua evolutionary tracks and solar abundance) and these are shown in Figure 3 as filled squares (H$\beta = 2.1$) and circles (H$\beta = 1.9$). It is seen from the lower panel that the Hβ indices and theoretical $F_{24\mu m}/F_{3.6\mu m}$ ratios for both NGC 584 and 6703 are inconsistent unless $f_{young} \lesssim 1\%$.

The formal disagreement between Balmer and mid-IR ages and low upper limits for f_{young} must be regarded as somewhat provisional because of the obvious difficulties associated with theoretical estimates of the mid-IR SED apparent in Figures 1 and 2. We stress again that the preceding estimates of the young population ages allowed by the SEDs of Piovan et al. (2003) plotted in Figure 3 has ignored the offset of the observations at 12 Gyrs in Figure 2.

It may be possible in the near future to reduce the uncertainty in the mid-IR age estimates when the remaining calibration errors in the *Spitzer* data reduction are better understood. It is also important to increase the statistics by observing more normal elliptical galaxies with Balmer ages in the 3 - 5 Gyrs range. Finally, in view of the obvious discrepancies between the observed and predicted SEDs in Figure 1, it would also be useful to observe young clusters of known ages and with metallicities similar to those of elliptical galaxies to establish empirical SEDs for young single stellar populations.

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TABLE 1
Basic Properties of the sample and Integrated Photometry[a]

Name NGC	Log L_B[b] ($L_{B\odot}$)	R_e ($''$)	Hβ[c]	age[d] (Gyr)	central[e] dust?	$F_{3.6\mu m}$ (mJy)	$F_{4.5\mu m}$ (mJy)	$F_{5.8\mu m}$ (mJy)	$F_{8\mu m}$ (mJy)	$F_{24\mu m}$ (mJy)	$F_{8\mu m}/F_{3.6\mu m}$	$F_{24\mu m}/F_{3.6\mu m}$
0584	10.39	27.4	2.08±0.05	2.8	yes,4	153.3	82.6	46.5	33.9	15.5	0.22 ±0.06	0.10±0.03
1316	10.91	80.7	2.07±0.03	3.2	yes,1,4	902.9	540.7	335.0	270.7	221.0	0.30 ±0.08	0.25±0.06
3923	10.78	53.3	1.87±0.08	3.3	...	334.5	189.6	109.3	72.8	⋯	0.22 ±0.05	⋯
4472	10.92	104	1.62±0.06	9.6	yes,1,4	1046.4	587.9	350.0	249.4	82.5	0.24 ±0.06	0.08±0.02
4552	10.47	30.0	1.47±0.05	12.4	yes,1,4	249.2	145.2	76.3	55.8	24.6	0.22 ±0.06	0.10±0.02
4649	10.75	73.6	1.40±0.05	14.1	no,1,4	770.1	437.1	243.6	164.8	⋯	0.21 ±0.05	⋯
5813	10.74	48.6	1.42±0.07	16.6	yes,1,2,4	143.6	83.2	46.9	31.5	⋯	0.22 ±0.06	⋯
5846	11.02	82.6	1.45±0.07	14.2	yes,2	314.4	181.3	102.3	69.6	⋯	0.22 ±0.06	⋯
6703	10.33	23.8	1.88±0.06	4.8	no,3	79.3	45.2	24.0	16.9	8.5	0.21 ±0.05	0.11±0.03

[a] All fluxes are measured within aperture of $R_e/2$.
[b] Luminosities and distances are calculated with $H_0 = 70$ km s^{-1} Mpc^{-1}.
[c] Hβ indices from Trager et al. (2000b).
[d] Ages from optical Balmer absorption lines.
[e] The references for optically visible dust are (1) von Dokkum & Franx (1995); (2) Tran et al. (2001); (3) Silge & Gebhardt (2003); (4) Lauer et al. (2005).
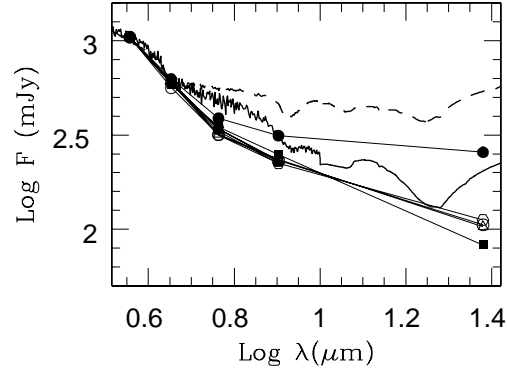
FIG. 1.— Observed fluxes at 3.6, 4.5, 5.8, 8 and 24μm for NGC 584 (open circles), NGC 1316 (filled circles), NGC 3923 (open squares), NGC 4472 (filled squares), NGC 4552 (open triangles), NGC 4649 (filled triangles), NGC 5813 (crosses), NGC 5846 (stars), and NGC 6703 (open hexagons). SEDs for single stellar populations from Piovan et al. (2003) are shown at 3 Gyrs (dashed line) and 12 Gyrs (solid line). All data and SEDs are arbitrarily normalized at $F_{3.6\mu m}$.
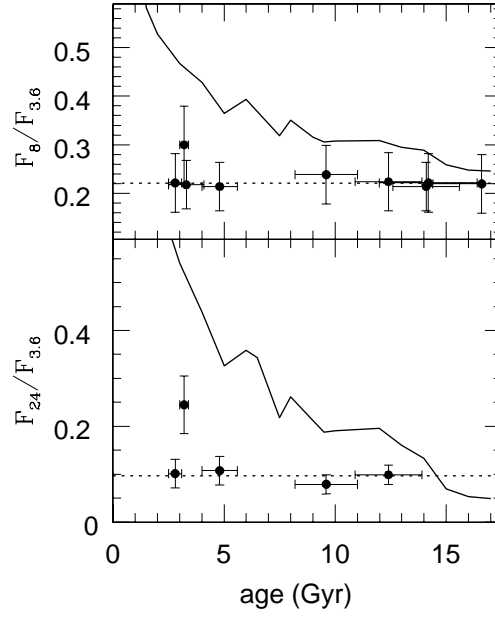
FIG. 2.— Observed flux ratios $F_{8\mu m}/F_{3.6\mu m}$ (upper panel) and $F_{24\mu m}/F_{3.6\mu m}$ (lower panel). The solid lines show the predicted flux ratios at each age for single stellar populations from Piovan et al. (2003). The dotted lines show the mean flux ratios excluding that of NGC 1316.
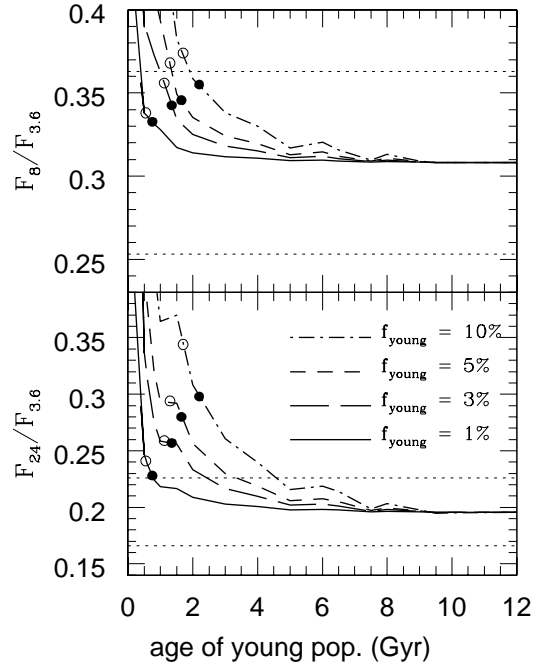
FIG. 3.— Flux ratios $F_{8\mu m}/F_{3.6\mu m}$ (upper panel) and $F_{24\mu m}/F_{3.6\mu m}$ (lower panel) for a combination of young stellar populations having ages on the horizontal axis with an old stellar population of age 12 Gyrs. Loci of young population mass fractions f_{young} of 1, 3, 5, and 10% are shown with solid, long dashed, short dashed, and dash-dotted lines respectively. The horizontal dotted lines show the estimated flux ratio errors of the *Spitzer* observations. The filled (empty) circles show values of f_{young} and young population age correponding to constant Hβ = 1.9 (2.1).