THE AGES OF ELLIPTICAL GALAXIES FROM INFRARED SPECTRAL ENERGY DISTRIBUTIONS

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ABSTRACT

The mean ages of early-type galaxies obtained from the analysis of optical spectra give a mean age of 8 Gyr at $z = 0$, with 40% being younger than 6 Gyr. Independent age determinations are possible by using infrared spectra (5–21 μm), which we have obtained with the Infrared Spectrograph on Spitzer. This age indicator is based on the collective mass-loss rate of stars, in which mass loss from AGB stars produces a silicate emission feature at 9–12 μm. This feature decreases more rapidly than the shorter wavelength continuum as a stellar population ages, providing an age indicator. From observations of 30 nearby early-type galaxies, 29 show a spectral energy distribution dominated by stars, and one has significant emission from the ISM and is excluded. The infrared age indicators for the 29 galaxies show them all to be old, with a mean age of about 10 Gyr and a standard deviation of only a few Gyr. This is consistent with the ages inferred from the values of $M/L_B$, but is inconsistent with the ages derived from the optical line indices, which can be much younger. All of these age indicators are luminosity weighted and should be correlated, even if multiple-age components are considered. The inconsistency indicates that there is a significant problem with either the infrared and the $M/L_B$ ages, which agree, or with the ages inferred from the optical absorption lines.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: ISM — infrared: galaxies — infrared: ISM

1. INTRODUCTION

Prior to the acceptance of the hierarchical paradigm for structure formation, monolithic collapse was proposed for the formation of elliptical and spheroid galaxies. In the monolithic model, an elliptical galaxy would form at high redshift from a gas cloud that produced a brief but intense epoch of star formation when most of the stars were formed. A subsequent galactic wind could keep the galaxy gas-poor for most of its life, preventing the accumulation of gas that could lead to ongoing star formation. This picture was in good agreement with the data (Pipino & Matteucci 2003, 2006), yet modern theories of hierarchical structure formation indicate that mergers should be important throughout cosmological time (e.g., Kauffmann & Charlot 1998).

In the case of elliptical galaxies, this means that existing galaxies would merge to form larger ones, with accretion possibly triggering a burst of star formation in the cold gas in these galaxies. If nearly all of the star formation were to occur early, it would imply important changes to the basic hierarchical model, so it is essential to have good knowledge about the age of elliptical galaxies.

Stellar ensembles that are less than 2 Gyr in age show prominent A or F star features, enabling unique age determinations. However, once the age of the system is a few Gyr, the colors and metal line strengths of the galaxy do not lead to a unique age, because of a degeneracy between the metallicity and age parameters. That is, an old metal-poor galaxy will have the same colors and metal line strengths as a younger metal-rich galaxy. To break this age-metallicity degeneracy, investigators measure the strength of the Balmer lines (notably Hβ; dominated by turnoff stars), along with a variety of metal line indexes in the spectrum of a galaxy (due to asymptotic giant branch [AGB] stars), which they compare to models (Worthey 1994; Worthey et al. 1994). There are a number of effects that can contaminate the age-dating, but Trager et al. (2000a) discuss the most likely candidates and argue that they are unlikely to cause problems. It would seem that this method should give a good estimate for the mean age of a single population.

Trager et al. (2000a) find that for stars within $r_c/2$, the metallicities are generally near solar and have a small range of abundance enhancements. The ages, however, show a much broader range, with a median value of 7–8 Gyr and nearly 40% of the galaxies with ages of 6 Gyr or less. These relatively young ages correspond to a median redshift of about 1, with about 40% of the sample having formed at $z < 0.6$. This supports the hierarchical model with recent merging events. Whereas some mergers are observed today, current surveys suggest that most of the stellar populations in elliptical galaxies have been evolving passively since at least $z \sim 1$. This is in apparent conflict with the age distribution of Trager et al. (2000a), so either their approach has unanticipated flaws, or multiple populations conspire to produce the observed ages. To help resolve this possible conflict, an independent age estimator is required, and the development of such a tool is the purpose of this paper.

2. INFRARED SPECTRAL ENERGY DISTRIBUTIONS AS AGE INDICATORS

The optical age-dating technique makes use of absorption lines that are produced in the photospheres of stars, generally at the turnoff and on the giant branch. In contrast, the infrared signature that we use is produced in the outflow of mass-losing giants, and in particular, the AGB stars. AGB stars have very substantial slow winds, within which the density is large enough for material to condense, leading to grain formation. Silicates are common, and they are formed close enough to the star to be heated to $\sim 300$ K. These silicates reradiate in a few broad regions, such as 9–12 μm and another centered near 18 μm. At shorter wavelengths (6 μm), the continuum is produced close to...
the stellar photosphere, so the 5–21 μm region contains both circumstellar emission and near-photospheric emission.

As an ensemble of stars ages, the overall luminosity of the population decreases roughly as $t^{-1}$, so it might seem that the best measure of age would be the mass-to-light ratio. However, the mass is the sum of the stellar component and the dark matter component, and one must have confidence that the stellar component dominates this ratio in the region where it is measured. Alternatively, one can seek spectral features that have different time dependencies, so that their ratios change monotonically with time. For example, models indicate that the 6 μm luminosity density decreases as $t^{-0.77}$ in solar-type populations (Fig. 1), while the emission from the silicate mass loss decreases more rapidly, as $t^{-1.00}$ (9.6 μm luminosity density). The ratio $L(9.6 \mu m)/L(6 \mu m) \propto t^{-0.32}$, so there is a mapping from this ratio to the mean age of the stellar population.

To calibrate this method, one can appeal either to models or to stellar systems whose metallicity and age are known. Eventually, we hope to apply the latter method, but for this study we used stellar evolutionary models. Only recently have stellar evolutionary models included the observable consequences of mass loss from AGB stars (Bressan et al. 1998; Lançon & Mouhcine 2002; Mouhcine & Lançon 2003), and here we use the models developed by Piovan et al. (2003). They have produced detailed spectral energy distributions from 0.1 to 100 μm for a single population of stars at a sequence of ages and for three different metallicities, including the solar value ($Z = 0.02$), used here. Their models include the effects of dust-enshrouded AGB stars, with emission from silicates, carbon, and silicon carbide, the latter two being important in massive stars.

We have analyzed their models, made available by the authors, to determine the most suitable infrared indices that can act as an age indicator over the wavelength region for which we have data, 5.2–21 μm. We find that the spectral slope, $d \ln F_\nu/d \ln \nu$, from 5.2 to 6.5 μm is a useful age indicator, as it steepens from about $-0.27$ at 2 Gyr to $-1.07$ at 16 Gyr (Fig. 2). There is scatter around this relationship due to the finite number of stellar models used in the calculations. That is, stellar models are calculated for every 0.1 $M_\odot$ near values of 1 $M_\odot$, and the turnoff ages are 9.3 Gyr for a 1 $M_\odot$ star, 6.5 Gyr for a 1.1 $M_\odot$ star, and 4.5 Gyr for a 1.2 $M_\odot$ star. Not only do the relative states of the core and envelope change in this mass range, but the dust properties change as well, so the change in the relative fractions of these stellar components can cause the observed nonsmooth behavior in the 6 μm slope (this is also true of the flux ratios that we use). Consequently, we have fit a smooth line through these model points (Fig. 2).

Aside from this slope, one can use the luminosities at 6 μm (from the power-law fitting to the 5.2–6.5 μm continuum), the luminosity at the local minimum of 8.3 μm (averaged 8.0–8.5 μm), and the luminosity at 9.6 μm (averaged over 9.2–10.0 μm, which measures the silicate excess). Of the ratios that can be formed with these luminosities, the $L(9.6 \mu m)/L(6 \mu m)$ and $L(6 \mu m)/L(8.3 \mu m)$ quantities are the best tracers of age. Another age indicator can be formed by using a luminosity at longer wavelength $L(14 \mu m)$, compared to $L(6 \mu m)$. The boundaries of these luminosities were chosen to avoid possible polycyclic aromatic hydrocarbon (PAH) bands (strongest at 7.7 and 11.3 μm), although PAH emission is rarely seen in the galaxies we observed. For the following analysis, we primarily use $L(9.6 \mu m)/L(6 \mu m)$, as it has the greatest range and the smallest relative uncertainty. The mapping between this ratio and the age is $t = 2.6(L(9.6 \mu m)/L(6 \mu m))^{-3.1}$ Gyr.

![Fig. 1.—Left: Decline of the 6 and 9.6 μm luminosities as a function of time for single-age populations, based on the solar-metallicity models of Piovan et al. (2003; data points). Because the silicate feature decreases more rapidly with time, the ratio of these luminosities forms an age indicator. Right: Evolution of the ratio $F(9.6 \mu m)/F(6 \mu m)$ as a function of age for a single stellar population with metallicity $Z = 0.02$. The dashed line represents the relation between the flux ratio and the age $t (t = 2.6F(9.6 \mu m)/F(6 \mu m))^{-1.1}$ Gyr.](image1)

![Fig. 2.—Slope near 6 μm decreasing with age in the solar-metallicity single-age populations of Piovan et al. (2003; circles). A third-order polynomial is fit to the data.](image2)
The models of Piovan et al. (2003) are the first at this level of detail and cannot be expected to be perfect, so the absolute calibration of the models may be somewhat incorrect. However, the relative trend should be reliable in identifying old and young systems.

3. SAMPLE SELECTION AND OBSERVATIONAL PROGRAM

Our sample is taken from a survey of 51 nearby elliptical galaxies for which high-quality optical spectra were obtained (Trager et al. 2000a and references therein). Although ages derived from absorption-line indices have uncertainties associated with the adopted stellar models and patterns of abundances when α-enhanced mixtures are adopted (Tantalo & Chiosi 2004), these galaxies have well-established age-metallicity determinations among nearby elliptical galaxies. Others have determined ages for nearby elliptical galaxies (summary by Terlevich & Forbes 2002; recent determinations by Thomas et al. 2005a), which are similar and are discussed further below.

From the Trager et al. (2000a) sample, we have taken a subset of galaxies with the properties $B_T < 12.5$ and $M_B < -19$ (no dwarfs) and no active galactic nucleus (AGN) activity (two 3C objects are excluded). This leads to a well-defined sample of 31 galaxies covering a broad range of implied ages, from 2 to 15 Gyr, with a fairly even distribution by age: eight galaxies have estimated ages of 2–5 Gyr, seven are between 5 and 8 Gyr, nine are between 8 and 12 Gyr, and seven are between 12 and 18 Gyr (Table 1; the metallicity $Z_H$ and ages are within $r_{e}/8$ as given in Trager et al. 2000a). The mean iron metallicity for the sample is $[\text{Fe/H}] = 0.06$, and the 25%–75% quartiles are $-0.04$–0.15, so the range is modest. This sample is representative of elliptical galaxies with optical luminosities near $L_\ast$. For one galaxy, NGC 3608, there were significant instrumental difficulties, and the resulting data are not reliable, so it is not included. For one other galaxy, NGC 4697, the spectrum is completely different than the rest, it is not useful for age determinations, and will be discussed elsewhere.

Based on the spectral model of Piovan et al. (2003) and observational data of AGB stars, it is important to define the underlying continuum, as well as the silicate feature, and this requires spectroscopic coverage from about 5 to 20 μm. This type of coverage was realized with the combination of Short-Low and Long-Low modules on the Infrared Spectrograph (IRS; Houck et al. 2004) on board the Spitzer Space Telescope (Werner et al. 2004). These modules together provide spectral coverage of the region 5.2–21.3 μm with a spectral resolution $R = \lambda/\Delta\lambda$ of 64–128, depending on the wavelength. Both segments of the Short-Low spectral region (5.2–7.7 μm for the SL2 module and 7.4–14.5 μm for the SL1 module) use the same slit size ($3.7''$ by $57''$) and position angle, but the Long-Low (14.0–21.3 μm for the LL2 module) slit is 10.5 by 168'' and is at a position angle about 90° different from the Short-Low. In this case, we match the spectra by using the overlap region at 14 μm.

The galaxies are not point sources, but are well contained within the slits, as the typical half-light radius is 30''. In the IRS staring mode, two spectra were obtained per setting, with each offset from the center of the slit by 1/3 of a slit length. This results in the endpoint of the Short-Low slit in the off position being 38'' from the center of the galaxies, where the galaxy signal is about 2% of the signal at the center, or 0.2 mJy on average (much
smaller than the measured signals). For the Long-Low, the offset is much greater, so the contribution from the galaxy in the off position is negligible. The integration time for each galaxy is the same, consisting of eight cycles of 14 s ramp time for Short-Low and six cycles at 30 s for Long-Low.

4. DATA PROCESSING

The standard IRS data reduction pipeline, version S12.0, at the Spitzer Science Center (SSC) was used to reduce the data. This reduction includes ramp fitting, dark-sky subtraction, droop correction, linearity correction, flat-fielding, and wavelength and flux calibration (Decin et al. 2004). Before performing the spectral extraction, the local background for the SL modules was subtracted using observations when the target was located in an alternate slit. At longer wavelengths, since we recorded data using only the LL2 module, the local background was subtracted by differencing the two nod positions along the slit. The spectra were then extracted from the sky-subtracted two-dimensional array images using the SMART (ver. 5.5.6) software package (Higdon et al. 2004) after the mean of the flux estimates from each ramp cycle were combined. We performed a “fixed column extraction,” because the emission from each galaxy did not resemble the point-source profile, showing substantial extended emission. In its current form, the SMART software is optimized to perform spectral extraction and flux calibration for point-source targets. In order to correct for the use of the standard flux conversion tables, which are based on point-source extraction, we applied a correction that accounts for the aperture loss due to the narrowing of the extracting column as a function of wavelength used by SSC and that in turn feeds back into the FLUXCON tables. Observations of the standard star HR 6348 were used to calibrate our target spectra. A spectrum of HR 6348 was constructed by combining a number of observations recorded in 2004 under the program ID 1404. Our spectra were calibrated by dividing the extracted spectrum of the source by the spectrum of the standard star, extracted with the same extraction parameters applied to our target sources, and multiplying by its template (Cohen et al. 2003).

For sources with extended emission and spatial structure, the spectrum is the convolution of the source brightness distribution with the beam profile. In such a case a rigorous flux calibration requires a reliable model of the source geometry and a characterization of the instrument’s beam profile. Since the beam profile, defined as the map obtained by moving a pointlike source across the aperture and measuring its variation with wavelength, is not publicly documented yet, we did not apply any correction for diffraction losses or gains in the slit that are inherent to extended sources. Because the wavelength dependence of such a correction may cause an additional slope in the observed spectra (Smith et al. 2004), we compared the extracted IRS fluxes with the measured Infrared Array Camera (IRAC) and Multiband and Imaging Photometer for Spitzer (MIPS) density fluxes for those galaxies that are listed in our sample and have broadband observations available in the Spitzer public archive. Figure 3 shows the low-resolution spectra of seven elliptical galaxies with data points from the four channels of the IRAC instrument and the MIPS 24 μm channel. For each galaxy, the broadband photometry, performed within an aperture equal to r_e/8, centered on the galactic nucleus, has been scaled to match the IRS spectrum at 8 μm. The spectral slope in the 4–8 μm region, as derived by IRS and IRAC measurements, is in good agreement, giving us confidence in the accuracy of the extracted spectra; any correction due to diffraction losses is likely to fall inside the calibration errors of IRAC and MIPS observations that are of the order of 20%.

Fluxes and slopes that have been extracted from these spectra (shifted to z = 0) are given in Table 2, where the slope at 6 μm is given in column (3), and the wavelengths (μm), fluxes (mJy), and uncertainties (mJy) are given at four wavelengths. The uncertainties in the fluxes are only due to the statistical errors obtained in the data reduction process. The individual spectra, without the small redshift corrections, are shown in Figure 4.

5. RESULTS AND INTERPRETATION

The results of the infrared age indicators are discussed first, followed by a comparison with the ages that one infers from the observed values of M/L_B.

5.1. Ages from the Infrared Data

We begin by inspecting a single typical spectrum, NGC 584, which is compared to a single-epoch stellar population model (Fig. 5). The models with ages of 5 Gyr or less are clearly ruled out, and the 5.3–9.6 μm continuum is best fit with the 14 Gyr model. None of the models are particularly accurate in reproducing the 10–21 μm continuum, but the 14 Gyr spectrum appears to be the best. Narrow atomic emission lines from [Ne ii] 12.8 μm and [Ne iii] 15.3 μm are common features and are discussed separately.

The other important spectral features that occur in this wavelength range are from PAH emission, where the strongest lines are usually at 7.7 and 11.3 μm. One galaxy, NGC 4697, shows PAH emission that dominates the spectrum, making it nearly impossible to remove from the underlying stellar spectrum; this

Fig. 3.—IRS low-resolution spectra (solid lines) of elliptical galaxies, along with IRAC and MIPS broadband photometric data (triangles connected with dashed lines). Spectra have been divided by arbitrary factors for clarity, and the broadband data are scaled to match the spectra at 8 μm. There is general agreement between the photometry and the spectral energy densities.
The only other galaxy with detectable PAH emission is galaxy is excluded from study here, but will be discussed elsewhere. The only other galaxy with detectable PAH emission is NGC 3379, but the lines are weak, so the stellar spectrum can be analyzed. The 7.7 μm feature can contaminate the L(6 μm)/L(8.3 μm) ratio, which may have occurred in the case of NGC 3379.

Spectra for the 29 galaxies in the sample show tremendous similarity (Fig. 4). There is no obvious difference in the spectral energy distribution between galaxies that have young or old ages, according to Trager et al. (2000a). For example, none of the galaxies in the sample are similar to a 3 Gyr population, all appearing to be older populations (Fig. 5). To quantify this, we use the L(9.6 μm)/L(6 μm) ratio as an age indicator, as it has the greatest leverage on the age, is insensitive to the precise bands used to define the ratios, and has a typical uncertainty of 5%–10%. The distribution of this ratio has a mean value of 0.580 ± 0.008, where σ = 0.041 for quartile points of 0.55–0.66 (Fig. 6). According to the models of Piovan et al. (2003), this would imply a mean age of 13 Gyr and a range defined by the quartiles of 9 and 16 Gyr (Table 3).

We are not confident that the models of Piovan et al. (2003) have sufficient absolute accuracy, as some of the deduced ages are greater than the age of the universe, 13.5 Gyr for a ΛCDM universe with H₀ = 70 km s⁻¹ Mpc⁻¹. This is due mostly to the many uncertainties still affecting the modeling of the low-mass AGB stars, which, at older ages, dominate the AGB population. Temi et al. (2005a) found a similar offset in the absolute calibration of the Piovan et al. (2003) models when comparing broadband mid-infrared ratios with the predicted flux ratios for a small sample of elliptical galaxies. If we were to shift the scale of Piovan such that the mean age is 10 Gyr, the range in L(9.6 μm)/L(6 μm) implies an age range of 8–13 Gyr.

The inferred age range seems moderately restricted, but it is likely to be narrower, since the uncertainties introduced by measurement error are similar to the σ inferred from the distribution (see below). When the L(9.6 μm)/L(6 μm) age indicator is compared to the ages of Trager et al. (2000a), there is no correlation (Fig. 7). This is to be expected if the values of L(9.6 μm)/L(6 μm) lie in a random scatter about a mean value, but it does pose a conflict between these two age indicators, discussed below. Finally, we find that there is no correlation between L(9.6 μm)/L(6 μm) and M/Lg, which also is explained if the galaxies all have similar ages.

Potentially, the second best of our infrared age indicators is the 6 μm spectral slope (Fig. 8). The mean value is −0.95, and nearly all of the galaxies are within 2 σ of this value, so a considerable amount of the range is due to measurement error. The conversion from slope to age may be somewhat incorrect, since a slope of −0.95 corresponds to 14 Gyr, which is slightly greater than the age of the ΛCDM universe. Assuming that the slopes are dominated by photon statistics, the observed distribution requires variation in the age distribution. If the true mean age is assumed to be 10 Gyr and the underlying age distribution is Gaussian, its corresponding σ ≃ 3 Gyr. As with the above infrared age indicator, there is no correlation with the ages of Trager et al. (2000a).

### 5.2. M/L as an Age Indicator

The property of a single stellar population that changes the most with age is the luminosity, so we can examine whether the ratio M/L contains useful age information and whether the
optical or infrared age indicators are related to $M/L$. The choice of $L$ is not particularly important, since most decline with age as $t^{-1}$, but here we choose $L_B$, for which the models show that $L_B \propto t^{-0.95}$ in the age range of interest (Bruzual & Charlot 2003). The mass within $r_e$ is proportional to $r_e\sigma^2$, and even the very thorough determination of the mass by the SAURON effort (Cappellari et al. 2006) finds that this is a reasonable quantity to use (the difference in the mass between the two methods is small compared to the range of $M/L$ in the sample). We use the value of $M/L_B$ as given by Trager et al. (2000a), but since this quantity is known to increase as $L_B^{4/3}$, we correct this quantity for this effect, normalizing the values of $M/L_B$ at $B_{TOT} = -21$ (this reduces the scatter in the ensuing figures). A plot of $M/L_B$ versus the Trager et al. (2000a) ages shows a modest correlation, but a large amount of scatter (Fig. 9). The data are inconsistent with the time evolution of a single-age population.

Another approach for obtaining ages is to assume that the shape of the mass distributions is similar for galaxies, so that $M/L_B$ translates into an age. For this approach to yield correct results, the dark matter–to–luminous matter ratio should be either small or constant, which appears to be the case (Kronawitter et al. 2000; Saglia et al. 2000; Thomas et al. 2005b). Also, a correct age determination would require that $M/L_B$ should be dominated by a single-age population. Inferring ages from their $M/L_B$ values (using the calibration of Bruzual & Charlot 2003), the galaxies cluster in age at 8.0–12.4 Gyr (25%–75% quartile ages), with a median at 9.4 Gyr and an effective $\sigma$ for the distribution of 2.8 Gyr (Fig. 10; Table 3). The quantity $M/L_B$ depends on $r_e\sigma^2$, $M_B$, metallicity, and distance $d$, which each have uncertainties, and when added incoherently, leads to a typical uncertainty in an individual $M/L_B$ value of 25%, which would introduce an uncertainty in the age of about 2.5 Gyr. Therefore, much of the range of inferred ages may be related to observational uncertainties in determining $M/L_B$. There are a few galaxies with ages near 20 Gyr, one of which is the well-studied system NGC 1399, which was also observed by Saglia et al. (2000). Using a detailed dynamical model, they found $M/L_B = 10$, which corresponds to an age of 13 Gyr. This points out that these large ages can be due to the uncertainties of the method of determining $M/L_B$.

5.3. Are There Any Young Galaxies in This Sample?

We have searched for the most likely young galaxies by examining those that have the youngest ages as given by Trager et al. (2000a) and Thomas et al. (2005a), while also having low $M/L_B$ and high $L(9.6 \mu m)/L(6 \mu m)$ ratios (Tables 2 and 3). Two galaxies fit that category, NGC 3377 and NGC 1700. For NGC 3377, Trager et al. (2000a) list an age of 3.7 Gyr, $M/L_B = 4.3$ (5.3 ± 1.3 Gyr), and $L(9.6 \mu m)/L(6 \mu m) = 0.67 \pm 0.07$ (9 ± 2.5 Gyr). This galaxy is a relatively rapid rotator, so the mass may have been underestimated, which would raise $M/L_B$ and the inferred age. There are no obvious signs of a recent merger in the structural properties of the galaxy (Schweizer & Seitzer 1992), and while the infrared ratio is higher than average, it is within 2 $\sigma$ of the mean, and its nominal value, 9 Gyr, does not imply a young age. The evidence is not compelling for NGC 3377 being a young galaxy.

The other system, NGC 1700, has one of the youngest ages listed by Trager et al. (2000a), 2.3 Gyr, and values for $M/L_B$ and $L(9.6 \mu m)/L(6 \mu m)$ of 4.4 and 0.66 ± 0.07, respectively; also, the other two infrared ratios indicate a galaxy younger than the sample average. The age inferred from $M/L_B$ is 5.5 ± 1.4 Gyr.

Fig. 4.—Flux density as a function of wavelength as obtained with the IRS on Spitzer. The signal-to-noise ratio is generally poor at the longest wavelengths.
and the age inferred from the infrared ratio is 9.3 ($\pm 1.5$) Gyr; it would be 1.5 Gyr younger if we were to change the normalization so that the median galaxy age is 10 Gyr). The 3 $\sigma$ lower limit on the age from the infrared indicator is 4.8 Gyr (4.0 Gyr for the 10 Gyr median galaxy normalization). Other observers also suggest a young age, but not as young as the Trager et al. (2000a) value. Statler et al. (1996) suggest an age of 3–6 Gyr based on the extent of the region of relaxed dynamics near the center, while Schweizer & Seitzer (1992) give an age of 6 Gyr based on the galaxy color. The study of the globular cluster population (Whitmore et al. 1997) shows that it is typical of normal old elliptical galaxies, for which the population lies between the predictions for an old, metal-poor population (15 Gyr) and a solar-metallicity population (5 Gyr). Using the online model of Worthey with solar metallicities, while for the infrared ages we use the solar-metallicity Piovan et al. (2003) models. As the fraction of the younger population is increased, the inferred age naturally decreases, with the $M/L_B$ indicator least affected by the addition of a younger component and the H$\beta$ age indicator most strongly affected (Fig. 11). The apparent age decreases by a factor of 2 with the addition of the 1 Gyr stellar component of 2.2%, 4.3%, and 9.8% (total mass) for the age indicators of H$\beta$, infrared, and $M/L_B$, respectively. In order for the inferred age to be greater than 10 Gyr, the young population can only account for 0.52%, 0.87%, and 2.1% of the total mass of the galaxy for the H$\beta$, infrared, and $M/L_B$ age indicators. This is also consistent with the required mass fraction of young stars ($\lesssim 1\%$), as derived by the observed flux ratio $F(24\,\mu m)/F(3.6\,\mu m)$ when theoretical mid-infrared single stellar population models are combined (Temi et al. 2005a). A remarkable implication is that when the H$\beta$ indicators show an old age (e.g., 13 Gyr), it suggests that there has been virtually no star formation during the recent lifetime of the galaxy.

The general similarity between these three luminosity-weighted age indicators implies that there will be a strong correlation between the ages determined from the three methods. As discussed above, the uncertainties in the ages derived from the infrared and
Fig. 4.—Continued

Fig. 5.—Flux density of the spectral models of Piovan et al. (2003) for a single-age stellar population at solar abundances. Left, Spectral steepening with age and the weakening of the 10 \( \mu \text{m} \) silicate feature; right, comparison between these same models and the galaxy NGC 584. The best fit appears to lie between 10 and 14 Gyr, in conflict with the age derived from the optical absorption line indices of 2.5 ± 0.3 Gyr.
M/L_B methods are responsible for most of the observed range, so the lack of a correlation between the two methods is not surprising. However, the range of ages from the H/β age indicator is significantly larger than the errors, so finding a statistical correlation with the other quantities should be possible. There is no correlation of the H/β age indicators with the infrared indicators, and the correlation with M/L_B is quite weak and has the wrong slope. We conclude that the introduction of a second, younger population will not lead to age determinations that are consistent between the H/β method and either the infrared method or the M/L_B method. The discrepancy with the Trager et al. (2000a, 2000b) ages remains, indicating that either the infrared and M/L_B correlation of the H/β age indicators with the infrared indicators, and the correlation with M/L_B is quite weak and has the wrong slope. We conclude that the introduction of a second, younger population will not lead to age determinations that are consistent between the H/β method and either the infrared method or the M/L_B method. The discrepancy with the Trager et al. (2000a, 2000b) ages remains, indicating that either the infrared and M/L_B

![Fig. 6.—Distribution of the ratio L(9.6 μm)/L(6 μm), with the corresponding age derived from Piovan et al. (2003) along the bottom in italics. The mean ratio corresponds to an age of 13 Gyr and a σ value of about 3 Gyr, but much of that range is due to uncertainties in the measurements, for which the median error is shown.](image)

**TABLE 3**

| Number | Name     | t(Trager) (Gyr) | Error (Gyr) | t(Thomas) (Gyr) | Error (Gyr) | M/L_B,corr (M_*/L_β 1) | t(M/L_B) (Gyr) | t(IR) (Gyr) |
|--------|----------|----------------|-------------|----------------|-------------|-----------------|----------------|-------------|
| 1       |          | 2.5            | 0.3         | 2.8            | 0.3         | 5.6             | 7.0            | 14.6        |
| 2       |          | 6.36           | 0.7         | 4.4            | 0.6         | 4.8             | 6.0            | 15.9        |
| 3       |          | 7.20           | 2.3         | 5.4            | 2.4         | 6.7             | 8.4            | 10.8        |
| 4       |          | 8.21           | 1.2         | 8.9            | 1.2         | 8.8             | 11.4           | 13.2        |
| 5       |          | 13.39          | 4.8         | ...            | ...         | 9.9             | 12.8           | 14.4        |
| 6       |          | 13.51          | 3.3         | ...            | ...         | 12.0            | 15.7           | 16.4        |
| 7       |          | 13.74          | 2.6         | ...            | ...         | 6.8             | 8.6            | 13.4        |
| 8       |          | 13.79          | 2.9         | ...            | ...         | 14.6            | 19.3           | 12.9        |
| 9       |          | 13.99          | 2.4         | ...            | ...         | 6.7             | 8.5            | 11.2        |
| 10      |          | 14.04          | 2.5         | ...            | ...         | 10.2            | 13.2           | 12.0        |
| 11      |          | 14.27          | 1.6         | ...            | ...         | 9.5             | 10.8           | 14.4        |
| 12      |          | 14.53          | 1.9         | 9.4            | 1.6         | 9.6             | 12.4           | 14.4        |
| 13      |          | 14.75          | 4.2         | ...            | ...         | 8.6             | 11.0           | 16.1        |
| 14      |          | 17.00          | 0.3         | 2.6            | 0.3         | 4.4             | 5.5            | 9.3         |
| 15      |          | 23.00          | 1.5         | 7.3            | 1.5         | 14.1            | 18.7           | 12.8        |
| 16      |          | 33.77          | 0.8         | 3.6            | 0.5         | 4.3             | 5.3            | 8.9         |
| 17      |          | 33.79          | 1.4         | 10             | 1.1         | 7.4             | 9.4            | 9.6         |
| 18      |          | 14.47          | 1.7         | 9.6            | 1.4         | 6.4             | 8.0            | 11.7        |
| 19      |          | 44.78          | 2.3         | 5.3            | 1.2         | 4.0             | 5.0            | 20.6        |
| 20      |          | 45.52          | 1.2         | 12.4           | 1.5         | 8.8             | 11.4           | 13.2        |
| 21      |          | 46.49          | 1.5         | 14.1           | 1.5         | 8.8             | 11.3           | 10.2        |
| 22      |          | 15.38          | 1.4         | 9.5            | 0.9         | 6.4             | 8.1            | 12.0        |
| 23      |          | 5.812          | 1.1         | 6.5            | 1           | 6.5             | 8.2            | 16.0        |
| 24      |          | 58.13          | 2.3         | 16.6           | 2.2         | 6.3             | 8.0            | 17.4        |
| 25      |          | 58.31          | 0.3         | 3              | 0.4         | 7.7             | 9.9            | 14.4        |
| 26      |          | 58.46          | 3.3         | 14.2           | 2.2         | 8.7             | 11.1           | 10.1        |
| 27      |          | 67.03          | 0.7         | 4.8            | 0.8         | 6.6             | 8.3            | 12.2        |
| 28      |          | 75.62          | 1.6         | 8.6            | 1.3         | 5.7             | 7.2            | 17.6        |
| 29      |          | 76.19          | 2.2         | 15.4           | 1.4         | 8.3             | 10.6           | 16.4        |
Methods are flawed or that their approach is flawed. Trager et al. (2000a, 2000b) have considered the prime candidates for contamination of H$_\beta$ and shown them to be unimportant or possible to correct for. Therefore, if their method is incorrect, there would have to be a very significant contamination channel that is not yet recognized. The problem does not lie with the method, because independent studies using line indices yield similar results (Denicol\'o et al. 2005a, 2005b).

Insight into the formation ages of elliptical galaxies can be obtained from studies of galaxies at higher redshifts, although the results are not entirely clear. There is broad agreement that at redshifts beyond $z = 1$, and even $z > 2$, massive red (early type) galaxies have little star formation present, indicating very old populations (Daddi et al. 2005a, 2005b; Labb\'e et al. 2005; Cappellari et al. 2006). For reference, redshifts of 0.5, 1.0, 2.0, and 3.0 correspond to ages of 5.0, 8.6, 10.3, and 11.4 Gyr in a ΛCDM universe, while the age of the universe is 13.5 Gyr. Less massive galaxies appear to have more star formation (Treu et al. 2005), and if this aspect remains in the galaxies today, it might be seen in present-day data. However, we find no correspondence between the Trager et al. (2000a) ages (or our IR ages) and the masses of our sample galaxies (Fig. 12). Merging is likely to have occurred since $z = 1$, because the number of early-type galaxies has doubled since that time. In order not to produce

**Fig. 8.** The 6 μm spectral slope for objects by increasing right ascension, including the statistical uncertainties and the mean value. The mean value of $-0.95$ (dashed line) corresponds to 14 Gyr. If systematic errors are smaller than statistical errors, some variation in ages is required, a result driven by a few objects with small errors.

**Fig. 9.** Value of $M/L_B$ as a function of age, from Trager et al. (2000a), with the objects in our sample shown as filled circles. The $M/L_B$ values have been corrected for the luminosity dependence of the fundamental plane (normalized to $M_B = -21$). The open circles represent the additional objects given by Trager et al. (2000a), with the exception of M31 and M32. The solid line shows the evolution of a single-age population with time. While there are slightly more objects in the low-age, low-$M/L_B$ part of the figure, in general there is almost no relationship between $M/L_B$ and age.

**Fig. 10.** Ages derived from $M/L_B$ given by Trager et al. (2000a), after correcting for the luminosity dependence of the fundamental plane. The filled bars represent the galaxies in this sample, while the hatched bars represent the other objects in the list of Trager et al. (2000a), excluding M31 and M32. The distribution is similar to a Gaussian with a peak at 10.1 Gyr ($\pm 0.4$ Gyr) and $\sigma = 2.8$ Gyr ($\pm 0.5$ Gyr), excluding the outliers at 20 Gyr. Most of this spread can be accounted for by measurement error.

**Fig. 11.** Two populations combined, the older one a 12 Gyr (dot-dashed line at top edge) and the other a 1 Gyr population. The apparent age is the value one would infer by interpreting the mixed population as a single population. Ages inferred from the infrared index (solid line), the optical H$\beta$ index (dashed line), and $M/L_B$ (dotted line) are shown for a solar-metallicity model.
galaxies that are too blue, we theorize that star formation probably was not a significant part of these mergers (Bell et al. 2004, 2005; Faber et al. 2005). It is still unclear whether this degree of merging would destroy rather tight correlations, such as between velocity dispersion and Mg line strength. Finally, there needs to be an analysis as to whether the age distribution found by Trager et al. (2000a) is consistent with the observations at higher redshift and the expected mergers.

The calibration of the infrared spectral energy distributions is one of the important aspects of our technique that needs to be improved. At present we rely on the models of Piovan et al. (2003), which despite their sophistication are the first to predict the level of detail that we use. As with all models, there are significant improvements that can and will be made in the future, and at some point we hope that the data and models will be calibrated well enough that we can make credible maximum likelihood fits between the two. As a complement to using improved models, we hope to use the infrared spectra of globular clusters with known ages and metallicities as the basis set for comparison with the data. This year, we have a program to observe a few globular clusters over a range of ages and metallicities, and this program holds the prospect of making a comparison with the galaxies, leading to an independent age for these systems.

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Fig. 12.—Ages given by Trager et al. (2000a) and derived from M/L_B as a function of galaxy mass for 49 galaxies in the original survey, excluding M31 and M32. Neither group shows a correlation with mass. Based on the Trager et al. ages, young galaxies occur at all mass scales.