An Extended Star Formation History for the Galactic Center from Hubble Space Telescope/NICMOS Observations

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ABSTRACT

We present Hubble Space Telescope (HST) Near-Infrared Camera and Multiobject Spectrometer (NICMOS) observations as evidence that continuous star formation has created much of the central stellar cusp of the Galaxy. The data are the deepest ever obtained for a Galactic Center (GC) population, being $>50\%$ complete for $m_{F205W} < 19.3$, or initial stellar masses $\gtrsim 2 \, M_{\odot}$. We use Geneva and Padova stellar evolution models to produce synthetic luminosity functions for burst and continuous star formation scenarios, finding that the observations are fit best by continuous star formation at a rate that is consistent with the recent star formation activity that produced the three massive young clusters in the central 50 pc. Further, it is not possible to fit the observations with ancient burst models, such as would be appropriate for an old population like that in Baade’s Window or NGC6528.

Subject headings: Galaxy: bulge — Galaxy: center — stars: formation — infrared: stars

\(^1\)Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract No. NAS5-26555.
1. Introduction

The Milky Way Galaxy is composed of several distinct stellar components, including the disk, the bulge, and the halo. In addition to these well-known populations, new evidence suggests that there is yet another stellar population in the central part of the bulge, comprised of both young and old stars. The old component has often been associated with the inward extension of the ancient bulge, and the young stars are generally clustered in the central parsec and in two massive clusters about 30 pc to the north of the center. Stars in the central region are currently forming in several molecular clouds, i.e. Sgr B2. On scales covering a few hundred parsecs, Serabyn and Morris (1996) identify a peak in the infrared surface brightness distribution, scaling as 1/r in COBE data, associating this feature with light from a massive cluster of stars having a 1/r² volume density distribution, the “r⁻²” cusp (Hiromoto et al. 1984). Serabyn and Morris (1996) suggest that the cusp is composed of stars created continuously over the lifetime of the Galaxy. Launhardt, Zylka, & Mezger (2002) find a central disk in the COBE imagery of the Galactic center (GC), and identify this component with the central cusp.

Catchpole, Whitelock, & Glass (1990) resolve this cusp (over degree scales) into individual bright stars, and argue that the overall stellar population was likely to be intermediate aged, with the youngest population more concentrated toward the center. Others find similar evidence in support of an intermediate-age stellar population in the Galactic Center (mostly in the central few arcminutes), i.e. Rieke (1993), Haller (1992), Haller & Rieke (1989), Rieke (1987), Lebofsky & Rieke (1987), Blum, DePoy, & Sellgren (1995), Narayanan, Gould, & DePoy (1996), and Sjouwerman et al. (1999). Frogel, Tiede, & Kuchinski (1999) present some of the strongest evidence associating the r⁻² cusp with an intermediate population, finding that the density of young stars near the GC declines much more rapidly with galactocentric radius than does the density of the ancient bulge population.

The evidence for very recent (<10 Myr) star formation in the GC abounds. The Lyman continuum flux emitted in the central few degrees of the Galaxy is \( \sim 10^{52} \) photons/s (Cox & Laureijs 1989), half coming from stars in the three massive young clusters in the central 50 pc (Figer et al. 1999a, 2002). This represents about 10% of the total Lyman continuum flux for the whole Galaxy, and the number of massive stars \( M_{\text{initial}} > 20 M_\odot \) in the context of this paper in the clusters is also about 10% of the number in the whole Galaxy. However, the star formation rate in the GC is \( \sim 1\% \) of the total star formation rate in the Galaxy, as judged by simply dividing the mass in known, recently formed, stars by the duration of the star formation episodes that formed those stars, i.e. \( 5(10^4) M_\odot / 5 \ Myr \sim 0.01 \ M_\odot \ yr^{-1} \), giving a star formation rate density of \( 10^{-7} \ M_\odot \ yr^{-1} \ pc^{-3} \). This rate is roughly a factor of 250 higher than the mean rate in the Galaxy, and about the same factor lower than the...
rate in starburst galaxies. Such a low star formation rate compared to Lyman continuum photon production necessarily follows from the relatively flat initial mass function (IMF) slope estimated by Figer et al. (1999b) and used in estimating the mass of stars formed in the young clusters.

The young stellar clusters in the GC are extraordinary. The Central cluster is located within the central parsec and contains over 30 massive stars (Genzel et al. 1996). Only 30 pc distant, by projection, from the center are the Arches (Cotera et al. 1994; Figer 1995a; Nagata et al. 1995; Cotera 1995; Cotera et al. 1996; Serabyn et al. 1998; Figer et al. 1999b, 2002) and Quintuplet clusters (Okuda et al. 1990; Nagata et al. 1990; Glass, Moneti, & Moorwood 1990; Moneti, Glass, & Moorwood 1992, 1994; Geballe et al. 1994; Figer, McLean, & Morris 1995b; Figer et al. 1999a,b). The Arches cluster contains at least 150 O-stars within a diameter of 0.6 pc, making this cluster the densest in the Galaxy (Figer et al. 1999b). A list of the 30 most massive stars in the Quintuplet cluster is given in Figer et al. (1999a). All three clusters are quite similar in most respects, except for age; the Central and Quintuplet clusters are \( \approx 3\text{--}5 \) Myr old (Figer et al. 1999a; Krabbe et al. 1995; Najarro et al. 1997), while the Arches cluster is substantially younger, \( \tau_{\text{age}} = 2.5\pm0.5 \) Myr (Figer et al. 2002). With such a collection of young, massive clusters, is it possible that we are witnessing an extraordinary burst of star formation in the GC, or has the center hosted similar bursts of star formation throughout its long history? Further, what is the fate of these massive clusters?

Kim, Morris, & Lee (1999), Kim et al. (2000), and Portegies-Zwart et al. (2001) argue that the young clusters in the GC will be tidally disrupted in \( \lesssim 10\text{--}50 \) Myr. This might explain the absence of older clusters of similar masses in this region. Gerhard (2001) argues that such clusters should spiral into the central parsec on relatively short timescales, i.e. that the HeI stars in the central cluster might contain stellar products of a dense cluster formed well outside the central parsec. In this scenario, the stars are drawn inward to the central parsec by dynamical friction between the cluster and the tidal field of the GC. Kim, Morris, & Figer (2003) and Kim & Morris (2003) explore this possibility using N-body simulations, finding that dynamical friction is unlikely to have produced the population presently seen in the central parsec.

Clearly, the GC has formed a plethora of stars in the past 5 Myr, but it is less apparent when the bulk of stars in the central 50 pc formed. If we assume that the star formation rate in the past was similar to the present rate, then the total mass of stars formed over the past 10 Gyr is \( \approx 10^8 M_\odot \) within a radius of 30 pc of the GC, or an order of magnitude greater than this amount over the whole Central Molecular Zone, as first suggested by Serabyn & Morris (1996).
This paper reports new, deep imaging of several fields in the central 100 pc of the Galaxy. Our imaging solidly reaches the helium-burning clump giant stars and just reaches the old main sequence turn-off point. We model the luminosity functions to explore the star formation history of the Galactic center. We argue that the best fit to the total number of stars and to the luminosity functions requires an approximately continuous star formation history over the last $\sim 10$ Gyr.

2. Observations

The Galactic Center observational data are taken from Figer (1995a), Gemini/AO science verification observations\(^7\), and NICMOS observations obtained as a part of HST program GO-7364. The field locations are shown in Figure 1 and listed in Table 1.

The Lick data cover 40 fields, in a mosaic, obtained at the Shane 3-m telescope at Lick Observatory in the $H$ ($\lambda_{\text{center}}=1.65$ $\mu$m) and $K'$ ($\lambda_{\text{center}}=2.12$ $\mu$m) filters. The individual images cover $3' \times 3'$ of area, while the mosaic spans $24' \times 14'$ of area oriented with the long axis north-south and centered $6'$ to the north of the GC. The exposure times were 35 seconds for each image.

The Gemini/AO data were obtained as part of the Gemini North commissioning observing run using the Hokupa’a+Quirc instrument in $H$- and $K'$-bands. The field size is $20'' \times 20''$. These data cover 4 fields (#1, 2, 5, and 6), arranged in a mosaic centered about $15''$ to the north and east of the GC. Both the “short” ($\tau_{\text{exposure}}=1$ second) and “long” ($\tau_{\text{exposure}}=30$ seconds) exposure images were used.

The NICMOS data include 12 fields obtained with the NIC2 camera (19''2 on a side) in the F110W ($\lambda_{\text{center}}=1.10$ $\mu$m), F160W ($\lambda_{\text{center}}=1.60$ $\mu$m), and F205W filters ($\lambda_{\text{center}}=2.05$ $\mu$m). We selected these fields based on a number of criteria: avoidance of crowded regions (thus excluding the centralmost region), avoidance of young star clusters, avoidance of regions of high extinction, and inclusion of fields ranging over a variety of Galactic latitudes and longitudes. Because extant near-IR maps of the Galactic nucleus, i.e. from 2MASS, show extensive regions of deep extinction just above and below the actual GC, our observations consisted mainly of a vertical strip of positions at a Galactic longitude offset, $\Delta l$, of 12' from

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\(^7\)Based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Particle Physics and Astronomy Research Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil) and CONICET (Argentina).
our Galaxy’s central radio point source Sgr A* (our “b strip”), as well as one field located along the true galactic plane, at half the longitude offset of our vertical strip (our 1/2 position). Observation of these undistinguished “background” fields in the nuclear cluster was obtained in concert with our observations of the young “Arches” and “Quintuplet” clusters. Those cluster observations also included four “off” positions surrounding each cluster. The exposure times were 255 seconds for each image.

We use aperture photometry with \( d_{\text{aperture}} = 4''2 \), or 6 pixels, for the Lick data set, with zero-point calibration set by photometry of several bright stars in the mosaic area from the literature. We used PSF-fitting photometry for both the HST/NICMOS and Gemini/AO data sets. Zero-point calibration for the HST/NICMOS data was taken from MacKenty (1997), with specific details relevant to our data set, including completeness corrections, discussed in Figer et al. (1999b). The Gemini/AO zero-point calibration was set by photometry of several stars in Blum, Sellgren, & Depoy (1996). The Gemini and Lick \( K' \) data were converted into \( K \) data using the observed \( H-K' \) values and the relation of Wainscoat & Cowie (1992).

### 3. Analysis and Results

#### 3.1. Color-magnitude Diagrams

Color-magnitude diagrams (CMDs) for the three data sets are shown in Figure 2. We can see that the NICMOS data continue down to about \( m_{\text{F205W}} = 21 \) (\( M_{\text{initial}} \sim 1.2 \, M_\odot \)), roughly the magnitude for which the S/N ~ 5. This is about 4 magnitudes fainter than the Gemini/AO data, and about 1 magnitude fainter than the data in Genzel et al. (2003). The data are complete at the 50% level at \( m_{\text{F205W}} = 19.3 \) (\( M_{\text{initial}} \sim 2.2 \, M_\odot \)), averaged over all fields. The Gemini/AO data go just faint enough to distinguish the “red clump” near \( K \sim 15.5 \). The Lick data are already incomplete at \( K \sim 12 \), but they cover a much larger area than the other data sets, giving us more complete statistics at bright magnitudes.

CMDs for the individual NICMOS fields are shown in Figure 3. The trend in extinction for these fields is as expected in that the fields closest to the Galactic Center suffer the greatest extinction, e.g., the zd field. Apparently, stars in the za, qc, and ac fields are comingled with ambient molecular material that serves to spread their locations in the diagram; the same effect is observed in the Lick data for this location. The red clump population is prominent in all of the fields, although the feature in the zc panel is weak. Differential reddening is prominent in each field and broadens the clump distribution in color along the direction of reddening (to the lower right). The rise in the luminosity function at the main sequence
turnoff point (e.g. at \( m_{F205W} \approx 19 \) and \( m_{F160W} - m_{F205W} \approx 1.6 \) in the za field) is seen clearly in all fields, except for zd (closest to the Galactic Center) where confusion sets in at brighter magnitudes.

The presence of the clump and the main sequence turnoff in the luminosity function makes a prominent gap in the stellar CMD, an indication that much of the population must be older than a few \( Gyr \). The relatively wide (\( \sim 4 \, mag \) gap between the clump and main sequence turnoff seems consistent with a population older than 10 \( Gyr \). As we proceeded with this interpretation, however, we tried to fit old globular cluster luminosity functions to our Galactic Center data and noticed that the red clump was too bright to be consistent with a purely old stellar population. After considerable rechecking and verification of our photometry, this puzzle led us to proceed with the analysis we report in this paper.

### 3.2. Luminosity Functions

In order to compare the observations to model predictions, we construct dereddened luminosity functions (LFs) by subtracting individual reddening values for each star based upon its color in \( H - K \), or \( m_{F160W} - m_{F205W} \), and the assumption that each star has intrinsic colors of a red giant. We estimate the intrinsic colors of a typical red giant by convolving the spectral energy distribution of a K4III star from the Pickles (1998) library with the filter profiles, finding \( (H-K)_0 = 0.11 \) and \( (m_{F160W} - m_{F205W})_0 = 0.24 \). We deredden the photometry using the redenning law of Rieke, Rieke, & Paul (1989), i.e. \( A_\lambda \propto \lambda^{-1.53} \). LFs for the individual NICMOS fields are shown in Figure 4.

Figure 5 shows the combined dereddened luminosity functions for the NICMOS, Lick, and Gemini data. The “NICMOS” curve represents the sum of all the NICMOS fields, and it is scaled to account for the much larger area covered by the Lick survey. We find that \( (m_{F205W} - K)_0 < 0.05 \) for red clump stars, as measured by convolving the filter profiles with a spectral energy distribution of such stars; we thus make no explicit correction when comparing photometry in the two filters. The Lick data are confusion limited for \( K_0 > 9 \), where the counts begin to roll over. The NICMOS luminosity function appears to be a straight line, except for a bump at \( K_0 = 12 \), which represents the red clump. The two luminosity functions appear to join for brighter magnitudes. The Gemini counts have been arbitrarily divided by 9 in order to scale them to match the NICMOS counts; the large difference in observed surface number density is expected, given that the Gemini fields are located much nearer to the GC than the NICMOS fields. The Gemini, Lick, and NICMOS data match very well, except for the weakness of the red clump in the Gemini data, a feature that is likely due to the incompleteness of the Gemini data.
3.3. Star Formation Models

We now infer the star formation history responsible for the observed populations by comparing their observed luminosity functions to models built with both the Geneva and Padova isochrones. The Geneva models are described in Schaller, Schaerer, Meynet, & Maeder (1992); Schaerer et al. (1993); Schaerer, Meynet, Maeder, & Schaller (1993); Charbonnel et al. (1993); Meynet et al. (1994). They cover a grid of metallicities \(Z/20, Z/5, Z/2.5, Z, \) and \(2Z\), initial stellar masses (0.8 \(M\) to 120 \(M\)), and two mass-loss rate laws for stars with \(M_{\text{initial}} > 12 \ M\) (the “canonical” and “enhanced” mass-loss rate laws). We interpolate the evolutionary tracks and produce isochrones for a variety of masses and ages, extrapolating below 0.8 \(M\). The Padova models were kindly provided by Leo Girardi, and based on work described in Girardi et al. (2002). They cover the same metallicities as the Geneva models, and initial stellar mass between 0.15 \(M\) and 80 \(M\). We do not use the Padova isochrones to model starbursts that are young enough to still include stars with \(M_{\text{initial}} > 80 \ M\) (several million years).

The model luminosity functions for a given star formation history are produced by summing individual luminosity functions for separate star formation events, under the constraint that the total mass in stars formed is equal to \(2 \times 10^8 \ M\), the mass inferred from velocity measurements in McGinn, Sellgren, Becklin, & Hall (1989) within a projected radius of 30 pc of the Galactic Center. The individual events start at an age of 10\(^7\) years and are separated by 10\(^7\) years up to 10\(^9\) years, at which point they are spaced by 10\(^9\) years, up to 10\(^{10.1}\) years. The number of stars formed in each event determines the normalization of the integral over a mass spectrum of stars given by a power-law with index of \(-0.9\), i.e. \(dN/dm=m^{-0.9}\), as opposed to the “Salpeter” value of \(-1.35\) (Salpeter 1955); this value is motivated by the measurements for the Arches cluster (Figer et al. 1999b; Yang, Park, Lee, & Lee 2002; Stolte et al. 2003). The upper mass limit is 120 \(M\), and the lower mass limit is 0.1 \(M\). These masses are transformed to absolute magnitudes in the \(V\) band through the models. These are converted to absolute magnitudes in the band of interest, i.e. \(K\), through a lookup table that relates color index to temperature (which comes from the models). The apparent magnitude in the band of interest is then simply the absolute magnitude plus the distance modulus (14.52, i.e. \(d=8 \ \text{kpc}\)). We then sum the histogram to produce the luminosity function, and sum the individual luminosity functions to produce the final luminosity function for a given star formation history. The normalization to apparent surface density is fixed by dividing the model luminosity functions by an “appropriate” area, \(\pi(30 \ \text{pc})^2\) throughout this paper. Note that this normalization produces a single “average” density for the whole area, i.e. no attempt was made to scale the densities with Galactocentric radius.

Figure 6 shows a subset of starburst luminosity functions that we use in constructing the
summed luminosity functions for various model star formation histories. In this figure, we illustrate a range of single starburst models, some of which are ultimately used in constructing our more complicated star formation models histories. We consider a range of ages, assuming the Geneva models with $Z=Z_⊙$ and canonical mass-loss rates. The Lick data are overplotted for comparison at the bright end ($K<9$), where the data are reasonably complete. The luminosity functions for young starbursts have a gap between the red supergiant stars and fainter stars that are still on the main sequence, a feature not seen in the Lick data. For older starbursts, the supergiants are gone and a horizontal branch/red clump forms (at $\sim 500$ $M_{yr}$). 

Note that the red clump magnitude shifts to fainter, then brighter, over the time interval from 500 $M_{yr}$ to 2 $Gyr$. This effect is most clearly demonstrated in the plot adapted from Girardi et al. (2002) in Figure 7. This figure agrees well with observed data of red clump stars for the ancient population of Baade’s Window, for which $m_{RC}=13.12$ (Alves 2000).

3.4. Star Formation History

The observations cannot be fit by any single starburst population. However, there is promise in reproducing the observed features by constructing a model for episodic, or continuous, star formation histories. We construct a model (Figure 8) by assuming that the GC region continuously produced stars that evolved according to the Geneva models (Meynet et al. 1994). We assume that there was a burst every 10 $M_{yr}$ from 10 $Gyr$ ago to the present, with an average rate of 0.07 $M⊙ yr^{-1}$. We choose this rate so that the model curve fits the observed curve, but note that it is approximately seven times the rate corresponding to the star formation that produced the three young clusters. The Tiede, Frogel, & Terndrup (1995) data of Baade’s window stars were arbitrarily scaled such that the counts roughly match the counts in the scaled NICMOS data. The bright stars from the Lick data are well matched by our model. Indeed, the bright end of the luminosity function can only be fit by stars younger than $\approx 100$ $M_{yr}$. Our model also matches the red clump at $K_0 \sim 12$ very well. Most importantly, the model fits the absolute number of stars formed over the region modelled.

Figures 9 and 10 show alternate star formation scenarios, with the model counts modified by the observed completeness fractions from Figer et al. (1999b). The star formation histories are of three families: ancient bursts, continuous star formation, and bursts plus continuous star formation. In all cases, the histories produce $2(10^8) M⊙$ in stars within a radius of 30 pc.

There are five constraints provided by the models: 1) the counts in the bright end ($K_0 <8$), 2) the slope at intermediate magnitudes ($10<K_0 <15$), 3) the brightness of the red clump, 4) the counts at the faint end ($K_0 >15$), and 5) the absolute counts per unit area.
The counts in the bright end are controlled by the extent of recent star formation. The slope is controlled by the presence of a red giant branch; note that any star formation history that includes some ancient stars will produce a red giant branch, and thus an intermediate magnitude slope that is a relatively constant function versus specifics within that history. The brightness of the red clump is related to the extent of star formation activity at intermediate age. The counts at the faint end are controlled by ancient star formation. The total number of counts in each bin is controlled by the strength and overall age of the star formation. So, we find that we can constrain the relative amounts of recent, intermediate, and ancient star formation activity through the use of these luminosity functions, in addition to the absolute productivity of the star formation.

Figures 9 and 10 show that all five constraints are best fit by the continuous star formation model. Indeed, the ancient bursts do not reproduce a bright end at all. The observed brightness of the red clump is too bright for intermediate age bursts, whereas the continuous star formation scenario fits this constraint well. The counts at the faint end are overpredicted in the ancient burst models, but reasonably well fit by the continuous star formation model. Note that the data are much more than 50% incomplete for the faintest few bins. Most importantly, the absolute numbers of stars at intermediate magnitudes cannot be reproduced by the ancient burst models. Indeed, the ancient burst models fail badly at reproducing the number of stars seen, by two orders of magnitude in the brightest bins, even though the bursts assume a burst mass of $2(10^8) M_\odot$.

The qualitative analysis above begs the question of uniqueness. In order to determine the sensitivity of our technique, we attempt to model the old populations in Baade’s Window and in the Galactic globular cluster, NGC6528. Because we do not have reliable total mass constraints, unlike the situation for the GC, we scale the observed counts arbitrarily to achieve the best fit. Figures 11 and 12 show the results for Baade’s Window data. For Baade’s Window, the ancient burst model provides the best fit, reproducing the faintness of the red clump and the counts at the faint end. Note, however, that the number of stars having $8<K<10$ is not reproduced by the ancient burst models, because the models fail to faithfully model the upper tip of the AGB luminosity function. The AGB is the most poorly understood evolutionary phase, and therefore will be most poorly fit by any theoretical model. Further, the AGB luminosity has relatively low sensitivity to age, at Solar metallicity. Finally, the lifetimes are short, so the number counts of stars tend to be low. For these reasons we do not place most of the weight on the bright end of the AGB. The next best fit is provided by the continuous star formation model, although the counts at the faint end and the brightness of the red clump are not well reproduced.

Figures 13 and 14 show the results for NGC6528. We use models for metallicity twice
that of the Solar value, in accordance with the measured abundances in the NGC6528 cluster stars (Carretta, Cohen, Gratton, & Behr 2001). Again, the figures show that the ancient burst model provides the best fit. The observed red clump is more pronounced than seen in the Geneva model, and it is very well fit by the Padova model, as is a second bump one magnitude fainter ($K=14.0$). As in the case of Baade’s Window, the next best fit is given by the continuous star formation scenario. Just as before, this model for this scenario fails to match the observed faint end and the brightness of the red clump.

Next, we investigate the star formation history as a function of field location. Figures 15, 17, 19, and 21 show the completeness-corrected models overplotted on the individual observations in the z-fields for the Geneva models, and Figures 16, 18, 20, and 22 show the same for the Padova models. The luminosity functions show that brighter stars are preferentially located closer to the Galactic center and are absent for the $zc$ field ($m_{F205W}<9$). Note that this is not a sampling effect, given that the fields are the same size. The brightness of the red clump is well-fit in all cases, although the observed clump for the $zd$ field extends over several bins. The overall number of stars is also noticeably elevated for the $zd$ field. We suggest that all of these effects are owed to more recent star formation closer to the Galactic center. With greater areal sampling, we hope to constrain the star formation history as a function of position in the Galactic center beyond the suggestive variations we already see in the $z$ fields.

### 3.5. Uniqueness

We also ran models for a lower-mass cutoff ($m_{\text{lower}}$) of 1 $M_\odot$, instead of 0.1 $M_\odot$. That primarily resulted in a vertical shift upward of the luminosity functions for $K_0<22$. While this elevated lower mass cutoff is consistent with the observations, we note that the absolute vertical scale for the models is more uncertain that the difference seen between the two cases of lower mass cutoffs. The results are also generally robust against variations in $m_{\text{upper}}$, $\dot{M}$, $Z$, and $\Gamma$, within a factor of two in each parameter.

### 4. Discussion

Although the presence of the red clump population is consistent with a population older than 1 $Gyr$, our modeling of the observed luminosity function points strongly in the direction of a continuous star formation history. The number counts and shape of the luminosity function are inconsistent with a population dominated by an ancient burst, or by a small
number of bursts older than 1 Gyr. We favor a continuous star formation history with a rate of \( \sim 0.02 \, M_\odot \, yr^{-1} \), or twice the rate inferred by the presence of the bright young clusters in the region. This rate appears to produce too few stars to match the observations, but it is bounded by the present enclosed mass of \( 2 \times 10^8 \, M_\odot \) within 30 pc of the GC. A more refined estimate of the rate will depend on careful normalization of the modelled surface number density. The young clusters presently observed were formed at an average star formation rate of 0.01 \( M_\odot \, yr^{-1} \), over the past 5 Myr, in good agreement with the conclusions of this paper.

4.1. Comparison to Other Work

There is an abundant body of work noting the very young stellar population \( (\tau_{\text{age}} < 10 \, Myr) \) in the central few arcminutes, and additional studies noting intermediate-age populations on size scales observed in this paper. In particular, Narayanan, Gould, & Depoy (1996), Haller (1992), and Blum, DePoy, & Sellgren (1995) note an overabundance of bright stars in this region, compared to Baade’s Window. Frogel, Tiede, & Kuchinski (1999) also note a dramatic increase in the number of bright stars compared to Baade’s Window. Our observations are consistent with these studies in showing an increase in the number of bright stars from the furthest field \( (z_a) \) to the closest field \( (z_d) \) to the GC. Our results are consistent with previous work finding evidence for an intermediate-age stellar population in the GC. Sjouwerman et al. (1999) identified a population of OH/IR stars having high wind velocities, suggesting a starburst \( \sim 1 \, Gyr \) ago. Our analysis rules out the possibility that the bulk of stars in the region formed in such a burst, although the analysis could accommodate a modest sized burst at \( t = 1 \, Gyr \), if accompanied by continuous star formation at other times.

Genzel et al. (2003) published a K-band luminosity function for stars in the central parsec, obtained with VLT/AO. Their Figure 9 shows the observations and a fit by a an ancient single starburst model, noting the good agreement in the brightnesses of the red clump and the overall slope, after accounting for young stars at the bright end in the observations. It is somewhat difficult to compare our results with those in Genzel et al. (2003) for several reasons. First, the Genzel et al. (2003) data are displayed in one magnitude wide bins, potentially smoothing the effect of a bright red clump. Second, the data are presented in the reddened reference frame with a single extinction value being applied to the model. Our observations are first dereddened individually for each star and then compared to the models. This subtle difference can affect the detailed shape of the red clump in the case that differential extinction is important. Finally, a detailed comparison would require that a single extinction law and common wavebands be used in both cases. Indeed, we infer a
larger extinction for the central parsec than for our NICMOS fields, as shown in Figure 23, yet the extinction value in Genzel et al. (2003) ($A_K=3.2$) is similar to the average extinction values for our NICMOS fields.

We do note, however, that our data produce a broad hump in the luminosity function between $K$ 10 and 13 in the reddened frame (Figure 8), similar to that seen in Figure 9 of Genzel et al. (2003). The fact that we see the feature in our data and in the Genzel et al. (2003) data leads us to believe that the feature is common to the central bulge, a result of ongoing star formation, and not solely a product of the very recent star formation in the central parsec.

4.2. Mass Budget

The molecular clouds in the GC provide the material that feeds the star formation at a rate of at a few hundredths of a solar mass per year (Morris 2001; Figer & Morris 2002). The star formation occurs within the Central Molecular Zone (CMZ), a disk-like region of enhanced molecular density within a radius of $\sim 300$ pc, and having a thickness of $\sim 50$ pc. The amount of molecular mass in the CMZ, about $5(10^7) \ M_\odot$ (Morris & Serabyn 1996), would be consumed by star formation over relatively short timescales, $2-4(10^8)$ yrs. Therefore, there must be a source of replenishment. The ring of molecular material which circumscribes the CMZ at a galactocentric distance of 150 - 180 pc is hypothesized to be material condensed into molecular form by shocks occurring along the innermost, non-self-intersecting X1 orbit in the Galaxy’s barred potential (Binney et al. 1991; Morris & Serabyn 1996). This feature is fed from the outside by gas migrating into the GC from the rest of the Galaxy. After shocking and condensing, the gas continues its inward migration and moves onto x2 orbits inside the ring, where most of the molecular material in the CMZ resides (Regan & Teuben 2003). The inflow rate of material from the ring can be estimated by dividing the mass in the ring by the orbital period, $8(10^6) \ M_\odot/2(10^7) \ yrs=0.4 \ M_\odot \ yr^{-1}$. This is an order of magnitude greater than the star formation rate estimated in this paper; however, the mass budget also includes a term for mass lost through a thermally driven wind (0.03 - 0.1 $M_\odot \ yr^{-1}$). Clearly, all of the terms in the mass budget have errors that are large enough to permit the level of star formation claimed in this paper.
4.3. Relationship to Extragalactic Nuclear Populations

Other than for the Milky Way, nuclei which harbor black holes and show no evidence of an AGN spectrum have stellar populations consistent with formation in an ancient burst (Magorrian et al. 1998). One must emphasize that black holes are more difficult to detect in galaxies with active star formation, so the kinematic sample is biased. Within the Local Group, the nuclei of M31 and M32 can be so characterized; while M32 may contain some fraction of few Gyr old stars, there is no evidence of recent star formation in the M32 nucleus. The unusual star formation history in the Galactic Center may be related to bar-induced feeding of gas into the central region, and subsequent star formation (Regan & Teuben 2003).

Our demonstration that the star formation history of the nuclear population is continuous has additional implications, and raises several questions. Has the black hole grown in mass along with the stellar population, or was most of the mass of the black hole in place, perhaps within a Gyr of the Galaxy’s formation? Further, how can a galaxy with a bulge population well demonstrated to be as old as the oldest globular clusters (Ortolani et al. 1995; Kuijken & Rich 2002; Zoccali et al. 2003), have formed at early times without simultaneously forming the bulk of the stars presently seen in the nuclear population?

We thank Leo Girardi for graciously providing the Padova model isochrone files. We acknowledge very useful discussions with Mike Regan, Paco Najarro, Bob Blum, Laurant Sjouwerman, and Jay Frogel. We also thank the Gemini North Science Verification Team for obtaining the Galactic Center data used in this paper. Support for this work was provided by NASA through grant number GO-07364.01-96A and AR-08751.02-A from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5-26555. Mark Morris is supported by NSF through AST9988397.
Table 1. Log of Observations

<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td>h m s</td>
<td>° ′ ″</td>
<td>degrees</td>
<td>pc</td>
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<td>pc</td>
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</tr>
<tr>
<td>Quintuplet</td>
<td>17 43 04.80</td>
<td>−28 48 26.0</td>
<td>0°1664</td>
<td>31.6</td>
<td>−0°0611</td>
<td>−1.5</td>
<td>HST/NICMOS</td>
</tr>
<tr>
<td>Arches</td>
<td>17 42 39.90</td>
<td>−28 48 13.0</td>
<td>0°1218</td>
<td>25.4</td>
<td>0°0182</td>
<td>9.5</td>
<td>HST/NICMOS</td>
</tr>
<tr>
<td>za</td>
<td>17 42 34.47</td>
<td>−28 45 57.1</td>
<td>0°1435</td>
<td>28.4</td>
<td>0°0549</td>
<td>14.6</td>
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</tr>
<tr>
<td>zb</td>
<td>17 42 10.96</td>
<td>−28 42 45.9</td>
<td>0°1435</td>
<td>28.4</td>
<td>0°1559</td>
<td>28.7</td>
<td>HST/NICMOS</td>
</tr>
<tr>
<td>zc</td>
<td>17 41 47.47</td>
<td>−28 39 34.4</td>
<td>0°1435</td>
<td>28.4</td>
<td>0°2569</td>
<td>42.9</td>
<td>HST/NICMOS</td>
</tr>
<tr>
<td>zd</td>
<td>17 42 43.68</td>
<td>−28 54 13.2</td>
<td>0°0439</td>
<td>14.5</td>
<td>−0°0461</td>
<td>0.5</td>
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</tr>
<tr>
<td>GC</td>
<td>17 42 30.00</td>
<td>−28 53 00.0</td>
<td>0°0350</td>
<td>12.7</td>
<td>0°0070</td>
<td>7.4</td>
<td>Lick/Gemini</td>
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<tr>
<td>Gemini #1</td>
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<td>−28 59 19.4</td>
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<td>0.13</td>
<td>−0°0455</td>
<td>0.11</td>
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</tr>
<tr>
<td>Gemini #2</td>
<td>17 42 29.37</td>
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<td>0.83</td>
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<td>Gemini/AO/Hokupa'</td>
</tr>
<tr>
<td>Gemini #5</td>
<td>17 42 30.73</td>
<td>−28 59 19.5</td>
<td>−0°0519</td>
<td>0.53</td>
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<td>−0.54</td>
<td>Gemini/AO/Hokupa'</td>
</tr>
<tr>
<td>Gemini #6</td>
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<td>−28 58 59.5</td>
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<td>−0°0476</td>
<td>−0.17</td>
<td>Gemini/AO/Hokupa'</td>
</tr>
</tbody>
</table>

aValues are with respect to Galactic Center, located at (−0°0557, −0°0463).
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Fig. 1.— Fields covered by observations. Labels are overplotted for the NICMOS “z-fields” (za, zb, zc, and zd), the cluster control fields (ac and qc), and the Gemini/AO fields (the four fields nearest the GC label). The Lick field is marked by the large irregularly-shaped box (Figer 1995a). Coordinates for the fields are given in Table 1. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 2.— Observed color-magnitude diagrams for NICMOS data (upper panel), Gemini data (middle panel), and Lick data (lower panel). The “red clump” can be seen best in the NICMOS data, starting at H−K≈1.5 and K≈15, and continuing to the lower right; the extension toward the lower right is a result of differential reddening dispersing the stars along the reddening vector. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 3.— Observed color-magnitude diagrams for individual NICMOS fields. Indications of a red clump can be seen in all fields at locations that are dependent on the average extinction for each field. For example, the red clump has a color of $m_{F160W} - m_{F205W} \approx 1.5$ for the zd field, the field that is nearest to the GC and that suffers the highest extinction of the six fields. The zc field is furthest from the GC, and therefore has the lowest extinction and a red clump that is relatively blue compared to the other fields. Note that the gap between the main sequence ($m_{F205W} \approx 19$) and the red clump ($m_{F205W} \approx 15.5$) is more populated for fields nearer to the GC, i.e. in the zd field, suggesting a trend of younger stars toward the center. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 4.— Dereddened luminosity functions for individual NICMOS fields, as extracted from the color-magnitude diagrams in Figure 3; the data have not been corrected for incompleteness. The red clump can generally be seen near $m_{F205W} \approx 12.5$, although it is shifted toward brighter magnitudes for fields closer to the GC. Evidence of relatively young stars (hundreds of Myr old) in the main sequence gap (e.g. Figure 3) can be seen in the luminosity function for the zd field. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 5.— Dereddened luminosity functions for the Galactic Center NICMOS (dot-dashed), Lick (light) fields, and Gemini/AO fields; the data have not been corrected for incompleteness. The three luminosity functions match quite well over the magnitude ranges for which they are complete. The Lick data are already seriously incomplete at $K_0 \approx 9$, and the Gemini data begin to be incomplete at $K_0 \approx 12$, or roughly the magnitude of the red clump. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 6.— Theoretical (heavy) and observed (light) luminosity function for the Galactic Center Lick field. The figure legends give the ages of the single starbursts assumed for the models. We assume solar metallicity and the “canonical” mass-loss rates in the Geneva models. The starburst models used in making this figure are used in creating the summed luminosity functions for more complex star formation histories in later figures. Note that we have not normalized the counts in this plot. The plots show that the observed counts at the brightest magnitudes cannot be reproduced by any single starburst. Note, also, that the counts at the bright end require the presence of some young stars. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 7.— Dereddened $K$-band magnitude of red clump for a model starburst population in the Galactic Center as a function of age, adapted from Girardi, Bressan, Bertelli, & Chiosi (2000), assuming solar metallicity. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 8.— Theoretical (solid) and observed luminosity functions for Baades Window (dashed) and the Galactic Center fields (dot-dashed). The theoretical curve was produced using the Geneva models, assuming solar metalicity and a constant star formation rate of $0.07 \, M_\odot \, yr^{-1}$ from 10 Gyr ago to the present. The Baade’s window stars were arbitrarily scaled such that the counts roughly match the counts in the NICMOS data. Note the fainter red clump in the Baade’s Window data. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 9.— Model luminosity functions (heavy, right) as a function star formation scenario (left) for \( Z = Z_\odot \) and the canonical mass-loss rates of the Geneva models, compared to the observed luminosity function for the Galactic Center fields (light, right). The model counts have been multiplied by the completeness fraction of the observations. The models have been constrained to produce \( 2 \times 10^8 \) \( M_\odot \) over a circular area having \( r < 30 \) pc. Continuous star formation histories fit better than ancient bursts. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.

Fig. 10.— Same as Figure 9, except using the Padova models. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 11.— Model luminosity functions (heavy) as a function star formation scenario for Z=Z⊙ and the canonical mass-loss rates of the Geneva models, compared to the observed luminosity function for the Baade’s Window fields (light). The models have not been scaled for mass, but rather have been arbitrarily scaled along the vertical axis to match the observed counts in the K=11.0 bin. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.

Fig. 12.— Same as Figure 11, except using the Padova models. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 13.— Luminosity functions (heavy, right) as a function star formation scenario (left) for $Z=2Z_\odot$ and the canonical mass-loss rates of the Geneva models, compared to the observed luminosity function for the NGC6528 field (light, right). The models have not been scaled for mass, but rather have been arbitrarily scaled along the vertical axis to match the observed counts in the $K=11.0$ bin. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 14.— Same as Figure 13, except using the Padova models. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 15.— Model luminosity functions (heavy, right) as a function star formation scenario (left) for Z=Z⊙ and the canonical mass-loss rates of the Geneva models, compared to the observed luminosity function for the Galactic Center za field (light, right). The model counts have been multiplied by the completeness fraction of the observations. The models have been constrained to produce 2(10^8) M⊙ over a circular area having r<30 pc. Continuous star formation histories fit better than ancient bursts. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 16.— Same as Figure 15, except using the Padova models. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 17.— Model luminosity functions (heavy, right) as a function star formation scenario (left) for $Z=Z_\odot$ and the canonical mass-loss rates of the Geneva models, compared to the observed luminosity function for the Galactic Center zb field (light, right). The model counts have been multiplied by the completeness fraction of the observations. The models have been constrained to produce $2(10^8)\ M_\odot$ over a circular area having $r<30\ pc$. Continuous star formation histories fit better than ancient bursts. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 18.— Same as Figure 17, except using the Padova models. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 19.— Model luminosity functions (heavy, right) as a function star formation scenario (left) for $Z=Z_\odot$ and the canonical mass-loss rates of the Geneva models, compared to the observed luminosity function for the Galactic Center zc field (light, right). The model counts have been multiplied by the completeness fraction of the observations. The models have been constrained to produce $2(10^8)\ M_\odot$ over a circular area having $r<30\ pc$. Continuous star formation histories fit better than ancient bursts. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 20.— Same as Figure 19, except using the Padova models. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 21.— Model luminosity functions (heavy, right) as a function star formation scenario (left) for $Z=Z_\odot$ and the canonical mass-loss rates of the Geneva models, compared to the observed luminosity function for the Galactic Center zd field (light, right). The model counts have been multiplied by the completeness fraction of the observations. The models have been constrained to produce $2(10^8) M_\odot$ over a circular area having $r<30$ pc. Continuous star formation histories fit better than ancient bursts. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 22.— Same as Figure 21, except using the Padova models. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.
Fig. 23.— Extinction map ($A_K$), as inferred from the Lick data (Figer 1995a). Sgr A* is located at (0,0). The offsets are in arcseconds along RA and Dec. See text for discussion. All figures may be obtained in the version of this paper at: http://www.stsci.edu/~figer/private/papers/gcsfrate/ms.ps.