

The Star-Formation History in the Vicinity of NGC 1866 in the Large Magellanic Cloud¹

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ABSTRACT. To expand on the recent single WFPC2 field obtained in the vicinity of this cluster, we have measured the luminosity function in a one-third by one-half degree field in the LMC with the 40-in. telescope at Siding Spring Observatory. Combining our results with recent 4-m and WFPC2 observations, we examine the constraints on the star-formation history of the field from 10^8 to 10^{10} years ago. The simple model derived from the WFPC2 data with an increase in the star-formation rate ~ 3 Gyr ago fits the combined data. However, this rate increase seems to have been unique. This event notwithstanding, the smooth luminosity function from $V=16$ to $V=22$ suggests steady star formation rather than a star-formation history dominated by intense bursts.

1. INTRODUCTION

Butcher (1977) was the first to derive a main-sequence luminosity function for the Large Magellanic Cloud (LMC), using a field about 4° away from the bar. He found that in this region there is a change in the luminosity function (LF) slope that occurs at $M_v = +3$. This change in slope occurs one magnitude brighter than the similar slope change in the Local Solar Neighborhood LF. It is thought to correspond to a major epoch of star formation occurring at $\sim 2\text{--}5 \times 10^9$ years ago as opposed to the expected $10\text{--}15 \times 10^9$ years.

That an epoch of star formation did occur between 1 and 5×10^9 years ago has also been suggested by a number of other authors. Stryker et al. (1984) consider three different star-formation scenarios and also conclude that although star formation may have occurred 10×10^9 years ago its strength must have been less than that at $\leq 5 \times 10^9$ years. However they, like Butcher, were limited to absolute magnitudes of less than +4. Hardy et al. (1984) used evolutionary models of clump red giants and the morphology of their color-magnitude diagram (CMD) to conclude that star formation in the LMC is continuing, and most star formation started between 1 and 3×10^9 years ago. This age is also verified by Frogel and Blanco (1983) who used an infrared CMD to locate the position of the asymptotic giant branch. They found two such branches suggesting two populations, one $3\text{--}5 \times 10^9$ years old, identifying this with the star-formation burst suggested by Butcher, and also by Stryker, and the second from an event a few times 10^8 years ago. Bertelli et al. (1992) investigated three fields in the LMC by means of deep 4-m CCD luminosity functions. They concluded that all three fields, including the NGC 1866 field, showed evidence for a major burst of star formation 4 Gyr ago in the LMC.

In this paper we present a composite luminosity function for the NGC 1866 field spanning the range (16,24) in visual magnitude. We combine the data from three sources, 668 sq. arcmin surveyed with the 40-in. telescope at Siding Spring Observatory, 15 sq. arcmin from Bertelli et al., and 5 sq. arcmin surveyed with the Wide Field and Planetary Camera II (WFPC2). The color-magnitude diagram for the same WFPC2 field is presented by Gallagher et al. (1996), and its initial mass function has been inferred by Holtzman et al. (1997). Our aim in the present paper is to provide much better statistics on the number of brighter stars in this field and thus to contribute to the description of the overall star-formation history in this field.

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2. OBSERVATION, REDUCTIONS, PHOTOMETRY, AND CALIBRATION

2.1 40-in Photometry

We observed three fields adjacent to and including the *HST* field on the night of 1994 December 6 with the Mount Stromlo and Siding Spring Observatories 40-in (1-m) telescope. The images were obtained using a GEC 2186×1152 chip at the RC focus with a plate scale of $0''.58 \text{ pixel}^{-1}$. The conditions were photometric with the seeing ranging between $1''.8$ and $2''.5$. We obtained 1000-s exposures in both *V* and *I* filters. Additional multiple exposures of two standard star fields were obtained at a number of airmasses for the purpose of flux calibration.

The data were bias subtracted and flat-fielded; the IRAF implementation of DAOPHOT (Stetson 1987) was used to carry out the photometry. Standard stars were used to determine the magnitude zero points, and determine the color transformations from our instrumental magnitudes to the Cousins *VI* color system. This gave overall transformations, including the airmass (*Z*) and zero-point terms, of:

$$V = V_{\text{instr}} + 21.34(\pm 0.02) - 0.18 \times Z - 0.0324(V - I)_{\text{instr}}, \quad (1)$$

$$I = I_{\text{instr}} + 21.55(\pm 0.02) - 0.08 \times Z - 0.0321(V - I)_{\text{instr}}. \quad (2)$$

We see very small color terms in these equations with negligible uncertainties in the coefficients. The cluster NGC 1866 was in the field of one of our images; however, cluster members were not included in this analysis. A very bright star just off the edge of one of our frames meant that a portion of this frame was affected by scattered light. After the removal of these two regions the total area sampled by our three frames (assuming a distance of 52 kpc, 1 arcsec corresponds to 0.25 pc) is 0.15 kpc^2 .

Figure 1 is a classic LMC CMD with a well-defined su-

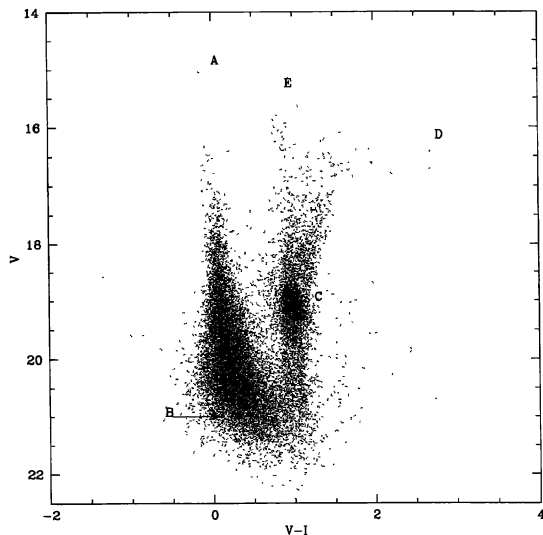


FIG. 1—The color-magnitude diagram from the 40 in. survey. “A” marks the location of massive main-sequence stars and blue supergiants. The main sequence stretches to the limit of completeness at “B.” “C” is the clump; “D” the likely location of carbon stars; red supergiants are labeled “E.”

TABLE 1
Hess Diagram from Fig. 1

	-0.6	-0.4	-0.2	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0-4.0
14.2	0	0	2	0	0	0	1	2	0	0	0	0	0	0
14.4	0	0	0	0	0	0	2	2	1	1	0	0	0	0
14.6	0	0	0	0	0	0	1	3	0	1	1	0	0	0
14.8	0	0	0	0	0	1	0	2	1	1	0	0	0	0
15.0	0	0	3	2	1	0	3	2	0	0	1	0	0	1
15.2	0	0	1	0	0	0	0	1	1	1	0	0	0	0
15.4	0	0	3	0	1	0	4	5	3	1	0	0	1	0
15.6	0	0	1	1	1	0	2	6	4	1	0	1	2	0
15.8	0	0	2	1	0	1	4	10	6	0	3	2	0	1
16.0	0	1	3	0	2	2	6	15	1	3	3	3	1	5
16.2	0	1	5	2	1	1	6	21	7	8	4	5	3	3
16.4	1	0	9	8	4	1	6	7	20	20	7	6	3	13
16.6	0	0	5	5	4	1	3	15	17	19	21	14	10	1
16.8	1	0	15	6	0	3	5	20	20	16	12	9	5	4
17.0	0	0	11	18	1	2	8	27	22	20	22	3	1	7
17.2	0	2	13	37	7	3	10	24	24	47	18	4	0	1
17.4	0	0	19	43	6	6	12	34	31	51	13	1	1	0
17.6	0	0	23	48	7	11	8	35	45	50	11	2	2	6
17.8	1	2	30	94	12	7	16	71	72	63	5	3	2	1
18.0	1	2	44	146	17	9	15	82	98	59	5	3	0	1
18.2	2	1	39	144	31	12	27	115	139	42	5	0	0	4
18.4	1	1	38	218	36	12	37	137	115	43	4	1	2	5
18.6	4	4	52	280	64	21	52	209	151	25	3	4	4	7
18.8	0	5	78	312	93	28	73	453	253	13	11	8	1	11
19.0	1	3	92	405	158	31	55	562	484	22	7	6	2	6
19.2	8	12	102	476	240	49	65	387	396	26	11	7	2	8
19.4	6	19	142	513	300	81	51	241	182	34	10	5	5	14
19.6	10	13	157	586	413	104	42	140	150	18	7	6	6	15

pergiant region, main sequence, and clump. It shows a broad giant branch with $V-I \approx 1.0$, at $V=20$ mag. Colors range from $V-I=0.8$ (corresponding to very low metallicity stars of a few Gyrs) to 1.2 (corresponding to old stars of $Z \sim 0.01$). Table 1 is a representation of Fig. 1 as a Hess diagram, showing the density of stars as a function of color and magnitude.

2.2 WFPC2 Photometry

Four observations with the three wide-field chips and single planetary chip were made in the WFPC2 filters F555W and F814W. The total integration time was 4000 s. The data are discussed more fully by Gallagher et al. (1996).

The first part of the reduction procedure was the construction of the bias frames. As described by Holtzman et al. (1995a) there was a significant difference in the bias values between odd and even columns of the WFPC2 chips. So bias frames with separate odd and even values were created. Although in some cases the difference between the column biases were statistically significant, in the majority of cases this was not so. The other important feature of the bias frames was that for some of the images, specifically those from the planetary camera, the bias value was greater than or very close to the total background count value. The sky counts in the images are not expected to be large; however, this discrepancy meant that after the complete reduction pro-

cedure the sky had negative counts in some frames. This in itself is not a problem for the photometry, but it did certainly make the cosmic-ray removal less efficient.

After bias subtraction a further superbias was subtracted in order to remove some structure which remains in the zero exposure time frames. The superbias we used were based on the combination of a number of on-orbit biases which better probe the present bias structure. Two dark frames were then removed, a superdark and a deltadark. The superdark is once again the summation of a number of darks taken with the right gain state and temperature, 14 electrons and -88°C , respectively, for our data. The superdarks are designed to remove the constant dark rate for each pixel and also those pixels which have been hot for a period of time. In order to remove any new features in the dark current, such as pixels which may only recently have become hot, a deltadark is used. This is created from a few dark frames nearest in time to the frame which is being reduced.

A number of different cosmic-ray removal techniques were tried due to the importance of making sure that the residuals of the removal were not at a signal level which would affect our magnitude limit. Difference frames are calculated and then inspected for remaining cosmic rays. The grazing incident, multiple pixel, events were the most difficult to remove with coincidences meaning that some residual often remained. The cosmic-ray removal technique we adopted was to average the four observations and then do a min-max rejection.

The brightness of the stars in the frames were measured using DAOPHOT as part of the IRAF¹¹ package. The analysis was basically the same for both the wide field and planetary cameras except for changes in the FWHM and sky values. The DAOFIND task was used to identify the stars and assign them positions as a starting point for the photometry routines. PHOT was then used to calculate initial centers, sky values, and magnitudes. The results of PHOT were used as the input values for the nonlinear fitting routine ALLSTAR.

In order to run ALLSTAR a functional representation of the point-spread function (PSF) is required. All six standard fitting functions in DAOPHOT, Moffat, $\beta=2.5$, 1.5, penny1, penny2, Gauss, and Lorentz were tried in order to best fit the PSF of the frames. However, using the frames as the source of the PSF proved to be very unsatisfactory. Even when the PSF was allowed to vary across the frames the number of counts left in the residuals after subtraction of the PSF fitted star was large. So a PSF based on the TINYTIM PSF was created.

The variable TINYTIM PSF (Krist 1993) was created for a number of different chip positions, and these were then placed on a false image and used to define a PSF. The best-fit function was a Lorentz with a variable PSF. After subtraction of the PSF there was still some power in the wings of the stars; however the overall fit was better and the fitting errors subsequently lower. Once a PSF had been created for each of the separate chips the task ALLSTAR was run. This

task is an iterative procedure which groups, fits, and then subtracts the fitted stars. The iterative nature enables some stars which may be in the wings of brighter stars to be recovered. The photometry was done relative to an aperture radius of 0.69 arcsec and 1.5 arcsec for the planetary and wide field cameras, respectively.

Possible error due to the charge transfer effects outlined by Holtzman et al. (1995a) has not been corrected in this analysis. Tests conducted by the team suggest that CTE effects are negligible at the background levels of these data. A total of 3500 stars were measured over the four chips. The transformation to the V and I filters was that described by Holtzman et al. 1995b.

In order to check the consistency of the magnitudes, 37 stars which were common to both the 40-in data and wide field chip No. 2 were compared. The difference between the magnitudes in the V and I bands were 0.0 ± 0.1 mag.

3. THE COLOR-MAGNITUDE DIAGRAM

Figure 1 exemplifies what is seen throughout the LMC. Luminous main-sequence stars are present, beginning at 14th magnitude in this field. Massive stars, upwards of $10 M_{\odot}$, judging by standard mass-luminosity relations, extend through $V=16$ mag, but in modest numbers. Less massive blue supergiants and evolved main-sequence stars are mixed in with them. There is little discrimination between them in a $(V, V-I)$ CMD.

The main sequence dominates the CMD, extending to the limit of completeness at $V=21$ at approximately $1.7 M_{\odot}$. Other prominent features are the core helium burning clump on the red giant branch (point C in Fig. 1) and the extended asymptotic giant branch, where carbon stars are likely to reside at $V-I > 2$. Red supergiants, progeny of the luminous main-sequence stars, stretch vertically from these luminosities to those of the brightest blue supergiants in the field.

4. MAIN-SEQUENCE LUMINOSITY FUNCTION

Figure 2 shows the main-sequence luminosity function for this field from four combined sources. From $V=16$ to $V=20$ the ground-based luminosity function is smooth with slope of 0.7 dex/mag (this paper). At the faintest magnitudes (Holtzman et al. 1997) the slope is shallower (~ 0.15 mag/dex). In Table 2 we can compare the counts from three sources in 0.5 mag bins centered on the V magnitude indicated in the first column. The second column gives the main-sequence-star count in the 40-in field. The third column reproduces Table 2 of Bertelli et al. (1992) (cumulative counts). The final column gives the main-sequence star count in the 5.1 sq. arcmin WFPC2 field.

5. THE STAR-FORMATION HISTORY

Figure 3 shows theoretical luminosity functions computed from the *Revised Yale Luminosity Functions* (Green et al. 1984) by integrating the star-formation rate $\text{SFR}(t)$:

$$N(V) = \int \text{SFR}(t) \frac{dn(V)}{dt} dt, \quad (3)$$

¹¹IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

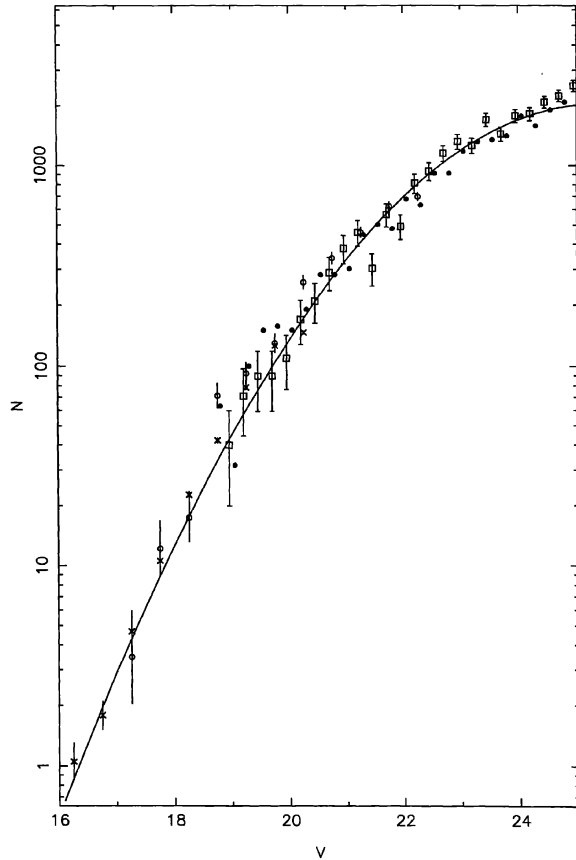


FIG. 2.—The combined luminosity function for the NGC 1866 field. Crosses are 40-in data; open circles are the data of Bertelli et al. Boxes are photometry from WFPC2 data reported here; the solid symbols are from the study by Holtzman et al. (1997). The function fitted to the data is a parabola.

where

$$\text{SFR}(t) \propto 1 + ce^{-t/t_0} \quad (4)$$

and

$$n(m)dm \propto m^{-s}dm \quad (5)$$

represent the star-formation history and a power-law initial mass function.

We have calculated theoretical luminosity functions with $s=2.35$, and metal abundance, $Z=0.01$. Models with $c \sim 3$ and $t_0 \sim 0.5$ Gyr produce good fits to the data. Since the mass range spanned in the main-sequence luminosity functions presented here cover a factor of five, there is considerable degeneracy in luminosity function fits between t_0 and s . The slope of the IMF, however, is best determined from a non-evolving portion of the CMD. Holtzman et al. (1997) have shown that $1.6 < s < 3.1$.

Figure 3 shows theoretical luminosity functions assuming the star-formation history found by Holtzman et al. to fit the WFPC2 data, in this case with a single metal abundance, $Z=0.01$. The solid line is a model with a step function $\text{SFR}(t)$ starting 10 Gyr ago and increasing by a factor of two 3 Gyr ago. The dashed line is a model without the step function, but with a burst of star formation quadrupling the SFR

TABLE 2
Combined Luminosity Function Data

V	N(40'')	N(4 m)	N(WFPC2)
14.25	3	0	0
14.75	4	0	0
15.25	9	0	0
15.75	12	2	0
16.25	35	0	0
16.75	78	0	0
17.25	157	2	0
17.75	323	7	0
18.25	622	10	2
18.75	1129	41	5
19.25	2055	53	16
19.75	3298	75	20
20.25	3803	149	38
20.75	2734	196	67
21.25	837	264	76
21.75	129	358	105
22.25	7	400	174
22.75	0	344	247
23.25	0	168	298
23.75	0	8	323
24.25	0	0	394
24.75	0	0	476
25.25	0	0	482

between 2.5 and 3.5 Gyr ago. The dot-dashed line is the solid-line model with a burst with $\text{SFR}=10 \langle \text{SFR} \rangle$ between 175 and 275 Myr ago. The corresponding star-formation histories are represented in Fig. 4.

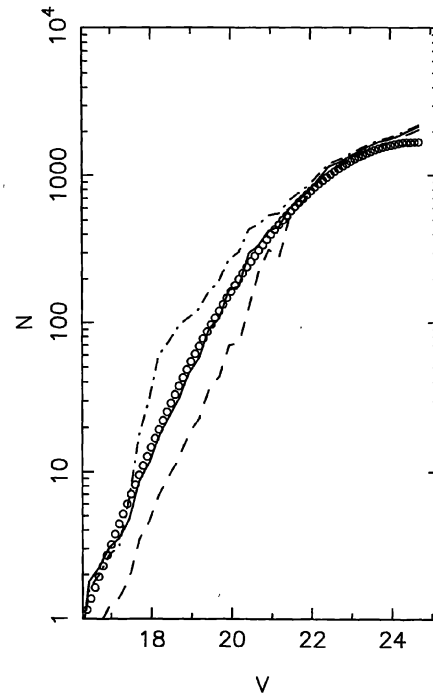


FIG. 3.—Theoretical luminosity functions with $s=2.35$, $Z=0.01$. The solid line is a model with star formation continuing from 10 Gyr ago and increasing by a factor of two 3 Gyr ago. Models with two other star-formation histories described in Fig. 4 are denoted by the dashed and dot dashed lines. The fit to the observations in Fig. 2 is plotted as open circles.

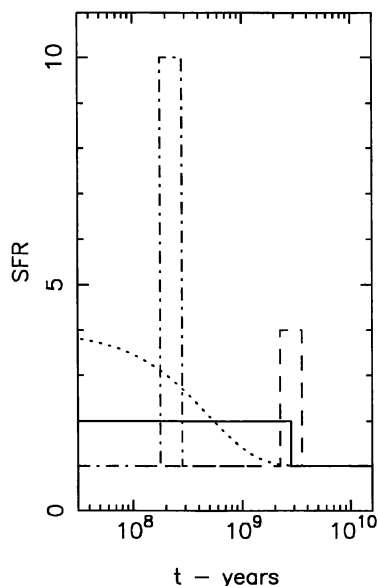


FIG. 4—The solid line is a model with a step function $SFR(t)$ starting 10 Gyr ago and increasing by a factor of two 3 Gyr ago. The dashed line is a model without the step function, but with a burst of star formation quadrupling SFR between 2.5 and 3.5 Gyr ago. The dot-dashed line is the solid-line model with a burst with $SFR=10$ ($\langle SFR \rangle$) between 175 and 275 Myr ago. The corresponding luminosity functions are denoted in Fig. 3 in the same way. In addition, the dotted line represents Eq. (4) with $c=3$ and $t_0=0.5$ Gyr.

Star-formation bursts produce signatures in the models which are not seen in the data. A significant constraint, can therefore be put on the strength of bursts of star formation in this field. Bursts of star formation $SFR(t) \delta t$ exceeding $\langle SFR(t) \rangle t$ are ruled out by the lack of marked discontinuities in the observed luminosity function. The presence of two free functions in these models (the IMF and SFR) suggests that we should not try to artificially tighten these constraints.

The population of the Hertzsprung gap unambiguously shows a burst of star formation between 2 and 3 Gyr ago in this field (Gallagher et al. 1996). Figure 3 suggests that it represents no more than a quadrupling of the star-formation rate for a Gyr (or perhaps a somewhat more intense burst for a shorter time δt). Conversely, the uniform population of the Hertzsprung gap in Fig. 1 between $V=18$ and $V=20$ suggests a burst-free star-formation history between 0.1 and 1 Gyr ago and a fairly steady star-formation rate.

These conclusions fully support those of Gallagher et al. (1996) and Holtzman et al. (1997) in their analysis of this

field. What we have added by examining a wider field is support for the star-formation history deduced by Holtzman et al. in the age interval from 10^8 to 10^9 years ago. This results from our improved statistics at brighter magnitudes.

6. SUMMARY

Determination of the IMF slope in this field by Holtzman et al. (1997) has reduced the degeneracy between constraining the star-formation history and specifying the IMF in LMC studies. The main-sequence luminosity function in the NGC 1866 field can be successfully modeled with a star-formation rate which has risen over the last 3 Gyrs and remained high. The data presented here complement Holtzman et al. by providing a much larger statistical sample constraining model fits to younger and brighter populations than WFPC2 could study. Bursts $SFR(t) \delta t$ exceeding $\langle SFR(t) \rangle t$ are ruled out by the lack of marked discontinuities in the observed luminosity function.

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