

EXPLAINING THE MYSTERIOUS AGE GAP OF GLOBULAR CLUSTERS IN THE LARGE MAGELLANIC CLOUD

KENJI BEKKI,¹ WARRICK J. COUCH,¹ MICHAEL A. BEASLEY,² DUNCAN A. FORBES,²
MASASHI CHIBA,³ AND GARY S. DA COSTA⁴

Received 2004 April 16; accepted 2004 June 17; published 2004 July 2

ABSTRACT

The Large Magellanic Cloud (LMC) has a unique cluster formation history in that nearly all of its globular clusters were formed either ~ 13 Gyr ago or less than ~ 3 Gyr ago. It is not clear what physical mechanism is responsible for the most recent cluster formation episode and thus the mysterious age gap between the LMC clusters. We first present results of gasdynamical N -body simulations of the evolution of the LMC in the context of its Galactic orbit and interactions with the Small Magellanic Cloud (SMC), paying special attention to the effect of tidal forces. We find that the first close encounter between the LMC and the SMC about 4 Gyr ago was the beginning of a period of strong tidal interaction that likely induced dramatic gas cloud collisions, leading to an enhancement of the formation of globular clusters that has been sustained by strong tidal interactions to the present day. The tidal interaction results in the formation of a barred, elliptical thick disk in the LMC. The model also predicts the presence of a large diffuse stellar stream circling the Galaxy, which originated from the LMC.

Subject headings: galaxies: interactions — galaxies: star clusters — galaxies: stellar content — Magellanic Clouds

Online material: color figures

1. INTRODUCTION

Tidal interactions between galaxies are suggested, both from observations and from theory, to dramatically change the formation rates of field stars and globular clusters because of the tidal compression of gas clouds and their efficient conversion into stars (Kennicutt 1998; Ashman & Zepf 1992; Noguchi & Ishibashi 1986; Bekki & Couch 2001; Bekki et al. 2002). The Large and Small Magellanic Clouds (LMC and SMC), which are the nearest pair of interacting galaxies in our vicinity, have served as unique laboratories for studying the interplay between galactic dynamical evolution and star formation activity in galaxies (Westerlund 1997; van den Bergh 2000). A major curiosity in this context is that globular cluster formation—which is considered to be a special mode of star formation (Harris & Pudritz 1994; Elmegreen & Efremov 1997)—is observed to be ongoing in the Clouds but not in the Galaxy. Clearly the physical conditions required for cluster formation currently exist in the Clouds but not in the Galaxy (Westerlund 1997; van den Bergh 2000). Moreover, the age distribution of the LMC clusters shows a gap extending from 3 to 13 Gyr—with only one cluster in this age range—suggesting that a second epoch of cluster formation started abruptly in the LMC about 3 Gyr ago (e.g., Da Costa 1991; Geisler et al. 1997; Rich et al. 2001; Piatti et al. 2002). The origin of the “age gap,” which has not been observed for the SMC, has remained elusive so far (e.g., Da Costa 1991). The purpose of this Letter is to provide a new explanation for the origin of the mysterious age gap of the

LMC’s globular cluster system. The present study also tries to explain the latest observational results of the LMC’s structural and kinematical properties (e.g., Alves & Nelson 2000; van der Marel et al. 2002).

2. THE MODEL

We present here a new numerical model of the dynamical evolution and the star formation history of the LMC as it orbits the Galaxy and is gravitationally influenced by both the Galaxy and the SMC, in an attempt to explain the origin of the age gap. We first determine the most plausible and realistic orbits of the Clouds and then investigate the evolution of the LMC using fully self-consistent N -body models. In determining the orbits, we adopt the same numerical method as those in previous studies (Murai & Fujimoto 1980; Gardiner et al. 1994; Gardiner & Noguchi 1996), in which the equations of motion of the Clouds are integrated backward in time, from the present epoch until ~ 9 Gyr ago. Figure 1 shows the best orbit model for the Clouds calculated in this way, where it can be seen that they experience a very close tidal encounter (at a pericenter distance of 6.4 kpc) around 3.6 Gyr ago ($T \sim -3.6$) and then become dynamically coupled. If dynamical friction between the Clouds and the mass of the LMC ($10^{10} M_{\odot}$) are considered—something that has not been done in previous studies (e.g., Gardiner et al. 1994)—then the present-day binary nature of the Clouds cannot have existed for a Hubble time: They must have been separate objects in the past.

Using gasdynamical N -body simulations (Bekki et al. 2004), we investigate dynamical evolution and star formation histories of the LMC for the best orbit model. The LMC is modeled here as a bulgeless gas-rich disk embedded in a massive dark matter halo with a mass 2.3 times larger than the disk mass, whereas the SMC is treated as a point mass with the mass of $3 \times 10^9 M_{\odot}$. The exponential old disk of the LMC is taken to have a scale length of 2.6 kpc (Kinman et al. 1991) and a maximum circular velocity (V_m) of 71 km s^{-1} , consistent with recent observations (van der Marel et al. 2002). The gas disk

¹ School of Physics, University of New South Wales, Kensington Campus, Old Main Building, Kensington, Sydney, NSW 2052, Australia; bekki@bat.phys.unsw.edu.au.

² Center for Astrophysics and Supercomputing, Swinburne University of Technology, Mail 31, P.O. Box 218, Hawthorn, VIC 3122, Australia; mbeasley@mania.physics.swin.edu.au.

³ Astronomical Institute, Tohoku University, Aoba-ku, Sendai 980-8578, Japan; chibams@crocus.ocn.ne.jp.

⁴ Research School of Astronomy and Astrophysics, Institute of Advanced Studies, Australian National University, Cotter Road, Weston Creek, ACT 2611, Australia; gdc@mso.anu.edu.au.

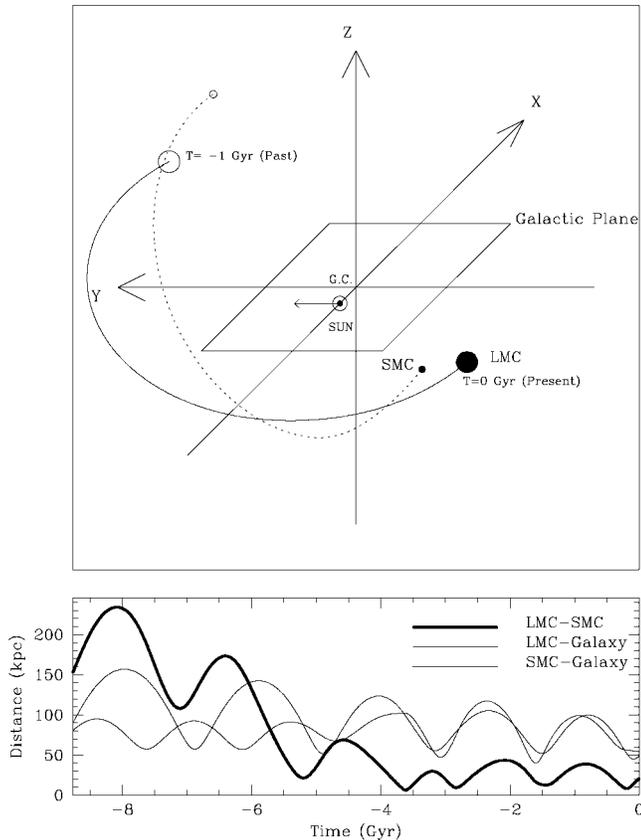


FIG. 1.—Schematic view of the Galaxy and the Magellanic Clouds (*top*) and the orbital evolution of the Clouds (*bottom*). The current Galactic coordinate (b, l), where l and b are the Galactic longitude and latitude, respectively, is $(-32^\circ 89, 280^\circ 46)$ for the LMC and $(-44^\circ 30, 302^\circ 79)$ for the SMC, and accordingly the current positions (X, Y, Z) in units of kiloparsecs in the figure are $(-1.0, -40.8, -26.8)$ for the LMC and $(13.6, -34.3, -39.8)$ for the SMC. The current distance and the Galactocentric radial velocity of the LMC (SMC) is 80 (7) km s^{-1} . The total masses of the LMC and the SMC are 1.0×10^{10} and $3.0 \times 10^9 M_\odot$, respectively. These values were based on those derived from the latest observations (e.g., Kroupa & Bastian 1997; van der Marel et al 2002) and consistent with previous simulations (e.g., Gardiner & Noguchi 1996). In the Clouds’ orbital calculations with the backward integration scheme (Gardiner et al. 1994), we assume that the current space velocities (V_x, V_y, V_z) [or (U, V, W)] in units of kilometers per second are $(-5, -225, 94)$ and $(40, -185, 171)$. We chose these values first because the Magellanic Stream can be self-consistently reproduced in previous models for these values, and second because they are broadly consistent with the latest proper-motion data. The Galactic gravitational potential Φ_G is represented by $\Phi_G = -V_0^2 \ln r$, where V_0 and r are the constant rotational velocity (220 km s^{-1} in this study) and the distance from the Galactic center. A Plummer potential is adopted for the LMC/SMC with a softening length of 3 (2) kpc for the LMC (SMC). For the adopted velocities and positions, the orbits of the Clouds are nearly polar with the Clouds leading the Magellanic Stream. Negative values of the time, T , represent the past, with $T = 0$ corresponding to the present epoch. Note that the LMC-SMC distance (*thick magenta line*) remains very small (<40 kpc) over the last 4 Gyr ($T > -4$ Gyr) because of the dynamical coupling of the LMC and SMC. [See the electronic edition of the *Journal* for a color version of this figure.]

is represented by a collection of discrete gas clouds that follow the observed mass-size relationship (Larson 1981). Each pair of two overlapping gas clouds collides with the same restitution coefficient of 0.5 (Hausman & Roberts 1984).

Globular cluster formation in the present model is discriminated from field star formation as follows: The gas is converted into field stars according to the Schmidt law with the observed threshold gas density (Kennicutt 1998). We use the cluster formation criteria derived by previous analytical works (e.g., Kumai

et al. 1993) and hydrodynamical simulations with variously different parameters of cloud-cloud collisions on a 1 – 100 pc scale (Bekki et al. 2004) in order to model globular cluster formation. A gas particle is converted into a cluster if it collides with other high-velocity gas (ranging from 30 to 100 km s^{-1}) and having an impact parameter (normalized to the cloud radius) less than 0.25 . This model is strongly supported by recent observations (e.g., Zhang et al. 2001) that have revealed that there is a tendency for young clusters to be found in gaseous regions with higher velocity dispersion, where cloud-cloud collisions are highly likely. Chemical evolution of the gas with an assumed effective chemical yield of 0.005 is also incorporated in the simulations. Our numerical results on field star formation histories in the LMC do not depend strongly on the above parameters of gas-dynamics (e.g., gas mass fraction) and star formation (the exponent of the Schmidt law) for a reasonable set of parameters.

In the present Letter, we show only the results of the best model in which the Clouds first came together about 4 Gyr ago. It should be here stressed that this conjunction is not a unique characteristic of the best model: About 95% of the orbital models have a disintegration of the LMC-SMC binary—recall that the integrations are done backward in time—occurring within the last 4 Gyr for models with the orbital parameters consistent with observations. We have investigated orbital evolution of the Clouds for 4×10^8 models with the current space velocities (V_x, V_y, V_z) ranging from -320 to 320 km s^{-1} for the Clouds and thereby derived the epoch when the Clouds become separated. We have confirmed that (1) it is highly unlikely that the Clouds were a binary system more than 6 Gyr ago, and (2) they most likely came together around 4 Gyr ago. Thus our main conclusions on the epoch of the commencement of cluster formation in the LMC do not depend so strongly on orbital parameters.

3. RESULTS

As seen in Figure 2, the combined tidal effects of the SMC and the Galaxy distort the LMC disk ($T = -6.6$ and -3.3 Gyr) to form compact stellar and gaseous bars in its center after a few pericenter passages ($T = -3.3$ Gyr). Consequently, young stars are formed repeatedly in the tidally compressed high-density gaseous regions, in particular the central bar, where the star formation rate is at a maximum at $0.38 M_\odot \text{ yr}^{-1}$. The tidal interaction significantly increases the degree of random motion of the gas clouds so that they collide much more frequently with one another. However, the cloud-cloud collisions with moderately high speed (between 30 and 100 km s^{-1}) and small impact parameter (less than 0.25), required for cluster formation, do not occur until the LMC begins to interact violently with the SMC when the two are less than 10 kpc apart ($T = -3.6$ Gyr). The dynamical evolution over the last ~ 3 Gyr results in about 0.5% of the initial gas cloud mass being converted into clusters. The new globular cluster system has a flattened “disky” spatial distribution with nearly all clusters within the central ~ 3 kpc and confined within ~ 1 kpc from the LMC disk plane (i.e., an indication of a structure similar to the Galactic thick disk). They are supported mainly by rotation with the central velocity dispersion of only 20 km s^{-1} and with a fairly asymmetric radial dispersion profile caused by recent tidal interaction with the Galaxy and the SMC. The derived structure and kinematics of clusters are broadly consistent with the observed ones for intermediate-age clusters (Schommer et al. 1992). Because of the rapid chemical enrichment associated with this star formation activity, the mean metallicity of clusters increases from

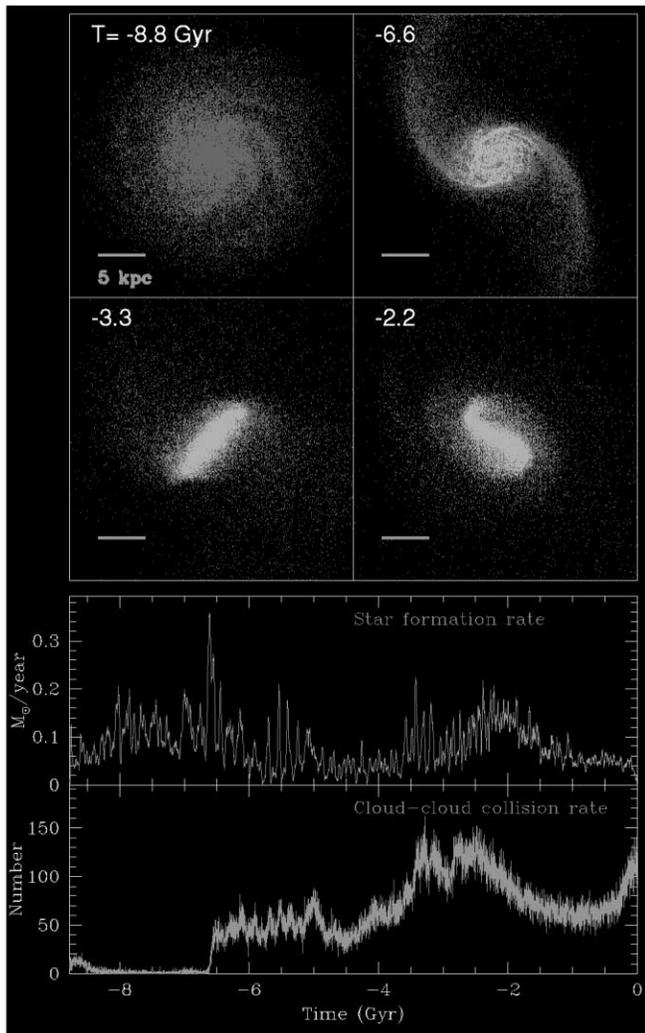


FIG. 2.—Morphological evolution of the LMC for the last ~ 9 Gyr (top) and the time evolution of the star formation rate and the number of cloud-cloud collisions (bottom). Magenta and blue represent “old” stellar and gaseous components and “new” stars, respectively. Here old and new stars mean field stars initially in the LMC disk and those newly formed from gas, respectively. The total number of particles used in the simulation is 1.4×10^5 . Star formation rates are measured in units of $M_{\odot} \text{ yr}^{-1}$. The number of high-velocity cloud-cloud collisions with relative velocities ranging from 30 to 100 km s^{-1} (required for globular cluster formation) are counted at each time in the bottom panel. Note that a bar composed of new stars is formed through repetitive tidal interaction until $T = -3.3$ Gyr. Note also that the cloud-cloud collision rate becomes very high after the first close encounter (at $T \sim -3.6$ Gyr) of the LMC/SMC. The star formation rate also becomes moderately high during close tidal encounters. [See the electronic edition of the *Journal* for a color version of this figure.]

$[\text{Fe}/\text{H}] = -0.91$ to -0.33 over this period. Such a recently formed cluster population consequently has a narrower age distribution than the new field stars (Fig. 3). Thus the origin of the age gap and in particular the trigger for the most recent episode of globular cluster formation in the LMC may well be related to the commencement of strong tidal interactions among the LMC, the SMC, and the Galaxy.

The tidal interaction among the three may also play an important role in changing the structural and kinematical properties of the LMC. Because of the strong tidal perturbation, the initial thin nonbarred disk is dynamically heated to form a thick barred disk with an outer stellar warp. Furthermore, $\sim 17\%$ of the stars in the disk are spatially redistributed to form an outer

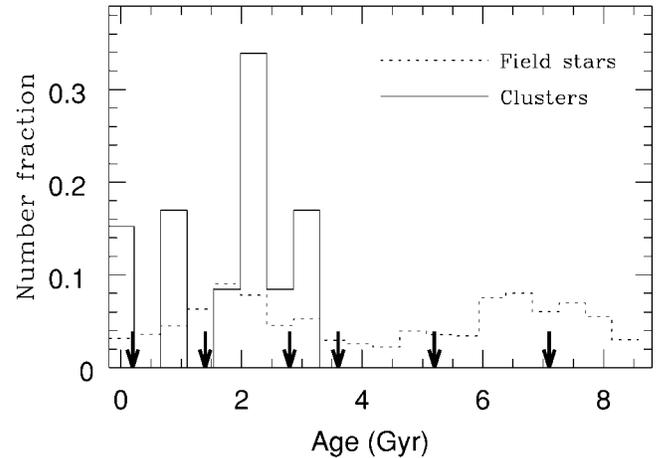


FIG. 3.—Final age distribution of newly formed field stars and star clusters. New field stars and clusters are represented by dotted and solid lines, respectively. The six epochs of the LMC-SMC pericenter passage are indicated by thick arrows for comparison. All clusters have ages younger than ~ 3.3 Gyr, whereas the field star population show a wide distribution of ages. This result reflects the fact that the field star formation is sensitive to local gas density, whereas the cluster formation can happen only when random motion of gas in the LMC becomes significantly large.

stellar halo with a velocity dispersion of $\sim 40 \text{ km s}^{-1}$ at a distance of 7.5 kpc from the LMC center. The kinematically hot stellar halo is dominated by old stars with the fraction of new field stars equal to only 2%, because most halo stars originate from the outer part of the initial thin disk. In contrast, $\sim 56\%$ of the stars within the central disk are new field stars formed from the triggered star formation. For example, our simulations indicate that the half-mass radius is ~ 2.1 kpc for the old field populations and ~ 0.9 kpc for the new populations (i.e., the different structure of the different aged populations). The stellar kinematics along the major axis shows the central velocity dispersion, σ_0 , to be $\sim 30 \text{ km s}^{-1}$ with V_m/σ_0 of ~ 2.3 . These results are broadly consistent with observations by van der Marel et al. (2002). These also suggest that the LMC stellar halo has a significantly larger fraction of young, relatively metal-rich ($[\text{Fe}/\text{H}] < -0.3$) stellar populations compared with the Galactic stellar halo dominated by very old, metal-poor ($[\text{Fe}/\text{H}] \sim -1.6$) stars.

The origin of the field stars formed in recent star formation activity in the LMC disk is one of the most important problems associated with the formation of the LMC (e.g., Butcher 1977; Olszewski et al. 1996; Gallagher et al. 1996). Our evolutionary model strongly suggests that such recent star formation is due to the repetitive tidal interaction between the LMC/SMC and the Galaxy. Field star formation is more sensitive to tidal perturbation than cluster formation, so that enhancement in field star formation can occur from the early evolutionary stage of the LMC (i.e., 6–7 Gyr ago). This can clearly explain why the “age gap” can be more clearly observed in cluster populations than in field ones. Chemical enrichment associated with the tidally triggered star formation provides a natural explanation for the observed rapid increase of metallicity both in clusters and in field stars (Da Costa 1991; Dopita et al. 1997).

What then are the fossil records of any past dynamical interaction? The tidal radius of the LMC, within which its stars are gravitationally bound, is linearly proportional to the pericenter of the orbit for the fixed masses of the LMC and the Galaxy (Gardiner & Noguchi 1996). Therefore, as the pericenter of the LMC orbit decreases as a result of dynamical

friction, it loses an increasingly larger number of stars. Figure 4 shows that the stripped stars in the simulation form a great circle—a relic stream in which the stars are diffusely and inhomogeneously distributed along the LMC’s orbit in the Galactic halo region. Such a stream has been predicted in previous studies (Weinberg 2000), but for the first time our simulations provide quite clear predictions on the spatial distribution and radial velocities of stars within the stream. Ongoing and future surveys for stellar substructure in the Galactic halo (Majewski et al. 2000) will allow these predictions to be tested. Indeed, preliminary observational results have already suggested that the coherent radial velocity structures among giant stars in fields encircling the Clouds are due to tidal debris that originated from the LMC (Majewski et al. 2000).

4. DISCUSSION AND CONCLUSION

How then can the model explain the observed different age distributions of clusters between the LMC and the SMC (Piatti et al. 2002)? We propose that such a difference can be understood in terms of the differences in the birthplaces and initial masses between the two. The LMC was formed as a relatively low surface brightness galaxy, being more distant (~ 150 kpc, corresponding to the apocenter of its early orbit) from the Galaxy so that the Galactic tidal field alone could not trigger cluster formation efficiently until it first encounters the SMC. In contrast, the less massive SMC, which is therefore more susceptible to the Galactic tide, was born less distant (~ 100 kpc) from the Galaxy and thus influenced by the Galaxy strongly enough to form globular clusters from the early evolutionary stage (several to 10 Gyr ago). Thus the difference in cluster formation histories could reflect the fact that the LMC/SMC were formed as different entities rather than as a binary protogalaxy.

Tidal interaction between the Clouds and the Galaxy has long been considered to be a physical mechanism responsible for the formation of the Magellanic Stream and the evolution of the SMC (Murai & Fujimoto 1980; Lin & Lynden-Bell 1982). We have demonstrated that such interaction can also cause dramatic changes not only in the formation history of field stars and globular clusters but also in the LMC’s structure and kinematics. Our model predicts that if globular cluster formation is associated with a dramatic increase in the random

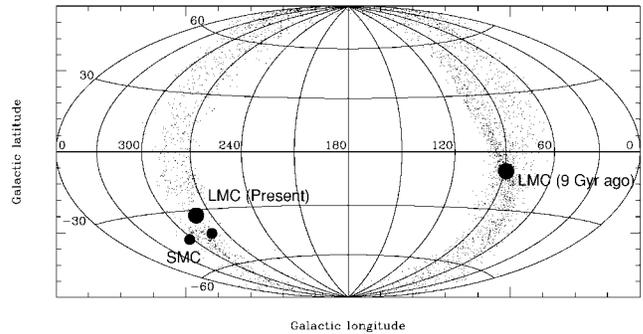


FIG. 4.—Distribution of old stars stripped from the LMC disk in an Aitoff projection. Only stars stripped from the LMC (corresponding to 17% of the initial LMC old stars) for the last ~ 9 Gyr are plotted. The locations of the LMC (larger filled circles) and the SMC (smaller filled circles) at the present (blue) and 9 Gyr ago (red) are shown for comparison. An appreciable crowding of stars can be seen around $60^\circ \leq l \leq 120^\circ$ and $-30^\circ \leq b \leq 30^\circ$ in the relic stellar stream. The distances of stars from the Galactic center range from 25 to 250 kpc with a mean of 91 kpc. The Galactocentric radial velocities range from -213 to 223 km s $^{-1}$ with a mean of -4 km s $^{-1}$. [See the electronic edition of the Journal for a color version of this figure.]

motions in the LMC’s interstellar medium, then the age, metallicity, and spatial distributions of these systems will be very much dependent on the orbital evolution of the Clouds. This can be inferred observationally from radial velocity and proper-motion measurements of their stars. Future proper-motion measurements with ~ 10 mas accuracy (Perryman et al. 2001), coupled with numerical simulations for different yet reasonable orbits of the Clouds, will therefore enable us to obtain an integrated and systematic understanding of the formation of the LMC clusters.

We are grateful to the anonymous referee for valuable comments that improved the present Letter. K. B., W. J. C., and G. S. D. acknowledge financial support from the Australian Research Council throughout the course of this work. The numerical simulations reported here were carried out on GRAPE systems kindly made available by the Astronomical Data Analysis Center at the National Astronomical Observatory of Japan.

REFERENCES

- Alves, D. R., & Nelson, C. A. 2000, *ApJ*, 542, 789
 Ashman, K. M., & Zepf, S. E. 1992, *ApJ*, 384, 50
 Bekki, K., Beasley, M. A., Forbes, D. A., & Couch, W. J. 2004, *ApJ*, 602, 730
 Bekki, K., & Couch, W. J. 2001, *ApJ*, 557, L19
 Bekki, K., Forbes, D. A., Beasley, M. A., & Couch, W. J. 2002, *MNRAS*, 335, 1176
 Butcher, H. 1977, *ApJ*, 216, 372
 Da Costa, G. S. 1991, in *IAU Symp. 148, The Magellanic Clouds*, ed. R. Haynes & D. Milne (Dordrecht: Kluwer), 183
 Dopita, M. A., et al. 1997, *ApJ*, 474, 188
 Elmegreen, B. G., & Efremov, Y. N. 1997, *ApJ*, 480, 235
 Gallagher, J. S., et al. 1996, *ApJ*, 466, 732
 Gardiner, L. T., & Noguchi, M. 1996, *MNRAS*, 278, 191
 Gardiner, L. T., Sawa, T., & Fujimoto, M. 1994, *MNRAS*, 266, 567
 Geisler, D., Bica, E., Dottori, H., Claria, J. J., Piatti, A. E., & Santos, J. F. C., Jr. 1997, *AJ*, 114, 1920
 Harris, W. E., & Pudritz, R. E. 1994, *ApJ*, 429, 177
 Hausman, M. A., & Roberts, W. W., Jr. 1984, *ApJ*, 282, 106
 Kennicutt, R. C., Jr. 1998, *ARA&A*, 36, 189
 Kinman, T. D., Stryker, L. L., Hesser, J. E., Graham, J. A., Walker, A. R., Hazen, M. L., & Nemecek, J. M. 1991, *PASP*, 103, 1279
 Kroupa, P., & Bastian, U. 1997, *NewA*, 2, 77
 Kumai, Y., Basu, B., & Fujimoto, M. 1993, *ApJ*, 404, 144
 Larson, R. B. 1981, *MNRAS*, 194, 809
 Lin, D. N. C., & Lynden-Bell, D. 1982, *MNRAS*, 198, 707
 Majewski, S. R., Ostheimer, J. C., Patterson, R. J., Kunkel, W. E., Johnston, K. V., & Geisler, D. 2000, *AJ*, 119, 760
 Murai, T., & Fujimoto, M. 1980, *PASJ*, 32, 581
 Noguchi, M., & Ishibashi, S. 1986, *MNRAS*, 219, 305
 Olszewski, E. W., Suntzeff, N. B., & Mateo, M. 1996, *ARA&A*, 34, 511
 Perryman, M. A. C., et al. 2001, *A&A*, 369, 339
 Piatti, A., Sarajedini, A., Geisler, D., Bica, E., & Claria, J. J. 2002, *MNRAS*, 329, 556
 Rich, R. M., Shara, M. M., & Zurek, D. 2001, *AJ*, 122, 842
 Schommer, R. A., Suntzeff, N. B., Olszewski, E. W., & Harris, H. C. 1992, *AJ*, 103, 447
 van den Bergh, S. 2000, *The Galaxies of the Local Group* (Cambridge: Cambridge Univ. Press)
 van der Marel, R. P., Alves, D. R., Hardy, E., & Suntzeff, N. B. 2002, *AJ*, 124, 2639
 Weinberg, M. D. 2000, *ApJ*, 532, 922
 Westerland, B. E. 1997, *The Magellanic Clouds* (Cambridge: Cambridge Univ. Press)
 Zhang, Q., Fall, S. M., & Whitmore, B. C. 2001, *ApJ*, 561, 727