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LUMINOSITY PROFILES OF MERGER REMNANTS

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ABSTRACT

Using published luminosity and molecular gas profiles of the late-stage mergers NGC 3921, NGC 7252, and Arp 220, we examine the expected luminosity profiles of the evolved merger remnants, especially in light of the massive CO complexes that are observed in their nuclei. For NGC 3921 and NGC 7252, we predict that the resulting luminosity profiles will be characterized by an $r^{1/4}$ law. In view of previous optical work on these systems, it seems likely that they will evolve into normal elliptical galaxies as regards their optical properties. Due to a much higher central molecular gas column density, Arp 220 might not evolve such a "seamless" light profile. We conclude that ultraluminous infrared mergers such as Arp 220 either evolve into elliptical galaxies with anomalous luminosity profiles or do not produce many low-mass stars out of their molecular gas complexes.

Subject headings: galaxies: evolution — galaxies: individual (Arp 220, NGC 3921, NGC 7252) — galaxies: interactions — infrared: galaxies — ISM: molecules

1. INTRODUCTION

The merger hypothesis for elliptical galaxy formation, as put forth by Toomre & Toomre (1972; see also Toomre 1977), posits that two spiral galaxies can fall together under their mutual gravitational attraction, eventually evolving into an elliptical-like remnant. An early objection to this hypothesis was that the cores of elliptical galaxies are too dense to result from the dissipationless merging of two spiral galaxies (Carlberg 1986; Gunn 1987; Hernquist, Spergel, & Heyl 1993). An obvious solution to this objection is to include a dissipative (gaseous) component in the progenitors (for other solutions, see, e.g., Veeraraghavan & White 1985; Barnes 1988; Lake 1989). Numerical experiments including such a component readily showed that gaseous dissipation can efficiently drive large amounts of material into the central regions (Negroponte & White 1983; Noguchi & Ishibashi 1986; Barnes & Hernquist 1991). Indeed, it was considered a great success for early hydrodynamical work to be able to reproduce dense knots of gas within the central regions of simulated merger remnants, similar to the gas concentrations observed in IR luminous mergers (Barnes & Hernquist 1991; Sanders et al. 1988). Since the inferred central gas mass densities in the observed gas knots are comparable to the stellar mass densities seen in the cores of normal elliptical galaxies ($\sim 10^2\ M_\odot\ \mathrm{pc}^{-3}$), it seems natural that they could be the seed of a high surface brightness remnant (Kormendy & Sanders 1992).

Subsequent numerical work by Mihos & Hernquist (1994, hereafter MH94) finds that the dissipative response of the simulated gas component is so efficient that the resulting mass profiles of the simulated remnants are unlike those seen in normal elliptical galaxies. In particular, ensuing star formation leaves behind a dense stellar core whose surface density profile does not join smoothly onto the de Vaucoleurs $r^{1/4}$ profile of the preexisting stellar population. Instead, the profiles exhibit a "spike" at small radii, with a suggested increase in surface brightness by factors of ~100. While the predicted break in the mass density profile occurs at spatial scales comparable to the gravitational softening length of the simulations, making the precise slope somewhat questionable, the conclusion that the profiles should exhibit a clear break was considered firm (MH94). This prediction, if confirmed, offers a means to constrain the frequency of highly dissipative mergers in the past by searching for their fossil remnants in the cores of nearby elliptical galaxies. However, the numerical formalisms used in MH94 to model gaseous dissipation, star formation, and energy injection back into the ISM from massive stars and supernovae ("feedback") are necessarily ad hoc in nature. As such, these predictions should be viewed as preliminary (as Mihos & Hernquist themselves note).

We investigate this question observationally by converting the observed gas column densities of ongoing or late-stage mergers into optical surface brightness by assuming a stellar mass-to-light ratio appropriate for an evolved population. This light is added to the observed luminosity profile after allowing it to age passively. The resulting luminosity profile is examined for anomalous features such as the sharp break predicted by MH94.

We conduct this experiment with the late-stage mergers NGC 3921 and NGC 7252 and with the ultraluminous infrared (ULIR) merger Arp 220. These systems were chosen because they have been observed in the CO (1–0) molecular line transition with resolutions (FWHM) of 2″–2.″5 (Yun & Hibbard 1999a; Wang, Schweizer, & Scoville 1992; Scoville, Yun, & Bryant 1997). The resulting spatial radial resolution (300–400 pc; $H_0 = 75\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$) is similar to the hydrodynamical smoothing length used in MH94 (~350 pc),[2] indicating that the molecular line observations have sufficient resolution to resolve the types of mass concentrations found in the simulations. The molecular gas surface densities of each of these systems are plotted in Figure 1, converted from CO fluxes by adopting a conversion factor of $N_{\mathrm{H_2}}/I_{\mathrm{CO}} = 3 \times 10^{20}\ \mathrm{cm^{-2}}\ (\mathrm{K\ km\ s^{-1}})^{-1}$ (Young & Scoville 1991). Detailed studies on each of these

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[2] Assuming scaling parameters appropriate for a Milky Way–like progenitor.

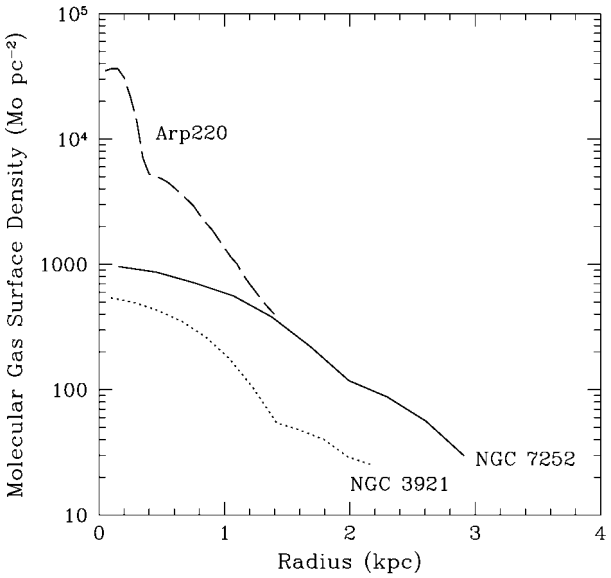

FIG. 1.—Radial surface molecular gas mass density profiles (in $M_\odot$ pc^{-2}) derived from the integrated CO flux maps plotted as a function of radius. The CO fluxes have been turned into mass densities by adopting a conversion factor of $N_{H_2}/I_{CO} = 3 \times 10^{20}$ cm $^{-2}$ (K km s^{-1})$^{-1}$. The data are from Yun & Hibbard (1999a) for NGC 3921 (*dotted line*), from Wang et al. (1992) for NGC 7252 (*solid line*), and from Scoville et al. (1997) for Arp 220 (*dashed line*).

systems, which fully discuss their status as late stage mergers, can be found in Schweizer (1996) and Hibbard & van Gorkom (1996) for NGC 3921, Schweizer (1982) and Hibbard et al. (1994) for NGC 7252, and Scoville et al. (1997) for Arp 220.

2. RESULTS

2.1. *NGC 3921 and NGC 7252*

For these moderately evolved merger remnants (ages of ~0.5–1 Gyr since their tidal tails were launched; Hibbard et al. 1994; Hibbard & van Gorkom 1996), the observed gas and luminosity profiles are used to predict the expected luminosity profile of a 2 Gyr old remnant. We assume that all of the molecular gas is turned into stars at the same radii, adopting an exponentially declining star formation history. The present luminosity profile is allowed to fade due to passive aging effects, and the final luminosity profile is the sum of these two populations. The molecular gas profiles plotted in Figure 1 are converted into gas mass densities by multiplying by a factor of 1.36 to take into consideration the expected contribution of helium. Optical luminosity profiles have been obtained by Schweizer (1982, 1996), Whitmore et al. (1993), and Hibbard et al. (1994), showing them to be well fitted by an $r^{1/4}$ profile over all radii, with no apparent luminosity spikes.

The gas surface density (Σ_{gas} in $M_\odot$ pc^{-2}) is converted to optical surface brightness (μ_B) by dividing by the stellar mass-to-light ratio (M_*/L_B) expected for a 2 Gyr old population. We adopt the stellar mass-to-light ratios given by de Jong (1995, Table 1 of chap. 4), which were derived from the population synthesis models of Bruzual & Charlot (1993) for an exponentially declining star formation history, a Salpeter initial mass function (IMF), and solar metallicity ($M_*/L_B = 0.82\ M_\odot\ L_\odot^{-1}$ at 2 Gyr). Noting that 1 $L_\odot$ pc^{-2} corresponds to $\mu_B = 27.06$ mag arcsec^{-2} (adopting $M_{B,\odot} = 5.48$), the conversion from gas surface density to optical surface brightness is given by $\mu_B(r) = 27.06$ mag arcsec^{-2} $- 2.5 \log [\Sigma_{gas}(r)/(M_*/L_B)]$.

The luminosity profiles of the evolved remnants are estimated from the observed *B*-band profiles (Schweizer 1996; Hibbard et al. 1994), allowing for a fading of 1 mag arcsec^{-2} in the *B*-band over the next 2 Gyr (Bruzual & Charlot 1993; Schweizer 1996) and adding in the expected contribution of the population formed from the molecular gas, calculated as above. We emphasize that this should favor the production of a luminous postmerger population, since it assumes that none of the molecular gas is lost to stellar winds or supernovae and the adopted IMF favors the production of many long-lived low-mass stars.

The results of this exercise are plotted in Figure 2. This plot shows that the observed gas densities in NGC 3921 and NGC 7252, although high, are not high enough to significantly affect the present luminosity profiles. The profile of NGC 3921 is basically indistinguishable from an $r^{1/4}$ profile. The profile of NGC 7252 does show a slight rise at small radii, but not the clear break predicted by MH94. Therefore, the resulting luminosity profiles of these remnants are now and should remain fairly typical of normal elliptical galaxies, and the conclusions of MH94 are not applicable to *all* mergers of gas-rich galaxies. Since both of these systems also obey the Faber-Jackson relationship (Lake & Dressler 1986) and NGC 7252 falls upon the fundamental plane defined by normal elliptical galaxies (Hibbard et al. 1994; Hibbard 1995), we conclude that at least some mergers of gas-rich systems can evolve into normal elliptical galaxies as far as their optical properties are concerned.

2.2. *Arp 220*

Since Arp 220 is an extremely dusty object, its optical luminosity profile is poorly suited for a similar analysis. Instead, we use a luminosity profile measured in the near-infrared, where the dust obscuration is an order of magnitude less severe. Arp 220 was recently observed with camera 2 of NICMOS aboard the *Hubble Space Telescope* (Scoville et al. 1998), and we use the resulting *K*-band luminosity profile kindly made available by N. Scoville. Since Arp 220 is presently undergoing a massive starburst, the fading factor is much less certain than for the already evolved systems treated above and depends sensitively on what fraction of the current light is contributed by recently formed stars. We adopt a situation biased toward the production of a discrepant luminosity profile by assuming that the entire population was preexisting, converting the observed *K*-band profile to an evolved *B*-band profile by adopting a $B-K$ color of 4, appropriate for a 10 Gyr old population (de Jong 1995). The contribution due to the population formed from the molecular disk is calculated exactly as before. The resulting profile is shown in Figure 2.

This figure shows that Arp 220 is predicted to evolve a luminosity profile with a noticeable rise at small radii. This is due to the peak in the molecular gas surface density at radii less than 0.5 kpc (Fig. 1). We conclude that Arp 220 has the potential to evolve a similar feature in its luminosity profile *if* indeed all of the current molecular gas is converted into stars. However, the expected rise of ~2 mag arcsec^{-2} in surface brightness (a factor of ~6) is considerably lower than the 2 orders of magnitude increase predicted by the simulations (see Fig. 1 of MH94).

3. DISCUSSION

From the above exercise, we conclude that neither NGC 3921 nor NGC 7252 are expected to show a significant deviation in their luminosity profiles and that the maximum rise expected

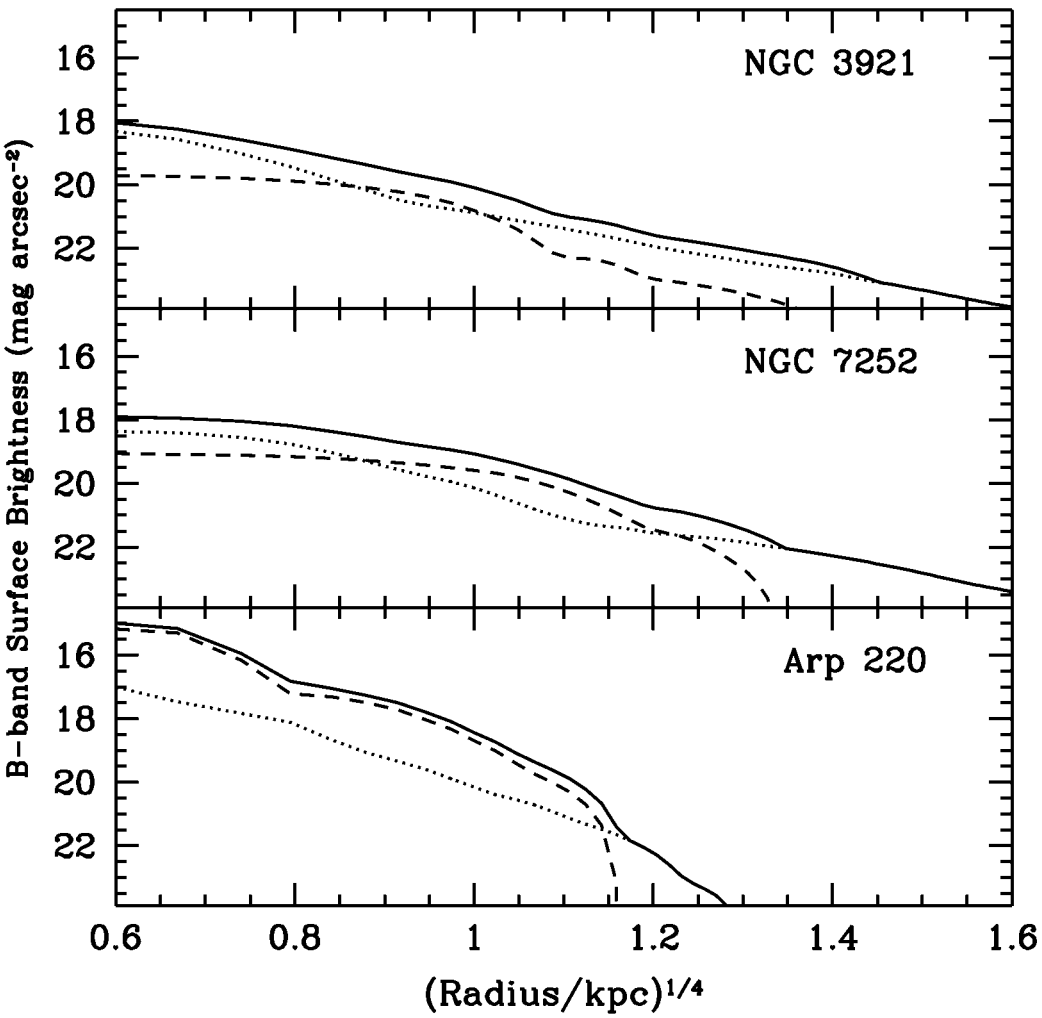

FIG. 2.—Predicted luminosity profiles as a function of the fourth root of the radius for the aged remnants of NGC 3921, NGC 7252, and Arp 220. *Dotted lines:* Expected contribution to the *B*-band profile by the present stellar component, after aging by 2 Gyr. For NGC 3921 and NGC 7252 this is calculated from the presently observed *B*-band luminosity profiles (taken from the data in Schweizer 1996 and Hibbard et al. 1994) and fading by 1 mag arcsec^{-2}. For Arp 220 we use the observed *K*-band luminosity profile (from Scoville et al. 1998) adopting $B-K = 4$ for a 10 Gyr old population. *Dashed lines:* Expected contribution to the *B*-band profile from the expected postmerger population if all the molecular gas is turned into stars. *Solid lines:* Expected *B*-band luminosity profiles after adding in the aged stellar and postmerger populations. No significant deviation from a pure $r^{1/4}$ law is expected for NGC 3921 or NGC 7252. Arp 220 does not show such a seamless profile, exhibiting a slight rise at small radii.

for Arp 220 is considerably lower than the 2 orders of magnitude increase predicted by the simulations of MH94. We conclude that the numerical formalisms adopted in the simulations to treat the gas and star formation are incomplete. Mihos & Hernquist enumerate various possible shortcomings of their code. For example, their star formation criterion is extrapolated from studies of quiescent disk galaxies and may not apply to violent starbursts. Perhaps most importantly, their simulations fail to reproduce the gas outflows seen in ULIR galaxies ("superwinds," e.g., Heckman, Armus, & Miley 1990; Heckman, Lehnert, & Armus 1993), suggesting that the numerical treatment of feedback is inadequate.

In spite of these results, it is still interesting that under some conditions there might be an observational signature of a past merging event in the light profile of the remnant. The question is, For which mergers might this be the case? Since Σ_{H_2} is tightly correlated with IR luminosity (Yun & Hibbard 1999b), we infer that only the ULIR galaxies retain the possibility to evolve into elliptical galaxies with a central rise in their luminosity profiles. While such profiles are not typical of elliptical galaxies in general, they are not unheard of. For example, ~10% of the Nuker sample profiles presented by Byun et al. (1996) show such anomalous cores (e.g., NGC 1331, NGC 4239). It is therefore possible that such systems evolve from ULIR galaxies. This can be tested by careful "galactic archaeology" in such systems to search for signatures of a past merger event (e.g., Schweizer & Seitzer 1992; Malin & Hadley 1997).

However, it is not a foregone conclusion that systems like Arp 220 will evolve anomalous profiles. This system presently hosts a very powerful expanding superwind (Heckman et al. 1996), which may be able to eject a significant fraction of the cold gas in a "mass-loaded flow" (e.g., Heckman et al. 1999). Such winds are common in ULIR galaxies (Heckman et al. 1990; Heckman et al. 1993). Another related possibility is that the IMF may be biased toward massive stars (i.e., "top heavy"; Young et al. 1986; Scoville & Soifer 1991). Such mass functions will leave far fewer stellar remnants than the IMF adopted here. A third possibility is that the standard Galactic CO-to-H_2 conversion factor is inappropriate for ULIR galaxies and that the high gas surface densities derived from CO observations (and thus the resulting stellar luminosity profile) may be

overestimated (see Downes, Solomon, & Radford 1993; Bryant & Scoville 1996).

Some support for the idea that central gas cores may be depleted by the starburst is given by a population synthesis model of NGC 7252, which suggests that it experienced an IR luminous phase (Fritze–von Alvensleben & Gerhard 1994a, 1994b). While the current radial distribution of molecular gas in NGC 7252 is flat and lacks the central core seen in Arp 220, it appears to connect smoothly with that of Arp 220 in Figure 1. Therefore, one may speculate that NGC 7252 did indeed have a radial gas density profile much like Arp 220 but has since lost the high-density gas core as a result of prodigious massive star formation and/or superwind blowout. However, the burst parameters are not strongly constrained by the available observations, and a weaker burst spread over a longer period may also be allowed (Fritze–von Alvensleben & Gerhard 1994a, 1994b). Further insight into this question could be obtained by constraining the past star formation history in other evolved merger remnants.

In conclusion, a comparison of the peak molecular column densities and optical surface brightnesses in NGC 3921 and NGC 7252 suggests that some mergers between gas-rich disks *will* evolve into elliptical-like remnants with typical luminosity profiles, even considering their present central gas supply. For ULIR galaxies like Arp 220 the case is less clear. Such systems will either produce an excess of light at small radii, as seen in a small number of elliptical galaxies, or require some process such as mass-loaded galactic winds or a top-heavy IMF to deplete the central gas supply without leaving too many evolved stars. If the latter possibility can be excluded, then the frequency of such profiles may be used to constrain the number of early-type systems formed via ULIR mergers.[3]

[3] We note that any subsequent *dissipationless* merging of these cores with other stellar system will tend to smooth out these profiles.

4. SUMMARY

1. Even under assumptions that favor the production of a luminous postmerger population, the dense molecular gas complexes found in the centers of NGC 3291 and NGC 7252 should not significantly alter their luminosity profiles, which are already typical of elliptical galaxies (Schweizer 1982, 1996). Since these systems also obey the Faber-Jackson relationship (Lake & Dressler 1986) and NGC 7252 falls upon the fundamental plane defined by normal elliptical galaxies (Hibbard et al. 1994; Hibbard 1995), it appears that at least some mergers of gas-rich systems can evolve into normal elliptical galaxies as far as their optical properties are concerned.

2. The dense molecular gas complex found in the center of Arp 220 may result in a moderate rise in the remnants' luminosity profile at small radii. Since the molecular gas column density is a tight function of IR luminosity (Yun & Hibbard 1999b), we conclude that this condition may apply to all of the ultraluminous infrared galaxies. However, this does not preclude a merger origin for elliptical galaxies, since (*a*) about 10% of the Nuker sample of elliptical galaxies (Byun et al. 1996) show such rises in their radial light profiles and (*b*) it is possible that much of the gas in such systems is blown into intergalactic space by mass-loaded superwinds (Heckman et al. 1999; Heckman et al. 1993).

3. The maximum expected rise in the luminosity profiles is considerably lower than the orders of magnitude increase predicted by the simulations (MH94). We therefore suggest that the numerical formalisms adopted in the simulations to treat the gas and star formation are incomplete.

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REFERENCES

Barnes, J. E. 1988, ApJ, 331, 699
Barnes, J. E., & Hernquist, L. 1991, ApJ, 370, L65
Bruzual A., G., & Charlot, S. 1993, ApJ, 405, 538
Bryant, P. M., & Scoville, N. Z. 1996, ApJ, 457, 678
Byun, Y.-L., et al. 1996, AJ, 111, 1889
Carlberg, R. G. 1986, ApJ, 310, 593
de Jong, R. S. 1995, Ph.D. thesis, Univ. Groningen
Downes, D., Solomon, P. M., & Radford, S. J. E. 1993, ApJ, 414, 13
Fritze–von Alvensleben, U., & Gerhard, O. E. 1994a, A&A, 285, 751
———. 1994b, A&A, 285, 775
Gunn, J. E. 1987, in Nearly Normal Galaxies: From the Planck Time to the Present, ed. S. M. Faber (New York: Springer), 455
Heckman, T. M., Armus, L., & Miley, G. K. 1990, ApJS, 74, 833
Heckman, T. M., Armus, L., Weaver, K., & Wang, J. 1999, ApJ, 517, 130
Heckman, T. M., Dahlem, M., Eales, S. A., Fabbiano, G., & Weaver, K. 1996, ApJ, 457, 616
Heckman, T. M., Lehnert, M., & Armus, L. 1993, in The Evolution of Galaxies and their Environment, ed. H. A. Thronson & J. M. Shull (Dordrecht: Kluwer), 455
Hernquist, L., Spergel, D. N., & Heyl, J. S. 1993, ApJ, 416, 415
Hibbard, J. E. 1995, Ph.D. thesis, Columbia Univ.
Hibbard, J. E., Guhathakurta, P., van Gorkom, J. H., & Schweizer, F. 1994, AJ, 107, 67
Hibbard, J. E., & van Gorkom, J. H. 1996, AJ, 111, 655
Kormendy, J., & Sanders, D. B. 1992, ApJ, 390, L53
Lake, G. 1989, AJ, 97, 1312
Lake, G., & Dressler, A. 1986, ApJ, 310, 605
Malin, D. F., & Hadley, B. 1997, Publ. Astron. Soc. Australia, 14, 52
Mihos, J. C., & Hernquist, L. 1994, ApJ, 437, L47 (MH94)
Negroponte, J., & White, S. D. M. 1983, MNRAS, 205, 1009
Noguchi, M., & Ishibashi, S. 1986, MNRAS, 219, 305
Sanders, D. B., Scoville, N. Z., Sargent, A. I., & Soifer, B. T. 1988, ApJ, 324, L55
Schweizer, F. 1982, ApJ, 252, 455
———. 1996, AJ, 111, 109
Schweizer, F., & Seitzer, P. 1992, AJ, 104, 3
Scoville, N. Z., et al. 1998, ApJ, 492, L107
Scoville, N. Z., & Soifer, B. T. 1991, in Massive Stars in Starbursts, ed. C. Leitherer, N. R. Walborn, T. M. Heckman, & C. A. Norman (New York: Cambridge Univ. Press), 233
Scoville, N. Z., Yun, M. S., & Bryant, P. M. 1997, ApJ, 484, 702
Toomre, A. 1977, in The Evolution of Galaxies and Stellar Populations, ed. B. M. Tinsley & R. B. Larson (New Haven: Yale Univ. Press), 401
Toomre, A., & Toomre, J. 1972, ApJ, 178, 623
Veeraraghavan, S., & White, S. D. M. 1985, ApJ, 296, 336
Wang, Z., Schweizer, F., & Scoville, N. Z. 1992, ApJ, 396, 510
Whitmore, B. C., Schweizer, F., Leitherer, C., Borne, K., & Robert, C. 1993, AJ, 106, 1354
Young, J. S., Schloerb, F. P., Kenney, J. D., & Lord, S. D. 1986, ApJ, 304, 443
Young, J. S., & Scoville, N. Z. 1991, ARA&A, 29, 581
Yun, M. S., & Hibbard, J. E. 1999a, ApJ, submitted
———. 1999b, ApJ, submitted