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FAINT FUZZIES AND THE FORMATION OF LENTICULAR GALAXIES

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ABSTRACT

We investigate the dynamical state of a new class of extended star clusters known as "faint fuzzies," which were discovered in two nearby S0 galaxies, NGC 1023 and NGC 3384. It is shown that the faint fuzzies of NGC 1023 lie in a fast-rotating ringlike structure within the galactic disk with mean radius of 5 kpc, rotational velocity of 200 km s^{-1}, and velocity dispersion of 115 km s^{-1}. We propose a scenario for the origin of faint fuzzies that is connected to the origin of S0 galaxies as a result of galaxy-galaxy interactions in dense environments. As is apparent in the Cartwheel galaxy and confirmed by numerical simulations, the passage of a small galaxy through, or close to, the center of a disk galaxy can form a ring of clumpy star formation with a radius comparable to the faint fuzzy ring radius in NGC 1023. In this case, the faint fuzzies are signposts for the transformation of spiral galaxies into lenticulars via such interactions.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: individual (NGC 1023) — galaxies: star clusters

1. INTRODUCTION

The discovery of the faint extended star clusters, now generally known as the "faint fuzzies" (FFs), has already been described in some detail in Larsen & Brodie (2000) and Brodie & Larsen (2002, 2003a, 2003b) along with detailed justifications of the assertion that these objects are unique within the cluster "family." Here we provide only a brief summary of their characteristics.

FFs were first discovered in a *Hubble Space Telescope* (*HST*) Wide Field Planetary Camera 2 (WFPC2) image of NGC 1023, a nearby (9.8 Mpc) SB0 galaxy (Larsen & Brodie 2000). They are distinct from normal compact globular and open clusters in a variety of respects. The effective half-light radius $R_{\rm eff}$ for the FFs is 7–15 pc, while a typical $R_{\rm eff}$ for globular and open clusters is $\sim$2–3 pc. In addition to its FFs, NGC 1023 has a normal population of compact globular clusters, which is subdivided into the red and blue subpopulations found in essentially all luminous galaxies (Larsen & Brodie 2002).

FFs have an annular distribution on the sky (see Fig. 1) and are not nearly as concentrated toward the center of the galaxy as are the compact sources. It was noted in Larsen & Brodie (2000) that they appeared to be associated with the *disk* of NGC 1023, based on the high degree of alignment with the galaxy isophotes. Larsen & Brodie (2000) also demonstrated that the lack of FFs in the galactic center is not due to greater difficulties of detection near the center. The annular distribution therefore seems to be real. NGC 1023 has 29 objects with half-light radii greater than 7 pc and $V < 24$ (i.e., M_V brighter than -6.2, the limit for secure size measurement). In Larsen et al. (2001), a smaller number of faint, extended objects similar to those in NGC 1023 were noted in another nearby (11.5 Mpc) lenticular, NGC 3384. An optical spectroscopic follow-up with the Low-Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) on the Keck telescope confirmed the association of the FFs with both of these host galaxies and allowed individual radial velocities and a mean value of metallicity to be measured in a subset of the NGC 1023 and NGC 3384 samples (Brodie & Larsen 2002). They found $[{\rm Fe/H}] = -0.58 \pm 0.24$ and $[{\rm Fe/H}] = -0.64 \pm 0.34$ for the FFs in NGC 1023 and NGC 3384, respectively. The sample of six FFs observed in NGC 3384 is currently too small for a further interpretation. The few available data points indicate a ringlike structure. However, the velocity distribution does not show any signature of rotation. More observations are required before any conclusion can be drawn about the kinematical and spatial structure of the system of FFs in NGC 3384. We therefore concentrate our analysis on the system of FFs in NGC 1023.

An additional seven candidate FFs were observed with Keck LRIS in 2004 November, using the same instrumental set-up as in Brodie & Larsen (2002). The total exposure time was 7 hr, split into 0.5 hr integrations with a seeing of about 1″. Of the seven objects, four were too faint to obtain usable spectra, one turned out to be a background galaxy at redshift $z = 0.313$, thus leaving only two new FF radial velocity determinations. In addition, two of the FFs observed by Brodie & Larsen (2002; NGC 1023-FF-12 and NGC 1023-FF-14) were reobserved during the 2004 November run. The new measurements for these clusters yield 539 ± 21 and 676 ± 13 km s^{-1}, while the previous measurements found 514 ± 8 and 725 ± 17 km s^{-1}. Thus, the true velocity errors may be somewhat underestimated, but no systematic differences are apparent between the old and new measurements.

Comparing measured values of [Fe/H] and Hβ to stellar evolutionary models (Maraston & Thomas 2000), Brodie & Larsen (2002) found that the most probable age for these clusters is $\sim$13 Gyr, although the error on this estimate was such that ages as low as 7–8 Gyr could not be ruled out. In any case, the FFs are clearly very old, and thus highly stable against disruption, which might indicate that they are on roughly circular orbits, as this would be likely to minimize disruptive tidal effects (disk/bulge shocking). Indeed, Figure 2, the radial velocity plot for FFs in NGC 1023, shows clear evidence for rotation of the cluster system with a kinematic signature that is similar but not identical to the rotation curve of the galaxy itself (*dashed curve*), as measured along the major axis by Simien & Prugniel (1997). The bulge effective radius for NGC 1023 is <2 kpc (Möllenhoff &

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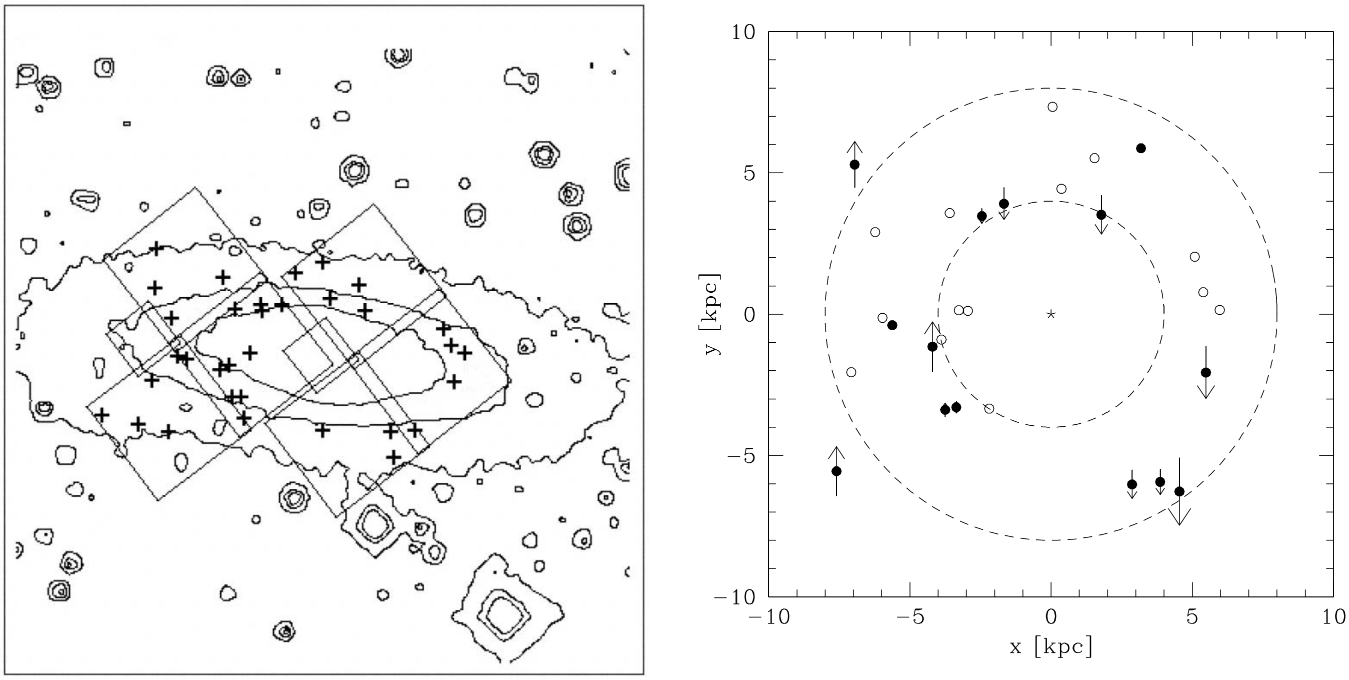

FIG. 1.—*Left*: The contours of an optical image of NGC 1023 overlaid with the two WFPC2 pointings. The distribution of FFs (*plus signs*) corresponds closely to the galaxy isophotes. *Right*: Deprojected location of the FFs for a galaxy inclination of 66°. Filled circles are FFs with measured line-of-sight velocities. Open circles are FFs identified from the *HST* images but without measured velocities. The arrows show the direction of rotation, inferred from the observed radial velocities, with the size of arrows being proportional to the measured line-of-sight velocity.

Heidt 2001), so the clusters are ~2 bulge effective radii from the galaxy center ($1' = 2.9$ kpc at the distance of NGC 1023). This strongly suggests that these objects are associated with the galaxy's disk rather than its bulge. In contrast to the FFs, there is no hint of rotation in the compact globular clusters in this galaxy.

While new *HST* Advanced Camera for Surveys (ACS) data can be expected to reveal additional examples of FFs in galaxies out to Virgo distances, it is currently unknown how common a phenomenon they represent, nor is it clear whether they are found exclusively in S0s. Of the four galaxies in the pre-ACS *HST* data archive with data quality sufficient for the detection of FFs (deep images of nearby galaxies), FFs have been detected in two (NGC 1023 and NGC 3384) and ruled out in the other two (NGC 3115, another lenticular, and NGC 3379, an elliptical). If it turns out that FFs are found exclusively in lenticular galaxies (a largely untested assumption) they might provide valuable insight into the formation of this class of galaxies. In addition, clues about the origin (and/or survival) of FFs may perhaps be found by asking what the S0 galaxies NGC 1023 and NGC 3384 have in common that differentiates them from the other lenticular NGC 3115. Interestingly, NGC 1023 is the dominant member of a well-defined group of 15 galaxies, and NGC 3384 is a member of the Leo I group. By contrast, NGC 3115 is isolated except for a dwarf companion at a projected distance of ~17.5 kpc. In addition, NGC 3115 is a highly bulge-dominated lenticular (actually transitional between E7 and S01), whereas NGC 1023 and NGC 3384 are both disk-dominated SB0s.

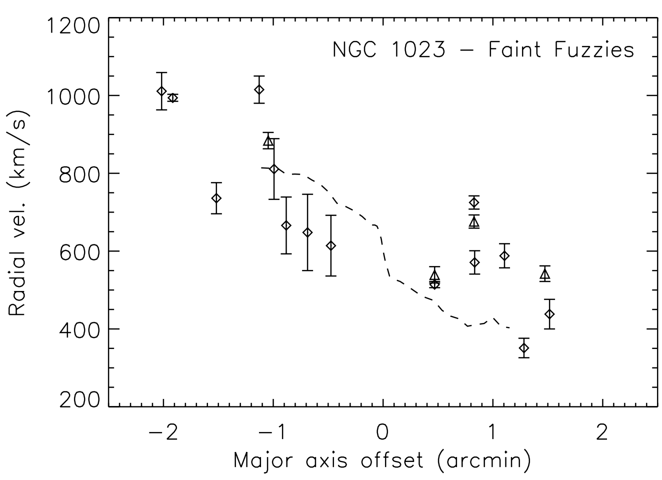

FIG. 2.—Radial velocity vs. projected distance from the galaxy center along the major axis for extended clusters in NGC 1023. The triangles show the new measurements. Note that the absolute values of the radial velocities differ from those of Brodie & Larsen (2002), who in a similar figure applied a correction of -133 km s^{-1} to all data points, based on a comparison with some spectra taken with the red side on LRIS. This correction is omitted in this figure. The dashed line indicates the rotation curve for NGC 1023 from a long-slit positioned along the major axis (Simien & Prugniel 1997).

2. KINEMATICAL ANALYSIS OF THE NGC 1023 SAMPLE

The right panels of Figures 1 and 2 show that the FFs of NGC 1023 rotate; however, their rotation curve differs significantly from that of NGC 1023. Instead of the expected extended region of constant rotation, the average radial velocity changes linearly with major axis offset. This is the characteristic signature of a rotating ring, seen in projection. In this case, the line-of-sight (here called radial) velocity v would depend on projected major axis offset x as

$$v(r) = v_c x/R + v_g, \qquad (1)$$

where v_g is the systemic velocity of the galaxy, v_c is the deprojected rotational velocity of the ring, and R is its radius. A linear fit through the data points gives $v_g = 649 \pm 141$ km s^{-1}, which, within the uncertainties, is in good agreement with the

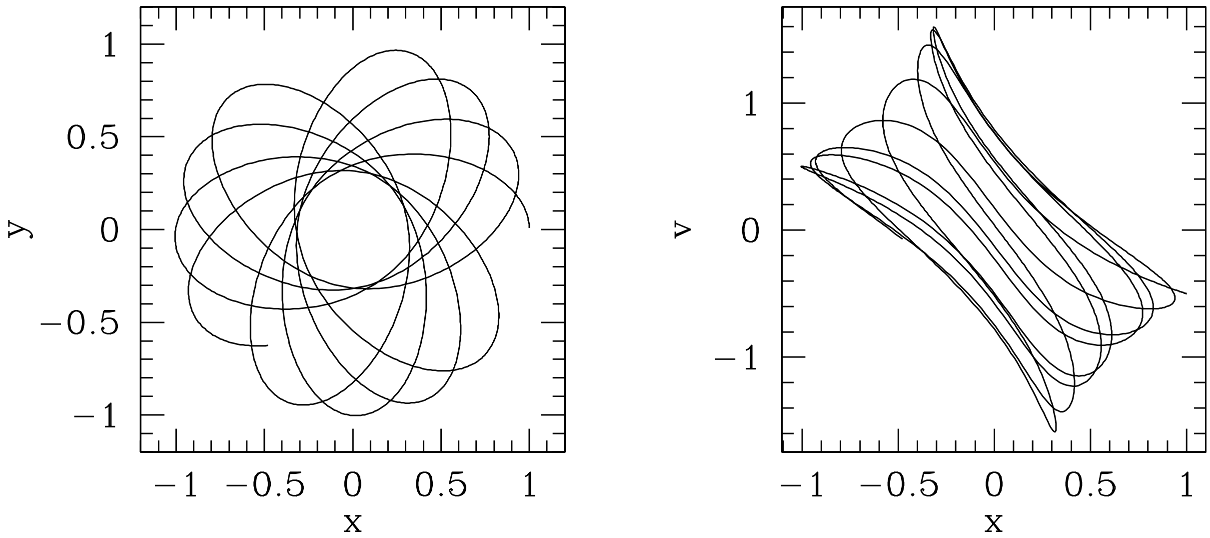

FIG. 3.—*Left*: The typical elliptical orbit of a cluster in a logarithmic galactic potential. *Right*: Its line-of-sight velocity as a function of projected galactocentric distance.

mean radial velocity of the galaxy (600 km s^{-1}) as determined by Simien & Prugniel (1997). In addition, we find $v_c = 200$ km s^{-1} and $R = 5$ kpc, which agrees nicely with the rotational velocity of the galaxy at a galactocentric distance of 5 kpc, as expected. The system of FFs also has a significant dispersion in the line-of-sight velocities of $\sigma = 115$ km s^{-1}, with some objects even appearing to counterrotate with respect to the rotational orientation of the galaxy.

This feature can be explained if the clusters move on elliptical orbits with mean radius R. As an example, Figure 3 shows in the left panel the orbit of a cluster moving in a galactic logarithmic potential $\Phi(r) = v_c^2 \ln r$, where r is the galactocentric distance. Such a potential produces a constant rotation curve $v_{\rm rot}(r) = v_c$. In the right panel the line-of-sight velocity of the cluster is plotted as a function of projected distance. Obviously, the width of the ring and the velocity dispersion are coupled. In order to reproduce the observations we investigate a simple model in which the clusters formed in a ring with radius R and width ΔR. The clusters move in a logarithmic potential with $v_c = 200$ km s^{-1} and start within the ring with initial rotational velocity equal to v_c. An isotropic Gaussian velocity dispersion σ is added to their rotational velocities. As a result of the additional velocity dispersion, the annular width of the system will increase with respect to its initial width ΔR. The final width of the ring therefore is determined by the combination of the two free parameters, ΔR and σ. If all objects formed at the same radius ($\Delta R = 0$), the width of the ring would be determined only by the velocity dispersion. In the more realistic case of $\Delta R > 0$, the width of the ring is a combination of the initial width and the velocity dispersion.

The orbits are integrated until the cluster system is phase mixed. Then its kinematical and spatial distribution is compared with the observations. The upper left panel in Figure 4 shows as a dashed line the number distribution of the observed cluster system as a function of deprojected galactocentric distance $R = (x^2 + y^2)^{1/2}$, where x and y are the deprojected disk coordinates of the clusters. The solid line shows the best-fitting model, which corresponds to a ringlike distribution with radius $R = 5.3$ kpc, width $\Delta R = 500$ pc, and velocity dispersion $\sigma = 80$ km s^{-1}. We find that the ring width ΔR mainly affects the width of the peak, whereas the shape of the wings is most sensitive to the adopted velocity dispersion. Both a negligible ring width and a negligible velocity dispersion can be ruled out. The upper right and lower left panels of Figure 4 compare the line-of-sight velocity distribution and the deprojected location of the modeled system of FFs (*open circles*) with the observations (*filled circles*). Note that the ringlike structure represents a stable solution that could in principle survive for many gigayears if the disk is not perturbed, e.g., by a gravitational interaction with a satellite or another galaxy.

3. ORIGIN OF THE RING OF CLUSTERS

The kinematical and spatial distribution of the FFs in NGC 1023 indicates that they formed in the equatorial plane in a fast-rotating ringlike configuration with a width 500 pc and velocity dispersion of ∼80 km s^{-1}. One possible solution for the origin of such a cluster ring is tidal disruption of FFs that are on orbits with perigalactic distances smaller than 3 kpc. A good approximation of the rotation curve in the inner 3 kpc of NGC 1023 is

$$v_c(r) = 200\left(\frac{r}{3\ \mathrm{kpc}}\right)\ \mathrm{km\ s^{-1}}. \tag{2}$$

Approximating the tidal radius r_t of a cluster with mass M by (Binney & Tremaine 1987)

$$r_t = r\left(\frac{M}{3\ M_g(r)}\right)^{1/3}, \tag{3}$$

where

$$M_g(r) = \frac{v_c^2 r}{G} \tag{4}$$

is the total mass of the galaxy within radius r, and G is the gravitational constant, we find that the tidal radius is independent of galactocentric distance r and given by

$$r_t = 32\left(\frac{M}{10^5\ M_\odot}\right)\ \mathrm{pc}. \tag{5}$$

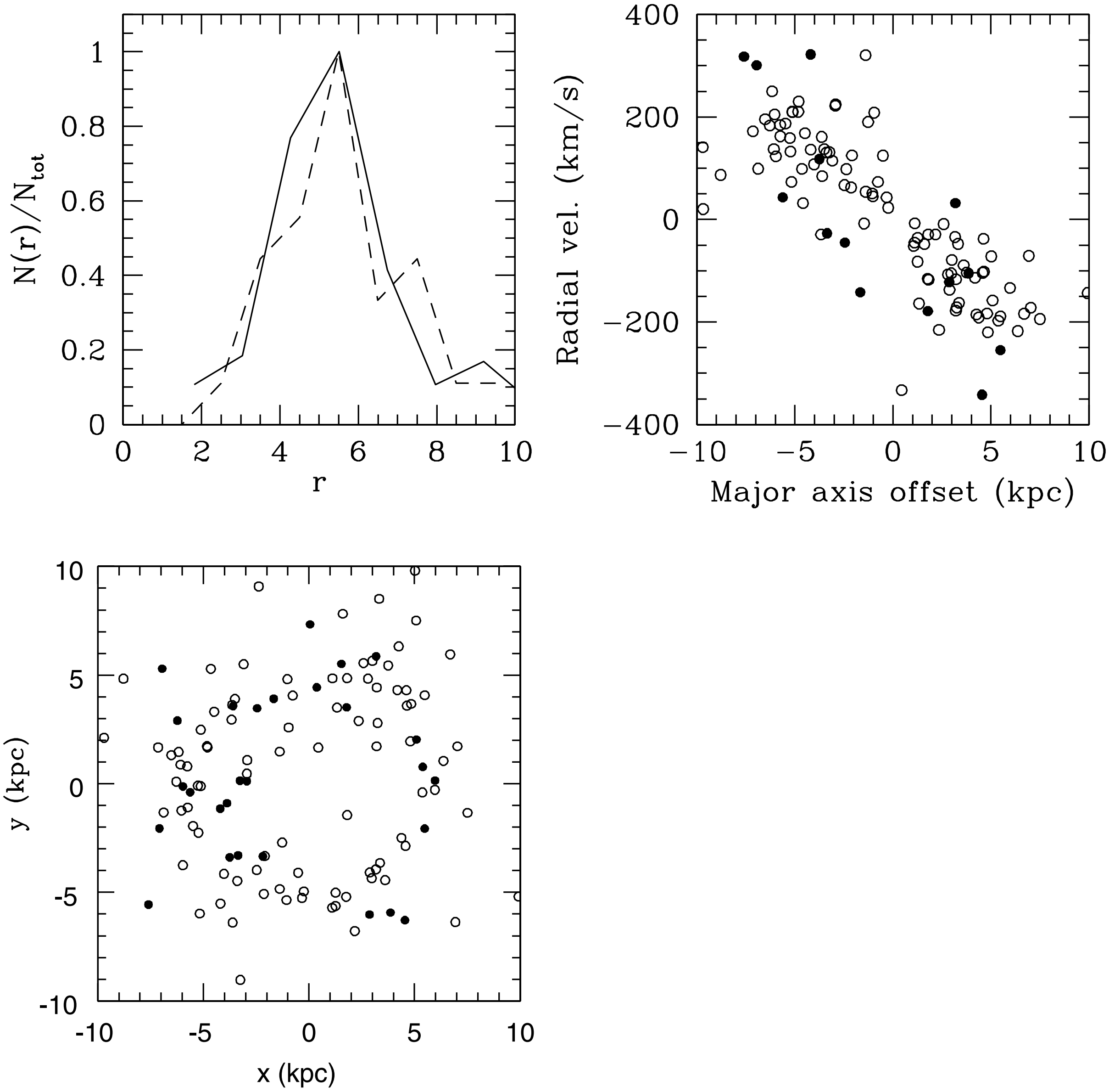

Fig. 4.—Kinematical and spatial distribution of a phase-mixed stable system of point masses forming in a ring with some initial velocity dispersion, compared with the observed FFs of NGC 1023. The upper left panel compares the observed radial distribution (*dashed curve*) with the simulation (*solid curve*). The upper right panel shows the distribution of line-of-sight velocities, with filled circles representing the observed sample, and open circles showing the simulated point masses. The lower left panel shows the stable ringlike structure that has formed in the simulation and compares the spatial distribution in the disk of the simulated objects (*open circles*) with the observed FFs (*filled circles*).

This value is large compared to the typical effective radii of the FFs (15 pc), which indicates that tidal effects probably cannot explain the central hole. More detailed numerical simulations would, however, be required to completely rule out this scenario.

The fact that the FFs orbit in a ringlike configuration around the galaxy center is difficult to explain if they arrived in ones and twos from parent dwarfs originally on random incoming orbits. They are too numerous for this to be a viable proposition, and their metallicities are too high for their origin to have been in dwarf galaxies. Nonetheless, it would be natural to suppose that more companion galaxies were present in the past in the vicinity of NGC 1023 and NGC 3384, so the presence of NGC 1023 and NGC 3384 in significant groups may be relevant to a triggering mechanism for forming the extended clusters in situ in the host galaxy. Taking this a step further, the mechanism that led to the formation of lenticulars may have induced FF formation.

There exists an intriguing similarity of the FF ring with a feature in the Cartwheel galaxy that is believed to have formed through a central collision with another galaxy. The Cartwheel galaxy displays an inner ring of clumpy star formation with a radius (∼4 kpc) similar to the FF ring radius in NGC 1023. Inspired by this observation (Arp & Madore 1987) and numerical simulations (Hernquist & Weil 1993) of the development of the star-forming rings and spokes in this galaxy, we speculate here that galaxy-galaxy interactions play a role in forming FFs. In this case, group (or galaxy cluster) membership may be a relevant criterion for selecting host galaxy candidates for FF searches. Note that central encounters are rare. Off-centered encounters could in principle also trigger the formation of lenticulars with FFs. However, the FFs would not organize themselves into a stable ringlike distribution that lasts for several gigayears.

4. DISCUSSION

Stars and stellar clusters form in giant molecular clouds (GMCs). FF masses are $\sim$10% of typical giant molecular cloud masses. Their radii are $\sim$10% of a typical GMC radius. This suggests that FFs may have formed inside a GMC. However, if every GMC produced a FF, they should be very common. So why are they not seen everywhere? The answer may be that, with only 10% of the gas turning into stars, such star clusters would remain bound only under certain (rare) conditions. Geyer & Burkert (2001; M. P. Geyer & A. Burkert 2005, in preparation) were able to create gravitationally bound, long-lived star clusters with the sizes and masses of FFs, provided that gas is compressed to densities of $n_{\rm sf} \geq 10^3$ cm^{-3} before star formation is allowed to start. In this case, the resulting distribution of stars is very clumpy with several subclusters. The subclusters are gravitationally bound and merge into a virialized cluster with a typical mass $\sim 10^5\ M_\odot$ and a typical radius of $\sim$10 pc. Fellhauer & Kroupa (2002) presented a detailed investigation of this process. They noted that in interacting galaxies like the Antennae (e.g., Whitmore et al. 1999), young stars are found in small star clusters that are part of larger groups (Harris 1998). If these groups are gravitationally bound, successive mergers of their constituent subclusters would lead to new, larger clusters, which they called superclusters. Clearly, the superclusters are larger than ordinary FFs, which might be a result of the fact that the FFs did not form in tidal arms. It is, however, possible that some central triggering mechanism, maybe a central collision with another galaxy, generated an outward-moving ringlike density enhancement, which condensed into small star clusters. This ring of cluster might later on have merged into larger objects. Numerical simulations, similar to those presented by Fellhauer & Kroupa (2002) but for expanding ringlike structures, would be required to explore this scenario in greater detail. Another interesting, unsolved problem is the difference between FFs and normal, dense globular clusters. The origin of globular clusters is still not well understood. Maybe globular cluster formation requires more violent trigger mechanisms such as supersonic cloud-cloud collisions, which convert the gas of a GMC efficiently into stars, instead of secular, dissipationless merging of small subclusters.

The evolution of the morphology-density relation with redshift has recently been explored by Smith et al. (2005), who find that the fraction of early type (E+S0) galaxies in dense environments has steadily increased from 70% at $z = 1$ to 90% at the present epoch. Evolution in groups (regions of intermediate density) occurs only from $z = 0.5$. No evolution is seen in the field. Smith et al. attribute the evolution observed in intermediate and dense environments to the transformation of spirals into lenticulars. If FFs formed in this process they therefore should be substantially younger than those found in NGC 1023. If the gas fraction in the spirals was already strongly reduced (e.g., by ram pressure stripping as a result of the galaxies' motion through the intercluster medium), no FFs would have been able to form, although a central encounter could still have converted the gas-poor spirals into S0s.

We have shown that the FFs of NGC 1023 are in a fast-rotating, stable ringlike substructure within the galactic disk, which most likely was not formed by tidal disruption of objects on highly eccentric orbits. In this case the most likely scenario is cluster formation in a dense ring of metal-enriched gas, similar to young massive cluster formation in tidal arms of interacting galaxies. More observations and numerical simulations are, however, required to investigate the various ways that FFs form and to understand their possible connection to the origin of lenticulars in more detail.

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