HUBBLE SPACE TELESCOPE DETECTION OF SPIRAL STRUCTURE IN TWO COMA CLUSTER DWARF GALAXIES

ALISTER W. GRAHAM
Department of Astronomy, University of Florida, P.O. Box 112055, Gainesville, FL 32611; Graham@astro.ufl.edu

HELMUT JERJEN
Research School of Astronomy and Astrophysics, Australian National University, Private Bag, Weston Creek Post Office, ACT 2611, Australia

AND

RAFAEL GUZMÁN
Department of Astronomy, University of Florida, P.O. Box 112055, Gainesville, FL 32611

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ABSTRACT

We report the discovery of spiral-like structure in Hubble Space Telescope images of two dwarf galaxies (GMP 3292 and GMP 3629) belonging to the Coma Cluster. GMP 3629 is the faintest such galaxy detected in a cluster environment, and it is the first such galaxy observed in the dense Coma Cluster. The large bulge and the faintness of the broad spiral-like pattern in GMP 3629 suggest that its disk may have been largely depleted. We may therefore have found an example of the “missing link” in theories of galaxy evolution that have predicted that dwarf spiral galaxies, particularly in clusters, evolve into dwarf elliptical galaxies. Key words: galaxies: dwarf — galaxies: elliptical and lenticular, cD — galaxies: formation — galaxies: individual (GMP 3292, GMP 3629) — galaxies: spiral — galaxies: structure

1. INTRODUCTION

Evidence for embedded, geometrically flat, stellar disks has been found in a steadily increasing number of objects that were once regarded as purely elliptical (E) galaxies (e.g., Capaccioli 1987, his § 5; Rix & White 1990; Vader & Vigroux 1991; Nieto et al. 1992; Cinzano & van der Marel 1994; Jørgensen & Franx 1994; Sahu, Pandey, & Kembhavi 1996). It has thus become a somewhat common trend for E galaxies to be reclassified as lenticular (S0) galaxies. This can happen when unsharp-masking of a galaxy’s image reveals features indicative of a disk, such as bars or spiral patterns, or after a closer examination of a galaxy’s surface brightness profile reveals multiple-component structure (e.g., Scorza et al. 1998). It can, and has, also occurred after the inspection of kinematic data reveals significant rotation, barlike dynamical behavior, or both (e.g., Carter 1987; Nieto, Capaccioli, & Held 1988; Capaccioli & Longo 1994; Scorza & Bender 1995; Graham et al. 1998; Rix, Carollo, & Freeman 1999).

Similarly, the existence of previously undetected disks in dwarf elliptical (dE) galaxies is now being realized. Although it has been known for nearly 20 years that some dE-like galaxies do have disklike morphologies (Sandage & Binggeli 1984; Binggeli & Cameron 1991), what is new—in addition to the rising number of disk detections—is that some dE-like galaxies actually have (stellar) spiral structures in their disk. After the initial surprise announcement of a tightly wound, two-armed spiral structure in the dE galaxy IC 3328 (Jerjen, Kalnajs, & Binggeli 2000b), Jerjen, Kalnajs, & Binggeli (2001) and Barazza, Binggeli, & Jerjen (2002) reported previously undetected spiral structure and bars (i.e., disks) in four more Virgo Cluster galaxies (two dwarf S0, one dE, and one low-luminosity E). De Rijcke et al. (2003) have in addition presented photometric and kinematic evidence for disks, and in one case spiral arms, in two edge-on Fornax Cluster dwarf lenticular (dS0) galaxies. The data to date suggest that up to 20% of bright early-type dwarf galaxies in clusters may have disks. We report here on the first-ever detection of spiral-like structure in two dwarf, early-type galaxies residing in the densest cluster environment studied so far, namely, the Coma Cluster.

The presence, or at least detection, of (stellar) spiral patterns in dwarf galaxies is a particularly rare phenomenon. Although dwarf versions of Sm and Irr galaxies have been known for a long time (e.g., van den Bergh 1960), referring to the early-type Sa–Sc spiral galaxies, Ferguson & Sandage (1991) wrote that “dwarf spiral galaxies do not appear to exist” (see also Sandage & Binggeli 1984; Sandage, Binggeli, & Tammann 1985). They are a rare species; indeed, their very existence was recognized only a few years ago (Schombert et al. 1995). Even then, Schombert et al. (1995) concluded that dwarf spiral galaxies only exist in the field. The harsh environment within a galaxy cluster—due to galaxy mergers, with each other or the intracluster medium, and/or strong gravitational tidal interactions—is commonly thought to have led to the destruction of the delicate spiral patterns in dwarf galaxies. A comparison of the number of such objects in low- and high-density environments may shed light on the nature of their existence.

By searching for signs of apparent spiral structure or bars in the optical images from the sample of 18 dE galaxy candidates presented in Graham & Guzmán (2003), we explore here which galaxies may have embedded stellar disks. The galaxy selection criteria are described in the following.
section, as is the image reduction process and analysis. Section 3 provides a brief quantitative analysis of the disks, and § 4 discusses possible evolutionary scenarios for dwarf disk galaxies in clusters. We take Coma to be at a distance of 100 Mpc and use $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$; 0.71 therefore corresponds to 47 pc.

2. GALAXY SAMPLE AND IMAGE ANALYSIS

Galaxies meeting the following conditions—discussed at length in Matković & Guzmán (2003)—were selected from the Coma Cluster field catalog (GMP; Godwin, Metcalfe, & Peach 1983). All galaxies have positions within the central 20' × 20' of the Coma Cluster: $-17.5 < M_B < -14.5$; 0.2 < $U-B$ < 0.6 and 1.3 < $B-R$ < 1.5; available Hubble Space Telescope (HST) Wide Field Planetary Camera 2 (WFPC2) images; and recession velocities between 4000 and 10,000 km s$^{-1}$. The spectral analysis and recession velocity derivation are also provided in Matković & Guzmán (2003). The above requirements were expected to result in the selection of Coma Cluster dE galaxies, and we obtained 18 such candidates. With the exception of GMP 2960, there were no preexisting morphological type classifications for these galaxies. GMP 2960 (=PGC 44707; Paturel et al. 1989) is classified in NED as an S0 galaxy, and according to the type-specific luminosity functions derived from three clusters (Jerjen & Tammann 1997), we conclude that GMP 2960 is either a low-luminosity S0 or a bright dS0 galaxy. The reduction process of the HST images is described in Graham & Guzmán (2003). Briefly, we used the IRAF task CRREJ to combine the HST-pipelined exposures, which we then further cleaned of cosmic rays using LACOS (“L.A.Cosmic”; van Dokkum 2001). Because of the stellar halos of nearby galaxies, we used the wavelet decomposition method of Vikhlinin et al. (1998) to simultaneously subtract this nonuniform light and the sky background. Foreground stars and overlapping background galaxies were searched for, and masked out, before we performed any image analysis or surface brightness fitting.

In order to search for nonsymmetric structures in the dwarf galaxy images, we subtracted the axisymmetric component of the galaxy light (see Jerjen et al. 2000b), leaving a “residual image.” Following Barazza et al. (2002) and De Rijcke et al. (2003), we have in addition used an unsharp-masking technique to verify the presence of features such as bars or spiral arms, which would indicate the presence of a flattened stellar disk. Although the majority of galaxies showed no sign of nonaxisymmetric structure, two galaxies (GMP 3292 and GMP 3629) were found to possess flocculent spiral arms (Figs. 1–2). Their basic properties are given in Table 1.

From our previous analysis of the radial light profiles (Graham & Guzmán 2003), we had already identified GMP 3292 as a likely bulge-disk system because of a clear break in its surface brightness profile marking the bulge-disk transition. With regard to GMP 3629, we had remarked upon the possibility of an outer disk—not dominating until radii greater than ~10'' (4.7 kpc)—but we could not and did not confirm this, because of the low surface brightness levels at these outer radii. We can however now confirm that both these galaxies possess stellar disks, as indicated by the presence of a spiral pattern. Using the velocity catalog of Edwards et al. (2002), Gutiérrez et al. (2003) derive a mean recession velocity of 6862 km s$^{-1}$, and a velocity dispersion of 1273 ± 145 km s$^{-1}$, for Coma dwarf galaxies fainter than $M_B = -17.5$ mag. The recession velocities of GMP 3292 (4955 km s$^{-1}$) and GMP 3629 (5219 km s$^{-1}$) are therefore consistent with membership in the Coma Cluster. Although these velocities are 1.5 $\sigma$ and 1.3 $\sigma$ from the mean cluster value, one may actually expect to find such an offset given the “infalling group” feeding mechanism for clusters (see, e.g., Zabludoff & Franx 1993; Conselice, Gallagher, & Wyse 2001; Drinkwater, Gregg, & Colless 2001).

From the full sample of 18 dwarf galaxies, in Graham & Guzmán (2003) we additionally found that neither GMP 2960 nor GMP 3486 could be described with a single Sérsic model; that is, their surface brightness profiles suggested the presence of more than one component (aside from nucleation). However, these two galaxies display no evidence of spiral, or in fact any asymmetric, structure in their residual images. GMP 3486 may therefore be, like the previously mentioned classification for GMP 2960, a lenticular galaxy with a large-scale disk displaying no obvious spiral structure. Neither the light-profile analysis in Graham & Guzmán (2003) nor the unsharp-masking techniques discussed above could verify the presence of a flattened stellar disk, even after careful examination of the images.

Fig. 1.—(a) HST F606W image of GMP 3292. (b) Residual image of GMP 3292: following Jerjen et al. (2001), the axisymmetric component of the galaxy has been subtracted. The labels “arm” are intended only to highlight the visible portions of the arms, and they do not necessarily imply that there are four arms; there may well only be two (broken) arms. (c) Result of unsharp-masking. The image size is 20' × 20'.
Guzmán (2003) nor the present residual image analysis provides evidence to suggest that the remaining 14 galaxies are anything but nucleated dwarf elliptical galaxies.

3. QUANTITATIVE RESULTS

The inwardly extrapolated exponential disk in GMP 3292 has a central surface brightness of \( \mu_{0,F606W} = 20.68 \) mag arcsec\(^{-2} \) (Table 2 of Graham & Guzmán 2003). Correcting this value for Galactic extinction \((-0.02 \) mag; Schlegel, Finkbeiner, & Davis 1998), \((1+z)^4 \) redshift dimming \((-0.10 \) mag), and \( K \)-correction \((0.02 \) mag; Poggianti 1997) gives a value of \( 20.58 \) mag arcsec\(^{-2} \). Assuming a \( B-F606W \) color of 1.08 (Fukugita, Shimasaku, & Ichikawa 1995) yields \( \mu_{0,B} = 21.66 \) mag arcsec\(^{-2} \), very close indeed to the canonical Freeman (1970) value of 21.65 \( B \) mag arcsec\(^{-2} \). The disk scale length is \( 2012 \), which translates to \( \sim 1 \) kpc. This is at the small end of the range from 1.0 to 2.5 kpc found in Schombert et al.’s (1995) sample of dwarf spiral galaxies. The total apparent galaxy magnitude is 16.74 \( F606W \) mag (Table 2 of Graham & Guzmán 2003).

Assuming a distance modulus of 35.0 gives a corrected absolute \( B \)-band magnitude of \(-17.28 \) \( B \) mag. Based on the luminosity functions of individual Hubble types (Jerjen & Tammann 1997, their Fig. 3), GMP 3292 is likely to be a small late-type (Sc–Sm) spiral galaxy. The placement of its disk in the \( \mu_{0}-\log h \) diagram (Fig. 3) is also consistent with this assignment, although it should be kept in mind that this region of parameter space containing small faint disks is far from fully explored. The second galaxy, GMP 3629, is modeled here in an identical fashion to Graham & Guzmán’s treatment of GMP 3292. A Moffat function was fitted to nearby stars or globular clusters on the \( HST \) WFPC chip containing the image of GMP 3629. The best-fitting Moffat function was then used to convolve the central Gaussian, Sérsic, and exponential models, which were simultaneously fitted to GMP 3629’s nuclear star cluster, bulge, and disk, respectively (see Fig. 4). The resultant central disk surface brightness of 25.58 \( F606W \) mag arcsec\(^{-2} \) translates into a corrected \( B \)-band value of 26.56 mag arcsec\(^{-2} \), 5 mag arcsec\(^{-2} \) fainter than the Freeman value, suggestive of depletion. This value is however somewhat poorly constrained, and a deeper exposure would be of great value for better quantifying the disk.

The total apparent \( F606W \) magnitude of GMP 3629 is 18.02 mag—derived from the best-fitting star cluster/bulge/disk models extrapolated to infinity. This agrees well

### Table 1

| GMP No. | \( m_{F606W} \) (mag) | \( M_B \) (mag) | \( B/D \) | \( \mu_{0,F606W} \) (mag arcsec\(^{-2} \)) | \( h_{F606W} \) (kpc) | \( B-R \) (mag) |
|---------|----------------|----------------|----------|------------------------------------------|-----------------|----------------|
| 3292    | 16.74           | -17.28         | 0.3      | 20.7                                     | 3.0             | 1.5            |
| 3629    | 18.02           | -16.00         | 2.6      | 25.6                                     | 3.1             | 1.4            |

Notes.—Col. (1), Godwin et al. 1983 catalog number; col. (2), uncorrected apparent \( F606W \)-band magnitude, derived by extrapolating the fitted models to infinity; col. (3), corresponding corrected (see text) absolute \( B \)-band magnitude; col. (4), bulge-to-disk luminosity ratio; cols. (5)–(6), uncorrected \( F606W \)-band central disk surface brightness and scale length; col. (7), global \( B-R \) color term from Mobasher et al. 2001 and R. Guzmán (2003, unpublished).
and faint dwarf galaxies (Ferguson & Binggeli 1994). This is also the limiting magnitude where Sandage et al. (1985) claimed fainter (Virgo Cluster) spiral galaxies did not exist (see also Ferguson & Sandage 1991). Assuming a $B - V$ color of 0.9, GMP 3629’s magnitude is equivalent to the magnitude of three of the six “dwarf spiral” galaxies presented by Schombert et al. (1995). Unlike GMP 3292, GMP 3629 is faint enough to meet Schombert et al.’s selection criteria for “dwarf spiral” galaxies.

In addition to faint magnitudes ($M_B \lesssim -16$ mag) and faint central surface brightness values ($23 - 24$ B mag arcsec$^{-2}$), Schombert et al. (1995) identified additional characteristics of their dwarf spiral galaxies. They found that the optical radii were small, with $R_{26} < 5 - 6$ kpc (see their Table 1). The Godwin et al. (1983) catalog gives an isophotal radius for GMP 3629 of $b_{26.5} = 10.0$ (4.7 kpc); although the $R_{26}$ radius is expected to be slightly larger, this is nonetheless a small galaxy. Schombert et al. also remarked on the presence of gas and dust. More specifically, they observed a floculent nature to the spiral arms and they measured “double horned” shapes in the H I line profiles of their galaxies. Their dwarf spiral galaxies therefore contain significant gas and their disks do rotate. Unfortunately, we have no rotational data for GMP 3629. As for the presence of gas and dust, there are no obvious signs of this either. However, if GMP 3629 has been somewhat harassed by the cluster environment, then we would indeed expect to find that the gas and dust have been stripped away from this galaxy’s disk or have sunk to the center of the galaxy, where new stars may have formed. We may also expect the stars in the original disk to have been heated up to create the bulgelike structure we see, and the spiral arms to have simultaneously broadened to their present state. It does therefore seem plausible that GMP 3629 may be one of the first dwarf spiral galaxies detected in a cluster, although undergoing a metamorphosis. Technically, it is no longer a dwarf spiral galaxy, but it is by no means (yet?) a dwarf elliptical galaxy either. From the decomposition of the light profile (Fig. 4), the disk has only 38% of the luminosity of the bulge—a very low value that may indicate that much of the disk has either been removed from the galaxy or redistributed. The disk-to-bulge luminosity ratios for the early-type dwarf spiral galaxies in Schombert et al. (1995) were such that their disks were, relative to their bulges, some ~200%–600% more luminous.

4. DISCUSSION

The nomenclature for dwarf galaxies identifies a number of different species. At least structurally, the dwarf elliptical galaxies ($-13 \leq M_B \leq -18$) are now known to be the low-luminosity extension of ordinary, bright ($M_B \leq -18$) elliptical galaxies (Jerjen & Binggeli 1997; Jerjen, Binggeli, & Freeman 2000a; Graham & Guzmán 2003). The gas-deficient (e.g., Skillman & Bender 1995; Young 2000), low surface brightness ($\mu_0 \geq 23$ B mag arcsec$^{-2}$) dwarf spheroidal galaxies (Ferguson & Binggeli 1991) have been detected surrounding the optical component of dSph galaxies (e.g., Carignan 1999; Blitz & Robishaw 2000).
oidal (dSph) galaxies are fainter still ($M_B \lesssim -13$; Grebel 2001). Their location in the magnitude–central surface brightness diagram reveals a continuous extension with the dE and E galaxies, and hence the division of galaxy classes is somewhat artificial. Reflecting this is the fact that many authors do not even bother to make the distinction between dE and dSph galaxies—although the latter may have a greater range of formation histories (e.g., Conselice 2002). They are also generally recognized as increasingly dark matter dominated (e.g., Carignan & Freeman 1988; Irwin & Hatzidimitriou 1995; Mateo 1997; Kleyla et al. 2002; but see Milgrom 1995, Klessen & Kroupa 1998, Klessen & Zhao 2002, and, in the case of Ursa Minor, Gómez-Flechoso & Martínez-Delgado 2003).

The gas-rich, clumpy (both optically and in H I gas) dwarf irregular (dIrr) galaxies may be the progenitors of some dSph, dE, and dS0 galaxies. Although dIrr galaxies are considered to be rotating disk galaxies, such a morphological transformation may occur via galaxy merging (Toomre & Toomre 1972; Toomre 1974; Barnes & Hernquist 1996; Bekki 1998; Burkert & Naab 2003), or via the somewhat less severe ram pressure (and turbulent and viscous) stripping of gas from a galaxy as it moves through the intracluster medium (e.g., Gunn & Gott 1972; Nulsen 1982; Lin & Faber 1983; Cayatte et al. 1994; Sofue 1994; van den Bergh 1994; Quilis, Moore, & Bower 2001; Fujita 2001; Tonazzio & Schindler 2001; Grebel, Gallagher, & Harbeck 2003; Lee, McCull, & Richer 2003), although this latter scenario cannot be applicable to the brighter dE galaxies, which are more massive than the dIrr galaxies (Bothun et al. 1986).

Another scenario is “galaxy harassment” (Moore et al. 1996; Moore, Lake, & Katz 1998; Mao & Mo 1998; Mayer et al. 2001), which considers not only the perturbing influence of the entire cluster’s gravitational field (e.g., Byrd & Valtonen 1990), but also tidal effects from repeated, fast flybys of massive galaxies. Tidal heating from galaxy-galaxy and galaxy-cluster interactions is expected to thicken a galaxy’s disk (see, e.g., Tóth & Ostriker 1992) and suppress spiral features, while ram pressure stripping can remove the gas and prevent further star formation—producing S0 and dS0 galaxies, which are characterized by their thick, featureless disks. In addition, “galaxy threshing,” an extreme example of tidal forces (Bekki, Couch, & Drinkwater 2001a), has been invoked to explain the formation of M32-like objects (Bekki et al. 2001b; Graham 2002) and the recently discovered “ultracompact” dwarf galaxies (Drinkwater et al. 2003)—purportedly the nuclear remnants of nucleated dE/dSph galaxies that have been severely tidally stripped. Lastly, “galaxy starvation”—the removal of halo gas, as opposed to disk gas, from spiral galaxies falling into a galaxy cluster—can also result in the diminished prominence of spiral arms and the eventual transformation to an S0 galaxy (Larson, Tinsley, & Caldwell 1980; Bekki, Couch, & Shioya 2001, 2002; Conselice et al. 2001, 2003). Most spiral galaxies would use up their disk gas within a few gigayears (Gallagher, Bushouse, & Hunter 1989).

The paucity of spiral galaxies in the central regions of nearby clusters, and the relative abundance of S0 galaxies relative to the field population (e.g., Michard & Marchal 1994), has been taken as evidence of the transformation of spirals into lenticular galaxies (e.g., Dressler et al. 1997). Indeed, observations at intermediate redshifts have revealed a higher percentage of spirals in clusters than is observed locally. The presence of spiral galaxies in the periphery of massive clusters (Oemler 1974; Melnick & Sargent 1977; Dressler 1980) has also been interpreted as testimony to their increased likelihood of survival in this lower density environment. But what about the dwarf galaxies?

The lower gravitational potential of dwarf galaxies is suspected to make them particularly susceptible to ram pressure stripping, although other factors, such as the velocity of the galaxy through the intracluster medium (ICM) and the density and temperature of the ICM, are also likely to be important. Whatever the case, if the disruption process is not too severe, at least for the stars, it may leave behind the spiral structure. Once the gas is removed, spiral patterns are expected to disappear in fewer than 10 galactic rotations (Sellwood & Carlberg 1984), which would suggest GMP 3629 was stripped within only the last couple of gigayears. The growing recognition of disks in intermediate-luminosity ($-18 \lesssim M_B \lesssim -20$) elliptical galaxies may be evidence of their increased ability to retain their disks, as compared with the fate of the lower mass/lower luminosity galaxies ($M_B \lesssim -18$).

If, in addition to the dIrr galaxies observed in nearby clusters, dwarf spiral galaxies were to have entered and/or resided within the hazardous environment of a galaxy cluster, they too would be subject to the aforementioned processes and therefore likely be transformed into early-type galaxies. But is there evidence that dwarf spirals were once a predominant population in clusters? And if so, is there evidence that they are the progenitors of today’s cluster population of dwarf elliptical galaxies?

For over 25 years, a substantial fraction of the galaxies in clusters at intermediate redshifts ($z > 0.3$) were seen only as fuzzy blobs in ground-based images (Butcher & Oemler 1978, 1984). HST images revealed that these objects are low-luminosity spiral galaxies, often exhibiting disturbed morphologies (Couch et al. 1994). Oemler, Dressler, & Butcher (1997) concluded that merging is an implausible mechanism (see also Ostriker 1980) to explain the disturbed morphologies, as the blue galaxy fraction is large and the merger probability is low. They also noted that disturbed spirals were observed throughout the cluster. This would argue against ram pressure stripping being responsible for the disturbed spiral structure, since this mechanism is expected to only operate efficiently near the cluster center. The “galaxy harassment” scenario (Moore et al. 1996), however, does provide a plausible explanation for the disturbed morphology of the low-luminosity spirals seen in intermediate clusters and their transformation into dwarf early-type systems by the present epoch. Although direct mergers are extremely rare in the cluster environment, every galaxy experiences a high-speed close encounter with a bright galaxy approximately once every gigayear. Moore et al. (1999) show that these flyby collisions have dramatic effects on the morphologies of the dwarf galaxy population. The first encounter leads to a pronounced bar instability. After several strong encounters, the loss of angular momentum, combined with impulsive heating, leads to a prolate shape supported equally by random motions and rotation.

The gas sinks to the very center of the galaxy and the stellar distribution is heated to the extent that it closely resembles a dwarf elliptical galaxy, although some may retain a very thick stellar disk and would have the appearance of a dwarf lenticular galaxy.

The remarkably faint spiral/disk in GMP 3629 suggests that we may indeed have an example of an incomplete...
morphological transformation of a dwarf spiral into a dE or dS0 galaxy. Although Jerjen et al. (2000b) stated that IC 3328 was not a dwarf spiral galaxy, the possible detection of spiral arms in the dS0 galaxy FCC 288 (De Rijcke et al. 2003) and the spiral patterns seen by Barazza et al. (2002) in three Virgo dwarf galaxies are strong evidence for this scenario. Although our observations do not provide conclusive evidence in support of the galaxy harassment model, there are additional hints in our data that make this model particularly attractive. For instance, there is the hint of a barlike structure in the residual images of GMP 3629. We also remark that the large amount of gas predicted to sink to the galaxy center may, in principle, provide the fuel for forming the large stellar clusters seen in nucleated dwarf elliptical galaxies.

Because of the deficit of galaxies with spiral structure in dense clusters, in such environments it is more common to think about how spiral density waves have been destroyed than to contemplate how spiral structure may form. If created, such spiral patterns must be a transient phenomenon—or at least they are destined to remain a faint feature—otherwise they would have already been observed. The bulge-disk decomposition in Figure 4 suggests that most of GMP 3629’s light is not from the disk component, therefore ruling out the option that swing amplification of noise, or clumps of material within the disk, may have caused the spiral-like pattern (Toomre 1981; Toomre & Kalnajs 1991). Nonsymmetric gravitational perturbations may invoke torques capable of generating spiral patterns in galaxy disks (e.g., Kormendy & Norman 1979). Rotating galactic bars (e.g., Schwarz 1981), triaxial bulges (e.g., Trujillo et al. 2002), and triaxial dark halos (e.g., Bureau et al. 1999; Bekki & Freeman 2002; Masett & Bureau 2003) have been proposed as the culprit, at least when it comes to modifying the gas distribution. With regard to bars, while the gas can be forced about, Sellwood & Sparke (1988) concluded that only the strongest of bars are likely to have a significant influence on the distribution of stars, a result confirmed by the structural analysis of bar and arm strength by Seigar & James (1998; see also Seigar, Chorney, & James 2003). Other mechanisms may be “ grooves ” in the distribution of the angular momentum density (Sellwood & Kahn 1991), or gravitational tides from the passage of nearby objects (e.g., Toomre 1974 and references therein; Noguchi 1987; Sundelius et al. 1987). At least in projection, all of the 18 galaxies reside close to luminous elliptical galaxies—and indeed, all of these dwarf galaxies reside in the same field as the HST pointings, which were actually directed at luminous elliptical galaxies in the Coma Cluster. Simulations, however, have shown that such “ harassment ” from massive neighbors within a galaxy cluster destroys, rather than creates, spiral patterns (Moore et al. 1996, 1998; Gnedin 2003).

Lastly, we remark that intermediate-mass black holes, having masses somewhere between those of stellar-mass black holes and supermassive black holes, may have formed in young compact star clusters via the runaway merging of massive stars (Rees 1984; Kochanek, Shapiro, & Teukolsky 1987; Matsushita et al. 2000; Ebisuzaki et al. 2001; Portegies Zwart & McMillan 2002; Marconi et al. 2003). If so, one might expect some of the dwarf elliptical galaxies containing central star clusters to harbor black holes. On the other hand, perhaps the star clusters are the result of the adiabatic growth of a preexisting black hole (e.g., van der Marel 1999). If this is the case, then tests of the adiabatic growth model that have excluded the nuclear component should be reconsidered (e.g., Ravindranath, Ho, & Filippenko 2002).

Clearly, more data are needed in order to provide conclusive evidence in support of or against the galaxy harassment model. In particular, HST STIS spatially resolved spectroscopy of our sample of Coma dE galaxies may yield a critical test of this model by measuring the amount of rotation and anisotropy in these galaxies, and also the ages of their nuclear clusters.

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9 The spiral arms in GMP 3629 do not appear to sprout from the galaxy center, but instead from the ends of a very faint bar—although poor contrast makes this claim tentative.

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