

VERY ISOLATED EARLY-TYPE GALAXIES

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ABSTRACT

We use the Karachentseva Catalogue of Very Isolated Galaxies to investigate a candidate list of more than 100 very isolated early-type galaxies. Broadband imaging and low-resolution spectroscopy are available for a large fraction of these candidates and result in a sample of 102 very isolated early-type galaxies, including 65 elliptical (E) and 37 S0 galaxies. Many of these systems are quite luminous, and the resulting optical luminosity functions of the E and early-type (E+S0) galaxies show no statistical differences when compared to luminosity functions dominated by group and cluster galaxies. However, whereas S0 galaxies outnumber E galaxies 4:1 in the CfA survey, isolated E outnumber S0 galaxies by nearly 2:1. We conclude that very isolated elliptical galaxies show no evidence of a different formation and/or evolution process compared to those formed in groups or clusters, but that most S0 galaxies are formed by a mechanism (e.g., gas stripping) that occurs only in groups and rich clusters. Our luminosity function results for elliptical galaxies are consistent with very isolated elliptical galaxies being formed by merger events, in which no companions remain. *Chandra* observations were proposed specifically to test the merger hypothesis for isolated elliptical galaxies. However, this program has resulted in the observation of only one isolated early-type galaxy, the S0 KIG 284, which was not detected at a limit well below that expected for a remnant group of galaxies. Therefore, the hypothesis remains untested that very isolated elliptical galaxies are the remains of a compact group of galaxies that have completely merged.

Key words: galaxies: elliptical and lenticular, cD — galaxies: individual (KIG 284) —
galaxies: luminosity function, mass function — X-rays: galaxies

1. INTRODUCTION

Because the two-point correlation function of galaxies is very steep (e.g., Peebles 1993), the best place to find a galaxy is next to another galaxy. Another way of saying this is that truly isolated galaxies are exceptionally rare in the universe. For example, Tully (1987) finds no completely isolated galaxies at all within the Local Supercluster; all are members of small or large bound groups or loose associations. And yet the mythical “field population” of galaxies continues to be referenced in the literature as a comparison to various cluster, group, compact group, and interacting galaxy studies (e.g., Zabludoff et al. 1996; Koopmann & Kenney 1998; Toledo et al. 1999; Christlein & Zabludoff 2003). Still, it should be possible to locate some galaxies that are very isolated relative to the much larger number that are members of clusters, small bound groups, or loose and still unbound associations. If the case can be made that a potentially isolated galaxy has not experienced a merger or interaction with another galaxy for a time much longer than the timescale of the physical process under study (e.g., 10^8 yr for a starburst, 10^7 yr for an active galactic nucleus active phase, or a few times 10^7 yr for spiral galaxy density wave generation), then these very isolated galaxies provide an excellent baseline comparison sample for that property. For example, Haynes & Giovanelli (1980, 1984) and Haynes,

Giovanelli, & Chincarini (1984) used an isolated galaxy sample as a baseline for the H I properties of galaxies; Adams, Jensen, & Stocke (1980) have shown that very isolated galaxies are deficient in radio continuum emission compared with other galaxies, and Koopmann & Kenney (1998) have shown that spirals in the Virgo Cluster have different structural properties than more isolated spirals. In all of these cases, the use of an isolated galaxy comparison sample allows us to infer something about the effects that an external environment can have on the internal characteristics of a galaxy. For this reason, a large sample of very isolated galaxies is extremely valuable, providing an important comparison sample that facilitates studies of environmental effects on galaxies.

Based on a visual inspection of all $\sim 30,000$ bright ($m_B \leq 15.7$) galaxies cataloged by Zwicky et al. (1957), Karachentseva (1973) listed over 1000 Zwicky galaxies that are very isolated. Because few redshifts of these galaxies were available at the time of Karachentseva’s work, she based her isolation criterion on the observed angular sizes and distances between galaxies. Thus, this sample is representative, not complete, because other isolated galaxies would not be included if they were projected onto foreground or background galaxies of comparable angular size (see below). Surprisingly, Karachentseva’s (1973) list contains over 100 galaxies that she classified morphologically as early types (E and S0).

The possible existence of very isolated early-type galaxies is unexpected based on the typical environment for such systems (e.g., Dressler 1984; Oemler 1992, on the morphology/density relationship). And yet recent theoretical (e.g., Barnes & Hernquist 1992; Barnes 1985; Athanassoula, Makino, & Bosma 1997) and observational work (e.g., Mulchaey & Zabludoff 1998, 1999; Zabludoff 2003) suggests that very isolated elliptical galaxies could be the final outcome in the evolution of dense groups of galaxies that have completely merged, leaving only a single, large elliptical galaxy behind. The detection of the isolated elliptical NGC 1132 as a diffuse X-ray source by Mulchaey & Zabludoff (1999) at a luminosity ($L_X \approx 5 \times 10^{42} h_{70}^{-2}$ ergs s $^{-1}$) comparable to the L_X of elliptical-dominated groups of galaxies is significant new evidence in favor of the merger hypothesis for forming elliptical galaxies in general. Thus, the number, detailed structure, and X-ray properties of very isolated elliptical galaxies provide new tests of the merger hypothesis for elliptical galaxies. Are these true elliptical galaxies or do they possess systematic differences from the elliptical galaxies found in rich groups and clusters? Similar questions could be asked about very isolated S0 galaxies, whose detailed histories are even more poorly understood. Proposed scenarios include ram pressure stripped spirals (Quilis, Moore, & Bower 2000), mergers of large galaxies with small companions (Mihos et al. 1995; Bekki 1998), and early starbursts, followed by passive evolution (Welch & Sage 2003). Only two of these possible histories can account for isolated S0 galaxies.

In this paper, we begin the study of very isolated early-type galaxies by scrutinizing a list of candidate very isolated early-type galaxies drawn from Karachentseva (1973), presenting a final list of very isolated E and S0 galaxies and computing the optical luminosity function (LF) for them. In addition, we present a single *Chandra* ACIS imaging analysis of one of the most luminous galaxies in this sample, a first attempt at testing the merger hypothesis for the formation of very isolated elliptical galaxies by detecting diffuse X-ray emission.

In the following section we describe the Karachentseva (1973) sample and present the sample of isolated early-type galaxies identified from it through further scrutiny. In § 3, we present the optical LFs of the elliptical and S0 galaxies in the sample. Section 4 presents the *Chandra* and optical imaging and spectroscopy results for the one isolated early-type galaxy observed by *Chandra*: KIG 284. Section 5 includes a brief discussion and conclusions drawn from this work. Throughout this work we adopt the NASA Extragalactic Database (NED) abbreviation for the Karachentseva (1973) galaxies (KIG) as well as $H_0 = 70$ km s $^{-1}$ Mpc $^{-1}$.

2. THE ISOLATED EARLY-TYPE GALAXY SAMPLE

The early-type galaxy sample we have selected is drawn from the Catalogue of Very Isolated Galaxies (KIG Catalogue) of Karachentseva (1973). This catalog contains 1051 galaxies with $m_B \leq 15.7$, chosen from the Catalog of Galaxies and of Clusters of Galaxies (CGCG; Zwicky et al. 1957) by inspecting the Palomar Observatory Sky Survey (POSS) for isolation. Since the CGCG contains more than 30,000 galaxies, demonstrably isolated galaxies are $\lesssim 3\%$ of the total galaxy population and so are very rare. However, the CGCG is a magnitude-selected sample and not an angular-size-selected sample like the Nilson (1973) catalog. As such, the CGCG selection method is now known to be biased against the selection of low surface brightness galaxies (McGaugh, Bothun, & Schombert 1995), and low surface brightness

galaxies may be systematically more isolated than higher surface brightness galaxies (McGaugh 1996; Impey & Bothun 1997). However, this selection bias is probably not important for early-type galaxies, since these objects have quite high central surface brightnesses because of their luminous bulge components.

The KIG Catalogue selection criterion uses the POSS alone by defining an isolated galaxy to be a CGCG galaxy that has no “companions” within 20 galaxy diameters. Companions are defined to be galaxies within a factor of 4 in angular diameter of the isolated galaxy candidate (i.e., about ± 2 mag in luminosity using the relationships in Hutchmeier & Richter 1987). While the exact density of the galaxy environment is difficult to measure for most galaxies due to projection effects, an apparently isolated galaxy cannot be “created” by projection effects. Thus, these KIG galaxies are truly isolated. For example, based on the above selection criteria, and assuming that the projected galaxy diameter on the sky is ~ 20 kpc, and that the peculiar velocity of these systems is ~ 300 km s $^{-1}$, a KIG galaxy has not suffered an encounter with another large galaxy for at least the past billion years (5–10 rotation periods for a large spiral galaxy). This is the case for these KIG galaxies unless the companion galaxy is much smaller or larger than the KIG candidate galaxy, or the isolated galaxy has merged recently with all of its neighbors.

Since it is surprising that the KIG Catalogue has 100+ galaxies that are suggested to be early-type systems (E and S0 galaxies), the verification of this sample and its properties are important. In order to be certain that no early-type galaxies were misclassified, a total of 206 KIG galaxies were examined on the POSS and, for the most part, their morphological classifications were confirmed. In the course of checking the morphologies, we also checked the isolation of these galaxies; only 13 galaxies were eliminated from consideration here owing to comparably sized companions, evidently missed by Karachentseva (1973). These multiple inspections (Adams et al. 1980) found the following breakdown of morphologies: 109 E and S0 galaxies, 56 uncertain classifications, but nonetheless not early types, and 28 spiral galaxies. However, some of these objects are faint and compact enough that these POSS-derived classifications are not persuasive in all cases. For this reason we obtained red optical images for 84 of the 109 E and S0 galaxies at the Mount Hopkins 0.6 m telescope in the mid-1980s and aperture spectra for all of them at the Lick Observatory 3 m and the Steward Observatory 2.3 m telescopes during the same time period. In addition, photographic images had been previously obtained for seven others by Adams et al. (1980). The optical imaging eliminated seven E and S0 galaxies, which are spirals with weak but visible spiral structure. The remaining 102 early-type KIG galaxies are listed in Table 1.

CCD imaging was obtained for 84 of these KIG galaxies at the Mount Hopkins 0.6 m telescope through an “F” filter (Schild 1984), a broadband filter whose combined throughput and CCD response mimicked the Kodak photographic F emulsions in use at the time. The effective wavelength of this filter is closely approximated by a Gunn r filter (Schild & Kent 1981). Of these images 66 were sufficient to allow detailed surface brightness profiles to be extracted and fitted to de Vaucouleurs $r^{1/4}$ laws. Objects well fit by $r^{1/4}$ -laws were classified as elliptical galaxies, while those objects showing even slight evidence for disks (at intermediate radii) were classified as S0. The dividing line between these two

TABLE 1
KIG ISOLATED EARLY-TYPE GALAXIES

KIG No. (1)	Galaxy Type (2)	m_{ZW} (3)	cz (km s ⁻¹) (4)	M_{ZW} (5)	Comments (6)
14 ^a	S0	14.7	5800	-20.1	
19 ^b	E	15.4	5440	-19.2	
25 ^b	E	14.2	5600	-20.5	
43.....	E	15.5	5280	-18.9	
57.....	S0	15.5	16930	-21.5	[O II], [O III]
83 ^a	S0	14.4	5260	-20.2	
89.....	S0 ^c	12.6	1910	-19.7	
91 ^a	S0	14.5	5030	-20.0	
93.....	E	15.7	13730	-21.0	
99.....	S0	15.5	9790	-20.4	H α
101 ^a	S0	15.2	6090	-19.6	
110 ^b	E	15.0	6250	-19.9	
111.....	E ^c	15.7	5500	-19.0	
118.....	E	15.5	8200	-20.2	
127.....	E	15.7	7680	-19.7	
128 ^a	S0	15.0	6430	-20.4	
141.....	S0	15.0	1990	-17.9	[O II], [O III], H β
164.....	E	15.5	9360	-20.6	[O II], [O III], H β
174 ^b	E ^d	15.4	10750	-20.8	
178 ^b	E	15.3	7750	-20.2	
179 ^a	S0	15.3	5850	-19.7	[O II]
189 ^b	E ^c	14.3	3150	-19.2	
228.....	E	15.6	8530	-20.0	
245 ^b	E ^c	15.4	4040	-18.5	
256.....	S0	15.5	6690	-19.5	
264 ^b	E	15.1	7530	-20.2	
284 ^a	S0	15.4	12990	-21.2	[O II], H β > [O III]; Balmer absorption
303 ^a	S0	13.3	4060	-20.6	
380.....	E ^c	15.7	5750	-18.9	
387.....	E ^c	15.6	9060	-20.0	
393 ^b	E ^d	14.2	3100	-19.0	[O II], H β > [O III]
396 ^a	S0	14.3	3250	-19.0	
413 ^a	S0	15.3	6320	-19.6	
415.....	E	15.5	11730	-20.7	
417.....	E ^d	15.6	9850	-20.1	
424.....	E ^c	15.6	7780	-19.6	Weak [O II], H β ; Balmer absorption
427.....	S0	15.5	7010	-19.5	
430.....	E	15.5	12650	-20.8	[O II], H β
437 ^b	E ^c	14.6	7430	-20.5	
452.....	E ^d	15.6	7100	-19.5	[O II]
480 ^a	S0	15.2	5570	-19.3	[O II], [O III]
490 ^a	S0	14.8	5380	-19.7	
501.....	E	15.5	7150	-19.6	CD-like; [O II]
503.....	S0	14.2	1160	-16.9	[O II], H β \gg [O III]
504 ^a	S0	15.2	6020	-19.6	[O II], H β ; Balmer absorption
517.....	E ^c	15.5	9640	-20.2	
555.....	E ^d	15.5	1140	-15.6	[O II], [O III]; Balmer absorption
556.....	E	15.5	1020	-15.4	[O II]; Balmer absorption
570 ^b	E ^d	15.4	5560	-19.2	
574.....	E ^d	15.7	11100	-20.6	
578 ^b	E ^d	15.2	9090	-20.4	
582.....	S0	15.7	10420	-20.2	[O II]:
589.....	E ^d	15.7	18600	-21.4	[O II]
599 ^a	S0 ^d	14.9	10860	-21.0	
602.....	S0 ^d	15.7	16180	-21.1	
614.....	E ^c	15.7	17170	-21.3	[O II]
623 ^a	S0 ^d	15.4	5660	-19.2	
636.....	S0 ^d	15.7	11870	-20.5	
640 ^b	E ^d	15.1	9150	-20.5	
670 ^b	E	15.1	12590	-21.2	
684 ^b	E	14.6	5760	-20.1	[O II]
685.....	E ^c	15.7	15540	-21.0	
690 ^a	S0	15.2	8020	-20.1	

TABLE 1—*Continued*

KIG No. (1)	Galaxy Type (2)	m_{ZW} (3)	cz (km s ⁻¹) (4)	M_{ZW} (5)	Comments (6)
701.....	E	15.6	24210	-22.1	
703.....	E ^d	15.7	6330	-19.3	
705 ^b	E	15.2	12160	-21.0	
722 ^b	E	14.9	10510	-21.1	
732 ^b	E	13.8	5820	-20.8	
735.....	E	15.6	9770	-20.1	
769.....	S0 ^d	13.5	310	-14.9	
770 ^b	E	15.1	12520	-21.3	
771.....	E	15.6	11040	-20.6	CD-like
792.....	E	15.5	9570	-20.5	
803.....	E ^c	15.5	8600	-20.0	
811 ^a	S0	15.0	8130	-20.5	
816.....	E	15.5	6880	-20.1	
820.....	S0	15.5	7290	-20.1	Balmer absorption
823 ^b	E	15.3	7030	-20.1	CD-like
824 ^b	E	14.8	5670	-19.9	Balmer absorption
826.....	E	15.6	9410	-20.2	
827.....	E	15.7	4600	-18.5	[O II], H β > [O III]
833.....	E	15.3	1840	-17.1	[O III]; Balmer absorption
835 ^a	S0 ^c	15.4	4170	-18.8	
836.....	E	15.6	14900	-21.2	Radio source
841 ^b	E ^d	14.0	6230	-20.9	
845.....	S0 ^c	15.5	5710	-19.2	
865.....	S0 ^c	15.6	7390	-19.7	
877 ^b	E ^c	15.2	8960	-20.7	[O II], [O III] \gg H β ; [Ne III]
896.....	S0 ^c	15.7	10440	-20.5	
898.....	E	15.7	15150	-21.3	
903.....	S0 ^c	15.5	5750	-19.3	[O II]
918.....	E	15.7	8400	-20.1	
920.....	S0	15.6	5200	-18.9	
921.....	E ^d	15.6	8560	-20.2	[O II], H γ ; [O III] > H β
928.....	E	15.7	7580	-19.7	[O II], H β
981 ^a	S0	15.1	8020	-20.4	Balmer absorption
1015 ^b	E	14.6	4710	-19.7	CD-like; Balmer absorption
1026.....	E	15.6	12780	-20.8	
1029.....	S0	15.7	12560	-20.7	[O II];
1031.....	E	15.5	1710	-16.7	[O II], H γ , H β \approx [O III]
1042 ^b	E ^c	14.8	13200	-21.8	
1045 ^b	E	13.0	4020	-21.0	

^a Member of complete sample for S0 luminosity function.^b Member of complete sample for E luminosity function.^c Type determined by visual inspection of new images.^d Type determined by visual inspection of POSS.

classifications occurred if more than five radial bins were in excess of the $r^{1/4}$ law fits by $\geq 1 \sigma$. The radial bins were set to the observed seeing in these images (typically 2"), and there were typically 15–25 bins in each profile. Only seven galaxies were close to the E/S0 dividing line, with four being classified as E galaxies. The remainder were either too close to bright stars and/or had sky too bright to allow an unambiguous extraction of the surface brightness profile. These were classified by eye either from the 0.6 m CCD images (12 objects) or the Adams et al. (1980) photographic images (seven objects) and have morphologies marked as “determined by visual inspection” in Table 1. We were unable to obtain new images of the remaining 18 galaxies in Table 1, whose classifications were made using the POSS. The morphologies of these 18 galaxies are marked as “determined by visual inspection of POSS.” The KIG early-type galaxy sample in Table 1 has 65 elliptical and 37 S0 galaxies. Thus, 80% of the E and 86% of the S0 galaxies were classified using new images.

A substantial difference exists in the relative numbers of E and S0 galaxies in the CfA survey volume (4:1 in favor of S0 galaxies; Marzke et al. 1994b) compared to the KIG Catalogue (1.75:1 in favor of E galaxies). This could be an indication of the relative difficulty in forming E and S0 galaxies in very sparse environments, as it is unlikely that the morphological typing could be this inconsistent. The Marzke et al. (1994b) typing is from de Vaucouleurs, de Vaucouleurs, & Corwin (1976) or Nilson (1973) with a few additions from J. Huchra in conjunction with Marzke et al. (1994b). All of the CfA morphological types were judged by visual inspection of available plate material, while those here are primarily based on surface brightness profiles. Thus, some systematic differences may be present between these two samples. But while we can imagine a few differences that might have allowed some bone fide S0 galaxies to be present in the Marzke et al. (1994b) sample of elliptical galaxies and for us to have misclassified some bone fide isolated E galaxies as S0, it is hard to

imagine that these differences are so great as to create the large population difference between these two samples. Thus, we believe that these morphological differences are real and that very isolated S0 galaxies are extremely rare.

The spectroscopy of all 102 galaxies in Table 1 was obtained using either the Lick 3 m spectrograph with the image dissector scanner detector or the Steward 2.3 m blue reticon spectrograph. The dispersion of these spectra was 7–8 Å covering 3400–6400 Å at a signal-to-noise ratio of 5–10 per resolution element. Individual emission and absorption lines were identified and redshifts obtained by measuring wavelengths of individual features. Most of these galaxy spectra showed only absorption lines typical of old stellar populations but a few had emission lines in their spectra. Where emission lines are present, they are indicated in Table 1. While not up to the standards of modern cross-correlation techniques, we estimate that the redshifts in Table 1 are accurate to $\pm 150 \text{ km s}^{-1}$, based on redshift agreement between spectral features measured. This accuracy is quite adequate for the determination of the LFs of these galaxies.

Table 1 gives the following basic information on the KIG E+S0 galaxy sample by column: column (1): KIG number; column (2): adopted morphological classification (see above); column (3): apparent Zwicky magnitude (m_{Zw}) given in the CGCG; column (4): Galactocentric recession velocities obtained from our spectra and corrected to the Galactic frame (km s^{-1}); and column (5): absolute blue luminosity derived from the values in columns (3) and (4), corrected for Galactic extinction and assuming $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The extinction corrections were calculated for each galaxy using the data from Burstein & Heiles (1982) to determine $E(B-V)$ and assuming $A_B = 4.0E(B-V)$. This approach was used to be consistent with a similar approach used by Marzke et al. (1994a, 1994b), with which we compare luminosity functions in the next section. Because the CGCG is restricted to higher Galactic latitudes, the extinction corrections are modest [$E(B-V) \leq 0.2$]. The final column (6) lists any emission lines or Balmer absorption lines present in our optical spectra. Any other comments about the individual objects are also placed here. The complete sample of elliptical (or S0) galaxies used in the next section to compute the luminosity function of E and E+S0 galaxies are indicated in Table 1.

3. LUMINOSITY FUNCTIONS OF ISOLATED ELLIPTICAL AND S0 GALAXIES

The interesting result apparent in Table 1 is that many of these isolated E and S0 galaxies are extremely luminous. In order to compare the absolute magnitude distribution with elliptical galaxies found in other surveys, we have computed the optical LFs of isolated E galaxies and all isolated early-type galaxies and compared them with the E and E+S0 LFs of Marzke et al. (1994a, 1994b), which are based on the expanded CfA galaxy redshift survey (Huchra et al. 1983).

It is well known that the CGCG shows evidence of incompleteness at the faint end ($m_{\text{Zw}} = 15.5\text{--}15.7$; Huchra 1976; Giovanelli & Haynes 1984). A $\langle V/V_{\text{max}} \rangle$ calculation for the entire list in Table 1 confirms incompleteness for this sample specifically. So we have set the limiting magnitude for luminosity function calculations at $m_{\text{Zw}} = 15.4$. In addition, Table 1 shows a relative dearth of KIG galaxies at lower redshifts. While this is partially due to the smaller volume sampled at lower recession velocities, it is likely that the sample selection criteria, specifically the isolation criterion, exclude lower recession velocity galaxies systematically. In most directions

$cz \leq 3000 \text{ km s}^{-1}$ places galaxies within the confines of the Local Supercluster, where there are few, if any, truly isolated galaxies (Tully 1987). While there are a few KIG galaxies in Table 1 that are at these recession velocities, the isolation selection criterion biases against their inclusion. Therefore, we have excluded the volume of the Local Supercluster from our search area, as well as those few galaxies with $m_{\text{Zw}} < 15.4$ that have $cz \leq 3000 \text{ km s}^{-1}$: one elliptical galaxy (KIG 833) and four S0 galaxies (KIG 89, 141, 503, and 769). The remaining sample sizes are 26 elliptical and 45 early-type galaxies total. A $\langle V/V_{\text{max}} \rangle$ completeness test for the 26 elliptical galaxies (45 E+S0) yields 0.532 ± 0.057 (0.556 ± 0.043), suggesting that these samples are complete (nearly complete). We used new images to classify 80% of the E and 86% of the E+S0 samples used to compute the LFs. If all KIG galaxies in Table 1 were included in the comparison below, it would not alter the conclusions.

Luminosity functions for these two samples are shown in Figures 1 and 2 computed using the N/V method (Felten 1976) in half-magnitude bins and compared with the functional fit to the elliptical and E+S0 LFs of Marzke et al. (1994b). The Schechter (1976) function parameters derived by Marzke et al. (1994b) from their data but converted to $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ are for elliptical galaxies, $M^* = -20.0$, $\alpha = -0.85$, and $\Phi^* = 5.1 \times 10^{-4} \text{ galaxies Mpc}^{-3} \text{ mag}^{-1}$; and for E+S0 galaxies, $M^* = -19.6$, $\alpha = -0.92$, and $\Phi^* = 3.4 \times 10^{-3} \text{ galaxies Mpc}^{-3} \text{ mag}^{-1}$.

The isolated galaxy LF data have been scaled upward in galaxy density by factors of ~ 100 and 200 to match the Marzke et al. (1994b) data for E and E+S0 galaxies, respectively, because we know that our selection criteria excludes most of the early-type galaxies in the survey volume. Therefore, this procedure is justified since we are testing the numbers of luminous and less luminous galaxies in the isolated sample, relative to the LF of early-type galaxies in general. No horizontal offsets are required since both our data and the Marzke et al. (1994b) data use Zwicky magnitudes (de Lapparent 2003). The important point of the comparisons shown in Figures 1 and 2 is that, once scaled, the overall shapes of the LFs match pretty well. The scaling was accomplished in both cases using a χ^2 fitting procedure for our data to the Marzke et al. (1994b) Schechter functions shown. The reduced χ^2 values are 0.39 and 1.02, respectively for the E and E+S0 galaxies. The larger χ^2 value for the E+S0 sample appears to be due to a slight excess in number density of KIG S0 galaxies at $M_{\text{Zw}} \leq M^*$; i.e., while the CfA redshift survey found a less luminous M^* value for E+S0 galaxies compared to E galaxies alone, our S0 sample is predominantly more luminous than $M_{\text{Zw}} = -19.6$, thus yielding a slightly poorer (but still acceptable) fit. If instead we fit our E+S0 data to the elliptical LF from Marzke et al. (1994b), the reduced χ^2 value is 0.23. The excellent fit to the E LF parameters by our E+S0 data could be due to some small inconsistencies in the morphological typing between these two samples as described in the previous section. However, the recent concerns described by de Lapparent (2003) involving contamination of early-type LFs by dwarf galaxies of uncertain types are not relevant here since our comparisons do not extend below $M \geq -19$.

At the high-luminosity end, the KIG elliptical sample contains one galaxy (KIG 701) at $\approx 7 L^*$. The absence of even more luminous isolated elliptical galaxies is not precluded because the sample volume is not nearly large enough to constrain their space density (note upper limits at high luminosity in Figs. 1 and 2). This is true either if the isolated

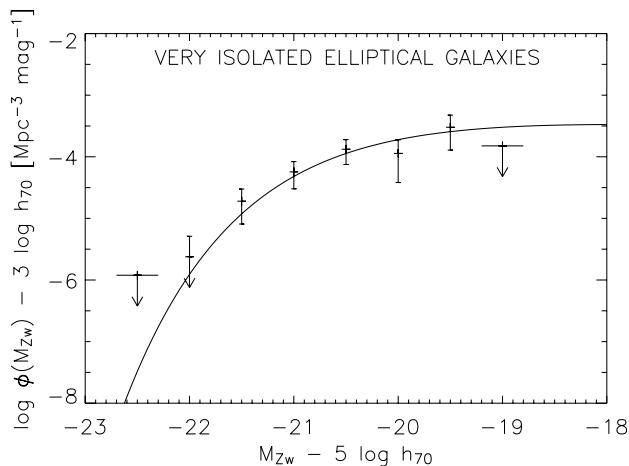


FIG. 1.—Luminosity function of the elliptical galaxy sample (26 members), vertically scaled to match the Marzke et al. (1994b) normalization. The solid line is the Schechter function fit to the Marzke et al. (1994b) data. The magnitude bins are 0.5 mag wide and the vertical error bars indicate \sqrt{N} statistics for each bin.

E galaxies obey a standard Schechter function or even if they have excess numbers above a Schechter function, as seen in rich clusters because of the cD galaxies. In other words, we cannot preclude the existence of very isolated cD-like galaxies, although it would require a much larger search volume to find one. In summary, there is no indication that the KIG sample is not drawn from the same parent population as the Schechter functions shown in Figures 1 and 2.

These χ^2 values do not change substantially even if all the KIG galaxies in Table 1 are included in the LF comparisons (factor of two larger χ^2 values, largely due to incompleteness; see above). Thus, we conclude that there is no evidence based on luminosities that very isolated elliptical and S0 galaxies are significantly different from early-type galaxies in clusters and dense groups.

4. X-RAY AND OPTICAL OBSERVATIONS OF KIG 284

To further test whether isolated early-type galaxies are similar to other early-type galaxies, *Chandra* ACIS imaging spectroscopy was obtained for one of the most luminous galaxies in the KIG sample in Table 1, KIG 284. This test is based on the recent discovery that some isolated elliptical

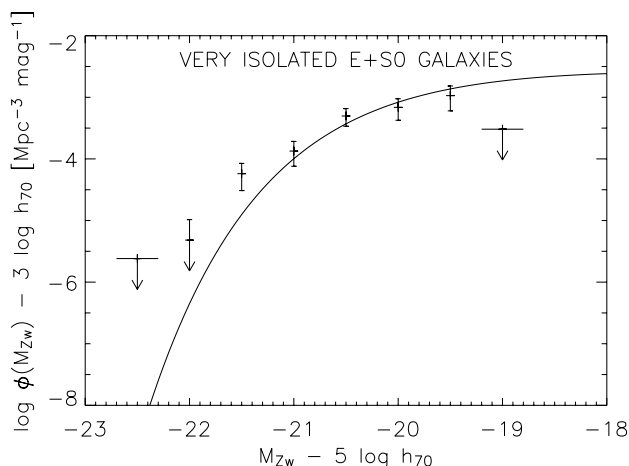


FIG. 2.—Same as Fig. 1, but for the E+S0 galaxy sample (45 members)

galaxies are surrounded by X-ray-emitting gas, similar in extent and L_X to that found in dense, elliptical-dominated groups of galaxies (Mulchaey & Zabludoff 1999). However, only some isolated E galaxies exhibit extended X-ray emission; Zabludoff (2003) finds that only 1 in ~ 5 isolated elliptical galaxies shows extended X-rays. This may indicate that at least two different merger scenarios are possible; i.e., these isolated E galaxies can be formed either from dense groups that already possessed an intragroup medium (like the elliptical-dominated groups studied by Mulchaey & Zabludoff 1999) or from ones that did not (the Local Group?). Therefore, several KIG galaxies would need to be observed in X-rays to test this hypothesis definitively.

Chandra ACIS-S observations were made of KIG 284 on 2001 March 14 for a usable integration time of 8.26 ks; a small amount of exposure time was removed because of high background. No obvious detections of this galaxy were made, and so we are able to set only upper limits on the X-ray flux of KIG 284. At the observed redshift of $z = 0.043$, $1'' = 850$ pc, and so we obtained limits on count rates within two apertures of the following radii: $58''$ ($50 h_{70}^{-1}$ kpc) and $140''$ ($120 h_{70}^{-1}$ kpc). We also searched for emission in a larger aperture ($200 h_{70}^{-1}$ kpc), but this aperture extended beyond the edge of the S3 ACIS chip onto the S2 chip, which is less sensitive; we did not detect any extended X-ray emission in this largest aperture either. The smaller and larger apertures were used to search both for emission related to the individual galaxy as well as for emission of the size expected for remnant emission from a pre-existing galaxy group. In a small X-ray survey of poor groups of galaxies, Mulchaey & Zabludoff (1998) found evidence for two X-ray components in the elliptical-dominated groups they detected. The first has a size ($30\text{--}60 h_{70}^{-1}$ kpc), location, and temperature (<1 keV) suggesting an association with the interstellar medium of the central, dominant elliptical galaxy in the group. The second component found was substantially larger, extending to $150\text{--}400 h_{70}^{-1}$ kpc, and was hotter. Mulchaey & Zabludoff (1998) identified this component with the entire galaxy group. For reference, the isolated elliptical NGC 1132, mentioned in § 1, has an observed X-ray core radius of $135 h_{70}^{-1}$ kpc, a full extent of nearly $350 h_{70}^{-1}$ kpc, and a total X-ray luminosity of $5 \times 10^{42} h_{70}^{-2}$ ergs s^{-1} (Mulchaey & Zabludoff 1999). Using only the softer portion of the ACIS-S energy band ($0.5\text{--}2$ keV), 3σ upper limits for the 50 and 120 kpc radii apertures were 0.06 and 0.09 counts s^{-1} , respectively. The smaller radius recorded a 1σ excess of counts above background, so we cannot rule out a very faint detection of this galaxy in our data. However, this possible small excess is not restricted to a small number of pixels and so is not a more definite detection of a point source. Use of the full $0.3\text{--}10$ keV band increases the background count rate and so provides poorer upper limits. Since the expected temperature for a poor group of galaxies or the diffuse emission from an individual elliptical or S0 galaxy is ~ 1 keV, the restricted energy band is appropriate in this case. At the luminosity distance of KIG 284 these limits correspond to less than 3×10^{41} and $4.5 \times 10^{41} h_{70}^{-2}$ ergs s^{-1} , respectively, if the emission is smoothly distributed throughout the entire aperture. But, where detections have been made of poor groups, the X-ray emission is quite centrally concentrated. So we use the first limit as a conservative upper limit on the X-ray luminosity from the KIG 284 vicinity. This limit is over an order of magnitude below the L_X of NGC 1132 and is also at least a factor of 5 less than the least luminous galaxy group detected by Mulchaey & Zabludoff (1998). Therefore, we can

rule out KIG 284 as a remnant group of galaxies, as Mulchaey & Zabludoff (1999) propose for NGC 1132. However, our X-ray upper limit is in the middle of the range ($L_X \sim 10^{40}$ – 10^{43} ergs s^{-1}) found for luminous elliptical galaxies by Eskridge, Fabbiano, & Kim (1995) and is a few times higher than the total L_X found for the nearby X-ray-faint S0 galaxy NGC 1553 (Blanton, Sarazin, & Irwin 2001). The possible 1σ excess count rate at the location of KIG 284 would be at approximately the same L_X as NGC 1553. So, KIG 284 could be a quite normal E or S0 galaxy based on the X-ray limits we have presented.

KIG 284 was included in our target list because its 0.6 m image appeared to show a low surface brightness excess at large radii, similar to what is seen in cD galaxies (although this galaxy is not nearly as luminous as a cD galaxy). In addition, our Steward 2.3 m reticon spectrum of KIG 284 contains emission lines that could be due either to recent star formation or to gas heated by other low ionization parameter processes like so-called cooling flows. Balmer absorption lines indicate the presence of young stars in this galaxy. Therefore, it is an interesting, although anomalous, member of this sample based on our imaging and spectroscopy.

In order to make certain that the properties of KIG 284 were as we had originally determined from the older image and spectrum, we obtained a new spectrum using the double imaging spectrograph (DIS) and a new (B , R) image pair using the “SPICAM” CCD imager at the Apache Point Observatory (APO) 3.5 m telescope.¹ The broadband images were obtained on 2002 February 8 in $1''.8$ seeing. No surface brightness irregularities due either to dust or to weak spiral structure were visible in the B - or R -band images. After removing the effects of a small companion galaxy to the southwest, the surface brightness profile obtained from the R -band image is shown in Figure 3. The exponential disk and $r^{1/4}$ -law profiles shown in the figure are least-squares fits to the surface brightness data. This profile verifies our previous classification of this galaxy as an S0 and shows no evidence for an extended outer envelope

that the 0.6 m image appeared to show. This mistaken impression was probably due to a slight misdetermination of the sky level in our original CCD image and rules out KIG 284 as a cD-like galaxy. Using the aperture photometry package (APPHOT) within IRAF, a blue magnitude of $B = 16.3 \pm 0.1$ and $B-R = 1.1 \pm 0.2$ were obtained. If we include a small companion to the southwest of KIG 284, the total magnitude increases to 16.1, which converts to $m_{Zw} = 15.5 \pm 0.4$ using the recent CCD photometry of Gaztanaga & Dalton (2000). The much larger magnitude error is due to the scatter inherent in the conversion found by Gaztanaga & Dalton (2000). Our measured galaxy magnitude is consistent with the Zwicky magnitude listed in Table 1.

The 3.5 m DIS spectrum was obtained on 2003 January 26 and covers 3600–9700 Å at ~ 6 Å resolution in two spectra, with somewhat lower sensitivity in the region of the dichroic (5200–5600 Å). This spectrum confirms the presence of strong, low-ionization emission lines, and adds $H\alpha$, [N II] $\lambda 6584$ Å, and the [S II] doublet ($\lambda\lambda 6717, 6731$) to the list of emission lines in KIG 284 listed in Table 1. The emission-line ratios are indicative of star formation based on, e.g., the theoretical work of Kewley et al. (2001), as are the presence of higher Balmer lines in absorption ($H\delta$, $H\epsilon$, etc; but not $H\gamma$, which is mostly filled in by emission at our spectral resolution). Using the observed $H\alpha$ luminosity from our spectrum, we infer a current star formation rate for this galaxy of $\approx 2 M_\odot \text{ yr}^{-1}$. Thus, this galaxy is a luminous S0 galaxy undergoing a starburst and not an anomalous elliptical or cD-like galaxy. Also, we do not observe a plethora of faint companions to KIG 284, as seen around NGC 1132, the isolated elliptical with detected extended X-ray emission (Mulchaey & Zabludoff 1999).

In summary, KIG 284 was not detected by *Chandra* at a level at least 5 times less than expected if it were the final stage in the merger history of a dense group of galaxies. But because we have shown that this galaxy is an S0, not a luminous E, the *Chandra* nondetection is not a definitive test of the merger hypothesis for very isolated elliptical galaxies.

5. CONCLUSIONS AND DISCUSSION

In this paper we present a sample of bright ($m_{Zw} \leq 15.7$), very isolated, early-type galaxies that can be used to investigate how early-type galaxies are formed. Starting with the KIG Catalogue of more than 1000 very isolated galaxies selected by Karachentseva (1973) from the CGCG, we used the POSS and deeper images to scrutinize more than 200 KIG galaxies as potential E and S0 galaxies. Table 1 presents the basic data, including luminosities and recession velocities, for the 65 elliptical and 37 S0 galaxies in the very isolated early-type galaxy sample that resulted from this detailed examination process. We emphasize that this sample is representative and not complete because it does not include very isolated galaxies that, by chance, are projected close to foreground or background galaxies that happen to have a similar angular size. We have used this sample to construct luminosity functions (LFs) for these galaxies and have compared them to the LFs of Marzke et al. (1994b) for elliptical and S0 galaxies found throughout the CfA redshift survey region (and therefore biased heavily toward elliptical and S0 galaxies in rich galaxy regions). After appropriate scaling, we find that the LFs for elliptical and S0 galaxies from Marzke et al. (1994b) are excellent matches to the very isolated E and S0 LFs. However, the relative numbers of E and S0 galaxies in the Marzke et al. (1994b) and the KIG samples are quite different. In the CfA survey S0 outnumber E galaxies $\sim 4:1$, but in the

¹ The APO 3.5 m telescope is operated by the Astronomical Research Consortium (ARC).

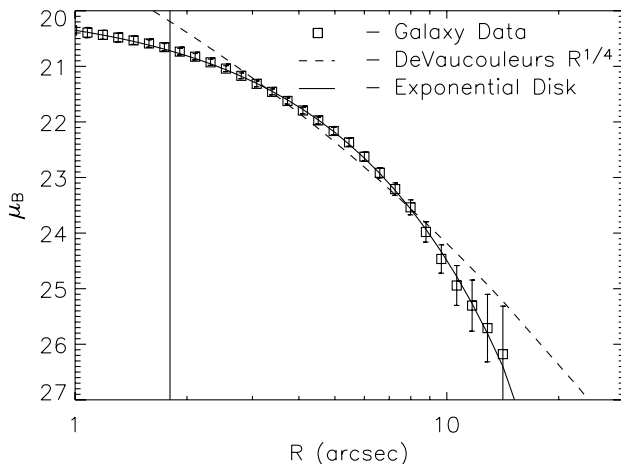


FIG. 3.—Surface brightness profile of KIG 284 (squares) with best-fit de Vaucouleurs $R^{1/4}$ (dashed line) and exponential disk (solid line) models overlaid. This galaxy is less centrally concentrated than elliptical galaxies, so this profile confirms our previous classification of KIG 284 as an S0 galaxy. The vertical line indicates the seeing ($1''.8$) in the image from which the surface brightness distribution was derived. The small companion galaxy to the southwest of KIG 284 has not been included in the surface brightness profile.

KIG Catalogue (see Table 1), elliptical outnumber S0 galaxies nearly 2:1.

We interpret these LF results to mean that very isolated environments are just as likely to form very luminous elliptical galaxies as are dense groups and rich clusters. Since it is now thought that many or perhaps all elliptical galaxies were formed by mergers of disk galaxies (Barnes & Hernquist 1992; Mihos 1995), our LF results for KIG galaxies are not inconsistent with the hypothesis that very isolated E galaxies formed by mergers as well. This is a particularly interesting suggestion for the most luminous elliptical galaxies, whose merger histories in clusters and dense groups could be quite different from the mergers that occasionally occur in sparser environments. If the very luminous E galaxies in the KIG sample formed through mergers, then they should be the best cases in the KIG sample for being the merger remnants of entire dense groups of galaxies.

We intended to further test the merger hypothesis for forming very isolated elliptical galaxies specifically by searching for extended X-ray emission around a few of the most luminous KIG E galaxies. Luminous diffuse X-ray emission would be expected if these elliptical galaxies were the final stage in the evolution of poor, compact groups of galaxies (Mulchaey & Zabludoff 1998). Mulchaey & Zabludoff (1999) reported the detection of one isolated elliptical, NGC 1132, at $L_X = 5 \times 10^{42} h_{70}^{-2} \text{ ergs s}^{-1}$ (see also Macagni et al. 1987), and Mulchaey & Zabludoff (1998) detected a few elliptical-dominated poor groups of galaxies at comparable L_X . Thus, we had hoped to observe several luminous KIG elliptical galaxies at or below this sensitivity limit to characterize the X-ray properties of isolated E galaxies. However, only one of our four proposed targets was observed with *Chandra* ACIS-S, and we have now shown this galaxy, KIG 284, to be a luminous S0 and not an elliptical. Therefore, our single nondetection at $L_X < 10^{41} h_{70}^{-2} \text{ ergs s}^{-1}$, a full factor of 10 below the NGC 1132 detection, does not significantly constrain the origins of the KIG isolated elliptical or S0

galaxies. Also, since our upper limit on KIG 284 is comparable to the L_X observed for some S0 galaxies (e.g., NGC 1553; Blanton et al. 2001), we have no evidence that KIG 284 has abnormal X-ray properties for an S0 galaxy. Therefore, further *Chandra* observations are required to test the merger hypothesis for these systems.

While there is now significant evidence that many or all elliptical galaxies were formed by the merging of disk galaxies, the origins of S0 galaxies are more obscure. Because most S0 studies have concentrated on cluster S0 galaxies, the proposed origins of these systems mostly involve processes that remove gas from disk galaxies and thus truncate star formation (Mihos et al. 1995; Quilis et al. 2000). However, some of these processes may not be relevant to the histories of very isolated S0 galaxies. The existence of isolated S0 galaxies at luminosities comparable to group and cluster S0's suggests that there are at least two ways in which S0 galaxies can form, one method that is operable in the presence of a dense intragroup or intracluster gas and one that does not require external gas. However, the dearth of S0 compared to elliptical galaxies (1:1.75) in the KIG sample is in great contrast to their relative abundance in the general population (S0 outnumber E galaxies 4:1 in the CfA survey). This argues that gas stripping or other removal processes that involve a dense external medium are the most efficient method for forming S0 galaxies.

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