NGC 1600: CLUSTER OR FIELD ELLIPTICAL?

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ABSTRACT

A study of the galaxy distribution in the field of the elliptical galaxy NGC 1600 has been undertaken. Although this galaxy is often classified as a member of a loose group, all the neighboring galaxies are much fainter and could be taken as satellites of NGC 1600. The number density profile of galaxies in the field of this galaxy shows a decline with radius, with evidence of a background at approximately 1.3 Mpc. The density and number density profile are consistent with that found for other isolated early-type galaxies. NGC 1600 appears as an extended source in X-rays, and the center of the X-ray emission seems not to coincide with the center of the galaxy. The velocity distribution of neighboring galaxies has been measured from optical spectroscopic observations and shows that the mean radial velocity is approximately 85 km s^{-1} less than that of NGC 1600, indicating that the center of mass could lie outside the galaxy. The velocity dispersion of the "group" is estimated at $429 \pm 57 \text{ km s}^{-1}$. The inferred mass of the system is therefore of the order of $10^{14} M_{\odot}$, a value that corresponds to a large group. NGC 1600 therefore shares some similarities, but is not identical to, the "fossil clusters" detected in X-ray surveys. Implications of this result for studies of isolated early-type galaxies are briefly discussed.

Subject headings: galaxies: elliptical and lenticular, cD

Online material: color figures

1. INTRODUCTION

The importance of isolated early-type galaxies in understanding galaxy and cluster evolution has led to a surge in the available number of catalogs of such objects (e.g., Colbert et al. 2001; Smith et al. 2004; Reda et al. 2004; Denicolo et al. 2005), with few galaxies in common between them. The variation arises from the different selection criteria used in the catalog construction. A common requirement is that there is no galaxy with a similar redshift within a certain distance, typically of the order of 1 Mpc. However, the incompleteness of current galaxy catalogs, and in particular the lack of complete redshift information, usually requires a visual inspection of the field as final confirmation that the galaxies are isolated. The catalog of Smith et al. (2004, hereafter SMG04) only used redshift information for the central galaxy and discounted any galaxies which had a bright galaxy nearby in projection. It thus contains the strictest isolation criteria and all galaxies in the sample are the most dominant member in the field by at least 2.2 mag within 500 kpc and 0.7 mag within 1 Mpc. Again, visual inspection confirmed that these galaxies were indeed isolated. The SMG04 catalog will miss several galaxies in the other samples, as no redshift information is applied. However, interpretation of the local faint galaxy environment is simplified by the lack of other bright galaxies nearby which may have their own dwarf population.

NGC 1600, an 11.9 *B*-magnitude $(K = 8.1)$[4] E3–E4 galaxy at a distance of approximately 64 Mpc (NED[5] and using $H_0 =$

73 km s^{-1} Mpc^{-1}) was included in the sample of SMG04 due to the large magnitude difference between it and other nearby galaxies, even though it is often quoted as being at the center of a loose group containing a number of NGC-cataloged galaxies, together with several other fainter galaxies. Denicolo et al. (2005) classify it as a field elliptical rather than isolated. The brightest galaxy within a projected distance of 1 Mpc is NGC 1594, a 13.9 *B*-magnitude $(K = 10.2)$ galaxy at least 800 kpc away. The two closest NGC galaxies, NGC 1601 and NGC 1603 at separations of 1.6′ and 2.6′ (30 and 48 kpc), respectively, are both almost 3 mag fainter than NGC 1600. Thus, although there are several neighboring galaxies in the field of NGC 1600, it is by far the dominant galaxy in the group. There is a poor group of galaxies (Zwicky cluster 0430.8−0424B; Zwicky et al. 1961–1968) at a distance of 53′ to the north of NGC 1600, with a mean velocity of 5030 km s^{-1} (Baiesi-Pillastrini et al. 1984), a velocity similar to that of NGC 1600 (4715 km s^{-1}). The brightest galaxy in this group still satisfies the isolation criteria of SMG04, i.e., it is more than 2.2 mag fainter than NGC 1600.

The galaxy has been the subject of several previous studies. In a photometric study, Matthias & Gerhard (1999) found the galaxy to have boxy isophotes, while kinematic studies (Bender et al. 1994; Faber et al. 1989) found that there was little rotation in the stellar component, with a maximum of 30 km s^{-1}, while the central velocity dispersion is typical of larger elliptical galaxies (321 km s^{-1}). There is evidence of past and possible ongoing star formation, with the presence of Hα regions (Trinchieri & di Serego Alighieri 1991) and dust (Ferrari et al. 1999). Thus, it is highly likely that NGC 1600 is a merger remnant (Matthias & Gerhard 1999), although, with broadband colors typical of elliptical galaxies (NED), this merger is likely to have occurred a long time ago. Estimates of the age of this galaxy hence range from 4.6 up to 8.8 Gyr (Trager et al. 2000; Terlevich & Forbes 2002). These results are in agreement with the study of a sample of isolated early-type galaxies by Reda et al. (2004), who found that several galaxies had boxy isophotes, evidence of dust and past merger activity but had remained relatively dormant for several gigayears.

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[4] All near-infrared magnitudes in this paper have been obtained from the 2MASS catalogs.
[5] The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

NGC 1600 is also a weak X-ray source (Sivakoff et al. 2004), showing extended emission out to at least $100''$ (corresponding to a physical radius of 30 kpc), with a possible central component associated with NGC 1600 and an outer emission region associated with the group. The extended outer emission is centered to the northeast of the central galaxy, suggesting that the center of the potential is slightly offset from NGC 1600. The presence of extended material around the galaxy is also suggested from the tailed X-ray structure around the nearby galaxy NGC 1603, indicating an effect of ram pressure stripping. The large magnitude difference between NGC 1600 and the other galaxies in its neighborhood, together with the extended X-ray emission, would suggest that NGC 1600 may be a fossil group.

Whereas the radius of about $200''$, or 60 kpc, total soft X-ray emission of 2×10^{41} ergs s^{-1} and absolute magnitude of $M_R = -22.5$ indicate that this galaxy does not satisfy the criteria to be a fossil group, as stated by Jones et al. (2003), it is worthwhile remarking that in recent work by Santos et al. (2007) some cases of fossil groups are identified which resemble some of the NGC 1600 group properties. Moreover, detailed studies by Mendes de Oliveira et al. (2006) and Cypriano et al. (2006) have measured properties of fossil groups that make them more similar to clusters than was initially expected. To distinguish between the various possible evolutionary scenarios (rich group, fossil group, or isolated galaxy) a more detailed investigation of the potential around NGC 1600 is thus necessary.

With a similar technique to that used by Zaritsky et al. (1993, 1997), it is possible to use the dynamics of the fainter galaxies to derive an estimate of the size and mass of the central potential. This should enable us to distinguish between the isolated or cluster hypotheses for the description of NGC 1600. From the dynamics of galaxies in groups, estimates of their mass are typically of the order of 10^{13} $M_\odot$ (e.g., Parker et al., 2005) while spiral galaxies have masses an order of magnitude smaller, even allowing for any dark matter component at large radii (e.g., Zaritsky et al. 1997). The radii of groups is also an order of magnitude greater than that of the individual galaxies themselves (e.g., Karachentsev 2005). The mass and extent of elliptical galaxies is at present very uncertain, with X-ray evidence that some are surrounded by dark matter halos (e.g., Fukazawa et al. 2006), while optical evidence may suggest not, with masses similar to that of spiral galaxies (e.g., Romanowsky et al. 2003). However, the large difference between the likely mass and extent of galaxy groups compared to isolated galaxies should enable us to distinguish between the group member and the isolated elliptical hypotheses for NGC 1600 through a dynamical study of the other neighboring galaxies.

The presence of X-ray emission around NGC 1600 can provide an estimate of the total mass of the galaxy, assuming hydrostatic equilibrium within the gas. Fukazawa et al. (2006), analyzing *Chandra* observations of a number of elliptical galaxies, determined a mass-to-light ratio for NGC 1600, at the effective radius of 14.5 kpc, of 10.58 $M_\odot/L_\odot$, corresponding to a total mass of approximately 10^{12} $M_\odot$. This is higher than that of many galaxies in their sample.

An investigation of the spatial distribution of galaxies around NGC 1600 may also help in distinguishing between the isolated and group hypotheses. SMG04 found a weak excess of galaxies around isolated elliptical galaxies out to at least 500 kpc, with an exponential slope of -0.6 ± 0.2. This is similar to that found for poor groups and around individual galaxies but is less steep than that found for clusters (e.g., Hansen et al. 2005). The number density of bright galaxies around isolated galaxies, however, is much lower than that found around groups and clusters.

2. OBSERVATIONS AND DATA REDUCTION

To obtain an estimate of the radial number density profile of galaxies around NGC 1600 we have used the APM scans of United Kingdom Schmidt Telescope (UKST) sky survey plates of a circular area of radius $1.5°$ (corresponding to a scale of 1.65 Mpc at the distance of NGC 1600) surrounding this galaxy. Only those objects brighter than 20th magnitude in B and classified as galaxies in both B and R were selected. NGC 1600 lies within $1°$ of the edge of plate 764 in the survey, and thus the adjoining plate, 765, must be matched in both position and magnitude. Using the TOPCAT package in the Starlink suite of astronomical data reduction packages, we have used the matching objects detected by the APM in the overlap region of plate 764 and 765 to determine the accuracy of matching both in magnitude and position. The average magnitude difference between galaxies that lie in the overlap region and are detected in both plates is less than 0.05 mag, and thus no magnitude difference is assumed. In addition, the number of matched objects varies by less than 5% when we vary the angular distance between $1''$ and $10''$ for those objects that are classified as matched. This indicates that the positional accuracy of the scans is less than $1''$. However, due to several errors, such as misclassification, vignetting and magnitude errors for bright galaxies, inconsistencies will arise between the galaxy samples derived from each plate, even though the mean density is almost identical and the magnitudes and positions agree for duplicate objects. The plates therefore cannot be merged, as this leads to an increase in the number density of galaxies within the overlap region. Thus, to overcome this problem and reduce vignetting problems at the edge of the plate, half the overlap region was taken from plate 764 and half from plate 765.

The APM scans, as in all automatic object detection methods, have difficulty with not only star-galaxy separation at faint magnitudes but also the correct selection of objects within the halos of bright stars and galaxies. For example, diffraction spikes are quite often split into several individual objects and their noncircular nature often leads to such structures being classified as nonstellar. There are several bright stars with diffraction spikes on the UKST plates of the field around NGC 1600. These are not in the immediate neighborhood of the central galaxy. However, to ensure that the effect of misclassification and extraneous objects was insignificant, we have overlaid the positions of the objects detected by the APM over the UKST image for a visual inspection of the detected objects. No objects were found corresponding to diffraction spikes from bright stars. The star-galaxy separation technique used by the APM is also not 100% accurate and depends heavily on the magnitude of the objects, becoming highly significant beyond $B = 20$ (e.g., Maddox et al. 1990). Thus, although it is likely that some objects are misclassified, by limiting the sample to $B = 20$, the percentage of misclassifications is small; and this is confirmed by a visual inspection of the detected objects. A study of the detected objects superimposed on the UKST Sky Survey plates showed that several of the bright galaxies in the field of NGC 1600 were not in the catalog derived from the APM scans. Many of these objects were classified as merged objects by the APM. To estimate the effect of these missed galaxies on the determination of the radial number density profile, these objects were added by eye, discounting faint objects that the eye has difficulty classifying and that may also fail the magnitude cutoff. This subjective technique introduces more errors into the analysis but will lead to some estimate of the true errors in the APM number densities.

For the dynamical study, all galaxies within a $25'$ radius of NGC 1600 were selected from the APM catalog (e.g., Lewis &
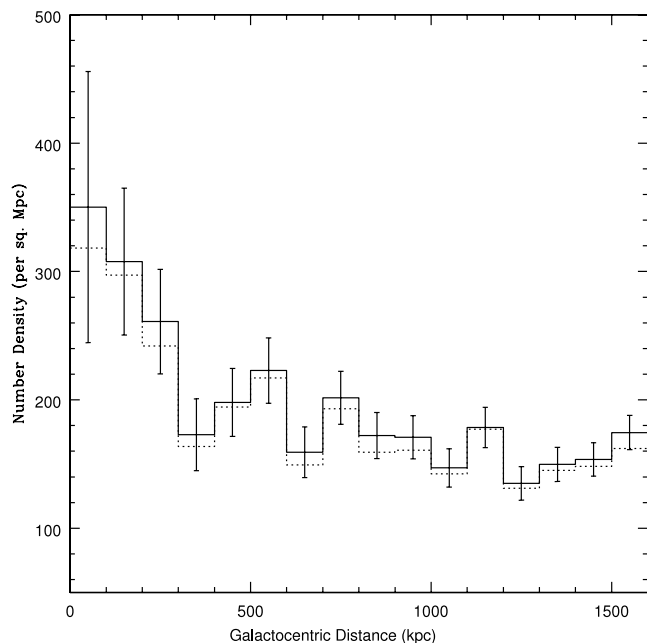
FIG. 1.—Projected density of galaxies brighter than $B = 20$ around NGC 1600. The solid line includes galaxies selected by eye, while the dotted line is only those galaxies detected by the APM. At the redshift of NGC 1600, $B = 20$ is equivalent to $M_B = -14$.

FIG. 2.—Same as Fig. 1, but for galaxies brighter than $R = 18$.

Irwin 1996) of the UKST survey plates. Each object had to be detected as a galaxy in both B and R to be selected, and a further visual check was made to ensure the correct identification as a galaxy. A magnitude cut of $R = 20$ was made to facilitate the possibility of getting a redshift. As mentioned above, several bright galaxies were not in the APM galaxy catalog due to misclassification and these were added to the sample by hand.

The field was observed during the nights of 2003 January 7 and 2005 January 12 using the Autofib2/WYFFOS multifiber spectrograph on the 4.2 m William Herschel telescope (WHT) on the island of La Palma. During the 2003 run the large, $2.7''$, fibers were used to maximize the signal from the extended sources, whereas in 2005 only the small, $1.6''$, fibers were available. In addition, in 2003 the CCD used only enabled 120 fibers to be used, while in 2005 the CCD had been replaced by a two $2k \times 2k$ EEV CCD mosaic, enabling the number of fibers available for objects to be increased to 150. The smaller CCD used in 2003 suffered from contamination of neighboring spectra when bright objects were observed. As most of the galaxies observed here were faint, this was not a significant problem.

The AF2configure program was used to configure the observations, with the brighter galaxies and those galaxies within the unvignetted field of $20'$ radius preferentially selected for observation. With the limitations imposed by the instrument it was impossible to observe all galaxies in the field during one run. At least four stars in the field were selected for guiding through the fiducial bundles, and unused fibers were placed on areas of the background field for sky subtraction. The data from the 2003 run were reduced, and the galaxies for which no redshift was obtained, together with a selection of previously unobserved galaxies, were selected for the 2005 run. On both runs, a wavelength range of approximately 3850–5450 Å was covered, with a pixel size of 0.4 Å. Wavelength calibration was warranted by frequent observations of a neon and helium arc. Seeing during the 2003 run was typically about $1''$ and a total of 5400 s integration time was obtained on the field. In 2005 the seeing was $1.4''$ on average, with 7200 s of integration on the field.
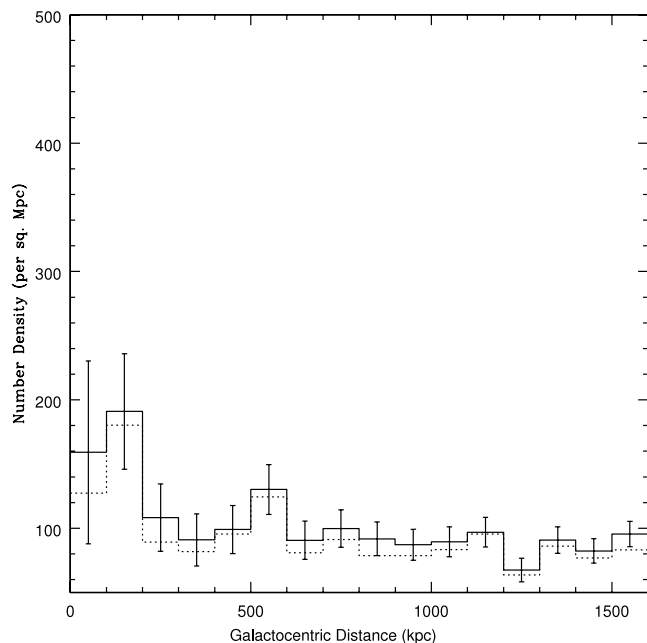
Due to the arrangement of the fibers on the spectrograph, the observed spectra are not uniformly placed on the CCD but are arranged in rows of three, with a shift of 60 pixels in the dispersion direction between three consecutive fibers. This leads to complications in the data reduction, and so the data were reduced using the observatory-supplied wyffosREDUC IRAF package. This package bias-subtracts, extracts the fibers, and subtracts the sky in an automated fashion. However, to ensure the reduction was satisfactory, each step was visually checked. As the sky subtraction in this package is not ideal inspections of the spectra were made to ensure satisfactory sky subtraction, with regions around possible sky emission lines removed. Redshifts were obtained using the IRAF xcsao package, with cross-correlation against a range of templates.

3. RESULTS AND DISCUSSION

Figure 1 shows the radial number density profile of galaxies centered on NGC 1600 estimated from the APM scans of the UKST sky survey plates of the region. There is a decline in the number density with radius and a strong suggestion that the background population has been reached at a radius of about 1.3 Mpc. The errors displayed are calculated assuming Poissonian statistics and are thus are likely to be an underestimate. Misclassification and problems with measuring bright galaxies will almost certainly increase the error estimates, while in the inner 150 kpc the small number of detected galaxies and the blanking factor due to the presence of NGC 1600 will lead to greater uncertainties. The difference between the profile determined purely by the APM detections and that with galaxies missed by the APM but selected by eye included lies within the errors.

Figure 1 clearly shows a decrease in the number density of galaxies with galactocentric distance. The background galaxy population density appears to be reached at a galactocentric distance of about 1.3 Mpc, for a number density of approximately 150 galaxies per square megaparsec. Fitting an exponential to this distribution gives a slope of -0.9 ± 0.3. Although slightly steeper than the -0.6 ± 0.2 slope found by SMG04 for their total sample of isolated ellipticals, they agree within the errors. However, the slope also agrees within the errors with the slope of -1.1

TABLE 1
GALAXIES IN THE NGC 1600 AREA OBSERVED IN THIS WORK (UPPER PART) OR IN THE LITERATURE

R.A. (J2000.0)	Decl. (J2000.0)	B Mag	v	Error	Comments
04 31 39.86..........	−05 05 09.6	11.93	4715	16	NGC 1600, parent, 4681 ± 8,[a] 4739 ± 33[b]
04 30 04.25..........	−05 00 35.6	15.32	4196	10	
04 30 09.00..........	−05 21 16.9	16.39	5321	9	
04 30 23.18..........	−04 53 33.0	16.40	3729	34	
04 30 42.73..........	−04 52 13.4	14.78	4009	10	IC 373
04 30 58.66..........	−05 13 56.4	19.77	4704	27	
04 31 07.69..........	−05 01 09.3	18.25	5209	30	
04 31 15.82..........	−04 57 03.2	16.16	4947	9	
04 31 28.66..........	−05 16 28.9	16.36	4422	10	
04 31 41.70..........	−05 03 37.4	14.80	4887	12	NGC 1601, 4997 ± 56[c]
04 31 43.18..........	−04 59 14.3	16.83	5704	19	
04 31 47.10..........	−05 16 07.2	16.74	4399	21	
04 31 49.94..........	−05 05 39.8	15.15	4990	13	NGC 1603, 4972 ± 14[d]
04 31 58.55..........	−05 22 11.6	14.46	4473	13	NGC 1604, 4544 ± 25[e]
04 32 03.30..........	−05 01 57.0	15.91	4802	23	NGC 1606
04 32 10.39..........	−05 08 12.1	16.14	4739	12	
04 32 24.86..........	−05 15 50.1	16.93	4562	26	
04 32 25.40..........	−05 11 18.9	16.13	5092	25	
04 32 30.37..........	−05 09 18.7	16.13	4630	7	
04 28 18.8...........	−05 10 44	14.35	4267	25	NGC 1580
04 28 25.7...........	−04 37 50	>15	4680	60	
04 28 26.0...........	−04 33 49	15.75	4846	39	
04 30 34.7...........	−05 31 54	17.72	4908	60	
04 30 51.6...........	−05 47 54	13.72	4329	4	NGC 1594
04 31 12.5...........	−05 31 44	16.26	5202	60	
04 31 38.8...........	−04 35 18	14.36	4008	8	NGC 1599
04 31 52.1...........	−05 45 25	15.47	4121	41	
04 32 03.1...........	−04 27 38	14.51	4255	3	NGC 1607
04 32 08.4...........	−04 12 43	15.74	4564	60	
04 33 01.0...........	−04 11 19	16.82	4904	15	
04 33 05.9...........	−04 17 51	14.40	4261	15	NGC 1611

NOTES.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. At the bottom part of the table, we list other galaxies within a projected separation of 1 Mpc and 1000 km s^{-1} of NGC 1600 but not observed by us. Data are from HyperLeda.
[a] NED, from Collobert et al. (2006).
[b] HyperLeda average.
[c] NED, from de Vaucouleurs et al. (1991).
[d] NED, from Simien & Prugniel (2000).
[e] NED, from Huchra et al. (1993).

found for groups and clusters by Hansen et al. (2005) and also for an isothermal distribution. From their study of a sample of 10 isolated ellipticals, Reda et al. (2004) claim that only the faint dwarf galaxies, with $M_R \gtrsim -15.5$, show any clustering around the central galaxy. At the distance of NGC 1600, the limiting magnitude of our sample corresponds to an absolute B magnitude of -14, and therefore we would expect to see the excess of neighbors. By increasing the limiting magnitude to $R = 18$, corresponding to an absolute magnitude of $M_R = -16$, the number densities decrease significantly and the error bars therefore increase. Figure 2 shows the resultant density profile for this brighter magnitude limit. Although there is evidence of a small excess of galaxies at small galactocentric distances and these objects are seen by visual inspection of the field, the error bars are large enough such that a uniform distribution, as suggested by Reda et al. (2004), is not ruled out.

The radial density profile thus indicates that there is a significant population of faint ($M_B \gtrsim -15$) galaxies in the neighborhood of NGC 1600, similar to that found, in general, from a sample of isolated ellipticals by SMG04. These results are in agreement with the results of Reda et al. (2004), who suggest that apparently iso-

lated galaxies do not have a large number of bright galaxies in their neighborhood but could be surrounded by fainter galaxies. The total excess of galaxies[6] within 500 kpc down to $M_B = -14.6$ is approximately 55, in good agreement with the average for the sample of 10 galaxies of SMG04. From the radial number density profiles, therefore, NGC 1600 does not appear unusual with respect to other isolated early-type galaxies with an extended population of neighboring faint galaxies but a lack of bright companions.

Galaxies in the field of NGC 1600 with measured redshifts are shown in Table 1. Previously measured redshifts are also given, together with those galaxies listed in NED and HyperLeda with redshifts between 3700 and 5700 km s^{-1} and within a projected distance of $57'$ of NGC 1600 (corresponding to a physical projected distance of 1 Mpc). Note that this latter list includes members of the galaxy group Zw 0430.8−0424B cataloged by Zwicky et al. (1961–1968).

[6] Compared to the background reached at approximately 1.3 Mpc, with a number density of approximately 150 $B < 20$ galaxies per square megaparsec, as seen in previous paragraphs.
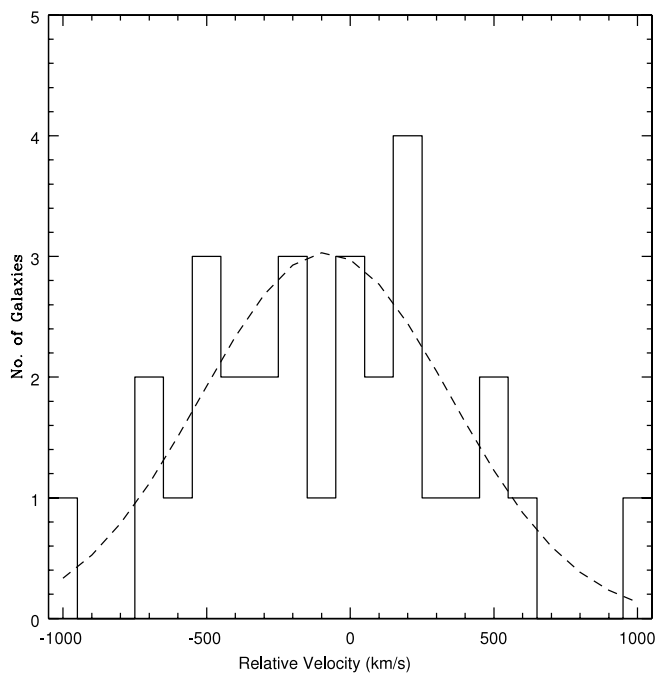
Fig. 3.—Histogram showing the velocity distribution of the galaxies in the NGC 1600 group, relative to NGC 1600 itself. The dashed line corresponds to the best-fit Gaussian, with $v_{cent} = -85$ km s^{-1} and $\sigma v = 435$ km s^{-1}.

With a total of 30 known galaxies within 1000 km s^{-1} of NGC 1600, our sample indicates that a very significant population of galaxies exists in the physical neighborhood of NGC 1600, as expected from previous observations by other authors and also the photometric study described above. The large number of measured redshifts allows an estimate of the velocity distribution of the galaxies in the field of NGC 1600 to be determined, together with an estimate of the mass. Figure 3 shows the relative velocity distribution of the 30 companions with respect to NGC 1600. Also shown is the best-fit Gaussian, with a mean relative velocity of -85 km s^{-1} and a velocity dispersion of 435 km s^{-1}.

In order to obtain a more precise and less model-dependent measurement of these parameters, we have also used the ROSTAT code to estimate the mean redshift of the group and its radial velocity dispersion (Beers et al. 1990), with the usual cosmological correction and the correction for velocity errors given by Danese et al. (1980). Given that there is a large number of redshifts available, the biweight estimators were used for both the location and scale (Beers et al. 1990). Errors were obtained in all cases by jackknifing the biweight. Using this machinery we measure the group's central location at 4634 ± 79 km s^{-1}, with a radial velocity dispersion value of 429 ± 57 km s^{-1}.

The redshift of NGC 1600 lies 1 σ away of the system central velocity, and thus it appears that NGC 1600 is not at the dynamical center of the group, even though it is the brightest member by over 2 mag. This is in agreement with Sivakoff et al. (2004), who found that the X-ray emission is centered slightly to the northeast of NGC 1600, also suggesting that the galaxy is not at the center of the gravitational potential. An estimate of the geometry of the system can be ascertained from Figure 4, where we show the positions and velocities relative to NGC 1600 of the galaxies for which a redshift has been measured.

On the other hand, the velocity dispersion of 429 km s^{-1} would imply a bolometric X-ray luminosity $L_X = 2.7 \times 10^{43}$ ergs s^{-1}, as in the empirical relation of Ortiz-Gil et al. (2004), which was measured from a sample of 171 clusters drawn from the REFLEX catalog. Sivakoff et al. (2004) measure an X-ray flux which is

2 orders of magnitude smaller.[7] Although the L_X-σ relation is not well defined, NGC 1600 is more than 3 σ away from the expected value, and hence lies significantly outside the scatter.

A velocity dispersion value of 429 km s^{-1} for an elliptical galaxy is very high, placing it well off the Faber-Jackson relationship (Faber & Jackson 1976). Hau & Forbes (2006) measured the radial distribution of the velocity dispersion for the Reda et al. (2004) sample of isolated galaxies. They find no galaxy with a similar velocity dispersion to that found here, with an increase in the V/σ with radius and a general decrease of velocity dispersion with radius, out to the effective radius. Velocity dispersions of loose groups are found to be of the order of a few hundreds of kilometers per second (e.g., Ramella et al. 1995), with a value of 429 km s^{-1} being at the upper limit for loose groups but at the lower range for clusters of galaxies. Making the somewhat arbitrary assumption that the group can be approximated by an isothermal sphere, it is possible to derive an upper limit for the mass of the group from $M(R) = (\pi\sigma^2 R)/G$ (Binney & Merrifield 1998). A simple application of this formula to the NGC 1600 "group" gives a mass of approximately 2×10^{14} $M_\odot$, typical of the richer groups or poorer clusters. Although only 30 satellites have been detected, we can also use the estimate of Bahcall & Tremaine (1981) to derive an estimate of the mass of the central object. Assuming that the galaxies are distributed uniformly on radial and circular orbits, the mass of the central object is given by $M = 48\langle r\Delta v^2/2G\rangle/\pi$. Applying this formula to the group data gives a mass estimate of 1.5×10^{14} $M_\odot$, in agreement with the isothermal sphere determination. Zaritsky & White (1994) have shown from extensive modeling that errors in such an estimate are not large as long as interlopers are excluded. However, the presence of interlopers can have a serious effect on mass determinations of galaxies and clusters (e.g., Chen et al. 2006). To estimate the effect of interlopers on our sample, we can remove from the sample those galaxies whose relative velocities are greater than 900 (500) km s^{-1}. This would drop the value of the mass from $1.5-1.2 \times 10^{14}$ (7.9×10^{13}) $M_\odot$. Further elimination of those galaxies at projected distances greater than 1 Mpc from NGC 1600 would drop the mass estimate even further to 2.1×10^{13} $M_\odot$, but for a sample of only 13 galaxies. This lower estimate is typical of loose groups (e.g., Parker et al. 2005) and is perhaps larger than that expected from dynamical observations of the inner regions of elliptical galaxies such as found from the study of planetary nebulae (e.g., Romanowsky et al. 2003). Fukazawa et al. (2006) have also used the X-ray emission to derive an estimate of 10.58 for the mass-to-light ratio for the NGC 1600 "group" out to the effective radius of 13.8 kpc, giving a mass of approximately 10^{12} $M_\odot$ at this distance. Extrapolating this estimate to larger radii is subject to considerable error but, if the radial mass-to-light ratio profile for NGC 1600 is similar to that found for other ellipticals by Fukazawa et al. (2006), the mass determination from the X-ray emission is not in major disagreement with that from our dynamical study. However, the variations associated with the different methods suggest that our estimates of the group mass are still subject to an uncertainty of about a factor of 2.

The results of the number density and radial velocity studies allow us to probe further our definition of an isolated galaxy. The former study indicates that there is a population of much fainter galaxies surrounding NGC 1600, with a small number of brighter galaxies in the immediate vicinity which are not seen in the sample of Reda et al. (2004). However, these bright galaxies have a

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[7] REFLEX luminosities are bolometric, while Sivakoff et al. (2004) measure only in the soft band. However, the corrections from soft to bolometric represent a factor between 1.1 and 2 for this kind of groups/clusters (Bohringer et al. 2004, Table 5).
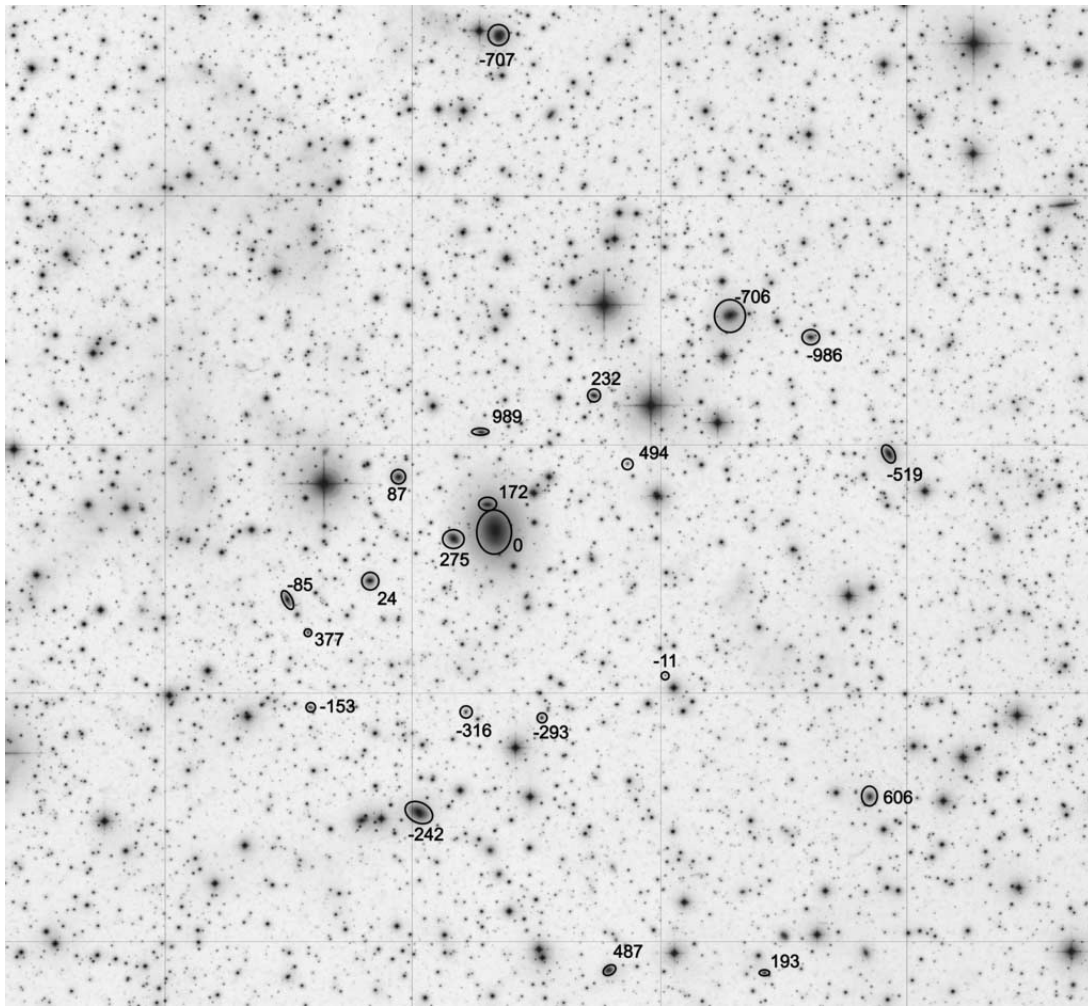
FIG. 4.—UKST Sky Survey 1° square image of the NGC 1600 field. Those galaxies for which a redshift has been measured are marked, and their velocity relative to NGC 1600 has been labeled. Notice that some galaxies in Table 1 are outside this field. Use of these images is courtesy of the UK Schmidt Telescope (copyright owned by the Particle Physics and Astronomy Research Council of the UK and the Anglo-Australian Telescope Board) and the Digitized Sky Survey created by the Space Telescope Science Institute, operated by the Association of Universities for Research in Astronomy (AURA), Inc., for NASA, and is reproduced here with permission from the Royal Observatory Edinburgh.

negligible effect on the overall number density profile around NGC 1600. The profile is therefore not significantly different from that found from other isolated early-type galaxies. The published photometric properties are also similar to those for isolated ellipticals, with little evidence of recent merging. The dynamical study, however, together with the X-ray data, indicates that NGC 1600 is not sitting at the center of the potential and is surrounded by a massive halo extending out to several hundred kiloparsecs. This would normally be taken as evidence that NGC 1600 is a member of a group of galaxies.

In any case, a simple comparison of the $J - K$ vs. K color diagram of the NGC 1600 group of galaxies with that of the Coma Cluster (Fig. 5) shows that there are similarities between both fields. The main differences are, of course, the large difference in richness and the already mentioned magnitude gap between NGC 1600 and the second brightest K-band galaxy in the group (NGC 1611), which is much larger than that in Coma.

There are several similarities between NGC 1600 and the fossil groups of Jones et al. (2003): the large magnitude difference between it and its neighbors, the presence of a surrounding faint population, and the presence of extended X-ray emission. In addition, the absolute magnitude of NGC 1600 ($M_R \sim -23.0$) lies within the range of luminosities found for other fossil group central
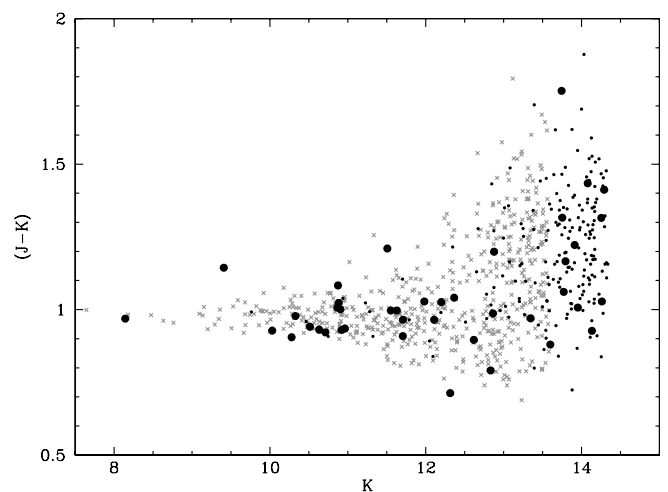

FIG. 5.—JK color-diagram of the NGC 1600 field. The dark large circles correspond to objects with redshifts that link them to NGC 1600, whereas the small circles are field objects without a redshift. As a comparison, the crosses mark the positions of galaxies in the Coma Cluster field, corrected to the distance of NGC 1600. *See the electronic edition of the Journal for a color version of this figure.*

galaxies, although at the fainter end of the range. Moreover, the measured velocity dispersion and absolute B-band magnitude position NGC 1600 perfectly in the σ_V vs. M_B relation for fossil groups, as described by Khosroshahi et al. (2006). If the scaling properties of the fossil groups as measured by D'Onghia et al. (2005) in their simulations apply, NGC 1600 would have been already in place (that is, more than 50% of the mass would already have been assembled) 7–8 Gyr ago, which matches the available age estimates. However, the X-ray properties of the NGC 1600 group are very different from those expected, with a much smaller extent and a much lower luminosity (Sivakoff et al. 2004). Thus, NGC 1600 could be taken as a new class of fossil group, where the central galaxy has grown from the merger of several fainter group members but is lacking the relatively intense X-ray emission normally associated with loose groups. Thus, it could be the result of a merger of a poor group, where the X-ray emission is expected to be much weaker. The presence of dust and emission regions within the galaxy support this merger hypothesis. NGC 1132, an isolated elliptical galaxy studied by Mulchaey & Zabludoff (1999), has similar properties to NGC 1600, with a faint extended X-ray envelope and surrounding excess population of dwarf galaxies, although the dynamical properties of the group are uncertain. Thus, NGC 1600 may not be the only example of such a past merger.

4. CONCLUSION

Although NGC 1600 is clearly surrounded by a number of other galaxies, the large magnitude difference suggests that it can be treated as an isolated field elliptical. Analysis of the APM scans of UKST Sky Survey plates shows that there is a clear excess of galaxies in the neighborhood of NGC 1600. In partial agreement with Reda et al. (2004), the excess is most clearly evident for the fainter galaxies, with galaxies brighter than $M_R = -16$ not showing such a clear excess. The number of galaxies around NGC 1600, together with their number density profile, is in agreement with the results of SMG04, indicating that this galaxy is not unique among isolated early-type galaxies.

Velocity measurements of galaxies in the field show a large excess at similar redshifts to NGC 1600. The dynamics of these galaxies indicates that the mass of the group is at least $10^{13} M_\odot$, a value typical of poor groups. Combining the data from these and previous studies indicates that NGC 1600 has many similarities to the fossil groups first detected in X-rays, although there are several differences, most notably in the X-ray properties. We therefore suggest that NGC 1600 is a new type of fossil group, the result of the merger of a loose group of galaxies, with the last merger occurring over 4 Gyr ago.

The similarity between NGC 1600 and other galaxies in the SMG04 sample of isolated ellipticals suggests that many such objects may be the result of the merger of loose groups. This will only be determined by a detailed photometric and dynamical study of a larger sample of isolated galaxies. As the majority of galaxies lie in loose groups, including our own, such an investigation would lead to a greater understanding of galaxy evolution.

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