COMPANIONS TO ISOLATED ELLIPTICAL GALAXIES: REVISITING THE BOTHUN-SULLIVAN SAMPLE

Barry F. Madore and Wendy L. Freedman

Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101; barry@ipac.caltech.edu, wendy@ociw.edu

and

Gregory D. Bothun

Department of Physics, 415 Willamette Hall, University of Washington, Eugene, OR 97403; nuts@moo.uoregon.edu

Received 2002 August 4; accepted 2004 February 9

ABSTRACT

We investigate the number of physical companion galaxies for a sample of relatively isolated elliptical galaxies. The NASA/IPAC Extragalactic Database (NED) has been used to reinvestigate the incidence of satellite galaxies for a sample of 34 elliptical galaxies, first investigated by Bothun & Sullivan using a visual inspection of Palomar Sky Survey prints out to a projected search radius of 75 kpc. We have repeated their original investigation using data cataloged in NED. Nine of these elliptical galaxies appear to be members of galaxy clusters; the remaining sample of 25 galaxies reveals an average of +1.0 ± 0.5 apparent companions per galaxy within a projected search radius of 75 kpc, in excess of two equal-area comparison regions displaced by 150–300 kpc. This is significantly larger than the +0.12 ± 0.42 companions/galaxy found by Bothun & Sullivan for the identical sample. Making use of published radial velocities, mostly available since the completion of the Bothun-Sullivan study, identifies the physical companions and gives a somewhat lower estimate of +0.4 companions per elliptical galaxy. This is still 3 times larger than the original statistical study, but given the incomplete and heterogeneous nature of the survey redshifts in NED, it still yields a firm lower limit on the number (and identity) of physical companions. An expansion of the search radius out to 300 kpc, again restricted to sampling only those objects with known redshifts in NED, gives another lower limit of 4.5 physical companions per galaxy. (Excluding five elliptical galaxies in the Fornax Cluster, this average drops to 3.5 companions per elliptical.) These physical companions are individually identified and listed, and the ensemble-averaged radial density distribution of these associated galaxies is presented. For the ensemble, the radial density distribution is found to have a fall-off consistent with $\rho \propto R^{-0.5}$ out to approximately 150 kpc. For non-Fornax Cluster companions the fall-off continues out to the 300 kpc limit of the survey. The velocity dispersion of these companions is found to reach a maximum of 350 km s$^{-1}$ at around 120 kpc, after which they fall at a rate consistent with Keplerian fall-off. This fall-off may then indicate the detection of a cut-off in the mass-density distribution in the elliptical galaxies’ dark matter halo at ~100 kpc.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: statistics

On-line material: machine-readable table

1. INTRODUCTION

Recently, the numbers of satellite galaxy companions to galaxies have received renewed interest in the context of cold dark matter (CDM) models for structure formation, where the theoretical expectation of the models exceeds the observed companions by approximately a factor of 100 (e.g., Moore et al. 1999; Klypin et al. 1999). This large number of expected companions results from the relative inefficiency of the galaxy amalgamation process from CDM seeds in which each large mass ($10^{12} M_\odot$) is surrounded by a large relic population. Given the nature of the large-scale structure, this relic population can either be confined to the group/cluster potential or bound to individual large galaxy halos. In addition, the incidence of physical companions can provide an important constraint on the merger history of galaxies and/or the role that dynamical friction plays in adding additional material to galaxies after they have formed. The lack of any observational counterpart to the theoretical expectation may be somewhat troubling, but there are a host of viable explanations for their absence. For instance, it is possible that the systems are just too diffuse to be detected, i.e., that they have been essentially heated/evaporated by an ionizing UV background and/or supernova winds due to star formation in the massive galaxies.

Some years ago, Bothun & Sullivan (1977, hereafter BS77) selected out a sample of 34 elliptical galaxies for a survey of their dwarf galaxy companions. These elliptical galaxies were defined to be isolated, based on a criterion that no other large/bright galaxy was found to be at a projected radius of 150 kpc of the elliptical. In retrospect, that isolation criterion was naive, but little was known about large-scale structure at that time. Using the Palomar Observatory Sky Survey (POSS) prints and a digitizer, BS77 claimed to have searched for companions down to a limiting diameter of 0′2, although recognizing galaxies at that limiting diameter on POSS prints is likely much more difficult than BS77 appreciated. From that survey, BS77 concluded that, statistically speaking, this sample of “isolated” elliptical galaxies had an excess of +0.12 ± 0.42 companions, i.e., indistinguishable from zero. This differed significantly when compared to a similar study by Holmberg (1969), who found +1.08 ± 0.37 companions.
around selected spiral galaxies. Both studies utilized the POSS prints and statistical background fields that were selected to lie relatively near the target galaxy. Again, given our knowledge of the extent of large-scale clustering, the control fields were, in general, placed too near the target galaxy.

In the ensuing years the study of companions has been continued by Zaritsky and by Vader, and each of their collaborators, in a series of papers (Zaritsky et al. 1993, 1997; Lorrimer et al. 1994; Vader & Sandage 1991; Vader & Chaboyer 1992 and references therein). Zaritsky studied the kinematics of the general population of companions orbiting spiral galaxies, while Vader specifically investigated the dwarf elliptical populations around central galaxies of diverse morphological types. Conclusions of direct relevance to this paper (see Table 1 for a concise summary) are that nearby field spiral galaxies typically have only one or two physical companions each, and of those, the early-type dwarf-elliptical companions are more preferentially concentrated around their parent galaxies. This may be indicative of a population of bound physical companions, similar to that seen around some cD galaxies in clusters (e.g., Bothun & Schombert 1990).

More recently, the Sloan Digital Sky Survey (SDSS) and the Two Degree Field (2dF) Galaxy Redshift Survey have each resulted in parallel and complementary investigations into the frequency and distribution of satellites around high-luminosity galaxies in those samples. Prada et al. (2003) report the theoretically expected falloff of velocity dispersion with radius for a sample of 283 SDSS primaries having at least one orbiting companion within a projected radius of 260 kpc. And similarly, Brainerd & Specian (2003) report on the kinematics of 1556 satellites orbiting 809 isolated host galaxies drawn from the 2dF Survey. And for completeness we also note, in passing, that weak gravitational lensing studies also bear on the question of companions and the distribution of dark matter around isolated galaxies, as exemplified by the study of McKay et al. (2001).

Finally, Garcia-Barreto et al. (2003) chose 78 SB galaxies from the Revised Shapley-Ames (RSA) Catalog (Sandage & Tammann 1981) and searched for neighboring galaxies out to 20 central-galaxy diameters (corresponding to radial separations up to 1 Mpc). They identified and listed 347 radial velocity–confirmed neighbors, leading to an average of 4.5 neighbors per barred galaxy. Omitting galaxies in the Virgo Cluster, such as NGC 4435, 4535, and 4654, drops the average to about three neighbors per SB galaxy.

In this paper our interest is refocused on the companion population surrounding elliptical galaxies, specifically the “isolated elliptical galaxies” studied by BS77. Although the procedures used in BS77 were documented, none of the surrounding galaxies counted in either investigation were individually identified or subsequently published, since the stated intent was to draw a statistical conclusion about the general incidence of companions, not to necessarily identify or follow up any particular galaxy grouping or any given (apparent) companion. The conclusion was that the environments of elliptical and spiral galaxies were significantly different, in the sense that isolated ellipticals were statistically devoid of companions, while spirals had on average one physical companion each.

In the intervening quarter-century, many new surveys (Two Micron All Sky Survey [2MASS], Automatic Plate Measuring Facility [APM], etc.) to fainter limiting magnitudes have been undertaken; follow-up radial velocity surveys (Updated Zwicky Catalog [UZC], 2dF, etc.) have been completed; and these published data are almost all now accessible in electronically searchable form through the NASA/IPAC Extragalactic Database (NED). As part of a larger, ongoing program to study the general distribution of companion galaxies, we have undertaken here to first revisit the BS77 sample. However, given the fainter magnitude limits and the radial velocities now available, it seemed worthwhile to extend their investigation and to search for true physical companions, rather than simply statistical excesses. These additional surveys should provide improved sensitivity to companion detection primarily because compact galaxies, often difficult to distinguish from stars on the POSS, are often emission line galaxies (e.g., Salzer et al. 1989; Bothun et al. 1989) that are easily detected at other wavelengths (IR, UV/X-ray). Hence, NED offers us the ability to perform the kind of multiwavelength search for companions that can greatly extend that which can be done by visual inspection alone.

Although NED taps many different surveys for galaxy detection, the nature of the radial velocity measurements for NED galaxies remains sparse and heterogeneous, so in that

### Table 1

**Previous Results on Companion Frequencies and Radial Falloff**

| Central Galaxy Type | Average Number of Companions | Search Radius (kpc) | Falloff Index | Reference |
|---------------------|-----------------------------|---------------------|--------------|-----------|
| S/S0                | 1.1 ± 0.1                   | 75                  | ...          | 1         |
| E                   | 0.1 ± 0.4                   | 75                  | ...          | 2         |
| S/S0                | ...                         | 75                  | −0.5 ± 0.2   | 3         |
| S                   | 1.5 ± 0.4                   | 75                  | −1.0 ± 0.2   | 4         |
| S/S0                | 1.0 ± 0.1                   | 16–270              | −1.22 ± 0.05 | 5         |
| E/S/S0             | 1.0                         | 260                 | ...          | 6         |
| E/S/S0             | 1.9 ± 0.1                   | 260                 | −1.1 ± 0.1   | 7         |
| E/S/S0             | 0.36 ± 0.02                 | 500                 | ...          | 8         |
| E                   | 0.74 ± 0.95                 | 75                  | ...          | 9         |
| E                   | 4.3 ± 0.4                   | 300                 | −0.5         | 9         |
| SB                  | 3–4                         | 1000                | ...          | 10        |

*The falloff index is given here for the surface density. Augment the index by −1 for the volume-density falloff. Mixed types of indices are published in the original articles.*

**References**—(1) Holmberg 1969; (2) Bothun & Sullivan 1972; (3) Lake & Tremaine 1980; (4) Zaritsky et al. 1993; (5) Vader & Sandage 1991; (6) McKay et al. 2002; (7) Brainerd & Specian 2003; (8) Prada et al. 2003; (9) This paper; (10) Garcia-Barreto et al. 2003.
sense NED cannot be used to any reliable completeness level for companion searches. However, despite the patchwork nature of NED, it does have the unique characteristic of being the largest on-line collection of galaxies available, with the most complete sampling of radial velocity data (291,000 out of 4.7 million objects in NED have published radial velocities) linked directly to the individual objects. In addition, the accessibility of these on-line data allows us to extend the BS77 companions position search to a projected radius of 300 kpc around each target galaxy, thereby increasing the area surveyed by a factor of 16. All radial velocity companions are identified and recorded and the source density as a function of radius calculated for all velocity-confirmed companions (Table 3). The obvious advantage here is that the process is no longer statistical, as in the previous sense of differentiating two large numbers in order to extract the companion signal from the background noise, but rather is physical and allows us to set very strict lower limits on the numbers, and the projected radial distances, of individually identifiable galaxies that are certainly physically associated with the isolated galaxies in this sample.

2. REWORKING THE BOTHUN & SULLIVAN (1977) SAMPLE

We start by repeating the BS77 experiment as closely as can be reconstructed from their published procedures. Their sample consisted of 34 elliptical galaxies originally drawn from the Reference Catalogue of Bright Galaxies (de Vaucouleurs & de Vaucouleurs 1964), falling north of $b = -45^\circ$, and having expansion velocities $V \leq 3000$ km s$^{-1}$. This yielded a master list of 90 elliptical galaxies, which was narrowed down to a sample of 34 after applying the aforementioned isolation criterion. Again, as in BS77, a projected search radius of 75 kpc was initially adopted (assuming $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and using the expansion velocities, corrected for solar motion, as originally tabulated in BS77). For this sample, the search radii ranged from 9$^\circ$ to 14$^\circ$. We do not have a diameter limit as in the BS77 study, since these are not available within NED; however, our aim is simply to search for potential companions, regardless of diameter. To assess the field-galaxy contamination rate around each target galaxy, we searched two equivalent circular areas 20$^\prime$–40$^\prime$ to the north and south of the primary position. (BS77 used similar comparison regions but chose to place them to the east and west of the central elliptical. Our north-south positioning was done for computational simplicity but should be statistically equivalent.) These regions were chosen to be close enough to be representative of the local background but sufficiently far afield as to minimize the possibility of them still containing physical companions. At these separations even objects having similar radial velocities would not have had sufficient time to make one orbital crossing and are unlikely to be in virial equilibrium with the target object. Searches were undertaken interactively. The version of NED searched had a public release date of 2003 June 19. Table 2 lists the results. Columns (1) and (10) identify the elliptical galaxy under consideration. Column (2) gives the total counts (in the 75 kpc circular area = N75), while columns (3) and (4) give the field counts ([N] and [S]), to the north and south, respectively. The statistical excess and its associated counting error is listed in column (5). For comparison, the numbers quoted on a galaxy-by-galaxy basis by BS77 are given in column (6), followed by the redshift in column (7). Columns (8) and (9) then give the number of radial velocity–confirmed companions inside 75 and 150 kpc search radii, respectively (see §3).

We find that within the 75 kpc search radius the isolated elliptical-galaxy sample has on average $+0.74 \pm 0.95$ cataloged companions per elliptical. (All errors reported and/or plotted in this paper are 1 $\sigma$.) This is the result of differentiating two rather large numbers (529 objects on target minus an average of 504 galaxies in the equal-area comparison fields), as confirmed by the large statistical uncertainty quoted. However, the result differs for galaxies inside and outside of clusters. We note that several of the galaxies (NGC 1351, NGC 1395, NGC 1426, NGC 1427, and NGC 1439) are probably members of the Fornax Cluster. In addition, NGC 3640, NGC 3818, NGC 4697, and NGC 6958 are each projected upon regions of the sky where galaxy counts are particularly rich and deep and may also be in loose clusters themselves (the NGC 3640 Group and AS0900, in particular). Examining the remaining 25 ellipticals, the source density of companions rises in both absolute terms and in relative significance to $0.96 \pm 0.54$ companions per elliptical. This is significantly higher in density than the result quoted by BS77 of 0.12 $\pm 0.42$ companions/galaxy. To first order, this indicates that the procedure used here, which accesses multiple galaxy catalogs, has a much higher detection efficiency than the visual approach adopted by BS77.

3. LOOKING BEYOND A 75 kpc RADIUS

We went through the BS77 sample a second time, increasing the search area a factor of 16 times (i.e., out to 300 kpc, which is equivalent to approximately half the distance from the Milky Way to M31). However, only those galaxies with cataloged radial velocities commensurate with them being physically associated with the central elliptical galaxy (i.e., generally within $\pm 800$ km s$^{-1}$) were counted and retained for further analysis and tabulation.

Table 3 lists the parent galaxy, each of its radial velocity confirmed (physical) companions, their radial separations from the central elliptical (in arcminutes), and their differential radial velocities (in the sense of companion minus central elliptical). Physical companions falling within the original BS77 search radius of 75 kpc are marked with an asterisk and are illustrated in Figures 1–9. The central velocity dispersion of the parent elliptical galaxy is given in parentheses following the galaxy name.

For the entire sample of 34 E galaxies we find 154 companions per parent galaxy located within a projected radius of 300 kpc and having published redshifts within $\pm 800$ km s$^{-1}$ of the central parent galaxy. The average number of companions is 4.5 per elliptical, but the variation in the number of companions per parent galaxy is large (ranging from none so far detected around NGC 0821, NGC 2974, NGC 2986, NGC 3962, NGC 4494, or NGC 5061, to an anomalous high of 28 associated companion galaxies in the case of NGC 1427, in the Fornax Cluster). Previously quoted statistical (counting) uncertainties do not apply here: this is a lower limit on the numbers, and the projected density of companions rises in both absolute terms and in relative significance to $0.96 \pm 0.54$ companions per elliptical. This is significantly higher in density than the result quoted by BS77 of 0.12 $\pm 0.42$ companions/galaxy. To first order, this indicates that the procedure used here, which accesses multiple galaxy catalogs, has a much higher detection efficiency than the visual approach adopted by BS77.

We now examine the radial density distribution of these physically associated galaxies. Figure 10 shows the ensemble radial density fall off as a function of normalized distance ($R_{700} = R/300$ kpc). If it were not for the fact that these galaxies are all radial velocity–confirmed to be physically associated with the central elliptical, it would be tempting to
suggest that there is some background (contamination) level at which the counts are going flat at large radii. However, these galaxies are in all probability actual physical companions. Therefore, it is likely that the general population of galaxies associated with these central ellipticals could extend even further out beyond 300 kpc. Alternatively put, the elliptical galaxies may not be all that isolated to begin with, and what we may be seeing here is the background level of their association with a more widely distributed cluster population.

To some degree, this observation may explain why the BS77 number is so low. It is reasonable to assume that they were differencing out physical companions by having their comparison field in so close to the parent galaxy that they had were not yet sampling the pure field contamination population. Given that most of the comparison fields in BS77 had only an average of two galaxies counted (and a maximum of 10 in two fields combined), the vagaries of small number statistics become problematic.

That said, it may also be true that our adopted velocity difference is too generous and tends to exaggerate the number of physical companions by being overly inclusive, especially in the outskirts of clusters. Indeed, the effect of narrowing the velocity window down to $\pm 300$ km s$^{-1}$ results in the loss of 51 companions from the 300 kpc sample and correspondingly drops the average number of “physical” companions down to 2.8 companions per elliptical.

4. DISCUSSION

Because of the inherent inhomogeneity of the NED holdings of both objects over the sky and radial velocities of selected subsets, little can be said about the absolute total numbers of galaxies physically associated with the isolated ellipticals in the BS77 sample; however, strict lower limits are obtained here. That is, the galaxies found to be radial velocity companions now will not go away with deeper surveys, with better statistics, or with more homogeneous studies. We therefore conclude that this sample of galaxies has 14 currently known physically associated companions, amounting to a lower limit average of 0.4 companions per galaxy within 75 kpc. Within a larger 300 kpc radius (16 times larger area), these numbers increase to 147 galaxies around 34 central objects, yielding at least 4.3 companions per galaxy. Excluding the five galaxies (NGC 1351, 1395, 1426, 1427, and 1439) in the Fornax Cluster gives an average of 3.5 companions per central galaxy.

It is of interest to use the satellites as probes of the halo mass and calculate the mass $M$ interior to the last radial bin, $R_{\text{max}}$. Using the simplest assumptions and assuming a relaxed equilibrium state, one estimate of the mass can be obtained

### TABLE 2
**Companion-Galaxy Counts within $R = 75$ kpc of Isolated Ellipticals**

| Name       | N75 | [N] | [S] | Excess | BS77 | $V_{\text{GR}}$ | S75 | L150 |
|------------|-----|-----|-----|--------|------|----------------|-----|------|
| NGC 0584   | 4   | 1   | 1   | $+3.0 \pm 2.2$ | $+1.5$ | 1837           | 1   | 4    |
| NGC 0636   | 3   | 3   | 2   | $+0.5 \pm 2.3$ | $+1.0$ | 1933           | 1   | 1    |
| NGC 0720   | 1   | 0   | 6   | $-2.0 \pm 2.0$ | $+0.0$ | 1826           | 0   | 6    |
| NGC 0821   | 2   | 0   | 0   | $+2.0 \pm 1.4$ | $-1.5$ | 1799           | 0   | 0    |
| NGC 1052   | 4   | 3   | 8   | $-1.5 \pm 3.1$ | $-0.5$ | 1455           | 2   | 4    |
| NGC 1351   | 80  | 80  | 96  | $-8.0 \pm 13.0$ | $+0.5$ | 1593           | 0   | 8    |
| NGC 1395   | 39  | 60  | 42  | $-12.0 \pm 9.5$ | $+0.0$ | 1622           | 0   | 5    |
| NGC 1426   | 4   | 1   | 25  | $-9.0 \pm 4.1$ | $+1.5$ | 1348           | 0   | 9    |
| NGC 1427   | 134 | 75  | 60  | $+65.5 \pm 14.2$ | $-0.5$ | 1263           | 2   | 28   |
| NGC 1439   | 2   | 3   | 6   | $-2.5 \pm 2.5$ | $+1.5$ | 1575           | 0   | 2    |
| NGC 2768   | 5   | 0   | 1   | $+4.5 \pm 2.3$ | $+0.0$ | 1444           | 0   | 3    |
| NGC 2974   | 6   | 1   | 2   | $+4.5 \pm 2.7$ | $+0.5$ | 1908           | 0   | 0    |
| NGC 2986   | 3   | 0   | 0   | $+3.0 \pm 1.7$ | $+1.0$ | 2097           | 0   | 0    |
| NGC 3078   | 0   | 0   | 0   | $+0.0 \pm 0.0$ | $-1.0$ | 2283           | 0   | 3    |
| NGC 3348   | 2   | 1   | 6   | $-1.5 \pm 2.3$ | $+0.0$ | 2960           | 1   | 1    |
| NGC 3585   | 0   | 0   | 1   | $-0.5 \pm 0.7$ | $+0.0$ | 1206           | 0   | 2    |
| NGC 3610   | 1   | 0   | 3   | $-0.5 \pm 1.6$ | $-0.5$ | 1770           | 0   | 4    |
| NGC 3613   | 3   | 2   | 2   | $+1.0 \pm 2.2$ | $-0.5$ | 2066           | 0   | 9    |
| NGC 3640   | 15  | 15  | 50  | $-17.5 \pm 6.9$ | $+0.5$ | 1198           | 1   | 8    |
| NGC 3818   | 46  | 80  | 49  | $-18.5 \pm 10.5$ | $+1.0$ | 1566           | 1   | 3    |
| NGC 3904   | 1   | 0   | 1   | $+0.5 \pm 1.2$ | $+0.5$ | 1393           | 0   | 4    |
| NGC 3923   | 5   | 0   | 1   | $+4.5 \pm 2.3$ | $+1.5$ | 1557           | 0   | 5    |
| NGC 3962   | 3   | 3   | 4   | $-0.5 \pm 2.5$ | $-0.5$ | 1666           | 0   | 0    |
| NGC 4125   | 9   | 2   | 2   | $+7.0 \pm 3.3$ | $+3.0$ | 1469           | 1   | 2    |
| NGC 4494   | 20  | 18  | 24  | $-1.0 \pm 6.4$ | $-0.5$ | 1343           | 0   | 0    |
| NGC 4589   | 9   | 1   | 3   | $+7.0 \pm 3.3$ | $+0.5$ | 2122           | 1   | 6    |
| NGC 4697   | 81  | 85  | 96  | $-9.5 \pm 13.1$ | $-2.0$ | 1141           | 0   | 6    |
| NGC 4742   | 6   | 9   | 10  | $-3.5 \pm 3.9$ | $-3.5$ | 1160           | 0   | 7    |
| NGC 5061   | 3   | 5   | 6   | $-2.3 \pm 2.9$ | $-0.5$ | 2525           | 0   | 0    |
| NGC 5322   | 4   | 3   | 6   | $-0.5 \pm 2.9$ | $+0.5$ | 1908           | 0   | 4    |
| NGC 5812   | 1   | 0   | 0   | $+1.0 \pm 1.0$ | $+2.0$ | 1911           | 1   | 3    |
| NGC 5813   | 3   | 0   | 0   | $+3.0 \pm 1.7$ | $+1.0$ | 1980           | 0   | 5    |
| NGC 5831   | 6   | 2   | 7   | $+1.5 \pm 3.2$ | $-0.5$ | 1665           | 2   | 11   |
| NGC 6958   | 24  | 29  | 25  | $+9.5 \pm 13.1$ | $-2.0$ | 2730           | 0   | 1    |
| TABLE 3—Continued |
|------------------|------------------|

| Central Elliptical (Central σ) Companion(s) | R (arcmin) | ΔV(comp–E) (km s⁻¹) |
|--------------------------------------------|-----------|-------------------|
| NGC 0584 (σ_e = ±225 km s⁻¹):              |           |                   |
| NGC 0586*                                   | 4.3       | +188              |
| IC 0127                                    | 24.0      | +193              |
| NGC 0596                                   | 24.7      | +74               |
| NGC 0600                                   | 37.2      | +40               |
| KUG 007 **                                 | 58.9      | –961              |
| NGC 0636 (σ_e = ±167 km s⁻¹):              |           |                   |
| MCG –01-050–2*                             | 16.8      | +96               |
| NGC 0702 (σ_e = ±237 km s⁻¹):              |           |                   |
| KUG 0150–138                               | 11.3      | –371              |
| LEDA 087906                                 | 14.8      | –249              |
| LEDA 087906                                 | 18.6      | –512              |
| MCG –02–050–74                             | 27.7      | +197              |
| LEDA 087900                                | 32.3      | –338              |
| MCG –02–050–72                             | 34.4      | –322              |
| KUG 0147–138 **                            | 50.2      | –296              |
| NGC 0821 (σ_e = ±209 km s⁻¹):              |           |                   |
| N/A/                                        |           |                   |
| NGC 1052 (σ_e = ±215 km s⁻¹):              |           |                   |
| [VC94] 023858–0826*                        | 9.3       | –58               |
| NGC 1047*                                   | 10.2      | –130              |
| NGC 1042                                    | 14.7      | –102              |
| NGC 1035                                    | 24.8      | –229              |
| NGC 1351 (σ_e = ±147 km s⁻¹):              |           |                   |
| FCC 100                                     | 19.1      | +146              |
| NGC 1351A                                   | 29.2      | –154              |
| MCG –06–08–025                             | 30.4      | –111              |
| ESO 358–015                                 | 31.3      | –126              |
| FCC 085                                    | 41.7      | –5                |
| FCCB 095                                   | 44.0      | –236              |
| ESO 358–006–6                                | 45.0      | –177              |
| LSBG F358–61                               | 45.9      | +609              |
| NGC 1373 **                                 | 57.4      | –280              |
| ESO 358–019–9                               | 58.9      | –260              |
| NGC 1395 (σ_e = ±248 km s⁻¹):              |           |                   |
| ESO 482–017                                 | 12.8      | –371              |
| NGC 1401                                    | 21.8      | –199              |
| ESO 482–018                                 | 23.7      | –30               |
| ESO 482–031                                 | 37.8      | –96               |
| NGC 1416                                    | 39.8      | +450              |
| NGC 1415 **                                 | 43.8      | –132              |
| NGC 3585 (σ_e = ±216 km s⁻¹):              |           |                   |
| 2MASX J03412708–2228220 **                 | 52.7      | +553              |
| ESO 546–070–2                               | 53.8      | –295              |
| ESO 482–036–2                               | 55.3      | –150              |
| NGC 1427 (σ_e = ±170 km s⁻¹):              |           |                   |
| CGF 10–18*                                  | 0.1       | +28               |
| FCCB 1554*                                  | 4.9       | +347              |
| FCC 274                                    | 8.9       | –315              |
| NGC 1428                                    | 14.3      | +252              |
| FCC 264                                    | 15.3      | +645              |
| FCC 266                                    | 15.4      | +170              |
| LSBG F358–37                               | 24.6      | +567              |
| LSBG F358–34                               | 25.5      | –291              |
| LSBG F358–33                               | 26.4      | +129              |
| FCC 252                                    | 28.0      | –111              |
| APMUKS(BJ) B033815.38–354624.4              | 29.5      | +656              |
| NGC 1427A                                   | 29.7      | –693              |
| FCSS J034007.2–353705                       | 30.1      | +670              |
| FCC 245                                    | 30.9      | +789              |
| ESO 358–051                                 | 31.7      | +346              |
| NGC 1436                                    | 31.9      | –1                |
| FCSS J033935.9–352824                      | 33.9      | +532              |
| FCC 298                                    | 34.3      | +331              |
| FCSS J033932.5–350424                      | 35.6      | –68               |
| NGC 3640 (σ_e = ±184 km s⁻¹):              |           |                   |
| NGC 3641*                                   | 2.5       | +441              |
| NGC 3642                                    | 29.8      | +640              |
| FCSS J034007.2–353705                       | 30.1      | +670              |
| FCC 245                                    | 30.9      | +789              |
| ESO 358–051                                 | 31.7      | +346              |
| NGC 1436                                    | 31.9      | –1                |
| FCSS J033935.9–352824                      | 33.9      | +532              |
| FCC 298                                    | 34.3      | +331              |
| FCSS J033932.5–350424                      | 35.6      | –68               |
TABLE 3—Continued

| Central Elliptical (Central σ) | Companion(s)       | $\bar{R}$ (arcmin) | $\Delta V$(comp–E) (km s$^{-1}$) |
|--------------------------------|--------------------|---------------------|----------------------------------|
| NGC 3643                       |                    | 14.0                | $+529$                           |
| NGC 3630                       |                    | 20.5                | $+171$                           |
| UM 442                         |                    | 44.2                | $+293$                           |
| UGC 06345                      |                    | 44.5                | $+288$                           |
| NGC 3664A                      |                    | 49.5                | $+12$                            |
| NGC 3664                       |                    | 49.8                | $+68$                            |
| UGC 06417                      |                    | 49.9                | $+50$                            |
| NGC 3818 ($\sigma_0 = \pm 198$ km s$^{-1}$): | 2dFGRS N113Z117** | 4.0                 | $+186$                           |
|                               | UGCA 242           | 21.4                | $+27$                            |
|                               | LCRS B113807.1–053433 | 26.4             | $-231$                           |
| NGC 3904 ($\sigma_0 = \pm 200$ km s$^{-1}$): |                    | 36.9                | $+292$                           |
|                               | ESO 440–014        | 37.9                | $+603$                           |
|                               | 2MASX J111532–284734 | 42.9              | $-103$                           |
|                               | ESO 440–023**      | 44.7                | $+386$                           |
|                               | ESO 440–018**      | 58.4                | $+90$                            |
|                               | UGCA 247**         | 59.2                | $+359$                           |
| NGC 3923 ($\sigma_0 = \pm 241$ km s$^{-1}$): |                    | 8.1                 | $-395$                           |
|                               | ESO 440–014        | 15.2                | $+311$                           |
|                               | ESO 440–023**      | 27.6                | $+94$                            |
|                               | UGCA 250           | 34.6                | $-86$                            |
|                               | NGC 3904           | 36.9                | $-292$                           |
|                               | FLASH J115153.41–281046.5** | 39.3           | $-237$                           |
|                               | UGCA 247**         | 42.8                | $+194$                           |
|                               | FLASH J114755.66–281156.2** | 54.8           | $-323$                           |
|                               | ESO 440–040**      | 58.0                | $+82$                            |
| NGC 3962 ($\sigma_0 = \pm 225$ km s$^{-1}$): |                    |                     |                                  |
|                               | N/A                |                     |                                  |
| NGC 4125 ($\sigma_0 = \pm 233$ km s$^{-1}$): |                    | 3.7                 | $+58$                            |
|                               | NGC 4081           | 49.6                | $+88$                            |
|                               | UGC 07020A**       | 59.3                | $+158$                           |
| NGC 4494 ($\sigma_0 = \pm 155$ km s$^{-1}$): |                    | 56.6                | $+2$                             |
| NGC 4562**                    |                    |                     |                                  |
| NGC 4589 ($\sigma_0 = \pm 225$ km s$^{-1}$): |                    | 7.5                 | $+225$                           |
|                               | NGC 4648           | 22.3                | $-506$                           |
|                               | UGC 07844          | 31.7                | $-117$                           |
|                               | UGC 07767          | 32.0                | $-698$                           |
|                               | UGC 07745          | 33.5                | $-790$                           |
|                               | UGC 07908**        | 43.3                | $-320$                           |
| NGC 4697 ($\sigma_0 = \pm 174$ km s$^{-1}$): | MCG –01-33-007      | 14.9                | $+91$                            |
|                               | DDO 148            | 32.8                | $+100$                           |
|                               | 2MASX J1250191–052146 | 36.7           | $+292$                           |
|                               | DDO 146            | 46.3                | $+234$                           |
| NGC 4731A                      |                    | 50.6                | $+254$                           |
| NGC 4731A                      |                    | 59.9                | $+256$                           |
| NGC 4742 ($\sigma_0 = \pm 102$ km s$^{-1}$): |                    |                     |                                  |
|                               | NGC 4757           | 17.6                | $-400$                           |
|                               | NGC 4781           | 38.6                | $-10$                            |
|                               | [KIC] J124959.6–093036 | 40.8           | $+48$                            |
|                               | NGC 4784           | 42.1                | $-423$                           |
|                               | NGC 4790           | 46.9                | $+87$                            |
|                               | UGC 308            | 55.0                | $+52$                            |
| NGC 5061 ($\sigma_0 = \pm 194$ km s$^{-1}$): | ESO 508–033**      | 28.1                | $+669$                           |
|                               | ESO 508–039**      | 36.0                | $-586$                           |
|                               | IC 0879**          | 41.4                | $-692$                           |
| NGC 5078**                    |                    | 41.6                | $-493$                           |
| NGC 5078**                    |                    | 49.1                | $+442$                           |
| NGC 5081 ($\sigma_0 = \pm 213$ km s$^{-1}$): | ESO 508–051**      | 55.5                | $-528$                           |

Notes.—Table 3 is also available in machine-readable form in the electronic edition of the Astrophysical Journal.

*Indicates an object that is within the $R = 75$ kpc sample.

**Indicates an object that is within the $R = 100$ kpc sample.

from $M = 3R_{\text{max}}\sigma^2/2G$, where $\sigma_0$ is the observed radial velocity dispersion and $G$ is the gravitational constant. Adopting a value of 300 km s$^{-1}$ as representative of the observed velocity dispersion, at a conservative distance of 100 kpc, the derived total mass $M_{100\text{kpc}}$ is calculated to be in excess of $3 \times 10^{12} M_\odot$. This can only be considered an indicative mass, given the wide range of possible mass models that can be used.
in inverting the projected velocity dispersion. (In this regard, the interested reader is referred to the more extensive modeling and discussion by Zaritsky & White 1994). However, if the falloff in velocity dispersion with radius, as indicated in Figure 12, is real, then this may be evidence that we have detected a truncation in the density profile of the dark matter halo.

The radial falloff in satellite surface density $\Sigma$ (Fig. 10) is consistent with the general correlation function (binned) down to 30 kpc, with $\Sigma \sim r^{\alpha}$, where $\alpha = -0.5$. This is entirely consistent with the almost identical conclusion drawn by Lake & Tremaine (1980) for the Holmberg (1969) spiral-galaxy companion data, from which they found that $\alpha = -0.5$ held from 40 kpc down to scales as small as 5 kpc. However, a significantly steeper slope to the radial falloff profile is quoted by Vader & Sandage (1991), where $\alpha = -1.22 \pm 0.05$ for $r = 16-270$ kpc (corrected to $H_0 = 75$ km s$^{-1}$ kpc$^{-1}$) for early-type dwarf companions around selected E/S0 galaxies.
gleaned from a visual inspection of photographic plates used to construct the RSA Catalog (Sandage & Tammann 1981) and the Carnegie Atlas (Sandage & Bedke 1994).

The analysis of BS77 predicts that within the entire sample of 34 isolated ellipticals only four (0.12; 34) galaxies will prove to be physical companions. Based on incomplete published radial velocity data, we find that there are at least 14 radial velocity–confirmed companions. As probes of the gravitational field or as indicators of the average number of companions per elliptical galaxy, the present study indicates that there are at least as many companions in the vicinity of ellipticals (0.4–1.0 companions per galaxy in the inner 75 kpc, and at least four companions per galaxy in the surrounding 300 kpc sphere) as there are around spiral galaxies (if Holmberg’s statistical numbers, giving 1.1 companions per spiral within 75 kpc, or if the Zaritsky et al. [1993] value of 1.5 companions per late-type spiral are used as fiducial).

And finally, using the physical companions with published radial velocities and differencing them against the redshift of the central elliptical, we can look at the ensemble falloff of the one-dimensional velocity dispersion as a function of radius.
Figure 11 shows the data. For the total sample there appears to be no significant trend, with the velocity dispersion holding at a level of about 350 km s$^{-1}$ over the entire range of radius. However, we note that in the subsample expunging the galaxies in wide groups and clusters (numbers shown in square brackets), there is the suggestion of a falloff in the observed velocity dispersion as a function of projected radial distance (starting from a high of $\sim 370$ km s$^{-1}$ in the second bin and dropping to 250–300 km s$^{-1}$ in the outer bins).

The above result is in general agreement with the larger study of Prada et al. (2003), which motivated Figure 12. There we have plotted the velocity dispersion as a function of radial separation binned so as to more closely balance the number of companions in each of the outer five bins. While a flat velocity-dispersion profile is consistent with the data and their error bars over the entire 300 kpc range, the dotted line is clearly a better fit to the data defining the five outermost bins.
(120–300 kpc). This line is a Kelperian falloff scaled to a velocity dispersion of 250 km s\(^{-1}\) at 300 kpc. The global significance of this fit and its consistency with the apparent flattening of the density profile for the companion galaxies awaits better statistics on a larger sample of galaxies.

In sum, we have demonstrated that NED is a useful resource for investigating the environments of galaxies as multiwavelength surveys continue to detect new galaxies. As a consequence, this updated catalog gives a much more robust measure of the phase-space density of galaxies in small targeted volumes, compared with earlier published visual estimates. We have used this technique to upgrade and update the results of BS77 with respect to physical companions around isolated elliptical galaxies. This new analysis clearly shows the limitations of the BS77 approach. In particular, the visual approach to galaxy detection adopted by BS77 did not find all the surrounding galaxies and was not able to identify individual physical companions. Furthermore, their early understanding of large-scale structure compromised even their statistical comparisons. Using a better defined sample and the now available redshift information, our new analysis has shown that most elliptical galaxies do have at least three physical companions bound by a relatively large velocity dispersion of ±300–350 km s\(^{-1}\), inside a radius of 300 kpc. The ensemble properties of these physical companions are consistent with halo masses of \(3 \times 10^{12} M_\odot\) out to an enclosing radius of 100 kpc. A falloff in the velocity dispersion with radial distances beyond 100 kpc may indicate that the edge of dark matter halo surrounding these elliptical galaxies may have detected.

This research was exclusively undertaken using the tools and data provided by the 2003 June 19 release of the Web-based version of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

APPENDIX A

COMMENTS ON INDIVIDUAL SYSTEMS

\textit{NGC 0584.}—NGC 0584 has one certain physical companion, NGC 0580, within the original 75 kpc search radius (Fig. 1). BS77 noted a second optical companion. Visual inspection strongly suggests that the object, 2MASX J0130541–064941 (diagonetically opposite to NGC 0580 across the central E galaxy) is also a physical companion based on its size, proximity, and morphology. No redshift yet exists for this 2MASS object, but follow-up studies of it would be useful.

Although NGC 0584 is the dominant member (in linear extent and luminosity) of a small chain of galaxies, it is interesting to note that all of the members with measured radial velocities have a positive redshift with respect to NGC 0584, suggesting that the elliptical is not the center of gravity of this grouping and that the velocities are probing a wider potential. Similar comments apply to several other groupings in this paper: All of the companions associated with NGC 1052 have negative radial velocities with respect to the elliptical under study. NGC 4697 has five companions, NGC 3640 has eight companions, and NGC 5322 has four companions, all of which have positive radial velocities with respect to their associated elliptical.

\textit{NGC 0720.}—This galaxy and its retinue of companions was studied extensively by Dressler et al. (1986). Their companion number 14 (PGC 006960), as well as one of the Vader & Charboyer (1994) objects, [VC94] 015113–1403.0, are good candidates for being physical companions. Indeed, two other galaxies, KUG 0147–138 (\(\Delta V = -556\) km s\(^{-1}\)) and DDO 015 (\(\Delta V = +35\) km s\(^{-1}\)), are also likely physical companions, albeit somewhat farther afield than our 300 kpc radial cut-off, being found 50' (345 kpc) and 73' (505 kpc) away from NGC 0720, respectively.

\textit{NGC 1052.}—In addition to the two radial velocity–confirmed objects, a visual inspection of the 75 kpc field surrounding NGC 1052 (Fig. 2) reveals two other highly likely companions that presently do not have confirming radial velocity data. They are [KKS2000] 04, a fine low surface brightness dwarf spheroidal, to the southeast, and 2MASX J0241351–081024 to the northeast. However, the grand-design spiral galaxy NGC 1042 is only 15' away, suggesting that the elliptical galaxy, NGC 1052, is by no means isolated but may share the potential with at least two other sizeable galaxies, the other being NGC 1035. This mixed-morphology triplet has already been cataloged and is known as KTS 018.

We also suggest that [VC94] 023858–0820.4 (which has a radial velocity, but at its published position has no obvious identification) should be identified with 2MASX J0241351–081024.

\textit{NGC 4589.}—There is a dwarf galaxy, [HS98] 162, about 5' to the northwest (Fig. 7). It is a prime candidate for being a physical companion for and for a follow-up radial velocity measurement.

\textit{NGC 5812.}—A visual inspection of the POSS image surrounding NGC 5813 (Fig. 8) reveals two prime candidates for physical companions (and radial velocity followup) that have gone unlisted in previous surveys. These are NGC 5812:[MFB03] 1, a nucleated (dNE) dwarf at R.A. = 15h00m55s, decl. = -07°24’59” (J2000), and NGC 5812:[MFB03] 2 at R.A. = 15h00m48s, decl. = -07°27’42”.

APPENDIX B

INTERLOPERS

Prada et al. (2003) have suggested that interlopers are a significant source of bias on the basis of their study of a much larger sample (2500 deg\(^2\)) of the sky. To assess the likelihood of interlopers in our specific sample, we undertook the following simple test. For each galaxy we re-interogated NED using the same search radius and the same velocity range but offsetting the search center by 5' to the north or south of the original target. Again we dropped Fornax Cluster galaxies from the test.

With the exception of NGC 4494, we found single radial velocity–selected “interlopers” in only six cases (NGC 3078, 3613, 3962, 4697, 5061, and 5813), two interlopers in the test of NGC 4742, and none in the remaining 21 galaxies studied. Some of
these interlopers (NGC 3631 and ESO 566–G30) are galaxies comparable in size to our central ellipticals, and as such they would not have been counted as companions or would have eliminated the original elliptical from the “isolated” category had they been accidentally in the field of view. For NGC 4494 we hit on a background grouping of four galaxies (reasonably associated with NGC 4250) at a redshift systematically higher than NGC 4494 by about 750 km s⁻¹.

From this test we conclude that our sample is probably contaminated at the 5%–10% level by Hubble-flow interlopers in the general field, but that is still well within the counting statistics of this modest survey.

REFERENCES

Bothun, G. D., Halpern, J. P., Lonsdale, C. J., Impey, C., & Schmitz, M. 1989, ApJS, 70, 271
Bothun, G. D., & Schombert, J. M. 1990, ApJ, 360, 436
Bothun, G. D., & Sullivan, W. T. 1977, PASP, 89, 5 (BS77)
Brainerd, T. G., & Specian, M. A. 2003, ApJ, 593, L7
de Vaucouleurs, G., & de Vaucouleurs, A. 1964, Reference Catalog of Bright Galaxies (Austin: Univ. Texas Press)
Dressler, A., Schechter, P. L., & Rose, J. A. 1986, AJ, 91, 1058
Garcia-Barreto, J. A., Carrillo, R., & Vera-Villamizar, N. 2003, AJ, 126, 1707 (astrop-ph/030718)
Holmberg, E. E. 1969, Arkiv. Astr., 5, 305
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Lake, G., & Tremaine, S. 1980, ApJ, 238, L13
Lorimer, S. J., Frenk, C. S., Smith, R. M., White, S., & Zaritsky, D. 1994, MNRAS, 269, 696

McKay, T. A., et al. 2001, ApJ, submitted (astro-ph/0108013)
Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P. 1999, ApJ, 524, L19
Prada, F., et al. 2003, ApJ, 598, 260
Salzer, J. J., McAlpine, G. M., & Boroson, T. A. 1989, ApJS, 70, 447
Sandage, A. R., & Tammann, G. A. 1981, Revised Shapley-Ames Catalog of Bright Galaxies, Carnegie Institution of Washington
Sandage, A. R., & Tammann, G. A. 1981, Revised Shapley-Ames Catalog of Bright Galaxies, Carnegie Institution of Washington, Publ. 635
Vader, J. P., & Chaboyer, B. 1992, PASP, 104, 57
———. 1994, AJ, 108, 1209
Vader, J. P., & Sandage, A. R. 1991, ApJ, 371, L1
Zaritsky, D., Smith, R. M., Frenk, C. S., & White, S. 1993, ApJ, 405, 464
———. 1997, ApJ, 478, 39
Zaritsky, D., & White, S. 1994, ApJ, 435, 599