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A CATALOG OF ELLIPTICAL GALAXIES WITH SHELLS

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ABSTRACT

We present a catalog of 137 elliptical galaxies south of −17° declination which exhibit shell or ripple features at large distances from the galaxy or in the outer envelope. Some of these galaxies show similar features in the inner envelope when suitable high resolution plate material is examined. Very few of the galaxies are associated with radio sources. We discuss the environment of shell galaxies, and the proportion of ellipticals which have these features. It appears that about half of the galaxies with shells are isolated and most of the rest are members of small groups. We discuss several individual examples which appear to be typical of this class of galaxy and others which probably illustrate an evolutionary sequence.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: structure

I. INTRODUCTION

There are many examples of galaxies with easily recognizable shells or ripple-like structures within their bright envelopes. These structures are generally concentric and are quite distinct from the more familiar spiral arms. Several examples are shown by Arp (1966) and others; in particular, NGC 1316 (Fornax A) and NGC 5128 (Cen A) have been discussed by Schweizer (1980) and Malin, Quinn, and Graham (1983), respectively. Malin and Carter (1980) described what may be another manifestation of the same phenomenon, the existence of apparently normal elliptical galaxies, which have large concentric shells, but of very low surface brightness often at a considerable distance from the nucleus.

Perhaps the best example of a galaxy with a low surface brightness shell is NGC 1344 (Malin and Carter 1980; Carter, Allen, and Malin 1982). The shell was revealed by application of a photographic amplification technique (Malin 1978) to deep plates from the UK Schmidt telescope. Many other examples have since been found, and it is now apparent that the shells around M89 (Malin 1979) are of a similar type.

During the initial investigation of plates from the UK Schmidt telescope, it was evident that some of the brighter shells could be detected by the educated eye without using the photographic amplification process, though subsequent amplification invariably revealed more faint detail. These structures were easier to see on film copies, where the sky background density is around 0.4, than they were on the original IIIa-J plates, where total densities (sky plus fog) of 1.3–1.7 were common. We decided therefore to carefully examine as many film copies of deep IIIa-J plates as possible to obtain a larger sample of shell-type galaxies.

II. THE SURVEY

When this work began, about half of the 606 fields of the ESO/SRC (IIIa-J) Southern Sky Survey had been issued as film copies. Fortunately, as part of the quality control process for making master positives, film copies of all accepted survey plates are retained in the UK Schmidt building at Siding Spring. Thus all but about 10 fields were available to us in the form of film copies. These few remaining fields were searched using original plates which had been rejected as unsuitable for the sky survey, usually because of minor cosmetic defects which were of no consequence for our purposes. The 606 fields examined cover the sky from the south celestial pole to −17° declination (i.e., about one-third of the celestial sphere).

From the examples described by Malin and Carter (1980), we established a working description of a shell-type galaxy which was used throughout this search. These galaxies appear at first sight to be normal ellipticals, but closer inspection reveals one or more edge-brightened structures either in the optical envelope or (more often) beyond the discernible limits of the elliptical galaxy. The shells may be somewhat diffuse; generally, however, they are sharp-edged and may be associated with other disturbances within the envelope

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of the galaxy. The shells never completely surround a galaxy; they tend to occur on the major axis. While we appreciate that this does not constitute a rigorous definition, we believe it is sufficient to specify what appears to be a new class of galaxy.

The photographs of galaxies which accompany this paper encompass this range of properties, though all of the pictures have been made with photographic techniques which enhance their peculiar features. We should emphasize that in the course of this work we have examined photographic images of many elliptical galaxies, both with and without enhancement procedures. It is clear that most ellipticals do not reveal shells or indeed any kind of internal or external irregularity.

The sky survey films were selected in no particular order and were visually scanned in strips about 30 cm wide. We found that the eye was more sensitive to the small density differences typical of shell-type galaxies if the films were scanned without an optical aid such as a loupe or microscope. As candidate galaxies were found, their positions on the films were noted and their suitability for inclusion in the catalog was confirmed (or not) by the other author. Generally we agreed with each other's detections but about one-third of the sample was rejected at this stage as being uncertain. On average each film took about 5 minutes to scan, crowded fields taking much longer. Fields near the galactic plane were quickly scanned to see if any extragalactic objects were visible. If none were seen, that film was not scanned in detail.

The raw, unsorted detections were recorded in terms of their distance in millimeters from the eastern and southern edge of the film image. Celestial coordinates were subsequently determined with reference to three or more SAO stars on the two-coordinate blink comparator ("Bolton machine") at either the UK Schmidt or at the AAO. We are grateful to Graeme Tubbenhauer and Michael Chapman for assistance with this part of the work. When the sample was finally sorted into right ascension order, many of our detections turned out to be duplicated on the substantial overlapping regions of the sky survey, giving us confidence that we could consistently identify shell galaxies.

The size of our sample is obviously limited by our visual acuity. We believe that we can reliably detect extended images with a surface brightness of 26.5 (B) mag arcsec^{-2} on the IIIa-J survey films. This value is the same as that of the brightest part of the shell of NGC 1344 (Fig. 1) which was measured by Carter, Allen, and Malin (1982). This shell is quite easy to see once its existence has been pointed out, and it is surprising that it was not reported earlier. However the jet of M89 (Fig. 5) is much more difficult to locate partly because it is fainter [26.9 (B) mag arcsec^{-2} (K. H. Elliott and D. F. Malin, unpublished] but also because it is diffuse. It is unlikely that M89 would have been selected as a catalog candidate using our search procedure. Similarly, the remarkable internal shells of NGC 3923 (Fig. 4) were not detected visually until its external shell was recognized; the discovery of their full extent required the application of an unsharp masking procedure (Malin 1977) to an original plate. The high contrast of the original plates, which is essential for the detection of faint objects, ensures that low contrast details within the bright envelope of a galaxy are often hidden from view. Our sample of shell-type galaxies is therefore biased toward those with sharp-edged or bright external shells and contains relatively few which were detected because of their internal structures.

We also present a supplementary list of shell-type galaxies (Table 2) which have been brought to our attention by colleagues or which have shells visible on published photographs (e.g., in Arp 1966), or were discovered on UK Schmidt plates of fields outside our survey region.

III. STATISTICAL PROPERTIES OF THE CATALOG

The sample consists of 137 galaxies (Table 1) which fit the definition given earlier. There are 121 galaxies of morphological types $T = -6$, -5, or -4 south of $-17°$ in the *Second Reference Catalogue of Bright Galaxies* (de Vaucouleurs, de Vaucouleurs, and Corwin 1976, hereafter RC 2); of these, 13 (10.7%) appear in our list. Some elliptical galaxies are classified as $T = -3$ or $T = -2$ in RC 2, an additional five galaxies in our list appear under these classifications. One, NGC 7070A, is classified as $T = 0$. Because the galaxies classified as $T = -2$ and -3 exhibit a wide variety of properties, it is difficult to make any statement concerning the clustering properties of these galaxies. However galaxies with $T = -6$, -5, and -4 form a fairly homogeneous, if somewhat incomplete, class of galaxies which are obviously ellipticals. Of the 121 galaxies in this class south of $-17°$ in RC 2, 16 (13.2%) lie in one of the three rich, nearby, southern clusters, Fornax, Hydra, and Centaurus. An additional 32 (26.4%) lie in fairly rich groups, including Antlia, the groups centered on IC 4329 and IC 4296; and the Local Group. Yet of the subsample of 13 galaxies which also appear in our lists, only one (NGC 6776) lies in what RC 2 describes as a group. Thus of the 73 isolated southern ellipticals in RC 2 we detect shells around 12 (16.5%). These statistics are also complicated by some doubt as to whether the shell features themselves might lead the compilers of RC 2 not to classify the galaxy possessing them as elliptical; for instance, one shell galaxy, IC 4329, despite being the brightest elliptical in a rich group, is mysteriously classified as $T = -3$, and the peculiar elliptical NGC 1316, which may be an outlying member of the Fornax cluster, is classified as $T = -2$.

Of our sample of 137 galaxies, we find that no less than 65 (47.5%), are isolated, 42 (30.9%) occur in loose

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TABLE 1

THE GALAXY CATALOG

Name (1)	Field (2)	W (3)	N (4)	R.A. (5)	Decl. (6)	Environment (7)	Comments (8)
0003−400 ...	293	38	168	$0^h03^m12^s$	−40°03′28″	G	Bright shell around small galaxy
0020−193 ...	539	178	202	0 20 24	−19 18 39	I	Shells to N
0048−424 ...	295	210	46	0 48 08	−42 24 29	I	Clear shell to the S
0050−654 ...	79	135	142	0 50 24	−65 29 43	G	
0051−390 ...	295	179	224	0 51 20	−39 00 10	G	Diffuse shell
0057−406 ...	295	116	138	0 57 27	−40 36 10	I	Group E probably background. IC 1609
0107−461 ...	243	65	105	1 07 42	−46 11 45	C	Shells W of cluster galaxy IC 1633
0124−388 ...	296	110	235	1 24 09	−38 51 12	G	Two companions
0124−377 ...	296	108	297	1 24 11	−37 43 00	I	Faint diffuse shells
0129−210 ...	542	99	114	1 29 55	−21 05 20	G	Shells N and S, in group of ~15
0132−246 ...	476	117	189	1 32 36	−24 41 47	I	Disturbed, dust lane?
0136−468 ...	24	55	71	1 36 55	−46 49 41	G	Faint diffuse shells S, group ~ 20
0140−658 ...	80	109	125	1 40 00	−65 52 03	G	Bright shells, two companions
0148−836 ...	3	223	241	1 48 13	−83 38 54	G	Clear shells S, two companions
0154−394 ...	298	333	197	1 54 29	−39 29 19	I	Faint shell E, inner shell W
0200−686 ...	52	92	239	2 00 28	−68 41 19	I	E-W shell. NGC 813
0201−196 ...	544	228	190	2 01 31	−19 38 49	I	Small galaxy, one clear shell S.
0239−283 ...	416	190	260	2 39 28	−28 23 01	I	IC 1833
0243−323 ...	416	140	45	2 43 54	−32 21 48	I	
0244−304 ...	416	137	148	2 44 02	−30 26 18	...	Probably interacting with NGC 1097
0247−833 ...	3	119	255	2 47 30	−83 20 50	G	Diffuse shell NE-SW, group of three
0304−259 ...	480	68	120	3 04 34	−25 54 38	I	Many shells, NGC 1210
0320−378 ...	358	337	44	3 20 47	−37 23 06	C	Many shells, Fornax A, NGC 1316
0321−426 ...	301	240	20	3 21 09	−42 51 22	...	Shells NW and S, possibly one companion
0326−312 ...	418	182	107	3 26 17	−31 14 26	I	Crisp shells out to 60 kpc. NGC 1344
0328−336 ...	358	263	298	3 28 07	−32 38 48	I	
0331−328 ...	358	220	289	3 31 57	−32 49 41	G	Asymmetric shells, could be in cluster
0333−553 ...	156	302	146	3 33 51	−55 23 09	G	In small group. Maybe interacting
0335−575 ...	156	284	34	3 35 32	−57 31 02	G	Diffuse shells.
0336−231 ...	482	217	268	3 36 19	−23 11 24	G	Low contrast shells. NGC 1395
0336−225 ...	482	210	303	3 36 59	−22 33 03	G	Faint shell NE, in group NGC 1403
0340−600 ...	117	223	169	3 40 25	−60 05 23	I	Very faint shells, N and S
0351−550 ...	156	172	170	3 51 01	−55 02 09	I	Diffuse shells
0358−606 ...	117	105	127	3 58 11	−60 48 57	I	Faint shell NE, possibly SW
0404−528 ...	156	160	56	4 04 51	−52 48 11	I	Displaced outer envelope NGC 1522
0410−291 ...	420	204	216	4 10 27	−29 11 09	G	Diffuse asymmetric shells, group ~10
0414−557 ...	157	240	112	4 14 39	−55 42 54	G	NGC 1549. Interacting with N 1553
0415−559 ...	157	243	133	4 15 05	−55 54 12	G	NGC 1553. Interacting with N 1549
0420−437 ...	250	89	239	4 20 33	−43 44 36	I	NGC 1571
0422−345 ...	360	187	194	4 22 40	−34 35 51	G	
0422−536 ...	157	183	241	4 22 50	−53 41 27	I	Very small; clear shells NE-SW
0422−476 ...	250	74	29	4 22 55	−47 38 25	I	Crisp shells.
0449−324 ...	361	157	307	4 49 24	−32 29 24	I	Peculiar galaxy with shell/extensions
0459−449 ...	252	251	175	4 59 56	−44 57 06	I	Small galaxy but clear shells
0515−541 ...	159	289	215	5 15 06	−54 09 32	...	Irregular shells, two companions
0517−251 ...	486	55	165	5 17 42	−25 06 50	G	Shells to S, tail to N. IC 2121
0526−398 ...	306	297	177	5 25 53	−39 53 23	I	Faint shell W
0526−798 ...	16	252	175	5 26 12	−79 53 44	I	Faint shell W and E. NGC 2012.
0540−479 ...	204	74	281	5 40 58	−47 57 54	...	Faint shell to SE, near cluster
0548−181 ...	555	278	268	5 48 40	−18 10 50	I	
0550−380 ...	307	310	273	5 50 48	−38 05 29	I	Faint diffuse shells
0558−553 ...	160	205	153	5 58 39	−55 19 59	I	
0610−625 ...	86	59	302	6 10 07	−62 31 34	...	Shell E, one companion. NGC 2205
0632−629 ...	87	191	281	6 32 54	−62 57 10	G	Double nucleus, diffuse shells
0657−498 ...	207	193	180	6 57 29	−49 51 28	I	Small and faint shell to N
0754−521 ...	209	219	55	7 54 34	−52 10 21	I	NGC 2502
0838−733 ...	36	207	259	8 38 40	−73 22 00	I	Many asymmetric shells.
0921−229 ...	497	33	278	9 21 14	−22 56 42	I	Chaotic outer structure. NGC 2865
0935−217 ...	565	69	76	9 35 24	−21 46 12	I	Faint structure N and S. NGC 2945
0944−213 ...	566	219	100	9 44 10	−21 20 38	I	Shells and jets. NGC 2996
0950−291 ...	435	266	214	9 50 07	−29 11 59	...	Interacting, shell E, faint companion
0951−270 ...	435	248	330	9 51 43	−27 03 04	I	NGC 3051

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TABLE 1—*Continued*

Name (1)	Field (2)	W (3)	N (4)	R.A. (5)	Decl. (6)	Environment (7)	Comments (8)
1013−341 ...	375	291	218	10 13 29	−34 09 50	I	Diffuse shells N and S
1035−285 ...	437	270	251	10 35 40	−28 31 27	G	Clear shell N, in group of ~10
1038−368 ...	376	270	70	10 38 55	−36 51 51	G	Shells E-W, in group of ~4
1046−194 ...	569	226	205	10 46 50	−19 24 23	...	Knotty shells, one companion
1127−361 ...	378	268	112	11 27 17	−36 06 58	...	Ill-defined shell, one companion. NGC 3706
1148−285 ...	440	225	250	11 48 29	−28 31 36	G	Many shells, loose group. NGC 3923
1152−374 ...	379	254	43	11 52 43	−37 25 06	I	Dumbell nucleus. IC 2977.
1200−433 ...	267	244	260	12 00 57	−43 22 31	I	Faint SW shell.
1208−337 ...	379	85	237	12 08 04	−33 46 44	G	Peculiar galaxy, many shells
1237−202 ...	574	148	155	12 37 57	−20 17 17	I	Small but clear eccentric shell
1241−339 ...	381	245	229	12 41 23	−33 55 41	G	Diffuse inner shells. Small group
1252−266 ...	507	139	90	12 52 54	−26 33 16	G	Shells S, inner structure, in group
1256−191 ...	575	172	215	12 56 54	−19 07 50	G	
1257−439 ...	269	236	229	12 57 41	−43 58 33	...	Shells NW and SE, 2 companions
1301−300 ...	443	182	169	13 01 16	−30 05 03	G	
1301−302 ...	443	179	160	13 01 33	−30 13 06	G	Disturbed elliptical, NGC 4936
1302−170 ...	575	105	330	13 02 11	−17 01 50	G	
1304−202 ...	575	72	155	13 04 49	−20 16 30	I	Very faint shell
1306−517 ...	219	118	80	13 06 36	−51 42 08	I	Shell S. IC 4200
1307−231 ...	508	229	275	13 07 05	−23 07 02	I	Two distinct shells. NGC 4993
1310−192 ...	576	269	210	13 10 20	−19 15 12	...	Shells and tail, two companions. NGC 5018
1322−427 ...	270	270	294	13 22 32	−42 45 30	I	Many shells, dust, NGC 5128.
1330−314 ...	444	106	95	13 30 45	−31 24 59	C	Diffuse shells around cluster galaxy
1346−300 ...	445	194	170	13 46 14	−30 02 48	C	Diffuse inner shells. IC 4329
1425−352 ...	385	162	158	14 25 13	−35 16 01	I	Very small, possibly shells
1432−457 ...	272	133	132	14 32 19	−45 45 43	I	Shells E-W. NGC 5670
1439−196 ...	580	200	189	14 39 58	−19 40 57	...	Two companions
1520−410 ...	328	67	117	15 20 39	−41 03 30	I	Crowded field but clear shell
1603−180 ...	584	200	274	16 03 51	−18 04 45	I	Disturbed outer envelope
1805−833 ...	10	277	242	18 05 50	−83 22 30	I	Faint inner shells
1837−614 ...	140	70	90	18 37 46	−61 29 42	I	
1920−639 ...	104	78	228	19 20 38	−63 57 27	I	Shell or loop, NE. NGC 6776
1927−645 ...	104	39	193	19 27 42	−64 31 14	...	Faint shell in NNE, one companion
2002−403 ...	339	103	153	20 02 53	−40 20 31	I	Low contrast inner shell. NGC 6849
2012−494 ...	233	66	200	20 12 30	−49 27 48	I	Inner shell in NE
2012−616 ...	143	194	80	20 12 31	−61 41 15	G	Clear but faint shell, near group
2026−645 ...	106	203	195	20 26 36	−64 32 43	I	Part hidden by star
2031−307 ...	463	295	128	20 31 26	−30 47 48	G	In group of ~10
2031−418 ...	340	78	74	20 31 44	−41 51 22	...	One companion galaxy
2045−302 ...	463	139	158	20 45 02	−30 17 34	G	
2045−358 ...	401	204	125	20 45 12	−35 51 36	I	Inner and possibly outer shells
2045−381 ...	341	200	269	20 45 30	−38 11 00	I	Distinct inner structure. NGC 6958
2048−300 ...	463	96	172	20 48 46	−30 02 06	...	Disturbance plus shell, one companion
2054−508 ...	235	220	127	20 54 20	−50 51 41	G	In small group
2059−673 ...	74	116	311	20 59 01	−67 23 00	I	Shells S and E, faint
2103−701 ...	74	101	164	21 03 43	−70 06 17	G	Clear shells, E-W, group of ~20
2105−381 ...	342	264	269	21 05 14	−38 10 31	G	Complete shell, in loose group
2121−407 ...	342	100	130	21 21 12	−40 45 09	I	Large shell in NE. IC 5105
2129−430 ...	287	167	275	21 29 36	−43 04 12	...	Dust lane, one companion, NGC 7070A.
2144−299 ...	466	246	176	21 44 41	−29 55 29	G	Faint inner shells N and S, in group
2146−351 ...	404	318	165	21 46 47	−35 06 37	G	Curious jet and shell. NGC 7135
2147−240 ...	531	54	222	21 47 37	−24 00 08	I	Faint shells W
2147−242 ...	531	54	210	21 47 37	−24 13 46	I	Shells N and S
2147−295 ...	466	210	204	21 47 45	−29 34 59	I	Shell S. Disturbed nucleus
2147−465 ...	288	246	90	21 47 55	−46 30 36	G	Outer loop N inner shells S
2149−276 ...	532	303	28	21 49 01	−27 39 26	...	Faint shells NE-SW, 1 companion
2150−482 ...	237	260	270	21 50 09	−48 15 55	...	Shell to NW. Close pair. NGC 7145
2151−557 ...	189	236	131	21 51 35	−55 45 17	G	Shell N-S. Group of ~20
2155−174 ...	601	267	310	21 55 31	−17 25 00	I	Clear shell E, disturbance W
2209−676 ...	108	126	28	22 09 05	−67 39 39	I	

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TABLE 1—*Continued*

Name (1)	Field (2)	W (3)	N (4)	R.A. (5)	Decl. (6)	Environment (7)	Comments (8)
2215−429 ...	289	261	282	22 15 07	−42 56 23	I	Loop to S of elliptical
2226−357 ...	405	146	133	22 26 27	−35 43 37	G	Shell SE, in small group. NGC 7289
2228−641 ...	109	262	216	22 28 40	−64 08 52	G	Asymmetric shells E-W, small group
2229−256 ...	533	85	136	22 29 22	−25 40 52	C	Shells SW and NE. In cluster. NGC 7294
2239−431 ...	290	293	269	22 39 43	−43 10 14	I	
2241−582 ...	147	221	276	22 41 00	−58 12 04	...	Shells E-W, one companion
2316−395 ...	347	250	196	23 16 35	−39 33 04	I	Peculiar elliptical and shell fragments
2330−452 ...	291	75	155	23 30 34	−45 17 33	G	Faint NE shell. Interacting? IC 5328
2334−452 ...	291	37	155	23 34 26	−45 17 16	G	Faint shell. Possibly in group
2335−477 ...	291	39	20	23 35 03	−47 46 59	I	Bright galaxy extension SE and possible shell NW
2335−470 ...	291	31	58	23 35 40	−47 05 03	G	
2347−357 ...	349	311	129	23 47 23	−35 45 20	G	Very faint shell SE; in group ~ 20
2351−428 ...	241	256	288	23 51 29	−42 49 33	G	Very small; E-W shells, group ~ 5
2355−218 ...	472	234	342	23 55 06	−21 51 31	I	Inner shells, possibly faint outer
2356−301 ...	471	58	165	23 56 05	−30 07 25	G	Shell S, in large group

EXPLANATION OF COLUMNS

Col. (1). The reference name of the object derived from the 1950 coordinates. The last digit is a decimal fraction of a degree, truncated.

Col. (2). The ESO/SRC field number (see Holmberg *et al.* 1974 for the nominal field centers).

Cols. (3) and (4). The distance in mm from the eastern and southern edge of the image on the film copies. Note that this differs from the standard UK Schmidt practice of measuring from the edge of the plate, since the plate edge does not appear on the copy.

Cols. (5) and (6). The 1950 position of the object, measured from the ESO(B) glass copies on the two-axis blink comparator (Bolton machine) using (at least) three SAO stars.

Col. (7). The environment of the sample galaxy. I indicates that the galaxy is isolated, i.e. it is not part of any small-scale density enhancement. G indicates that the galaxy is a member of a small group of no more than 10 galaxies, while C indicates that the galaxy is a member of a substantial cluster (see Turner and Gott 1976). An ellipsis in this column is explained in the next column and usually indicates a galaxy isolated but for one or two companions.

Col. (8). Comments.

groups (of these, 18 [13%] have one or two close companions), and only 5 (3.6%), including NGC 1316 and IC 4329 occur in clusters or rich groups. The remaining 25 (18%) occur in groups of two to five galaxies.

The statistics seem to indicate that shell galaxies do not occur in regions of high galaxy density, perhaps because the tidal effects of other galaxies rapidly disrupt the shell structures, or perhaps because the collisions between galaxies which lead to shell formation (e.g., Quinn 1982) are low velocity encounters, and regions of high galaxy density, such as clusters, are also regions of high relative velocity.

The ESO lists of nonstellar objects (Lauberts *et al.* 1981, and references therein) include 79 of our galaxies. Of these 45 are classified as S0 by Lauberts *et al.*, nine as E, 10 as E/S0, and 15 have other classifications or no classification. In view of the wide variety of galaxies, particularly faint galaxies which are classified as S0 by ESO we feel that further analysis of this subsample will prove unfruitful. The ESO lists contain 327 galaxies classified as E, E/S0 or something equivalent; we detect shells around 19 (5.8%) of them. Not surprisingly even though we have access to exceptionally high quality plate material, we detect fewer shell galaxies at fainter limiting magnitudes due to the finite spatial resolution of the SRC survey. The faintest galaxies in our sample are about 15th magnitude.

The positions of the 148 galaxies in Tables 1 and 2 have been correlated with the *Parkes Catalogue of Radio Sources*, 1979 edition (CSIRO Division of Radiophysics). Only two galaxies in the list are radio sources. They are 0321−376 (Fornax A) and 1323−427 (Centaurus A).

IV. COMMENTS ON INDIVIDUAL GALAXIES

0244−304 (NGC 1097A).— This galaxy appears to be interacting with the peculiar spiral NGC 1097, (Wolstencroft and Zealey 1975) though it is not mentioned by Arp (1976) in his study of the jets associated with the galaxy. Lorre (1978) finds that a considerable interaction appears to have taken place. We believe that the shells are due to a tidal interaction of the two galaxies.

0326−312 (NGC 1344).—The first to be discovered, this galaxy (Fig. 1 [Pl. 1]) is an excellent example of the phenomenon. The brightest part of the external NW shell (Fig. 1, *left*) has been examined at optical and infrared wavelengths on the AAT by Carter, Allen, and Malin (1982). The colors were found to be consistent with those of stars of spectral type between G5 and K4. The brightest part of the shell had a surface brightness

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TABLE 2

SUPPLEMENTARY LIST OF GALAXIES WITH SHELLS OUTSIDE MAIN SURVEY

Name	R.A.	Decl.	Comments
0041−043	$00^h41^m01^s$	−04°23′15″	IC 1575 Faint outer arcs and dust (Arp 231).
0043−137	00 43 55	−13 42 50	Disturbed galaxy with dust and shells (Arp 230)
0117+031	01 17 32	+03 09 18	Many shells and disturbed companions. NGC 474 (Arp 227)
0121+331	01 21 54	+33 06	NGC 505-8 (Arp 229)
0133−128	01 33 59	−12 53 03	Lenticular with diffuse shells
0147+103	01 47 18	+10 23	IC 162 (Arp 228)
0225−103	02 25 05	−01 22 42	Faint arcs in envelope NGC 936
1233+128	12 33 08	+12 50	Two or three shells and jet. NGC 4552 (M89)
1349+025	13 49 37	+02 34 16	Group of ~10. NGC 5329
1358−026	13 58 02	−02 37 02	NGC 5400
2101−125	21 01 55	−12 32 17	NGC 7010
2315−049	23 15 28	−04 55 18	Patchy diffuse shells. NGC 7585 (Arp 223)

of 26.5 mag arcsec^{-1} in B. Radio observations at 21 cm failed to detect the presence of neutral hydrogen in a 14′ beam which included both the galaxy and its outer shell, with an upper limit of 7.7×10^7 M_0 ($H_0 = 50$ km s^{-1} Mpc^{-1}). The remarkably sharp edge of the NW shell is quite distinctive and occurs in many of the galaxies in our sample. Inside the bright envelope of the galaxy other shell or ripple-like structures have been found by using deep plates from the AAT. These cannot be detected by simple visual inspection and have been revealed by using an unsharp masking technique. The diffuse patches E and W of the main body of the galaxy (Fig. 1, *right*) may be artefact of the process.

0336−231 (NGC 1395).—The shells of this galaxy are within the bright envelope and are difficult to see without some sort of photographic enhancement.

0414−559 (NGC 1549) and 0415−559 (NGC 1553).—Even on deep plates these galaxies (Fig. 2 [Pl. 2]) appear to be unconnected (Fig. 2, *left*) but a closer inspection shows faint outlying structured nebulosity, some of which is sharp-edged. Photographic enhancement of deep plates (Fig. 2, *right*) reveals a sharp-edged shell about 5′ E of NGC 1549 (the lower of the two galaxies in Fig. 2), and a similar structure is seen about 5′ N of NGC 1553. More intriguing is the very narrow jet with a greatly broadened tip westward of this galaxy. This structure is remarkably similar to the narrow jet in NGC 1097 (R2 in Wolstencraft and Zealey 1975). It seems quite clear that the outer parts of these galaxies are interacting, though it is possible that the shells existed before encounter.

0921−229 (NGC 2865).—This galaxy (Fig. 5, *left*) probably represents a somewhat earlier stage of shell formation than NGC 1344 or NGC 3923. There is evidence for a recent merger here; first, the colors of NGC 2865 are somewhat blue for an elliptical ($B-V=$ 0.92 from RC 2; $J-K=0.98$, as opposed to 1.05–1.08 for typical ellipticals, measured by A. J. Longmore and D. C. at UKIRT). Second, NGC 2865 has a large H I content (3.2×10^9 M_0, $H_0=50$) measured by K. J. Wellington and D. C. at Parkes. In deep pictures, a faint diffuse loop to the NW and sharp-edged shells to the E can be seen, and the appearance resembles deep images of NGC 1316 (Schweizer 1980). There is also some resemblance to M89 (Fig. 5, *right*) which is illustrated alongside for comparison.

0951−270 (NGC 3051).—NGC 3051 (see Fig. 3 [Pl. 3]) is an excellent example of a galaxy with a bright internal shell and fainter, sharp-edged outer one. However, it is unusual that the shells lie generally on the minor axis. It is possible that dust is present near the nucleus (Fig. 3, *right*), though the original from which this illustration was made was contaminated with some particles of (terrestrial) dust of similar appearance.

1148−285 (NGC 3923).—The NE outermost shell of this galaxy (see Fig. 4*a*–4*c* [Pl. 4]) is ~180 kpc ($H_0=50$ km s^{-1} Mpc^{-1}) from the nucleus though an even fainter and more distant one may be present SW of the galaxy (not shown). A complex series of inner shells is revealed by unsharp masking; about 18 can be counted on the photographs in Figure 4. The spacing of these shells appears to be alternate around the nucleus, with the most distant in the NE, the next one in the SW, the next in the NE and so on. The small dust cloud in Figure 4*c* is a real feature, confirmed on several plates.

1233+128 (NGC 4552, M89).—Although too far north for inclusion in the main catalog, M89 (see Fig. 5, *right* [Pl. 5]) is included in these comments to illustrate what may be an evolutionary sequence of galaxy mergers. When the optical peculiarities of M89 were first reported (Malin 1979), one of us at least did not appreciate that shells or jets could be produced by mergers. The work of Schweizer (1980) on NGC 1316 and Quinn's (1982) theoretical work suggests that M89 is a merged system,

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the jet being the remains of an absorbed galaxy. The galaxy also exhibits two shells, a sharp-edged one about 5′ S of the nucleus, a diffuse one about 7′ NW and an extremely faint but sharp-edged shell ~11′ NE. M89 is a prominent member of the Virgo Cluster and is one of the very small number of shell galaxies known to inhabit a rich cluster. Morphologically, it is similar to NGC 2865 (Fig. 5, *left*).

1322−427 (NGC 5128).—The two diffuse shells which are visible in the NE extension on the ESO/SRC J film (field 270) are the most obvious members of an extensive series which can be revealed by unsharp masking on large scale plates. A detailed discussion of the morphology of NGC 5128 will appear in a separate paper (Malin, Quinn, and Graham 1983).

2129−430 (NGC 7070A).—NGC 7070A is a galaxy with a low surface brightness spheroidal component, and a complex dust lane inclined at about 30° to the major axis. A kinematic study of this galaxy was made by Sharples *et al.* (1983), who found a very low velocity dispersion in the stellar component and rotation of the emission line regions in the dust lane, but not of the stellar component. The stellar kinematics suggest a triaxial system, highly flattened with its shortest axis along the line of sight. The gas kinematics and morphology of the dust lane suggest that the dust lane is not yet in equilibrium and point to a fairly recent accretion event. The shells are very nearly circular; some are nearly complete and are probably remnants of the same event which formed the dust lane.

IV. SUMMARY

We have detected low surface brightness shells around some 17% of isolated elliptical galaxies, but around a much lower proportion of ellipticals in clusters or rich groups. The photometric evidence of Carter, Allen, and Malin (1982) indicates that some of these shells have colors similar to those of the main galaxy, which, together with other optical peculiarities such as tails and dust lanes, leads us to believe that the shells are the result of encounters between ellipticals and cold stellar systems (e.g., disc galaxies). There is a clear tendency for shell galaxies to be found in regions of low galaxy density where the encounters would be of low relative velocity. In general, shell galaxies are not associated with the powerful radio sources which do occur in clusters and are probably the result of accretion of stripped gas rather than a merger of stellar system. The colors of the shells will vary and should indicate what type of galaxy was accreted to form the shells. Quinn's (1982) model of shell formation requires only that the accreted galaxy be cold dynamically.

We thank members of the UK Schmidt Telescope Unit for access to original survey plates and copy films, Graeme Tubbenhauer and Michael Chapman for measuring plates, and Margy Smith (née Porteners) for compiling an early version of Table 1. We also thank Ray Sharples and Tim Hawarden for access to the plate of NGC 7070A and Dave Hanes for the use of the plate of NGC 1549/1553.

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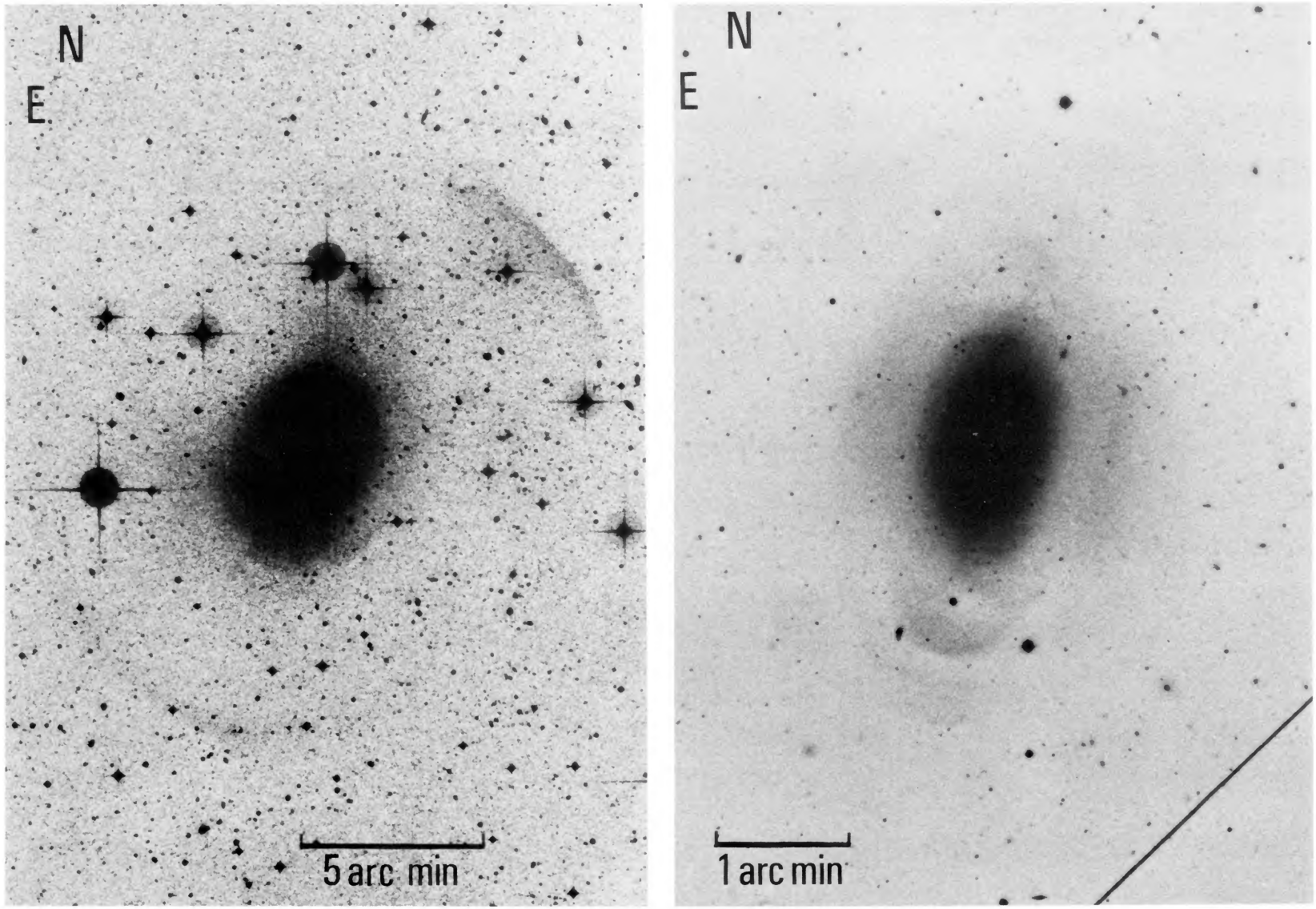

FIG. 1.—The shells around NGC 1344. The external shells (*left*) are revealed by photographic amplification and subsequent superimposition of three deep IIIa-J plates taken on the 1.2 m UK Schmidt telescope. The internal shells (*right*) are seen by applying an unsharp masking technique to a deep IIIa-J plate taken on the AAT.

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PLATE 2

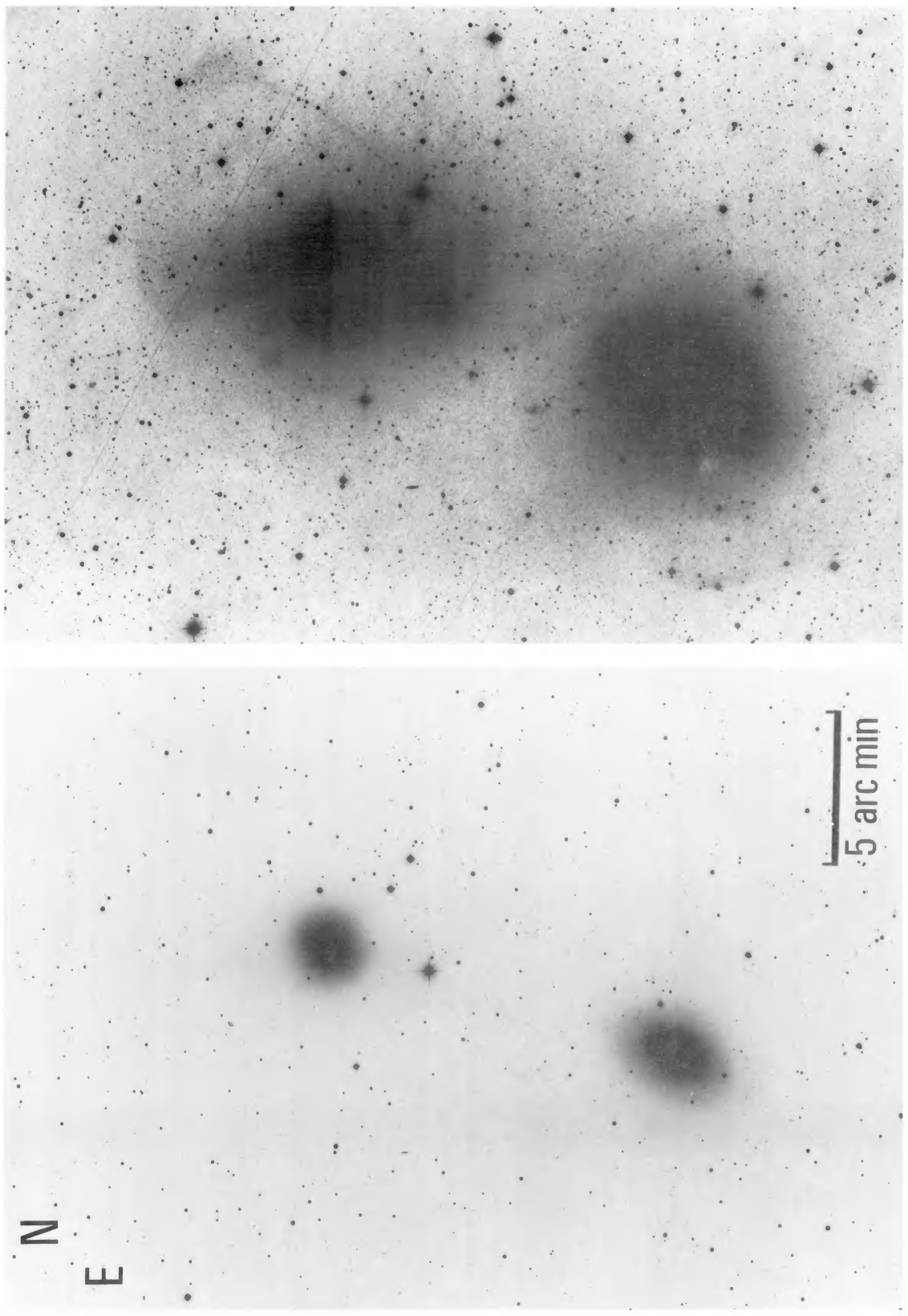

FIG. 2.—NGC 1549 (*lower*) and NGC 1553 appear to be at an early stage in an encounter, producing faint but distinct shells and a jet visible in the enhanced image (*right*). The visual appearance of the original AAT plate, printed with the same scale and orientation, is shown alongside for comparison (*left*).

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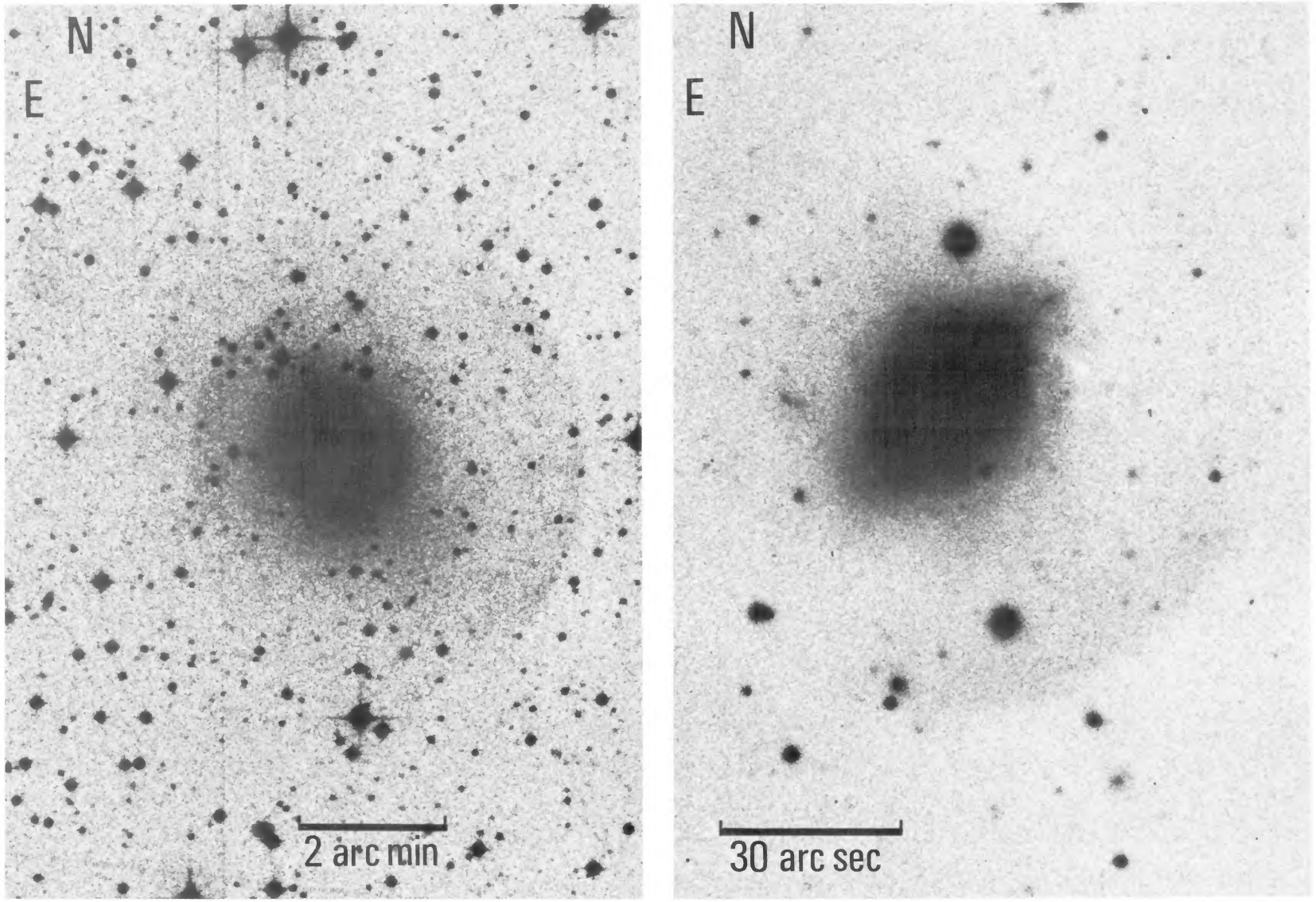

FIG. 3.—NGC 3051. The outer shells are revealed by adding together images derived from three UK Schmidt plates (*left*) while an inner shell is seen on an AAT plate (*right*).
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PLATE 3

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PLATE 4

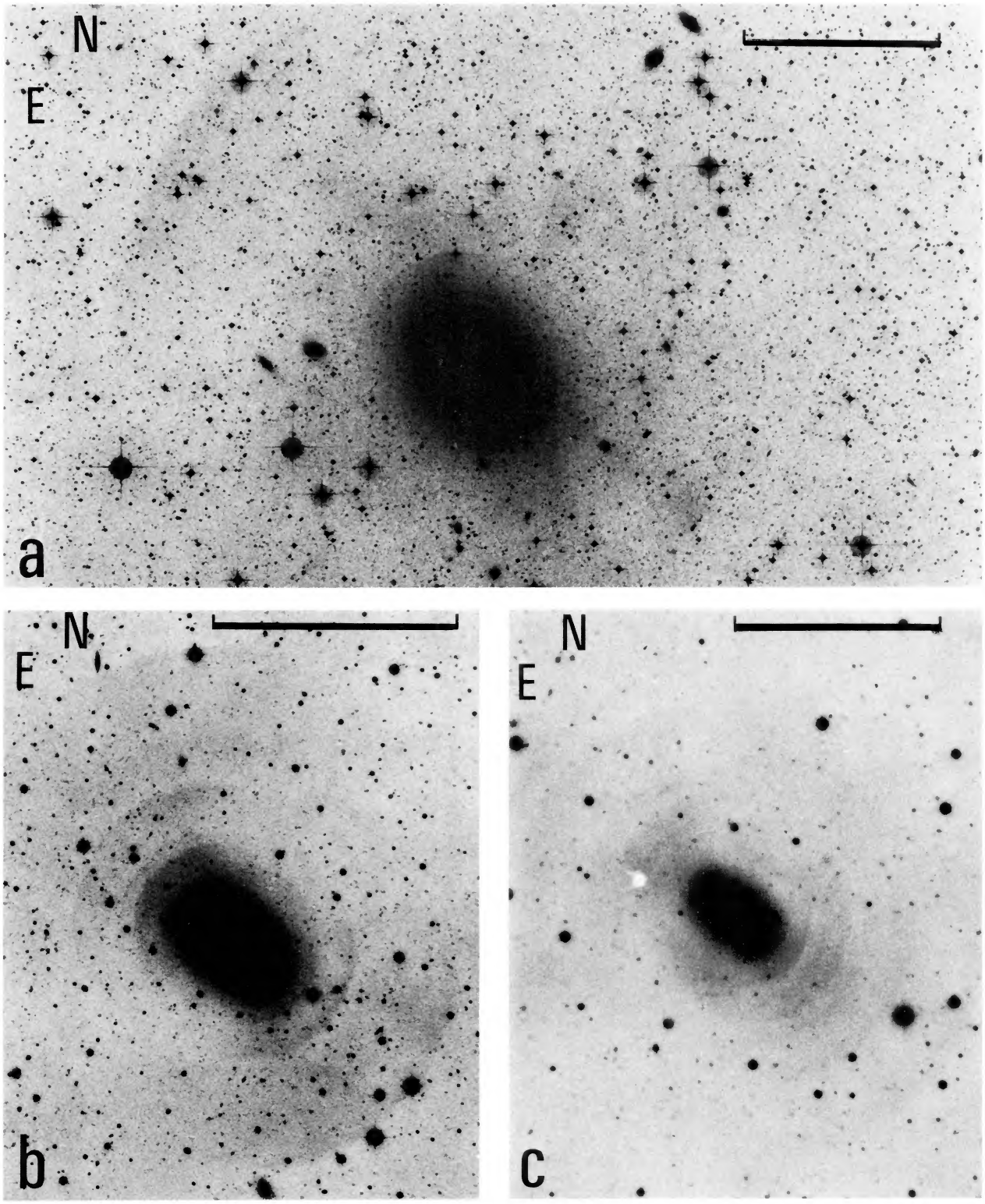

FIG. 4.—NGC 3923. The top picture (Fig. 4*a*) was made from three UK Schmidt IIIa-J plates, enhanced to show the NE shell. Scale bar is 10′. The lower pictures (Figs. 4*b* and 4*c*) were made from the same AAT plate printed through unsharp masks with different characteristics. About 18 shells can be counted. The dust cloud in Fig. 4*c* is real. Scale bars are 5′ and 2′ in Figs. 4*b* and 4*c*, respectively.

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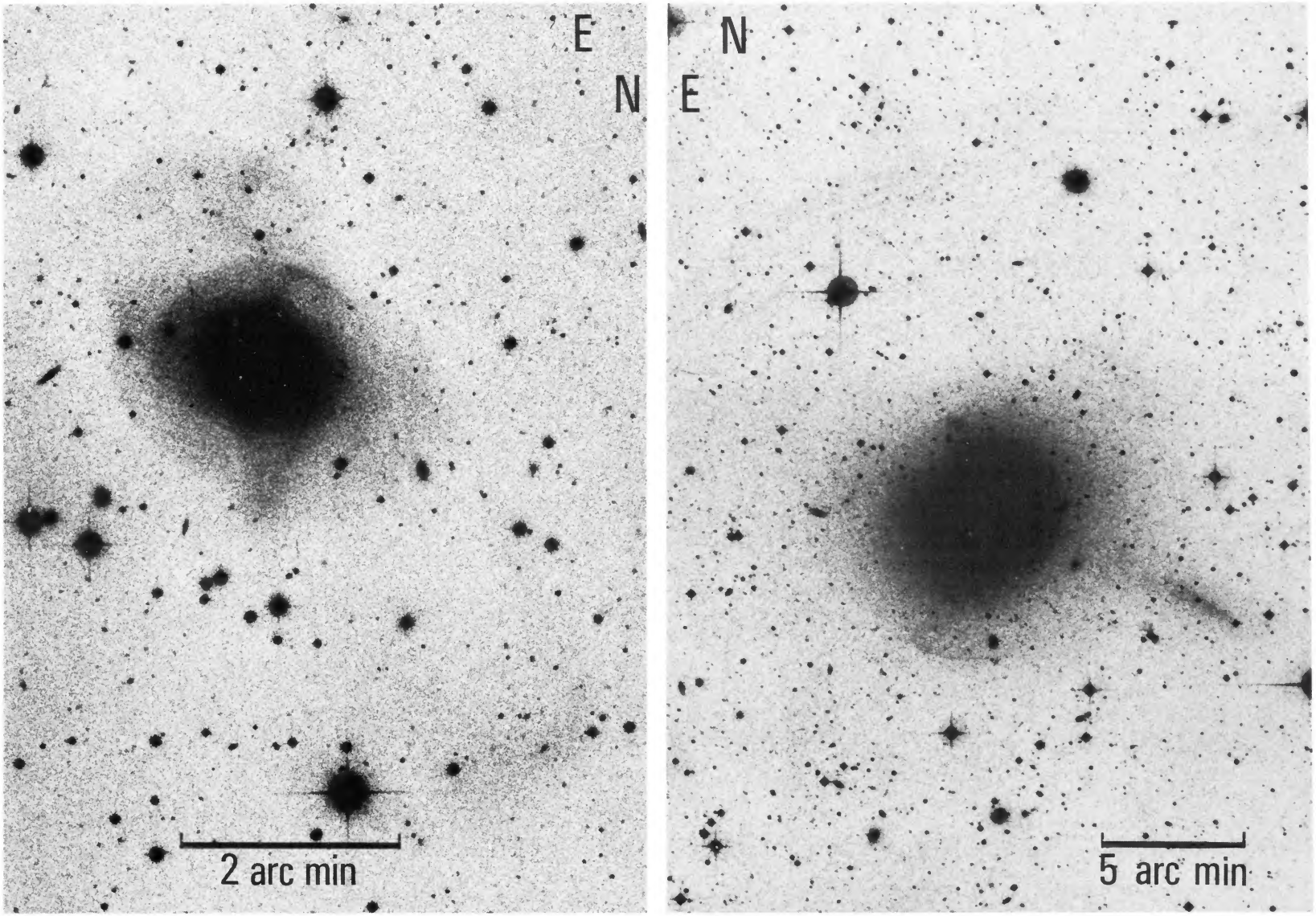

FIG. 5.—NGC 2865 (*left*, from an AAT plate) shows a clear resemblance to NGC 4552 (M89, *right*, from three UK Schmidt plates). Both reveal a combination of sharp and diffuse shells and protuberances which may be typical of the initial stages of galaxy merging.

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