INTERACTING GALAXIES IN THE VIRGO CLUSTER

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1. Introduction

The galaxies of the Virgo cluster have been observed extensively as members of one of the nearest moderately rich cluster. In view of the proximity of cluster members one to another, it might be expected that a significant fraction would be seen to be interacting with their neighbours, but simple inspection of deep plates of the cluster suggests otherwise. It is the intention in this note to show that a much higher number of apparent optical pairs are in fact involved in interactions but that this does not become apparent until special techniques are applied to reveal the faintest features on already deep photographs.

For the imaging techniques to be adequate to explore the faintest parts of bright galaxies, the original plates must be of excellent quality and have been obtained under dark conditions at a dark site. Plates from the UK Schmidt telescope at Siding Spring fit these requirements very well and a series of plates taken for other purposes have been used to show that a significant number of galaxies within 10 degrees of a nominal cluster centre (taken to be the giant elliptical galaxies M 84/M 86) are involved in interactions. The deep search has also revealed unprecedentedly deep images of some very large, low surface brightness galaxies and some interacting galaxies that appear to be in the background. Photographs of many examples are reproduced.

2. Observations and Techniques

Over the past several years, we have acquired a series of deep overlapping plates of the Virgo cluster from the UK Schmidt telescope. Most of the exposures have been made on the blue-green (395-530 nm) sensitive IIIa-J emulsion, hypersensitized with nitrogen and hydrogen in the normal UK Schmidt manner. Some exposures have also been made on IIIa-J's red sensitive equivalent, IIIa-F, which is filtered to respond to the 590-700 nm spectral range. More recently, we have had access to a series of deep exposures made on Kodak's Tech Pan film, Type 4415, which uses the same filter as IIIa-F but covers a slightly narrower bandpass, approximately 590-680 nm.

The availability of this large number of deep exposures of identical fields has encouraged us to combine derivatives from the best of them to reveal extremely faint features. This has already produced useful results on faint dwarf galaxies (e.g. Bothun et al. 1987, 1991) and led to the

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discovery of a uniquely massive disk galaxy in the background, reported by Bothun et al. (1988). Now, these techniques have been applied to some of the brightest galaxies in the cluster, including several that appear in Messier's catalogue. Some of these galaxies exhibit surprising evidence of interaction, often with apparently insignificant companion galaxies at large projected distances.

The techniques used for revealing the faintest features are photographic amplification and multiple image superimposition (see Malin 1990 for a review). Though multiple image addition is now possible using digital techniques, the initial stage of photographic amplification is still best accomplished with conventional contact copying processes. These are designed to improve the sensitometric signal-to-noise ratio without loss of information due to under sampling by scanning apertures that are large relative to seeing disk. This consideration is increasingly important with the introduction of Kodak's Tech Pan emulsion which has an effective pixel size of about 5 microns on sky-limited exposures.

Combining photographically enhanced copies of plates rather than the originals offers major operational advantages, some of which are shared with the digital processes. For example, it is not necessary to have all the original plates together at one time to add them together, and it is possible to correct deficiencies such as non-uniform backgrounds or widely varying sky background densities during the process. However, unlike digital processing, the photographic enhancement process is extremely rapid and is not limited by high fog and/or sky background densities of the originals. It has also been found to be extremely free from artefacts compared with digital enhancement (Couch et al. 1984) and is more than competitive with digital processes for revealing faint extended objects, which is the main purpose of this note. Finally, since large areas of the plates are enhanced in one simple operation, it is common for serendipity to play a part in the process of discovery.

However, photographic amplification and image addition is not a quantitative process; the main advantage of the direct photographic approach is its simplicity, speed and ability to produce results without expensive, custom-built scanning or computer equipment.

3. Scientific Background

Careful inspection of photographs has always been an important part of understanding many properties of galaxies, and van den Bergh (1960), when examining the early Palomar sky survey prints, noted subtle differences between field galaxies and those in rich clusters. The main difference seemed to by that many spirals had a 'fuzzy' outer spiral structure, possibly due to interactions with other cluster members. This idea has been revised and refined, and now some opinion seems to favour ram pressure stripping (Gunn & Gott 1972) as the cause of gas deficiency in the outer parts of cluster spirals. Supporting evidence for this is discussed by van den Bergh et al. (1990), in a paper that examines the classification of galaxies from CCD exposures.

Van den Bergh goes on to say that the anaemic outskirts of some spirals are a consequence of stripping. We note here that our deep photographs provide confirmation of the paucity of star formation in the outskirts of many of the bright galaxies listed by van den Bergh et al (1990) and several more examples where the effect is seen only at very low surface brightness levels. This is currently a contentious topic since it has been stated that the frequency of galactic collisions in the cluster has been under-estimated by a large amount. Valluri & Jog (1990) believe

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collisional gas removal is enough to explain the measured atomic hydrogen deficiency of spiral galaxies in the cluster without the need to invoke ram-pressure stripping by the intergalactic medium.

At the same time, much attention is being given to understanding the subtle signatures of interactions and mergers, especially in galaxy-rich environments such as the Virgo cluster (Schweizer & Seitzer 1992). One topic not usually included in such reviews is the presence of very low surface brightness extensions and distortions of bright galaxies. The possibility of producing high-quality images from readily available plate material provides additional observational input to both these topics.

Images of 20 or so galaxies were selected as being particularly interesting for a variety of reasons, and they are illustrated in the accompanying figures. The pictures were made by combining the photographically amplified derivatives of between 5 and 7 deep IIIa-J plates from the UK Schmidt. In all cases the limiting magnitude is 28 mag/arcsec^{-2} or fainter. Evidence of interaction of a number of bright galaxies is summarised below. Galaxy types and redshifts are from the Virgo Cluster catalogue (VCC) of Binggeli et al. (1985) unless otherwise stated.

In Fig. 1a the central region of the Virgo cluster is dominated by the giant elliptical galaxies NGC 4374 (M 84, E1) and NGC 4406 (M 86, S0/E3). Their low surface brightness envelopes appear to overlap, but it unlikely that they are in physical contact since the isophotes of NGC 4374 are remarkably uniform out to the limiting magnitude of this deep image. It should be noted however that the outer parts of M 86 do show some structure, especially at the NW end of the major axis. There a weak shell-like discontinuity is visible, beyond which there is an even fainter, elongated structure extending about 3 arcmin to the NW. M 86 was the subject of a detailed multi-wavelength study by White et al. (1991) but the structures reported here are beyond the confines of 14 arcmin square region reproduced in their paper. In the paper by Nulsen & Carter (1987) the discontinuity is noted, but their isophotes tend to mask its step-like nature and it is not discussed.

In the same field and identified on Fig. 1a is the well-known interacting pair of galaxies, NGC 4435/38 (left [east] of M 86), now seen to be shrouded in a large, mostly featureless envelope which has a very faint plume extending to the north. A rather similar LSB plume is seen to extend south from NGC 4425. Several other galaxies show LSB structure, most notably the Seyfert galaxy NGC 4388 (Phillips & Malin 1982). This highly inclined galaxy has LSB extensions at either end of its major axis. Combes et al. (1988) noted that the features they observed in both neutral and atomic hydrogen in NGC 4388 could only be accounted for by a close tidal interaction, not by ram pressure stripping. There are many possible candidates in the field, and it is impossible to invoke any one of them, however, the redshift of NGC 4388 is 2529 km/sec, placing it beyond the Virgo cluster, so the disturbing galaxy is unlikely to be either of the giant ellipticals M 84 or M 86.

NGC 4321 (M 100, Sc(s)I) is the brightest spiral galaxy in the Virgo cluster with prominent spiral arms that continue into the nucleus. The beautiful 'grand design' can be seen in colour photographs by Malin (1993). This picture also shows the asymmetric brightening of a considerable portion of the southern arm, which appears to be the result of enhanced star formation. This conspicuous feature serves to emphasise the perfect arc of the arm itself. Curiously for a galaxy with a bright central bulge, there does not seem to be evidence of a colour gradient across the face of the object, as seen in another, non-cluster Sc galaxy e.g. NGC 2997, or M 83, also illustrated in Malin (1993). The colour of the nuclear regions in M 100 is thus very similar to that of the bright spiral arms.

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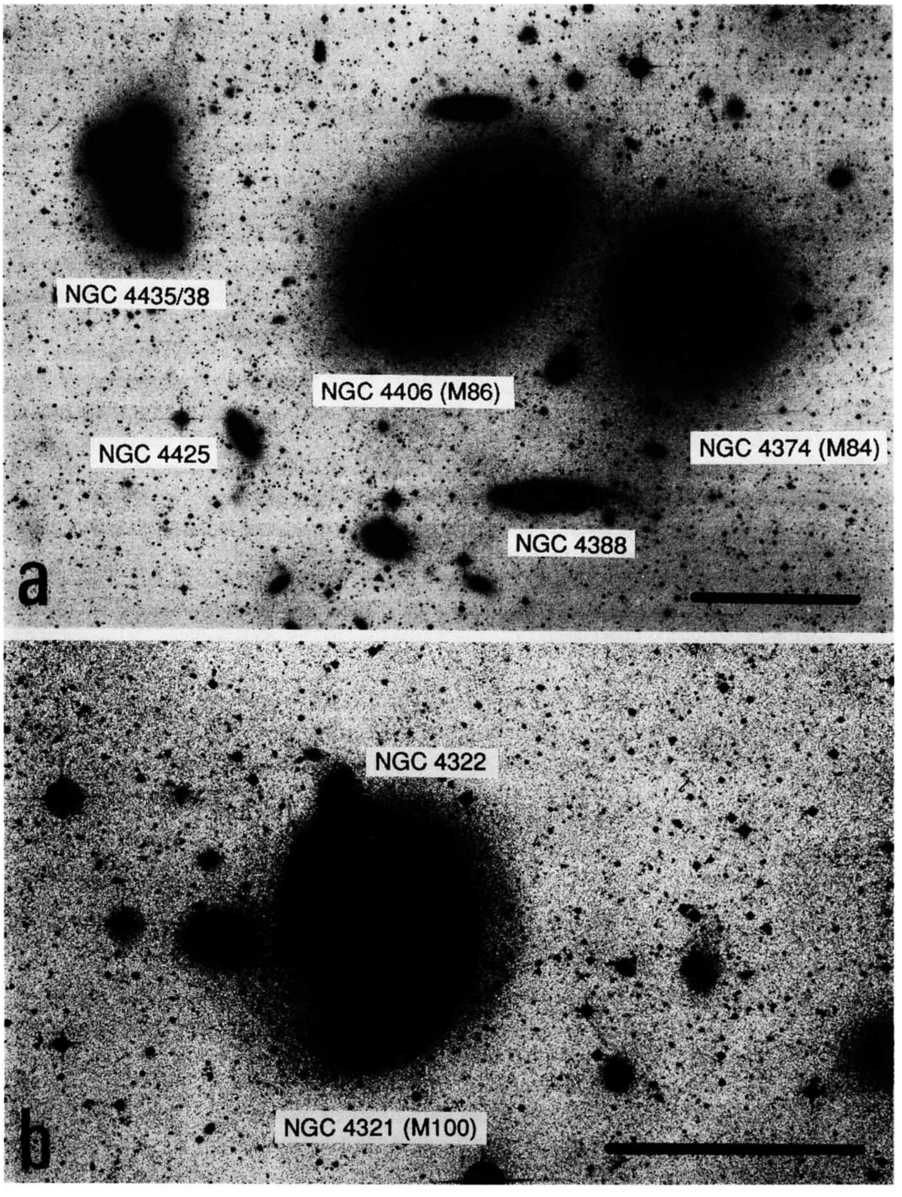

Figure 1. (North at top, east at left) **a.** A very deep image of the richest concentration of bright galaxies in the Virgo cluster. The biggest image here is that of M 86, which has some low surface brightness peculiarities. Faint extensions to other galaxies in the field are discussed in the text. Scale bar = 10 arcmin. **b.** A very deep image of NGC 4321 (M 100) reveals numerous dwarf galaxies and evidence of interaction with one of them, NGC 4322. Scale bar = 10 arcmin.

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Despite its almost perfect symmetry to the casual eye, long slit spectra by Rubin et al. (1980) show numerous velocity asymmetries. Like NGC 4254, discussed later, this galaxy also has an anomalous third arm noted by Elmegreen et al. (1992), though it is much less obvious here. In an earlier paper Elmegreen et al. (1989) discuss the spiral structure in some detail, though the possibility of interaction with companion galaxies is not considered. The star formation rate in NGC 4321 is high (Kenny & Young 1988), and it has an HII region-like nucleus (Giuricin et al. 1990).

The very deep picture (Fig. 1b) shows that the outer envelope of the galaxy is very diffuse, unlike most non-cluster spirals examined. This property has been noted by van den Bergh et al. (1990) as distinctive of Virgo spirals, and is ascribed to ram-pressure stripping of the outer parts of cluster galaxies. Van den Bergh also noted the colour uniformity of some Virgo spirals (such as NGC 4321), considering that it may be a mild, local manifestation of the Butcher-Oemler effect.

There is also evidence that NGC 4321 is an interacting galaxy. On the colour picture noted earlier, a bright, nucleated dwarf galaxy (NGC 4322) is seen 5 arcmin to the north. Though it appears quite normal on short exposures, in the much deeper Fig. 1a its outer isophotes are obviously distorted and it appears to be embedded in the faint extensions of NGC 4321. It also appears to have an even fainter companion, (VCC 619 — Virgo Cluster Catalog, Binggeli et al. 1985) 1 arcmin further north, which is also distorted. The effect of these galaxies on NGC 4321 is difficult to determine, but it is tempting to speculate that NGC 4322 is responsible for the large, diffuse arm that is displaced to the south of the bright spiral.

NGC 4254 (M 99, Sc(s)I.3) appears to be dominated by a 'three-arm' structure according to Elmegreen et al. (1992). The anomalous arm is well seen to the west of the galaxy in short exposure photographs (Fig. 2a). The new, deep photograph (Fig. 2b) shows a faint, even more anomalous arm extending from the south of the galaxy towards the west. There is another anomalous, faint loop extending to the NE.

Schweizer (1976) noted that the galaxy was exceptionally blue, suggesting a high current rate of star formation, an observation confirmed by the inclusion of NGC 4254 on Kenny & Young's (1988) list of galaxies with 'prodigious' star formation rates. The galaxy also has an HII region-like nucleus (Giuricin et al. 1990). All these signs suggest recent or ongoing interaction, but there is no obvious intruder, though there is one unusually compact, high surface brightness galaxy (IC 3177) 7.5 arcmin NE of the nucleus, arrowed on Fig. 2a.

NGC 4382 (M 85, S0 pec) is on the northern extremity of our series of plates, which accounts for the intrusive fiducial marks in Fig. 2c. Even on this normal contrast print, M 85 seems to be obviously disturbed, and possible tidal interactions were noted by van den Bergh et al. (1990). On our deep picture, Fig. 2d, the galaxy is clearly an addition to the range of galaxies which exhibit shells, with a relatively short, bright arc to the south and a fainter, more extended structure to the SW. The most obvious candidate for causing this disturbance is the Sb galaxy NGC 4394, about 7 arcmin east of M 85, however the faint outer structure of this spiral seems perfectly uniform. A more likely candidate therefore is the dwarf S0 galaxy IC 3292, which appears a similar distance to the west of M 85. On the deep photograph its isophotes are seen to be obviously distorted. There is also a small, distorted dE galaxy, VCC 797, 3 arcmin due south of M 85 (seen in Fig. 2c) which may be involved in the interaction.

NGC 4552 (M 89, E0) was the first 'shell' galaxy to be identified, though this was not recognised at the time (Malin 1979). As more and more plates are combined, ever fainter features become visible, and it is now apparent that 12.5 arcmin east of the galaxy is a nucleated dE

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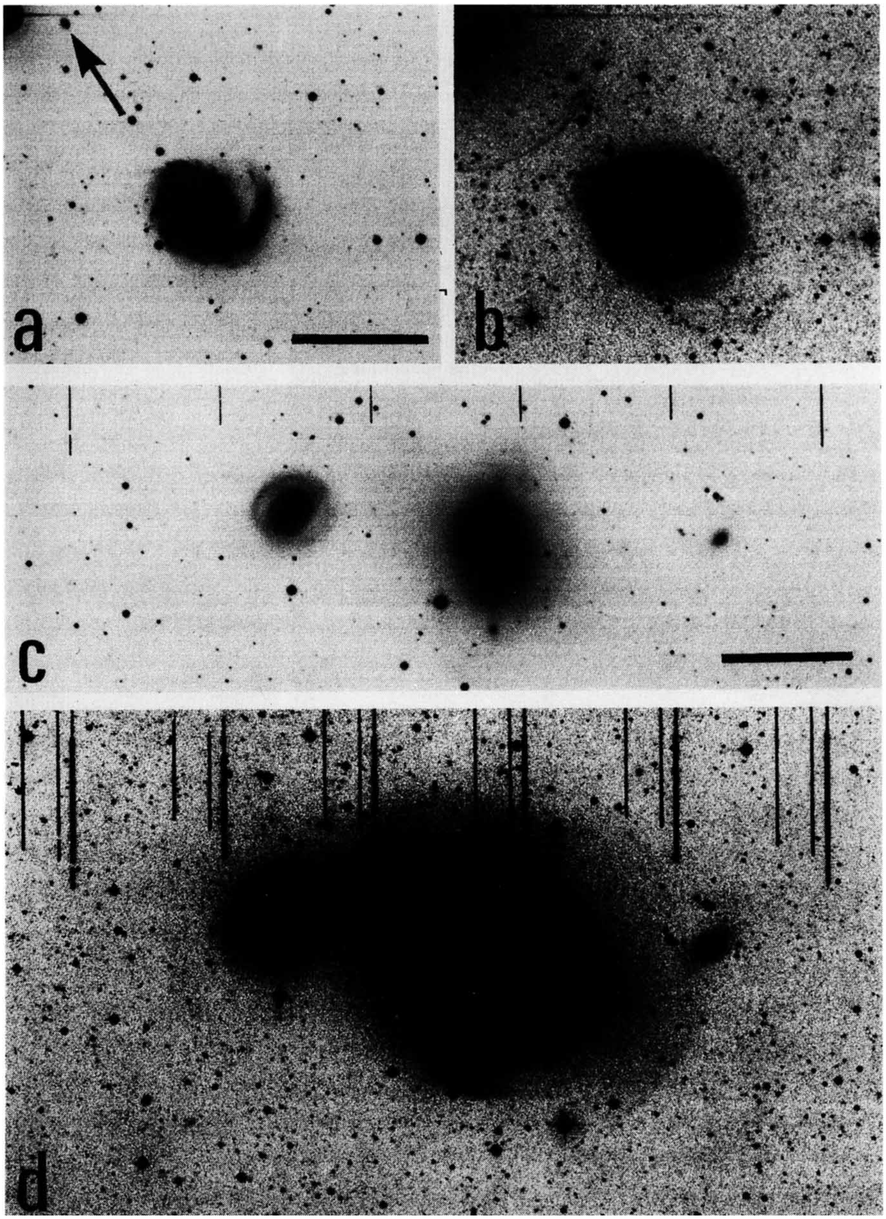

Figure 2. (North at top, east at left except where indicated.) Figures 2a and 2b illustrate the anomalies of NGC 4254 (M 99). IC 3177 is arrowed. Figures 2c and 2d show low surface brightness features in NGC 4382 (M 85) and the distorted outer envelope of IC 3292, 7.5 arcmin west of M 85. Scale bar = 5 arcmin.

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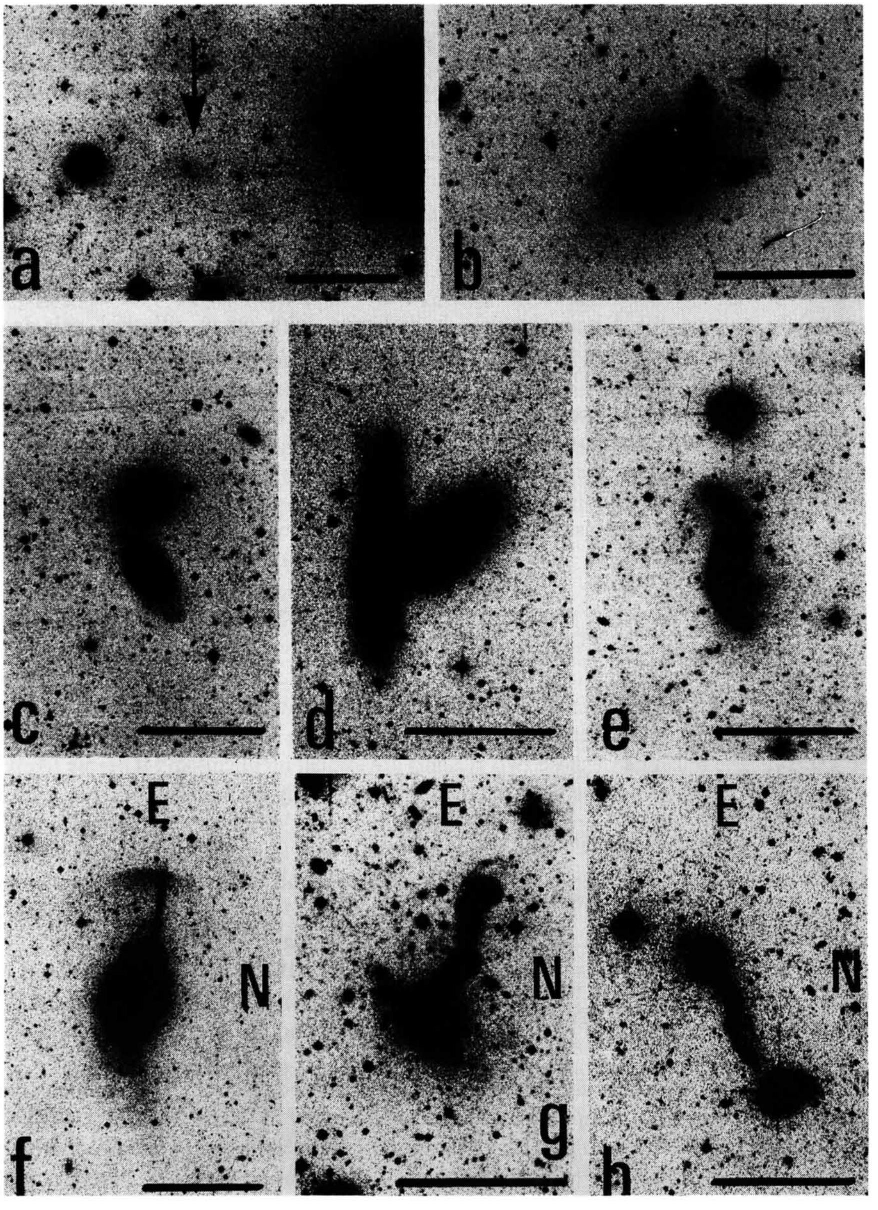

Figure 3. (North at top, east at left except where indicated) **a.** An unusually large and unusually faint, nucleated galaxy (arrowed) near M 89. **b.** The asymmetrical envelope of NGC 4168. **c and d.** The interacting pairs NGC 4305/4506 (c) and NGC 4298/4302 (d). **e.** Faint extensions to the unusual S0 galaxy NGC 4488. **f.** The jet and shells of NGC 4651. **g and h.** Background interacting systems NGC 4410 (g) and IC 4381 (h). All scale bars = 5 arcmin.

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galaxy of extremely low surface brightness and considerable angular extent (arrowed in Fig. 3a). The *maximum* surface brightness of the disk of this galaxy is about that of the faintest shell around M 89, or approximately 28.5 mag arcsec^{-2}. This object has an unusually flat luminosity profile, reminiscent of a disk galaxy, but no clumpy structures are seen in this photograph. The nucleus appears stellar. Apart from this note, nothing appears to be known about this intriguing galaxy.

4. Other Interacting Galaxies

NGC 4168 (Fig. 3b) is classified as an E2 galaxy, and with a radial velocity of 2316 km/sec is almost certainly beyond the Virgo cluster. In common with many elliptical galaxies the elongation becomes more extreme at low surface brightness, but it also becomes evident that in this galaxy the envelope is markedly asymmetrical, though free from small-scale structure such as shells or bars. The asymmetrical isophotes of NGC 4168 have also been noted by Bender et al. (1992). The galaxy appears to be interacting with a small E3 galaxy (NGC 4164, redshift not known) and may be a member of a small group.

NGC 4305 (Sa) and NGC 4306 (d:SB0(5),N) (Fig. 3c). NGC 4306 (the southern-most galaxy) has signs of a spiral structure, possibly induced by interaction with NGC 4306 (van den Bergh et al. 1990). The deep image also shows a large, faint, shell-like structure extending SW from NGC 4305.

NGC 4298 (Sc(s)III) and NGC 4302 (Sc) (Fig. 3d). NGC 4302 is an edge-on galaxy with a clear, apparently undisturbed dust lane, though the luminous envelope seems a little extended to the south on direct photographs. Combining photographically amplified images from seven deep IIIa-J plates shows that the low surface brightness envelope of the edge-on galaxy is considerably extended to the north, while the outer envelope of NGC 4298 is unusually extended and diffuse for an Sc galaxy. The redshifts of these two systems are almost identical, and it seems likely that they are interacting, especially since NGC 4298 is another galaxy with prodigious star formation rate (Kenny & Young 1988). There does not appear to be any other galaxy involved.

NGC 4488 (S0 pec), (Fig. 3e) is certainly a strange S0, with long, faint symmetrically curved but diffuse arms evident on the deep photograph. There is no obvious interacting candidate nearby, though NGC 4472 (M 49) is a possibility.

NGC 4651 (Sc) (Fig. 3f), has a well-known 'jet' on deep plates (Sandage et al. 1965), but it appears to be a normal Sc in the atlas of Sandage & Bedke (1985). However, the faint outer 'shell' at the end of the extension has not been noted previously. The galaxy is in the list of isolated LINER galaxies compiled by Giuricin et al. (1990) and has a high star formation rate (Kenny & Young 1988).

NGC 4410a/b (Fig. 3g). This interacting quartet of galaxies is a strong radio source and has been examined in some detail at optical and radio wavelengths by Hummel et al. (1986). It is of particular interest because it is unusual to find enhanced radio emission in extended interacting systems, especially when they are part of a large group of 10 or so galaxies. The group has a systemic velocity of about 7200 km/sec. This places it well beyond the Virgo cluster.

The two brightest components, identified as A and B in Fig. 1a of Hummel, are strongly reminiscent of the interacting galaxies of the Antennae, NGC 4038-9, and, like the Antennae these gas-rich galaxies have faint extensions emerging from them, forming an arc running from S to NW. Our picture (Fig. 3g) is somewhat deeper than Hummel's, and shows an extended region

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of optical emission around A and B. However, it is difficult to decide if the dwarf galaxies (E and F in Hummel) are part of this arc, or (less likely) are foreground dE galaxies in the Virgo cluster. Almost certainly the large LSB galaxy VCC 914 at the western edge of the photograph is a foreground Virgo galaxy. Though it is insignificant on the ordinary print it is saturated on the deeper picture.

IC 3481 (Fig. 3h) is in a group with a redshift of 7000 km/sec^{-1} so is well beyond the Virgo cluster. This appears to be an interacting trio of galaxies not unlike the NGC 4410 system mentioned above, but there appears to be little in the literature about this unusual object.

5. Summary

The illustrations reveal the usefulness of routine photographic enhancement of archival photographic plates. As demonstrated by the very LSB galaxy near M 89, the inclusion of more plates in the collection leads to the discovery of ever fainter objects. Photographic methods of adding plates are seen as complementary to digital methods. Photography provides a result quickly, generally with fewer artefacts and covers a very large area in one simple operation. But it is not quantitative in any photometric sense and should be considered principally as a convenient discovery tool.

Table 1. Table of major galaxies mentioned. Data from Binggeli et al (1985)

NGC/IC	VCC	B_T	TYPE	Rv
4168	49	12.2	E2	2316
4254 (M 99)	307	10.4	Sc	2413
4298	483	12.1	Sc	1135
4302	497	12.6	Sc	1149
4305	522	13.3	Sa	1888
4306	523	13.8	SB0	1508
4321 (M 100)	596	10.1	Sc	1568
4322	608	14.7	dE4,N	1830
4374 (M 84)	763	10.6	E1	1000
4382 (M 85)	798	10.1	S0(pec)	760
4388	836	11.8	Sab	2529
4406 (M 86)	881	10.1	S0/E3	-227
4410 A+B	904/7	14.5	Sab	7540
4425	984	12.8	SBa	1883
4486 (M 87)	1316	9.6	E0	1258
4440	1047	12.7	SBa	724
4488	1318	12.9	SO(pec)	980
IC 3481	1462	14.8	E2(pec)	7086
4651	*	11.3	Sc	794

* not in Virgo cluster Catalogue

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