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CHARACTERISTICS OF COMPANION GALAXIES

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ABSTRACT

From spectroscopic measures reported in a separate paper a class of objects consisting of 87 companion galaxies apparently associated with 61 larger galaxies has been selected. It is established that the spectral characteristics of the companions relative to the larger galaxy are: (1) the companions tend to have more emission and higher excitation; and (2) the companions tend to have earlier type absorption spectra.

The differential redshifts of the companions relative to the larger galaxy are analyzed in two categories: (1) Where Δz is ± 800 km s^{-1}, the companions would be conventionally accepted as physically associated; nevertheless, positive Δz's outnumber negative by 36 to 15. (2) The remaining Δz's range from $+4000$ to $+36,000$ km s^{-1}. The nature of these companions indicates not many can be accidental projections of background galaxies. Some new cases of strongly interacting companions with large discordant redshifts are presented in detail. Past evidence, as well as new independent evidence that companion galaxies have some component of intrinsic redshift, is reviewed.

Subject headings: galaxies: clusters of — galaxies: redshifts

I. INTRODUCTION

More than ten years ago it was pointed out that the well known companions to M31 and M81 as well as companions on ends of spiral arms exhibited a strong tendency to have positive redshifts with respect to their dominant galaxies (Arp 1970*b*). Later, at the Paris Colloquium, refined data on the Local Group and the M81 companions were considered, and it was shown that essentially all these companions had positive residual redshifts (Arp 1976). Bottinelli and Gougenheim (1973) meanwhile had confirmed on a larger body of data that companion galaxies had systematically higher ($+90$ km s^{-1}) redshifts. Collin-Souffrin, Pecker, and Tovmassian (1974) showed that a sample of compact companions had a systematic redshift of $+121$ km s^{-1} and that less compact companions had a shift of $+46$ km s^{-1}.

Since most of the available data had thereby been analyzed, progress could be made only by picking out new objects. It would be greatly advantageous if a completely independent sample of objects could be chosen, with the only prior criterion being that they fulfilled the definition of dominant galaxy with companions. The hypothesis that there was a systematic redshift effect could be given another, more stringent test. In addition the very important investigation could be made as to whether the companions with excess redshift had distinguishing spectra or morphological characteristics.

An opportunity to obtain such a new and untested sample of main galaxies with companions was provided by the systematic search of the southern sky for the *Catalog of Southern Peculiar Galaxies and Associations* (see interim report in Arp and Madore 1977). One category in that catalog consists of main galaxies with interacting companions, and another category consists of main galaxies with apparent companions—where companion was defined as any galaxy that appeared about one-half or less the size of the main galaxy. The whole southern sky south of declination $= -22°$ has been systematically searched and all those cases recorded where the companions were conspicuously interacting, or where the companions were conspicuously close to main galaxies in terms of populations in the surrounding fields. Since the galaxies nearest in space to our own Galaxy consist of dominant galaxies with companions, like M31 and M81, it is reasonable to expect many other physical systems like these spread throughout space. Further, since the new list contained only the most likely associations over the entire southern sky, it seemed reasonable to suppose that mostly these were physical associations. Later where the conventional criterion of redshift came out to be very similar for many companions and main galaxies, this was viewed as confirmation of their physical association.

During the years 1977–1979, Arp observed the most conspicuous groups spectroscopically with the du Pont reflector at Las Campanas. The data from those three years of observations are given in a separate paper (Arp 1981, hereafter Paper I). In the present paper, all data on redshifts of companions and main galaxies from Table 1 of Paper I are analyzed. Spectroscopic criteria are used insofar as they aid the analysis of the groups. At the end of this paper a moderately complete survey of the results appearing in recent literature is used in order to add yet

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another independent test of the companion redshift effect. Mostly these are separate H I investigations of large galaxies with companions nearby which happen to have H I response.

II. THE BASIC LIST OF Δz's

In Paper I the final heliocentric z for all objects measured was given in the last column of Table 1. In the present paper, Table 1 lists only those systems in which there is a dominant galaxy and apparent companion or companions. The differential redshift is given in the last column of the present Table 1. A plus sign means the redshift of the companion is greater.

As explained in Paper I, when spectra were taken on different nights, the final error of each z was about ± 50 km s^{-1}. That would make the average error of the difference of a companion and central galaxy taken on different nights come out to be ± 71 km s^{-1}. This is considered the basic average uncertainty of the Δz's listed in Table 1. However, many companions and central galaxies were taken either on the same image-tube spectrograph (ITSp) exposure or on succeeding exposures (same plate). In that case the error of each z was considered about equal to the average deviation of the lines from the mean redshift divided by the square root of the number of lines. In such cases, the errors for each individual z were added vectorially and listed next to the Δz in the final column of Table 1 of the present paper. They can be considerably more accurate. In a few cases of successive Varo-Reticon spectra taken in 1979, the same lines could be differenced in both the companion and central galaxy in successive exposures. These could give on occasion, particularly in the case of emission spectra, some very accurate Δz's. Redshift differences and errors derived in this latter fashion are marked (L) in the last column of Table 1.

a) The Classification of the Kind of Association

All these companions and central galaxies were picked originally as being the most conspicuous groups from the extensive Schmidt plate searches. Because of their marked contrast with surrounding field regions, each case was already very probably a physical association of galaxies. Nevertheless, when the galaxies were examined

TABLE 1

CENTRAL GALAXIES AND COMPANIONS

Position	Object	Assn. Class[a]	Spectrum[b]		Δz (km s^{-1})[c] (basic ave dev = ± 71)
19/10, −62/23	central Sb	...	1.0a	...	...
	compact I/A dbl	3.0	...	2.1e	−755 ± 31
	comp NW	3.0	1.7a	1.6e	−430
	low s. br. comp NW	2.0	...	2.3e	−3326
19/22, −55/03	lg Sb	...	1.0a	...	...
	comp NE	3.0	...	2.0e	+452 ± 46
19/50, −58/51	lg Sc	...	1.3a	...	...
	comp SE	2.0	1.4a	...	+9142
	comp W to comp SE	2.0	...	1.5e	+9164
20/01, −60/23	log spiral	...	1.5a	...	...
	I/A comp NW, brt NW	3.0	1.0a	...	+7298 ± 52
	I/A comp NW, ft dbl SE	3.0	1.0a	...	+7189 ± 64
20/28, −31/00	lg spiral	...	1.0a	...	...
	comp NE	2.0	1.8a	2.0e	−235 ± 48
20/38, −32/42	lg spiral	...	1.0a	1.6e	...
	comp B (sm, SW)	3.0		1.9e	+35,096
	comp A (lgr, further SW)	3.0	1.6a	1.5e	+31,528
20/52, −22/16	gal	...	1.0a	...	...
	comp E	4.0	1.0a	1.5e	+36,460 ± 35
21/05, −33/11	gal	...	1.1a	...	...
	comp NW	4.0	1.1a	2.4e	+126 ± 56 (L)[d]
21/07, −64/15	lg ring gal	...	1.0a	...	...
	comp E	2.0	1.0a	...	+25,162 ± 104
21/37, −42/46	lg E	...	1.0a	...	...
	comp NE	1.0	1.5a	...	+137 ± 47
	comp SW	1.0	...	1.5e	−243
22/30, −64/58	spiral	...	1.0a	1.6e	...
	comp SW	3.0	1.8a	2.0e	−52
23/15, −42/39	lg Sb	...	1.0a	2.0e	...
	comp A (in arm)	2.0	1.0a	...	+15,135
	comp B (further SW)	2.0	1.0a	...	+14,611
23/16, −66/59	gal	...	1.0a	...	...
	comp A (SE edge)	3.0	1.0a	...	+22,794 ± 97
	comp B (south of A)	3.0	...	1.5e	+23,244
23/19, −42/46	gal	...	1.2a	1.6e	...
	comp A (S of I/A dbl)	3.0	1.7a	...	+8792 ± 62
	comp B (N of I/A dbl)	...	1.6a	1.6e	+8832 ± 32

TABLE 1—*Continued*

Position	Object	Assn. Class[a]	Spectrum[b]		Δz (km s^{-1})[c] (basic ave dev = ± 71)
23/22, −82/11	lg spiral	...	1.2a	1.6e	...
	comp NW	3.0	1.5a	2.5e	−344
23/30, −45/19	lg E	...	1.0a	...	...
	comp SW	2.0	1.1a	1.5e	+771
23/35, −47/49	lg E	...	1.1a	...	...
	comp SE	2.0	1.9a	1.5e	+13,603
23/41, −32/14	lg Sd	...	...	2.0e	...
	comp A (NW of 3)	2.0	1.0a	...	+16,107
	B (E of 3)	2.0	...	1.7e	+16,138
	C (S of 3)	2.0	1.0a	...	+15,980
23/45, −30/48	lg Sc	...	1.0a	...	...
	comp SE	3.0	1.0a	...	+18,567
	comp A	3.0	...	1.5e	+18,034
00/03, −36/24	gal D (largest)	...	1.0a	...	...
	gal E	3.0	1.0a	1.5e	+534 ± 88
	gal A	3.0	1.0a	1.5e	+157 ± 55
	gal B	3.0	1.0a	1.5e	+301 ± 41
	gal C (smallest)	3.0	1.0a	...	+359
00/12, −60/36	SB spiral	...	1.0a	...	...
	comp N	4.0	1.9a	1.5e	+32,774
00/21, −62/34	gal	...	1.5a	1.6e	...
	comp W	4.0	...	2.1e	−113 ± 32
00/31, −56/53	gal	...	1.6a	2.4e	...
	comp A	4.0	1.6a	1.6e	+694 ± 77 (L)[d]
	comp B	3.0	1.6a	2.5e	+209 ± 11 (L)[d]
00/31, −28/06	lg spiral	...	1.4a	2.1e	...
	comp B (lo sbr, W)	3.0	...	2.0e	+276
	comp A (compact)	3.0	1.0a	...	+19,141 ± 37
00/36, −24/33	lg spiral	...	1.5a	2.0e	...
	comp S	2.0	1.7a	2.0e	+253 ± 37
00/36, −43/22	distbd spiral	...	1.7a	2.0e	...
	comp W	3.0	1.9a	2.0e	−531
00/40, −23/49	lg gal NW	...	...	2.5e	...
	sm comp SE	4.0	1.0a	...	+268 ± 79
00/41, −50/29	lg SB	...	1.1a	1.6a	...
	comp A (in disk)	3.0	1.6a	...	+271
	comp B (N)	3.0	...	1.8e	+24
00/50, −31/30	lg spiral	...	1.1a	1.9e	...
	comp N	3.0	1.6a	1.5e	+84
00/55, −49/12	lg spiral	...	1.1a	...	...
	comp W	3.0	1.2a	...	+32,586 ± 69
00/58, −40/25	spiral	...	1.0a	...	+9695 ...
	comp S	4.0	1.0a	...	...
01/10, −58/30	lg gal	...	1.0a	1.6e	+45
	integ. sign comp NE	3.0	1.5a	2.0e	+289
	comp SE	3.0	1.0a	...	...
01/25, −58/38	spiral	...	...	2.5e	+441
	comp NW	...	1.0a	...	...
01/35, −62/49	E gal	...	1.0a	...	+121 ± 89
	comp NE	2.0	...	2.0e	−1160 ± 56
	comp SW	2.0	1.7a	...	...
01/45, −53/01	spiral	...	...	2.5e	+142 ± 35 (L)[d]
	comp in disk (A, SE)	3.0	2.0a	2.0e	+5434 ± 41 (L)[d]
	comp NW (B)	2.0	1.0a	...	...
01/47, −35/10	lg Sb	...	...	1.6e	+396 ± 70
	dstb spiral NE	3.0	1.0a	...	...
01/52, −56/57	central E	...	1.2a	...	+314
	comp N (C)	3.0	1.0a	...	+363
	elong comp NE (B)	3.0	1.0a	...	...
01/56, −56/31	lg E gal (B)	...	1.0a	...	+223
	spiral NE (A)	2.0	1.0a	...	+64
	comp W of above spiral	2.0	1.0a	...	...
01/59, −22/01	spiral	...	1.0a	...	+245 ± 29
	comp in arm (NW)	4.0	1.0a	...	...
02/12, −25/03	ring spiral	...	1.3a	...	−605 ± 50 (L)[d]
	comp E	2.0	1.8a	2.1e	...

TABLE 1—*Continued*

Position	Object	Assn. Class[a]	Spectrum[b]		Δz (km s^{-1})[c] (basic ave dev = ±71)
02/13, −28/33	central spiral	...	1.8a	2.1e	+414 ± 88 (L)[d]
	comp SE (A)	4.0	1.8a	2.5e	+14,021 ± 29
	comp N (B)	4.0	1.6a	2.1e	...
02/19, −27/27	spiral	...	1.8a	2.1e	+12,630 ± 35 (L)[d]
	comp NW	2.0	1.9a	1.9e	...
02/24, −24/56	spiral	...	1.9a	1.9e	−273 ± 12 (L)[d]
	comp W	4.0	...	2.5e	
02/49, −55/12	spiral	...	1.0a	...	...
	comp NNW	3.0	1.8a	1.6e	+7798 ± 78
03/05, −67/00	gal	...	1.0a	...	...
	comp	1.0	1.0a	...	−54 ± 63
03/14, −63/12	gal	...	...	1.5e	...
	comp SW	2.0	1.6a	1.5e	+15,673 ± 38
03/40, −47/24	lg spiral	...	1.0a	1.8e	...
	comp NE	2.0	1.0a	...	+9133
03/59, −67/49	lg gal	...	...	2.1e	...
	comp SE	2.0	1.6a	2.0e	+7 ± 22
04/02, −54/14	lg Sb	...	1.0a	...	...
	comp SB	1.0	...	2.0e	+11.924 ± 63
04/02, −43/30	spiral	...	1.2a	...	...
	comp SW	4.0	...	2.5e	+282[e]
04/09, −46/09	gal	...	1.9a	2.1e	...
	comp NW	3.0	1.9a	1.9e	−45 ± 64
04/10, −32/59	spiral	...	1.0a	...	...
	comp NW	3.0	1.2a	1.6e	−134 ± 47
04/26, −47/57	E gal	...	1.0a	...	...
	spiral NE	2.0	1.9a	2.1e	+514
	pec gal SW	2.0	...	2.1e	+254
	IA dbl SW of spiral	2.0	...	2.3e	+31,426
04/36, −47/22	spiral	...	1.0a	1.6e	...
	I/A dbl comp S	3.0	1.6a	...	+7555
05/37, −22/01	spiral	...	1.0a + 1.7a	1.9e	...
	comp NW	4.0	1.7a	2.1e	−21 ± 92 (L)[d]
06/23, −60/52	gal	...	1.0a	2.1e	...
	comp S	4.0	1.9a	...	+674 abs ± 72 (L)[d]
06/55, −67/17	gal	...	1.0a	...	...
	comp W	3.0	1.0a	2.1e	+4,028
06/55, −28/18	spiral	...	1.1a	2.0e	...
	comp N	4.0	...	2.0e	+142 ± 50: (L)[d]
07/28, −66/50	spiral	...	1.0a	1.9e	
	comp SE	4.0	1.1a	1.9e	−35 ± 68.
09/07, −75/39	spiral	...	1.1a	2.1e	...
	comp S	4.0	1.2a	2.1e	+208 ± 47
11/08, −30/05	spiral	...	...	2.1e	...
	comp NNW	4.0	1.2a	...	+61

[a] See Table 2.
[b] See Table 3.
[c] Basic average deviation = ±71.
[d] See text, § II.
[e] H I $\Delta z = +69 \pm 9$ (see Hawarden *et al.* 1979).

in detail, there was in many cases strong evidence of interaction between the companion galaxy and central galaxy. Naturally, this was taken as confirmatory proof of physical association and lessened even further the chance that any given companion could be an accidentally projected background galaxy.

In order to at least partially quantify the degree of abnormality of the group compared to average expected background galaxies, I have assigned one of four numbers to each association. The significance of these numbers is explained in Table 2.

b) The Classification of the Kind of Spectra

Another observable quantity which could distinguish between random background galaxies and physically associated companions is any unusual spectral characteristics. Again, spectral characteristics are difficult to quantify strictly. A semiquantitative characterization of the spectra which is used here, however, is presented in Table 3.

In Table 3 the idea is that in the case of absorption spectra, we identify two extremes. One extreme is the old

TABLE 2

CLASSIFICATION OF ASSOCIATION

1.0.	Apparent (bright galaxies close together).
2.0.	Peculiar companion (irreg, compact, or disturbed) *or* disturbed main galaxy.
3.0.	Both pec comp *and* disturbed main galaxy.
4.0.	Linked with filament or jet.

TABLE 3

CLASSIFICATION OF SPECTRA

Absorption	Emission
1.0a, KHGMgINa	0, no emission
1.5a, HζKHGHβ	1.5e, [O II]
2.0a, H$\kappa\iota\theta\eta\epsilon\delta\gamma\beta$	2.0e, [O II]Hβ[O III]Hα
	2.5e, [O II][Ne III]H$\delta\gamma\beta$[O III]Hα[N II]

stellar type population that is found characteristically in E and lenticular galaxies and in the red bulges of spiral galaxies. Those spectra have conspicuous K and H absorption lines of Ca II; they have well marked G bands, and Mg I absorptions, and strong Na I absorptions. At the other extreme of absorption line spectra are those characterized by the presence of only early stellar type, Balmer absorption lines. These are characteristic of blue compact galaxies and blue spiral galaxy nuclei as well as companions on the ends of spiral arms (Arp 1969). In Table 3 we have called the two extremes 1.0a and 2.0a. We identify an intermediate classification where K, H, and the G band are still well marked but the Mg I and Na I lines are not seen and some Balmer lines like Hβ and Hζ are seen in absorption. The practice in the present paper has been to estimate where in this sequence a given absorption spectrum falls and assign it a number between 1.0 and 2.0.

In the emission spectra we have assigned a number roughly indicating the richness and excitation of the emission line spectrum. The least emission is where only one line is seen, usually [O II]. We assign that case number 1.5e, principally to indicate that it is more associated with the intermediate class absorption spectra than with the old stellar type absorption of 1.0a. Then, for 2.0e we have the common emission case of Hβ and the [O III] lines plus [O II] and Hα at either end of the spectrum. For the most extreme case, 2.5e, we designate the rich emission-line spectrum where most of the hydrogen lines are in emission, and higher excitation [Ne III] is seen, as well. Again, as in the absorption classification, we try to assign any given spectrum a number between 1.5e and 2.5e that generally represents its emission character.

III. ANALYSIS OF THE Δz's

The first result of Table 1 is to show that there are a large number of positive Δz's present in our sample. However, in order to select a sample of companions which are certain, by conventional standards, to be at the same distance as the central galaxy, we first examine only those companions which are at roughly the same redshift as the central galaxy.

a) Δz*'s Smaller than* ± 800 km s^{-1}

Examination of the residual reshift data shows that 51 companions have residuals less than $|\Delta z| = 800$ km s^{-1}. There is a gap, then, until the next Δz's are encountered at around $|\Delta z| = 4000$ km s^{-1}. A range (not dispersion) of 800 km s^{-1} in residual redshifts in groups of associated galaxies is quite reasonable from previous investigations. For example, Turner (1976*a*, *b*) shows a distribution of Δz's for double galaxies which cuts off at about $\Delta z = 800$ km s^{-1} (his Fig. 1) and matches quite well the Δz distribution found here. Peterson (1979) adopts a cutoff of $\Delta z = 750$ km s^{-1} for physical pairs for which he measured H I redshifts. Stockton (1978) finds a Δz range of about 750 km s^{-1} for galaxies supposedly associated with low redshift quasars, although in the Stockton case he finds a curiously flat distribution of Δz's compared to the distribution found here and in the other studies.

In the present study, since there is such a clear gap between the $\Delta z \leq \pm 800$ km s^{-1} group and the next largest Δz's which are encountered, we can be even more certain that essentially all the companions with $|\Delta z| \leq 800$ km s^{-1} are at the same distance from the observer as the central galaxy. A plot of these 51 companion Δz's is shown in Figure 1. The mean for all association classes is $\overline{\Delta z} = +122$ km s^{-1}. The average deviation of each Δz from this mean is 242 km s^{-1}, and therefore the mean and error of the mean for the 51 cases is:

$$\overline{\Delta z} = +122 \text{ km s}^{-1} \pm 34 .$$

Clearly, there is a significant excess of positive redshifts within this sample. Perhaps this is shown even more clearly in the numbers where it is seen there are 2.4 times as many positive Δz's as negative.

In order to make another check on whether there is any possible contamination by unassociated background galaxies, the Δz's are further analyzed by association class in the top of Figure 1. Association class 4 includes objects connected together by filaments and jets; class 3 objects are those where central and companion galaxies are both disturbed. Clearly, these two classes represent the maximum probability of associated objects.

The ratio of positive to negative Δz's goes up slightly to 2.5 in these two classes.

Because of this implication that there is some component of nonvelocity redshift present, no attempt will be made to analyze these Δz's as a velocity dispersion. Further comments are made in § VIII.

b) Δz*'s Greater than* 4000 km s^{-1}

Figure 2*a* shows the plot of all Δz's from Table 1. Between $\Delta z = 4{,}000$ and 38,000 km s^{-1} there are 34 companions with large excess redshifts. Are these companions also at the same distance as their central galaxies? This is a more difficult question to answer because unlike the previous group of $|\Delta z| \leq 800$ where conventional redshift distances would place them at the distances of their central galaxies, these large, positive

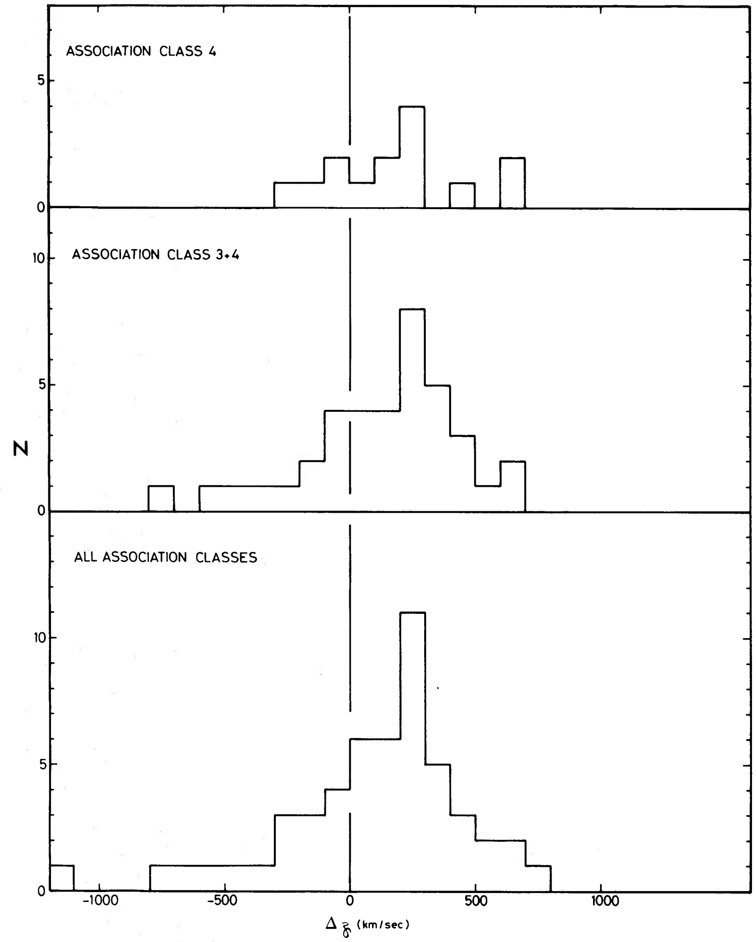

FIG. 1.—Distribution of differential redshifts (Δz's) from Table 1 between $-1{,}200$ and $+1{,}600$ km s^{-1}. Upper histograms represent most certain associations.

redshift residuals would conventionally place these companions at much larger distances in the background.

One attempt at answering this question is shown in the top of Figure 2*a*. There the two most certain classes of association, 3 and 4, are plotted separately. The ratio of large positive residuals to total residuals only changes from 0.65 to 0.50 for the most interactive classes. This implies that at least a good proportion of these large positive residuals are physically associated.

Another argument for their physical reality can be made by considering that the number of unrelated background galaxies should initially increase as the redshift cubed of the prospective companion galaxy. Both halves of Figure 2*a* show that the distribution of Δz's is much too flat (approximately $z \sim \Delta z$ for large Δz). This argument is made more precise in Figure 2*b*, where the distribution of the actual measured z's for companions is shown.

In Figure 2*b*, two possible kinds of increases for numbers of background galaxies are indicated schematically. Fainter than some limiting magnitude, which we estimate at approximately $m \approx 19$ mag, candidate companion galaxies were not measured. Therefore, background galaxies, with a similar magnitude cutoff, if they were distributed uniformly throughout space, would start deviating seriously downward from a z^3 increase at redshifts somewhat greater than $z = 30{,}000$ km s^{-1}(the average field galaxy in Humason, Mayall, and Sandage 1961 has an apparent magnitude near $m_{pg} \approx 19$ for $z \approx 0.1$). This downward deviation is due to the broad luminosity function which field galaxies possess. In the case of the present companions, however, it is clear from their photographs that we are not dealing with low surface brightness objects. Hence, a narrower luminosity function for comparable objects in the general field is appropriate. Another way of saying this is that the excess redshift companions considered in this paper are usually high surface brightness, morphologically similar objects. If they were field galaxies, they would probably not represent a large range in intrinsic luminosity, and therefore their law of increase should be fairly close to a z^3 law. The exact morphological classification of the companion galaxies analyzed in this paper would best await a systematic, high resolution study. But at this stage of the discussion, the exact quantitative details of how a popula-

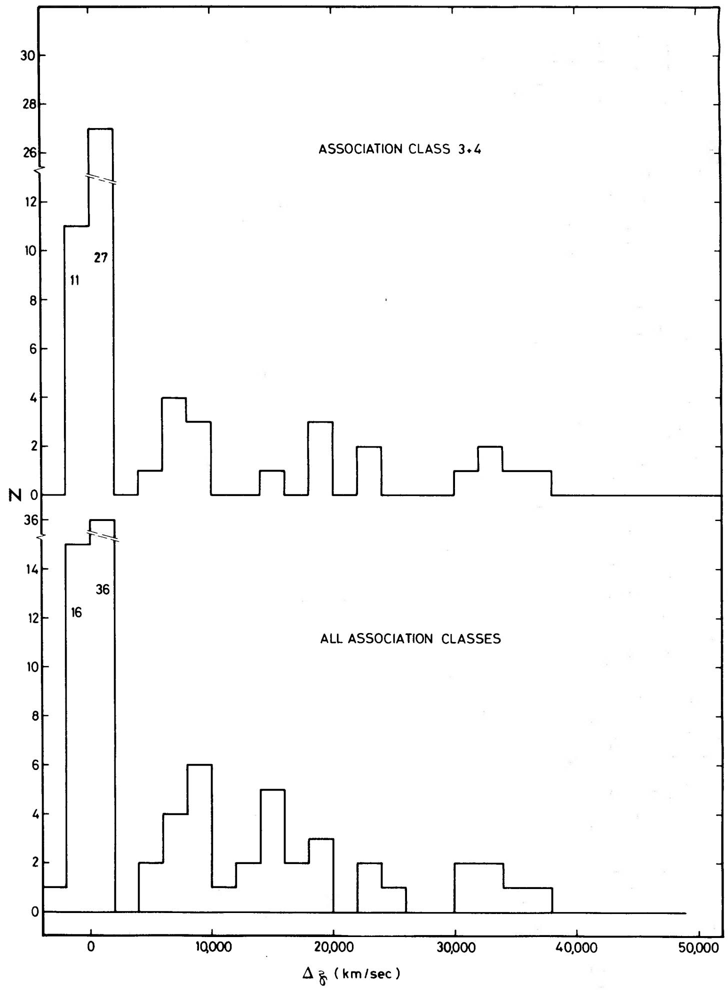

FIG. 2a

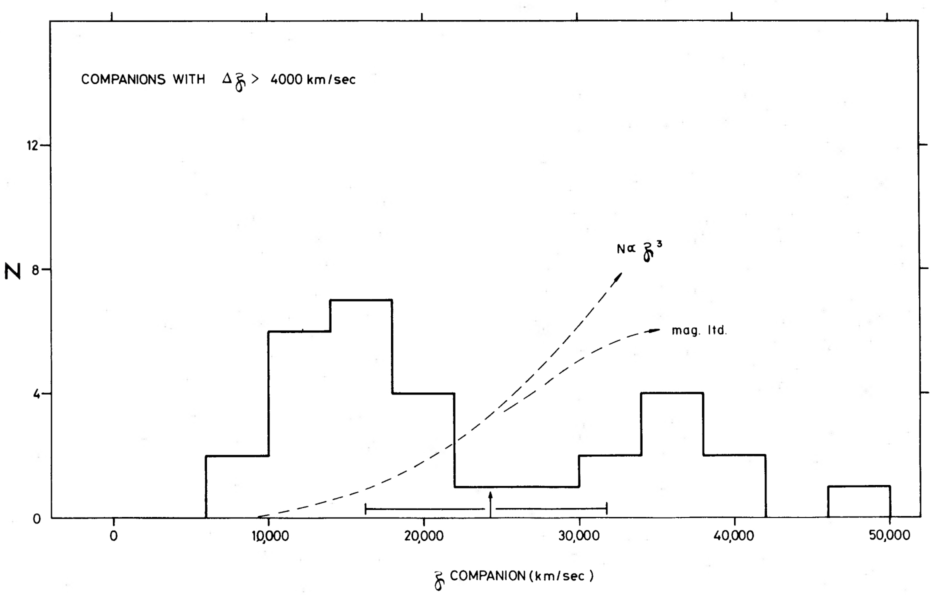

FIG. 2b

FIG. 2a.—Distribution of all Δz's from Table 1. Upper histogram represents most certain associations.

FIG. 2b.—Distribution of redshifts (z's) of those companions for which $\Delta z > 4000$ km s^{-1}. Two cases for increase of background galaxies are shown schematically. Background galaxies of given luminosity class which might resemble the companions would increase z^3. For a magnitude limited sample of background galaxies of a full range of luminosities, the increase would fall under the z^3 increase. Those companions which have $14{,}000 < \Delta z < 24{,}000$ km s^{-1} have z's between $16{,}000 \lesssim z \lesssim 32{,}000$ km s^{-1} with a mean at $z = 22{,}160$ km s^{-1} as shown by range bar and arrow in the bottom of the figure.

tion of field galaxies would increase with z is not of great pertinence. What Figure 2*b* does show is that the large number of $\Delta z > 4000$ km s^{-1} companions with z's in the 10,000 to 20,000 km s^{-1} range are very unlikely to be due to any kind of field galaxies because field galaxies would be falling steeply in number in this range.

In § V below, we discuss that in the range $14{,}000 < \Delta z < 24{,}000$ km s^{-1}, we have the highest probability that some of the companions are accidentally projected background galaxies. The range of measured z's for these particular companions is shown in Figure 2*b* as from 16,000 to 32,000 km s^{-1}, with a mean at $z = 22{,}158$ km s^{-1}. Even if we make the extreme assumption that *all* the companions with $14{,}000 < \Delta z < 14{,}000$ km s^{-1} are background galaxies, then Figure 2*b* tells us two things:

1. The same kind of background galaxies would contribute negligible numbers at lower redshifts, viz. in the $4000 < \Delta z < 14{,}000$ km s^{-1} range of associated companions.

2. The same kind of background galaxies would be more numerous at higher redshifts, viz. for the $\Delta z > 30{,}000$ km s^{-1} range of associated companions.

Since the numbers of candidate companions are not very large at $\Delta z > 30{,}000$ km s^{-1} and since the few candidates which are encountered give very strong evidence of interaction, we must conclude that the contribution of spurious background objects all along the Δz range of companions is very small indeed.

IV. ANALYSIS OF THE SPECTRA

Table 1 also contains classification of the spectra of the companions and central galaxies on the basis explained in Table 3. There are a number of interesting questions we can ask about these spectral data.

First, are there observed spectral characteristics of the companions which demonstrate that they are not random background galaxies? Second, for those companions which are conclusively associated with central galaxies, what is their physical state?

a) *Emission Characteristics*

Figure 3 shows that a number of companions have rich emission spectra. Is this a significantly greater incidence of emission than we would find in the general background field? The spectroscopic characteristics of the general background field of galaxies are difficult to know very exactly, and I will come back to that problem shortly. But it is possible to make a precise comparison of the incidence of emission in the companions compared to the incidence of emission in the central galaxies. Table 4 shows that 65% of the companions have emission, whereas only 48% of the central galaxies do. Since the central galaxies are interacting, in many cases strongly, with the companions we would expect that above normal emission would be stimulated in the central galaxies. Therefore, we would expect the general field galaxies to show something less than a 48% frequency of emission.

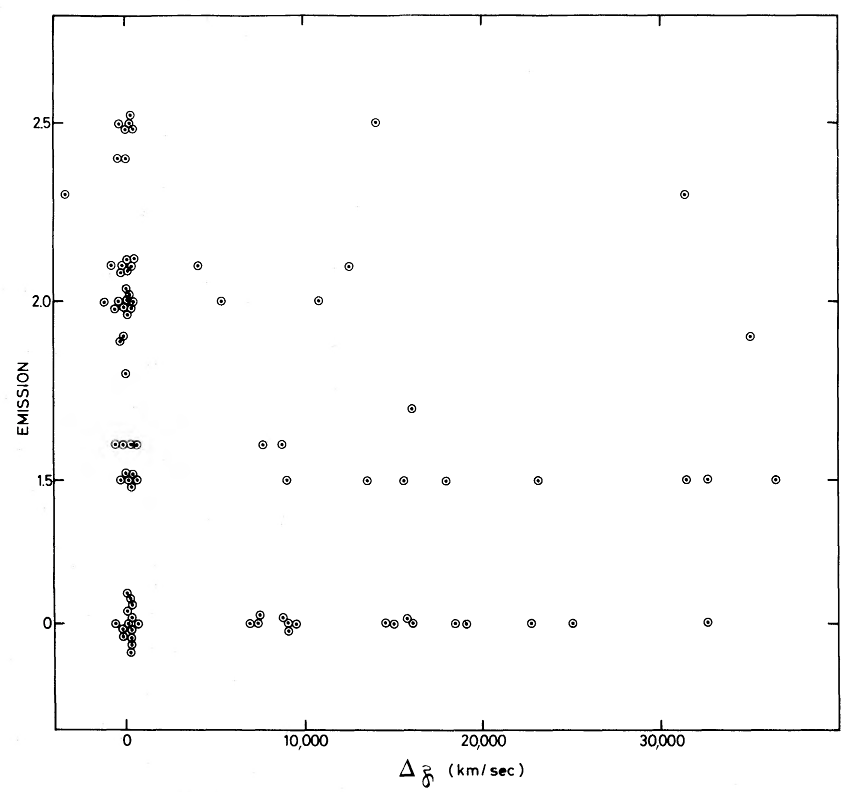

FIG. 3.—Plot of emission characteristics (0 = none, 2.5e = strongest) of companions vs. their Δz

TABLE 4

EMISSION CHARACTERISTICS

Objects	Emission	No Emission	Percentage Emission
All companions	56	30	65%
$\Delta z > 4{,}000$ km s^{-1}	18	16	53%
$\Delta z > 30{,}000$ km s^{-1}	5	1	83%
Central galaxies	30	32	48%
General field	...	...	10%–40%

How much lower is difficult to be certain without actually doing an extensive spectroscopic survey in a control background field. We can note, however, that Mayall (in Humason, Mayall, and Sandage 1956) finds about 46% of his galaxies showing generalized [O II] emission. Of course, he preferentially observed spiral galaxies which have higher frequencies of emission. In the same paper, Humason notes the incidence of [O II] emission in ellipticals is only about 18%. In general, deep Schmidt plates of fields away from bright galaxies give the impression of containing not many spirals but mostly lenticular and amorphous objects. Perhaps the investigation which comes closest to determining the nature of an arbitrary background field was done by Gregory and Thompson (1978). They measure 43 galaxies in an area between the Coma cluster and A1367. Only four showed [O II] in emission. Probably it would be safer to predict that the average background galaxy would have between a 10% and 40% chance of showing at least some [O II] emission, with values nearer 10% more likely.

In any case the companions as a class have a clearly higher than normal incidence of emission spectra. Since, as a class, they are interacting with their central galaxy, it is reasonable to suppose that either the interaction triggers the emission activity or that companion galaxies are intrinsically more active. To substantiate this conclusion we refer to Figure 4 where the association class is plotted versus the spectral class. We see that, on the average, the more strongly interacting companions tend to have the earlier (absorption) and more excited (emission) spectral class.

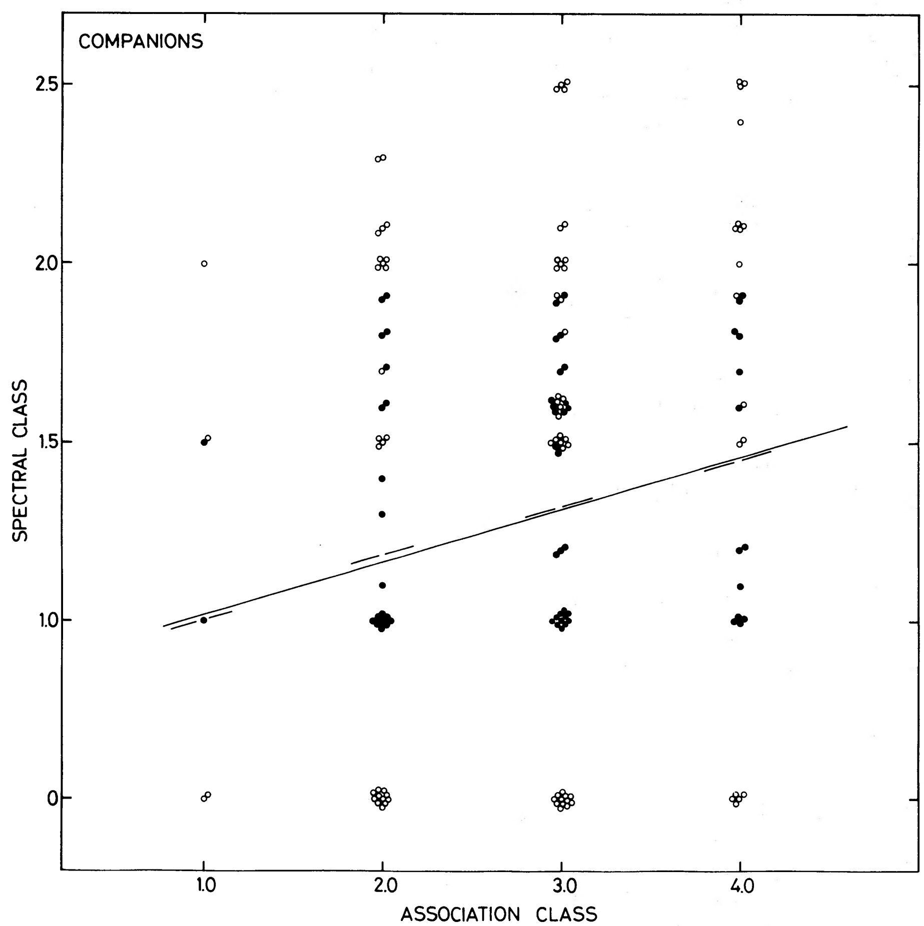

FIG. 4.—Association class is plotted vs. spectral class for companions. Filled circles represent absorption spectra; open circles are emission spectra. The trend is for the more interactive companions to have the earlier spectral class.

b) *Absorption Characteristics*

The most striking qualitative aspect of the companion galaxies is the high frequency of absorption spectra which display well marked hydrogen absorption lines. This effect was first discovered in companions on the ends of spiral arms (Arp 1969). In the present paper the effect is strikingly illustrated in Figure 5 where it is seen that a number of spectra are classed 1.5 or greater. In fact 56% of all companion spectra have absorption class spectra between 1.2 and 2.0 (Table 5). Comparing this to absorption spectra in the central galaxies, we see that only 27% of central galaxies have such early absorption spectra.

The general experience of the author with galaxy spectra is that hydrogen absorption lines in field galaxy spectra are fairly uncommon. In the Gregory and Thompson (1978) investigation quoted earlier only four cases out of 43 showed any hydrogen absorption lines whatsoever. The tendency of the companion galaxies to have early stellar type absorption spectra is the most striking spectroscopic difference of all between companion galaxies and field galaxies.

TABLE 5

ABSORPTION CHARACTERISTICS

Objects	Late-type (1.0–1.1)	Early-type (1.2–2.0)	Percentage Early-type
All companions	28	36	56%
$\Delta z > 4{,}000$ km s^{-1}	14	13	48%
$\Delta z > 30{,}000$ km s^{-1}	1	3	75%
Central galaxies	40	15	27%
General field[a]	39	4	10%

[a] Gregory and Thompson 1978.

Of course, field galaxies with the most extreme, almost pure hydrogen absorption spectra are even less numerous than 10%. Galaxies with absorption spectra like those we have classified here as 1.6a to 2.0a are very rare indeed. It is one of the primary conclusions of this paper that such a young stellar type, hydrogen absorption spectrum is the most certain indication that a candidate galaxy is a physical companion of a larger galaxy. In later discussion we will come to regard this as a sufficient condition for association but not a necessary one.

V. THE QUESTION OF SPURIOUS ASSOCIATIONS

We consider first that group of associations where $|\Delta z| < 800$ km s^{-1}. We saw from Figure 1 that the more interactive companions showed the same preponderance of positive Δz's as the less interactive companions. We use this result to argue that if there were spurious associations of projected background galaxies that they would be expected not to show interaction with the central galaxy. Among the less interactive companions, however, we do not find a greater percentage of positive Δz's. Therefore, this evidence indicates spurious background objects are not contaminating this sample of associations.

We can make the same kind of test using another criterion, that of the spectra of the companions. We have established from Figure 4 that the degree of interaction (association class) is related to the early absorption or emission character of the companion spectrum. Therefore, we can plot Figure 6 which shows that the companions with the most unusual spectra also have a predominance of positive redshifts. Companions with late type stellar absorption and no emission, which are most likely to be interloping field galaxies, cannot explain the preponderance of positive residual redshifts among the companions.

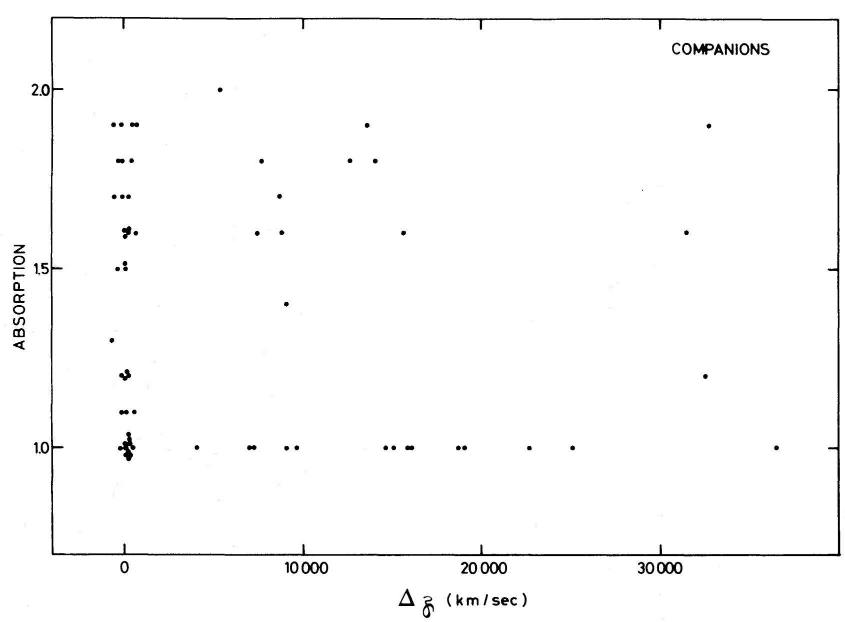

FIG. 5.—Plot of absorption characteristics (1.0a = old stellar type, 2.0a = young stellar type) of companions vs. their Δz

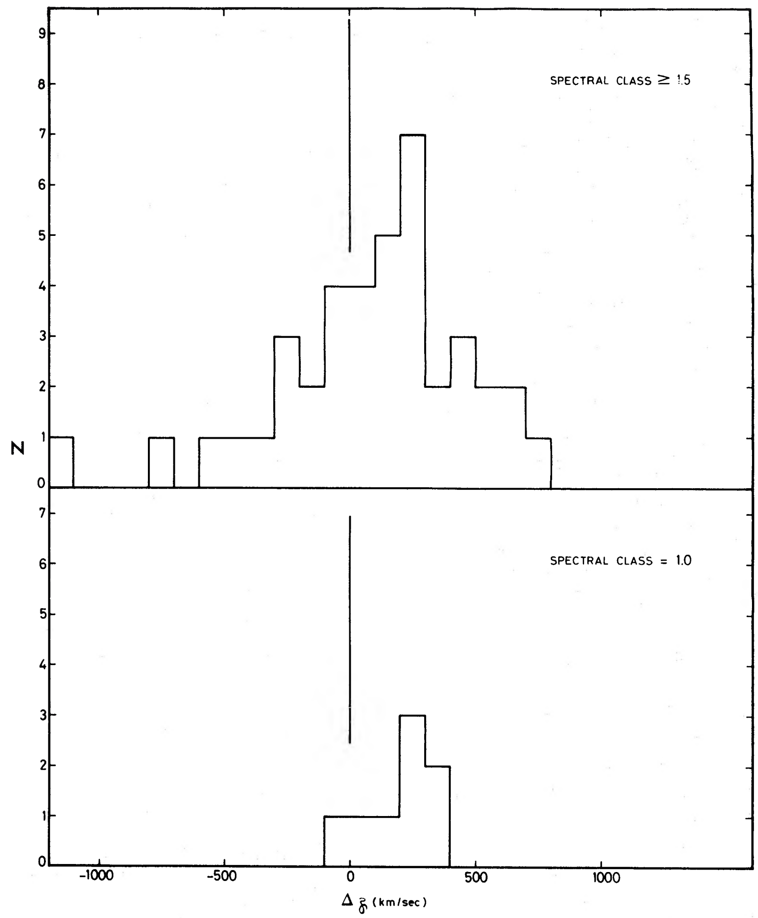

FIG. 6.—(*Top*) Distribution of Δz's for companions with spectral classes more excited than 1.5e (37 total) and earlier than 1.5a (3 total). (*Bottom*) Distribution of Δz's for companions with spectral class = 1.0 (eight old stellar type absorption spectra).

Another very strong argument that essentially all the $|\Delta z| < 800$ km s^{-1} companions are physically associated is the situation indicated in Figure 2. It is simply that if any appreciable number of $|\Delta z| < 800$ km s^{-1} companions were interloping field galaxies, then the numbers of higher ($\Delta z \approx z$) redshift interlopers would, with increasing z, quickly become enormous. This is simply another way of arguing that smaller galaxies, of roughly the same redshift as the larger galaxy, are of such low area density that there is a negligible chance of obtaining an accidental association.

The question of spurious associations amongst the $|\Delta z| > 4000$ km s^{-1} companions is less clear cut. The most relevant figures are Figures 3 and 5. It is seen that for $4000 < \Delta z < 14{,}000$ km s^{-1} and for $30{,}000 < \Delta z < 38{,}000$ km s^{-1} the spectral characteristics are still strongly toward early absorption and emission type, like the most certain associations in the $|\Delta z| < 800$ km s^{-1} group. But there is a range of $14{,}000 < \Delta z < 30{,}000$ km s^{-1} where the mean emission in the companion spectra drops down and the mean absorption spectra become of quite late-type. We might suspect that in this intermediate range of Δz we are encountering some accidental projections from the background.

This suspicion is substantiated by two further tests: first, we see in Figure 2 evidence that a relatively larger proportion of the $14{,}000 < \Delta z < 30{,}000$ km s^{-1} companions are from the less interactive associations class 1 and 2. Second, we see in Figure 7 a plot of z central galaxy versus Δz companion. For the small Δz's, we have central galaxy z's ranging from a few thousand to almost 15,000 km s^{-1}. For the large Δz's the central galaxies have z's compatible with this range. But for the $14{,}000 < \Delta z < 30{,}000$ km s^{-1} group of which we are suspicious, the mean z for the central galaxy is noticeably lower. It is as if we were dealing with some relatively nearby galaxies which included near their fairly large apparent diameters some accidentally projected background galaxies.

We would caution, however, that not even in this suspect range of $14{,}000 < \Delta z < 30{,}000$ km s^{-1} are all, or even most, of the associations likely to be spurious. In § III it was shown that the distribution of companion z's precluded any appreciable number of background galaxies. When individual cases are discussed later it will

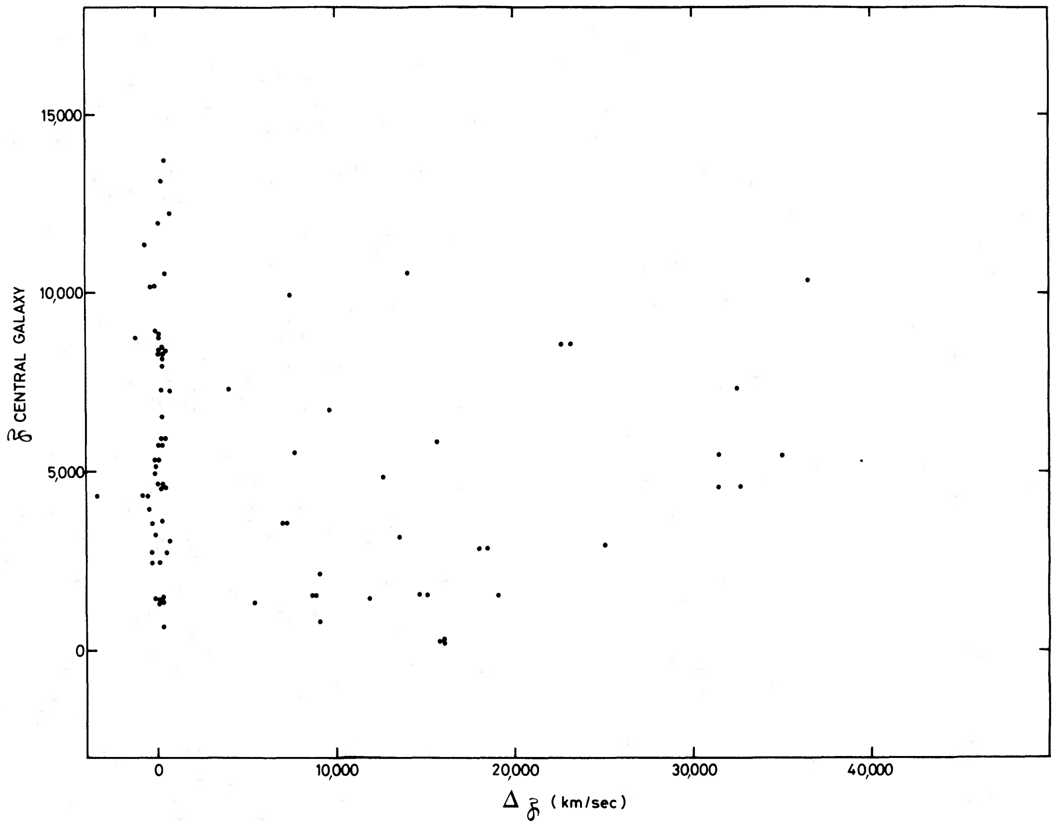

FIG. 7.—Plot of z for central galaxy vs. Δz of companions. A tendency for $14{,}000 < \Delta z < 30{,}000$ km s^{-1} companions to be associated with central galaxies of lower redshift is noticeable. See end of § V for discussion.

also be seen that there are some cases in this range which in fact give very strong evidence for being associated.

For the six cases of $\Delta z > 30{,}000$ km s^{-1}, the average spectral class, association class, and particularly the details of the individual associations support very strongly the reality of the associations.

A question has been raised whether any kind of postulated supercluster structure to the universe would be capable of explaining the results on companion galaxies which are reported here. I think the answer is no, for the following reasons:

1. If the excess positive Δz's were to be explained by background objects, there would need to be a group of such objects coming in strongly at about $\Delta z = +250$ km s^{-1} (see Fig. 1). Superclusters show Δz ranges up to 6,000 km s^{-1} (Tarenghi *et al.* 1979; Chincarini, private communication). Redshift differences of $\Delta z \sim 250$ km s^{-1} are small for clusters of galaxies or even for small groups (see, for example, Faber and Dressler 1977). It appears that the excess redshifts come at such small Δz's with respect to the central galaxy that there is no way of making their physical association other than close by.

2. As mentioned in § III, there is a class of physical, double galaxies which everyone accepts as interacting (Turner 1976; Peterson 1979). They show the same range and distribution of Δz's as the presently considered companions. There would be no reason for the galaxies to be considered physically associated in one case and not in the other.

3. Even more obvious arguments come from the actual distribution and morphology of the galaxies themselves. The companions are usually one or two objects, not a background "sheet" of objects such as would be required by the supercluster model. (The companions would then have to be hanging unexplainedly isolated in space if they did not belong to the main galaxy.) The point is simply that we know from the closest and best investigated cases that large central spirals like M31 and M81, etc., characteristically have physically associated, smaller companion galaxies. We look at more distant examples of such central galaxies and find the same kind of associated companions. There would be no justification for trying to explain them away as unassociated galaxies in a background supercluster.

4. The companions, as established at length in the present paper, are very peculiar both morphologically and spectroscopically. If they were merely background galaxies in an associated supercluster, there would be no reason why they should be peculiar.

VI. THE PHYSICAL STATE OF THE COMPANIONS

It appears that the degree of interaction (or certainly of association) is correlated with the appearance of the spectrum of the companion (Fig. 4). The simplest interpretation of this result is that the presence of the companion in close physical proximity with the central galaxy causes the spectrum of the companion to be unusual. One hypothesis might be that the companion is ejected or fissioned from the central galaxy, and while it is still in the vicinity of the central galaxy it is still quite young and active, and this is reflected in the spectral type. Another hypothesis could be the more current idea that when the companion is in the vicinity of the central galaxy that star formation is triggered by the gravitational disturbance or that material from the central galaxy is accreted onto the companion causing star formation.

In either case it would be reasonable to expect that the emission phase of spectral activity would accompany the initial star formation and activity and that later the gas would become used up or blown out. The young stars so formed, however, would age more slowly, leaving a spectrum marked by early-type absorption lines which would persist for a longer portion of the companion's lifetime.

There is some support for this from Figure 4 where it it is seen that the early emission spectra are correlated with degree of interaction. On the other hand, while the numbers are small, the early absorption spectra are only slightly, if at all, correlated with degree of interaction. The averages are shown in Table 6. Of course, such correlations could also occur if a compact object or protogalaxy were to emerge from a central galaxy and initially excite or carry along excited gas from the central galaxy.

The companions also apparently occasion some activity in the central galaxies. As Figure 8 shows, there is a general correlation between early-type emission activity and early-type absorption spectra. This correlation holds true for the central galaxies (*filled circles*) as well as the companions (*open circles*). But the average degree of activity for the central spirals is much less than for the companions. Of particular interest is the group of companions which has only moderate emission spectra (1.5e to 1.6e) but quite early-type absorption spectra (1.6a to 1.9a). The central galaxies do not show such early type absorption spectra unless they have richer emission spectra.

As for the physical nature of the companions with early type absorption spectra, they qualitatively resemble the spectra of the nuclei of spirals which have "blue" nuclei. Alloin (1973) showed that the nuclei of spirals in the red group had a spectrum which could be represented by a mixture of predominantly G stars, while the blue group nuclei could be satisfactorily accounted for by stellar mixtures comprised of predominantly A stars. An example of such an object is the nucleus of NGC 4569. The early absorption type spectra of the companions observed here appear from visual inspection to be similar (see, for example, Fig. 13 in § IX following). Of course equivalent line widths and continuum colors should be actually measured for some of the present companions to see that they are in fact capable of being represented by mixes of stellar spectra as in the examples that Alloin modeled. Prior to such analyses the best assumption seems to be, however, that the early type

TABLE 6

SPECTRAL CLASS VERSUS ASSOCIATION CLASS FOR COMPANIONS

Association Class	Mean Emission Class	Mean Absorption Class
4	1.49	1.40
3	1.27	1.35
2	1.02	1.32

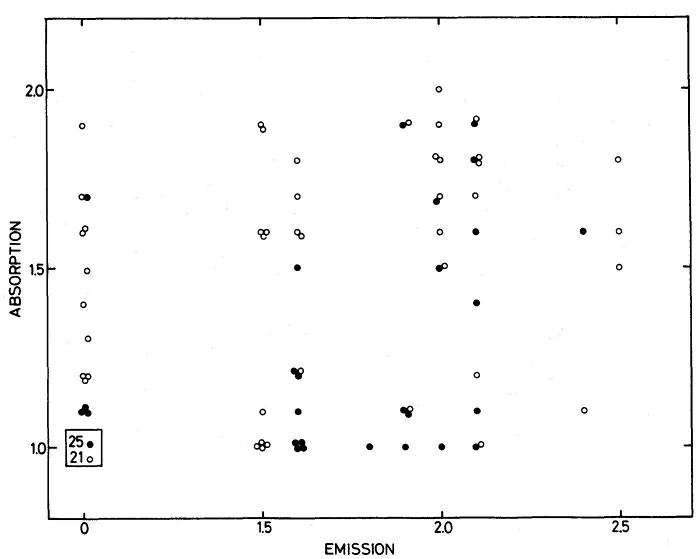

FIG. 8.—Plot of emission types vs. absorption types for companions (*open circles*) and central galaxies (*filled circles*). Note group of companions with early absorption spectra but only moderate emission excitation.

absorption spectra of the companions are caused by dominant numbers of relatively young stars.

VII. SYSTEMATIC EFFECTS IN REDSHIFT

We ask the question: is there any difference between main galaxy and companion spectra which could cause a systematic error in the measured Δz's? Surprisingly, there are two effects which could affect the Δz's.

The first is that, as we have shown, the absorption lines in the companion tend to be earlier than in the main galaxy. In particular, sometimes the H line in the main galaxy is predominantly Ca II 3968.5 Å, whereas in the companion it has a larger component of Hϵ 3970.1 Å. This could work in the direction of giving the companion slightly higher redshift. This has been compensated for in the present analysis by using the Hϵ rest wavelength for computation of redshift whenever the H line is appreciably more conspicuous than the adjoining K line. As a consequence the small, potentially systematic effect for this one line is distributed both plus and minus.

Another, more serious effect is that the main galaxy has often an old type stellar population which falls rapidly in intensity at the K and H break. Measuring K and H absorption lines with a visually set crosswire on this continuum falling to the blue could produce measured wavelengths shifted systematically to the blue. This effect was investigated in the present data by examining 15 cases of main galaxies in which K and H lines had been measured as well as at least two of the three other lines: G band, Mg I, and Na which are also typical of late-type spectra. The effect apparently exists since, on the average, the K and H lines were derived to be -80 km s^{-1} (± 27 km s^{-1}) relative to the other absorption lines which were not on a sharply falling region of the continuum. (I am indebted to Ivan King for a discussion which led me to test for the possible existence of this effect.) Referring back to Paper I where all the image tube spectra were reduced to the K and H region of the spectrum, this undoubtedly explains the $+82$ km s^{-1} which had to be added to bring those redshifts systematically onto the Reference Catalog system of redshifts.

Therefore, the question arises: What effect, if any, has this had on the computed Δz's listed in Table 1 of the present paper? First of all, we note that the redshifts of most main galaxies depend on a number of additional lines to the K and H so that the systematic effect of K and H on the final redshift is much diluted. Second, we note that a number of companions have to some degree a kind of spectrum similar to that of the main galaxy, so that an additional part of the effect cancels out in the differential Δz. Finally, a number of Δz's in Table 1 are derived from digital detector spectra where the position of the line was measured from the tracing of the line minimum. All these latter redshifts are unaffected as demonstrated by the absence of any systematic correction to the Reference Catalog redshifts. Nevertheless, all the redshifts in Table 1 of the present paper have been examined from the standpoint of this K and H effect in the main galaxy. Only the Δz of $+24$ km s^{-1} is possibly changed in sign from positive to negative. The maximum overall effect on the total Δz of the whole group of companions computed in § III is less than -20 km s^{-1} which is less than the ± 34 km s^{-1} uncertainty in the mean derived there. Therefore, we have not attempted to apply this small correction but only note that with additional measures some main galaxies could shift to slightly higher redshifts.

Overall, the compilation of neutral hydrogen redshifts from the literature which is performed in § X of this paper is the most independent check on the systematic redshifts of the Δz's of the companion. There it is shown that with redshifts which are of the order of 5 times more accurate than the optical, the percentage to negative Δz's is the same as for the optical data.

VIII. TESTING QUANTIZATION IN THE Δz's

It has been reported that differential redshifts between physically associated double galaxies are quantized in steps of 72 km s^{-1} (Tifft 1976). The Δz's measured in the current study are tested for this quantization in Figure 9. In the bottom half of the figure all the Δz's between $-300 < \Delta z < 400$ km s^{-1} are plotted. These 38 Δz's do not show much correspondence to the expected peaks at multiples of 72 km s^{-1} for negative Δz's. But for positive Δz's, four of the five predicted concentration of Δz's are matched by peaks in the histogram of observed values ($+72$, $+144$, $+288$, and $+360$ km s^{-1}). If we restrict ourselves to the most accurate Δz's in our Table 1, we find 15 with accuracies better than ± 60 km s^{-1} which have an average accuracy of ± 38 km s^{-1}. The only peak in this more accurate data coincides with a predicted quantization at $\Delta z = +144$ km s^{-1}.

The accuracies of our Δz's are not in general good enough for a critical test of the quantization. Also, the numbers of Δz's are too small. But insofar as the data is capable of testing the prediction, it does support the quantization for positive Δz's.

Although the results pictured in Figure 9 are inadequate for proof, we might, nevertheless, discuss briefly the suggested possibility that only the positive Δz's are quantized. There is an interesting difference in the present study from the Tifft quantization which was originally established from differences between more or less equal sized galaxies in pairs (and later in the Turner 1976 and Peterson equal pairs). In the present study, we have always measured the redshift of the smaller galaxy relative to the redshift of the larger galaxy. We find that the smaller galaxy has the excess redshift.

If we suppose that there is a distribution of equal numbers of positive and negative velocities around the central galaxy, due either to orbital or expansion velocity, then giving certain ones an intrinsic redshift of $+72$, $+144$, $+216$ km s^{-1} or greater will skew the distribution toward positive redshifts as we observe. But it will not produce peaks at these quantized values unless the companions all come from a very narrow peak around $\Delta z = 0$. This has always been the difficulty with the Tifft quantization; namely, that it allows very little amount for true velocity dispersions of the galaxies. The results here may ease the problem of quantization by suggesting that only positive increments of intrinsic redshift may be

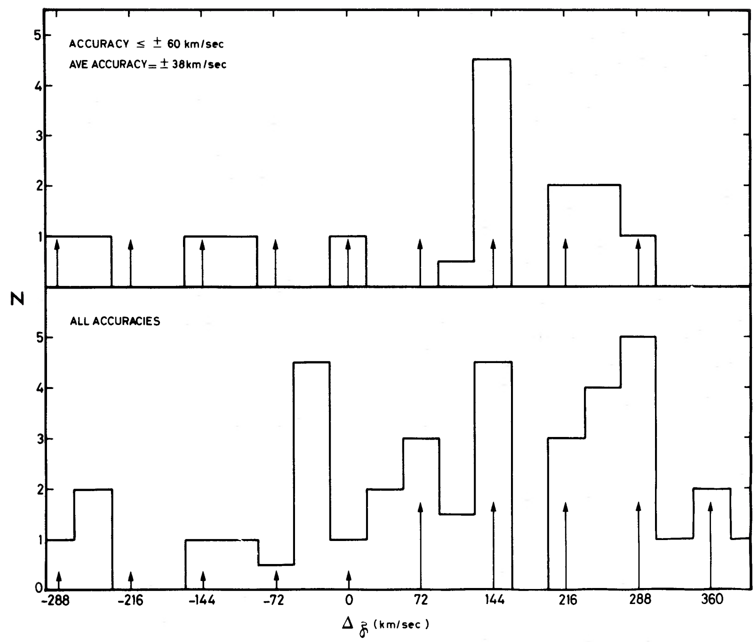

FIG. 9.—The distribution of all companions with $-300 < \Delta z < 400$ km s^{-1} is shown. Correspondence with the Tifft (1980) multiples of 72 km s^{-1} is shown by the arrows. In the top histogram only the most accurate Δz's measured in the present paper are shown.

added to companion redshifts. But the problem still remains of the very low, true velocity dispersion for these particular companions relative to the central galaxy.

In the present study we have too few negative Δz's, to be sure, but if they are not quantized, then they have a "normal" velocity distribution matched perhaps by an equal number of positive Δz's. The quantized Δz's would then have to be a separate population of low velocity dispersion objects. Of course, we cannot disprove the alternative urged by Tifft that all the redshifts are quantized.

It is interesting that on the expanded scale of Figure 9 that there is a noticeable absence of Δz's ~ 0 km s^{-1}. Does this suggest that the Δz's which should be near zero have been moved to higher redshift by addition of quantized amounts? If this absence of Δz's ~ 0 km s^{-1} is real, then it is a definite difference from the expected situation where the Δz's represent velocity residuals. In the pairs of equal double galaxies, the most populated cell was $\Delta z = 0$ km s^{-1} for Tifft and Peterson but probably not for Turner.

IX. INDIVIDUAL CASES OF ASSOCIATIONS

In Paper I, each peculiar galaxy and association was discussed briefly in its figure caption. Here we discuss only the central galaxies and companions which are listed in Table 1 of the present paper, and we discuss only the aspects that bear on the measured Δz.

1. *19/10, −62/23.* This is the only case investigated in the present paper in which all the ostensible companions have negative, rather than positive, Δz's. It is also unique in that two of the apparently associated companions are very low surface brightness, presumably dwarf, galaxies. The redshift of the one low surface brightness object that could be measured is very small. It is tempting to consider the central Sb spiral as an unrelated background object, but by the rules of the objects selected here, it must remain in the list and become part of the statistics.

2. *19/22, −55/03.* This is a prototype association with both galaxies disturbed and the companion having a pure, rich emission spectrum.

3. *19/50, −58/51.* Like the NGC 4151/4156 (Arp 1977) and Stephan's Quintet (Arp 1973*a*) apparent associations in the north, the two galaxies here show about the same resolution characteristics (presumably H II regions) despite their considerably different redshift.

4. *20/01, −60/23.* Two of the three companions which are interacting show late-type stellar spectra. The third companion should be measured as well as other galaxies in the field. This is a possible candidate for a background projection.

5. *20/28, −31/00.* The companion is large and obviously interacting. The smaller galaxy to the west of the companion also seems to be interacting and should be measured.

6. *20/38, −32/42.* This is one of the most certain associations of large Δz's. Companion B lies in one disturbed and peculiar arm of the central spiral. Companion A has a very bright apparent magnitude for such a high redshift. Companions A and B seem associated, but the 3,600 km s^{-1} difference in z between them would rule out a conventional association. Both A and B have unusual spectra.

7. *20/52, −22/16.* This is a strongly associated case discussed in a separate paper (Arp 1980*a*).

8. *21/05, −33/11.* This is a relatively large companion attached to the central galaxy by a filament. There is a

strong emission spectrum for the companion, but the underlying absorption spectrum is not particularly early-type.

9. *21/07*, *−64/15*. The large ring galaxy has a symmetric but very unusual bulge structure. The companion is very compact but under good seeing conditions at Las Campanas appeared unmistakably double! The tendency to doubleness and multiplicity seems characteristic of associated companions (Arp 1973*b*).

10. *21/37*, *−42/46*. The alignment of the two companions across this E galaxy is of interest. Further work on this system would be valuable.

11. *22/30*, *−64/58*. This interacting, similar z companion gives a good opportunity to study the early spectral nature of certain companions.

12. *23/15*, *−42/39*. The spiral arm near which one companion is seen seems not to be disturbed. Spectra are not unusual, and although they are along the minor axis of the large galaxy these two are candidates to be background objects.

13. *23/16*, *−66/59*. The central spiral is very disturbed, and the compact galaxies south are quite bright and highly discordant in z. Deep, high resolution plates are needed to study this apparent interaction further.

14. *23/19*, *−42/46*. The companions are the kind of strongly interacting galaxies which would be isolated in space if they were not associated with a larger galaxy. The central galaxy is disturbed on such a large scale that this large interacting pair seems to be the only possibility to account for such a disturbance. This appears to be a well substantiated Δz of about +8,800 km s^{-1}.

15. *23/22*, *−82/11*. The companion is relatively large and very disturbed, a certain interaction at probably higher velocity than escape.

16. *23/30*, *−45/19*. This is a rather high $\Delta z = +771$ km s^{-1} for two galaxies which are very probably interacting. Further study with high resolution plates would be important.

17. *23/35*, *−47/49*. The large, central E has faint tails and jets, and its nucleus is double. This could be a candidate for a merging or fissioning galaxy. The companion is very peculiar and very close by; it would be surprising if it were an isolated background galaxy.

18. *23/41*, *−32/14*. The central galaxy is a very low surface brightness, apparently low density, nearby dwarf. There seems to be no distortion or disturbance in the central galaxy, and therefore this object is probably one of the most likely candidates to represent and accidental projection and not a real association.

19. *23/45*, *−30/48*. Deep, high resolution plates are needed to study the apparent involvement of the arm of the spiral with the compact companion. When observed, the companion galaxy had an object a few diameters ESE which was not visible on prior photographs.

20. *00/03*, *−36/24*. The largest galaxy is in the center with a high surface brightness galaxy on one side and three interacting galaxies on the other side.

21. *00/12*, *−60/36*. This is the most certain case of a highly discordant redshift association. See Arp (1980*a*) for discussion.

22. *00/21*, *−62/34*. This is a classic M51 type. Absorption lines in the companion should be measured.

23. *00/31*, *−56/53*. A high resolution plate of this object is shown in Figure 10 (Plate 1). There the disturbed nature of the inner region, the absorption, and the intimate relation to companion B can be seen. The filament leading to companion A is best seen in the deep Schmidt plate in Paper I. It is important to see evidence of direct filamentary connection to a companion with $\Delta z = +694$ km s^{-1} such as A. The spectrum of A was difficult, however, and should be redone as a check.

24. *00/31*, *−28/06*. The low surface brightness companion is distorted, looks like a Magellanic Cloud system, and is obviously associated with the large spiral. The association of the high surface brightness system is less certain.

25. *00/36*, *−24/33*. The two companions are roughly aligned across the central spiral. Both are disturbed. It is surprising the NE companion spectrum did not register. It should be obtained.

26. *00/36*, *−43/22*. This is a very disturbed central spiral and very unusual companion, with companion apparently at greater than escape velocity. Internal motion of companion subparts should be studied.

27. *00/40*, *−23/49*. Near NGC 253, this interacting companion has a late-type stellar spectra, and the larger galaxy has strong emission.

28. *00/41*, *−50/29*. Companion A is apparently projected into disk; otherwise, more disturbance would be expected in central, barred spiral. Both companions appear to be physical companions.

29. *00/50*, *−31/30*. Companion N is low surface brightness, apparent Magellanic type companion which disturbs low surface brightness outer spiral arms of the large, central galaxy. Absorption z used for main galaxy is in Table 1.

30. *00/55*, *−49/12*. Compact companion to the W is bright and conspicuously near the disturbed spiral. Interacting doubles north and south of spiral should be measured spectroscopically as they are prototype examples of I/A dbl companions.

31. *00/58*, *−40/25*. This excellent example of a companion attached to a long, peculiar spiral arm is discussed in a separate paper (Arp 1980*a*).

32. *01/10*, *−58/30*. One Δz had to be taken from de Vaucouleurs' *Second Reference Catalogue* (RC 2) values for central galaxy and comp SE. That companion has faint jet. The whole association needs considerable further study (see Paper I). In Table 1 Δz is from RC 2 values.

33. *01/25*, *−58/38*. This is the best case of a Seyfert companion. The redshift difference, $\Delta z = +441$ km s^{-1}, is considerable and close to a multiple of 72 km s^{-1}.

34. *01/35*, *−62/49*. The companions are aligned across the E, and all galaxies are elongated along this line. The negative redshift is surprisingly large and has a rich emission spectrum. Is this a case of ejection?

35. *01/45*, *−53/01*. This is the particularly interesting case of NGC 685. High resolution photographs are shown in Figures 11 and 12 (Plates 2 and 3). We first see that the companion on the southeast edge of the spiral

is resolved into what seems like bright H II regions. There are three of them, aligned. The deep Schmidt plate of Paper I shows this companion is definitely interacting with this side of NGC 685. The high resolution plate in Figure 11 shows there is some nonemission nebulosity around the stellar, emission cores and for this reason, as well as to size and interaction, we support our classification of it as a companion rather than an unusually large H II region in NGC 685. The question of transition cases, however, may be an interesting one to explore (see Arp 1969 for examples.)

The high resolution plates of Figures 11 and 12 show the companion to northwest is just resolved into a nucleus and a pair of high surface brightness objects across the nucleus. It resembles a triple object inside a high surface brightness, compact galaxy. The spectrum of this companion is highly unusual. It is shown in Figure 13 where the strong hydrogen absorption lines can be seen all the way down to Hκ!

A photograph taken in the light of Hα (a 100 Å bandpass filter registering Hα at the redshift of NGC 685) is shown in Figure 12. The extraordinary feature of this photograph is that a line can be drawn through the center of NGC 685, perpendicular to the line between the two companions, and on one side of that line across NGC 685, there is strong Hα emission. On the other side of that line there is essentially no emission in NGC 685. Apparently there is some effect, due either to the companion on the SE or the companion on the NW, or both, that causes this strange behavior in the H II regions of NGC 685. The claim was originally made that interaction between two galaxies produced H II regions on the side of the interaction (Arp 1973*a*). Later Hodge (1975) claimed that in some examples the H II regions lay on the opposite side of the interaction. In any case there is prior evidence that interaction has some diametric effect on the location of H II regions. In NGC 685 it could thus be either companion A or B which was causing the peculiar effect in the H II regions.

Because of the unusual morphology, spectrum, and placement of the companion NW and because of the unusual nature of NGC 685, this companion to the NW is considered an almost certain assocation despite its $\Delta z = +5{,}400$ km s^{-1} higher redshift.

36. *01/47, −35/10.* More redshifts in this linearly disposed group should be measured.

37. *01/52, −56/57.* This is one of the Calan groups (Sersic 1974). See below.

38. *01/56, −56/31.* Both groups are dense and interacting but rather diffuse objects without emission.

39. *01/59, −22/01.* This looks like a spiral with one strong, knotted arm and companion as last knot in arm. Surprisingly, no emission or young stellar absorption lines are seen.

40. *02/12, −25/03.* This is an almost classical case of a ring galaxy with a nearby companion (Lynds and Toomre 1976; Theys and Spiegel 1977). The redshift difference, $\Delta z = -605$ km s^{-1}, is unusually negative for companions here.

41. *02/13, −28/33.* This is an especially important case involving a large redshift discrepancy. The Schmidt photograph in Paper I shows companion A well connected on the end of distorted spiral arm. It has a moderately excess redshift of $\Delta z = +414$ km s^{-1}. Companion B, which is almost buried in the image of the disturbed spiral on the Schmidt photograph, turns out to have a very young absorption and emission spectrum. The high-resolution photograph shown in Figure 14 (Plate 4) of this paper indicates that companion B, on the other side of the very disturbed spiral from companion A, is indeed interacting

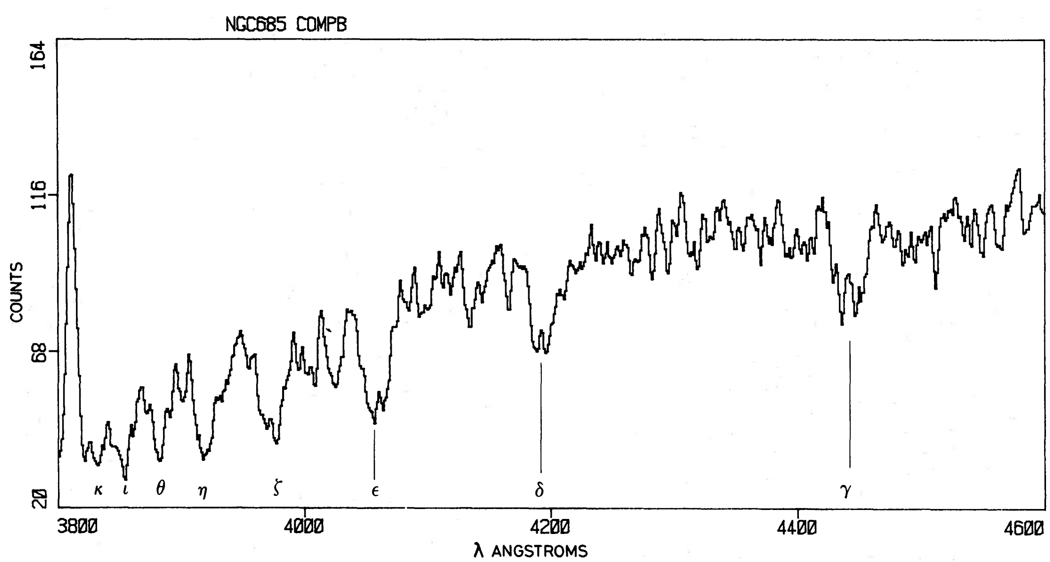

FIG. 13.—Spectrum of NGC 685 companion B (NW) taken with Shectman varo-Reticon on du Pont reflector at Las Campanas Observatory. The deep, strong hydrogen absorption lines are marked down to Hκ. Small emission cores are present from Hβ through Hζ.

with the central galaxy. Note particularly the strong tail or jet curving out of companion B to the west. Most important of all, note the short spiral arm segments curving from the center of the disturbed spiral directly to companion B. Regardless of what the redshifts of the other galaxies in the vicinity may turn out to be, the evidence of interaction of companion B with the central galaxy is so strong, in my opinion, that the $\Delta z = +14{,}021$ km s^{-1} redshift discrepancy must be accepted as real and therefore as principally nonvelocity.

42. *02/19*, *−27/27*. The companion is large, disturbed and has an excited spectrum. The only aspect which goes against this association is that the central galaxy does not seem especially disturbed.

43. *02/24*, *−24/56*. The Schmidt photograph in Paper I shows a strong connection going back to the spiral from the companion. The high-resolution photograph in Figure 15 (Plate 5) does not give any clues as to why the companion shows only an emission spectrum. It is important to get a redshift of the absorption component which should be present. It is interesting to note, however, that even though a good spectrum shows no absorption aspect of the spectrum, that the size and morphology of the companion would not enable us to classify it as an H II region belonging to the central barred spiral. The redshift indicates it is probably not bound to the central spiral.

44. *02/49*, *−55/12*. Both the large companion and central spiral are heavily disturbed. This is an almost certain case of a large redshift discrepancy, $\Delta z = +7{,}800$ km s^{-1}.

45. *03/05*, *−67/00*. These have not much sign of interaction; old stellar population types. Closeness may be mostly projection.

46. *03/14*, *−63/12*. This is both a peculiar central galaxy and roughly opposite peculiar companions. Association class is probably stronger than the indicated 2.

47. *03/40*, *−47/24*. This is a very compact companion with possible jets emanating from it. It is puzzling why the companion spectral type is 1.0a.

48. *03/59*, *−67/49*. Other apparently associated galaxies in vicinity need to be measured.

49. *04/02*, *−54/14*. There is not much sign of interaction; possible projected background.

50. *04/02*, *−43/30*. This is the famous case of NGC 1510/1512 (Hawarden *et al.* 1979), H I $\Delta z = +69 \pm 9$ km s^{-1}. There are some indications that central galaxy has a lower absorption line redshift than either emission or H I. Checks on this point are in progress.

51. *04/09*, *−46/09*. This is a very active central galaxy; the small companion opposite the one measured also needs to be measured.

52. *04/10*, *−32/59*. This is a very large, interactive pair. Extensive measures on this one are required before final Δz is adopted.

53. *04/26*, *−47/57*. Central galaxy is NGC 1595 with Carafe galaxy and NGC 1598 on either side. A number of quasars and high redshift stellar appearing galaxies in this group are being published elsewhere (Arp, in preparation).

54. *04/36*, *−47/22*. This is a very disturbed spiral and large, strongly interacting double companion. Deeper plates and spectra of additional galaxies in the region would be of interest.

55. *05/37*, *−22/01*. This is a very interactive, M51 type.

56. *06/23*, *−60/52*. Strongly connected, this companion has a well established redshift excess of $\Delta z = +674$ km s^{-1}. See Figure 16 (Plate 6) for high-resolution, superposition photograph.

57. *06/55*, *−28/18*. The companion has a companion in its tail (the latter has not been measured). The central galaxy is disturbed with heavy absorption.

58. *07/28*, *−66/50*. Companion is strongly interacting (on a filament).

59. *09/07*, *−75/39*. Companion is strongly interacting with edge of spiral.

60. *11/08*, *−30/05*. Companion is high surface brightness and multiple interacting with barred spiral. Spectrum of companion is of brighter component.

X. RECENT Δz'S FROM THE LITERATURE

Investigations of interacting galaxies and groups of galaxies are made from time to time and published as individual studies. In recent years, many of these have been made with radio telescopes at the hydrogen frequency. Such redshifts are usually very accurate. It is crucial now to collect the results of these redshift studies and analyze them from the standpoint of the positive Δz's we have found here. Since these investigations were made without any attention to the sign of the redshift differences obtained, it is difficult to see how any bias could have entered the measures. If the data collected together now at a later date supports the positive redshift excess, it would contribute greatly to establishing that result.

To that end I have searched the recent literature, particularly the *Astrophysical Journal* and *Astronomy and Astrophysics* plus preprints I have seen and private communications to which I have had access. A condition is that the companion galaxy must be smaller than about half the apparent diameter of the main galaxy. NGC 4485/90 is about on the border line. Table 7 collects together these new Δz determinations of companions. All except one set are HI determinations. The last column gives the source of the data. Figure 17 plots the data for Δz's between $+400$ and -300 km s^{-1}. It is seen that there is a well marked excess of positive redshifts. In fact, there are 16 positive against 7 negative in Table 7. This is a ratio of 2.3 almost exactly the same as the ratio of 2.4 found in the original analyzed in the present paper. If we take the most conservative approach and omit the $\Delta z = +591$ km s^{-1} value, the mean $\Delta z = +63 \pm 19$ km s^{-1}. This mean value is about half that found in the earlier part of this paper, principally because the total range in Δz's is much less. The smaller range in Δz, however, means that, on conventional grounds, an even more strongly associated sample of companions have been selected.

These new Δz's have been plotted in Figure 17 so that their agreement with the $\Delta z = 72$ km s^{-1} quantization can be judged. Again, there is no support for quantization of negative Δz's, but it is seen that the highest peak falls at $+72$ km s^{-1}. Other predicted peaks at $+144$ and $+216$,

TABLE 7

COMPANION REDSHIFTS[a] COLLECTED FROM RECENT LITERATURE

Central Galaxy	Companion	Δz (km s^{-1})	Source	Comments
NGC 1316......	NGC 1310	−70	Schweizer 1980	1
	NGC 1317	+170		
	NGC 1316C	+280	(no errors given)	
		+80		
NGC 1512......	NGC 1510	+69 ± 9	Hawarden *et al.* 1979	
NGC 1961......	Comp NE	+173 ± 22	S. Shostak 1979 private	
	UGC 3342	+8 ± 14	communication	
	UGC 3349	+325 ± 14		
NGC 2146......	UGC 3137	+102	Fisher and Tully 1976	
	UGC 3371	−86	(no errors given)	
	UGC 4173	−34		
	Mrk 5	−112		
	UGC 3439	+591		
NGC 2859......	UGC 4988	−36	W. W. Shane, N. Krumm, and	
	UGC 5004	+184	Norman quoted in	
	UGC 5020	−36	Arp 1980*b*	2
	UGC 5015	+29		3
NGC 3992......	UGC 6923	+20 ± 28	W. W. Shane and R. Sancisi 1979,	
	UGC 6940	+60 ± 28	private communication	
	UGC 6969	+70 ± 28		
NGC 4258......	NGC 4248	+29 ± 13	van Albada 1977	
NGC 4490......	NGC 4485	−105 ± 16	Viallefond, Allen, and de Boer 1980	
NGC 5383......	UGC 8877	+115 ± 11	Sancisi, Allen, and Sullivan 1979	4

[a] All H I redshifts except for NGC 1316 group.

COMMENTS.—(1) Schweizer considers NGC 1326 too far away to be a companion. (2) Fisher and Tully argue UGC 3439 is a background galaxy. By criteria of present paper, however, it is association class 3. (3) The redshift of NGC 2859 adopted here is $z = 1629 \pm 32$ km s^{-1} which is mean of Arp $z = 1607 \pm 40$ and $z = 1650 \pm 50$ estimated from Knapp, Faber, and Gallagher. When the redshifts were communicated to Arp by Shane *et al.*, it was not indicated that they had been corrected for galactic rotation. Subsequent measures by Arp and Sulentic in H I at Arecibo (unpublished) show that the redshifts by Shane *et al.* are more accurate than they quoted in Arp 1980b but need to be decorrected back to heliocentric velocity. (4) R. Sancisi (private communication) reports NGC 4562, the companion to NGC 4565, has $\Delta z = +115$ km s^{-1} with both redshifts accurate to about $+10$ km s^{-1}. This Δz has not been included in Fig. 17 or the discussion in the text.

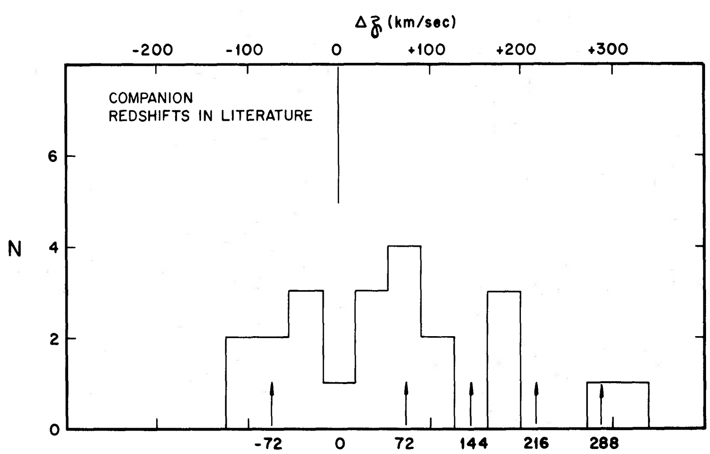

FIG. 17.—Distribution of Δ's for companions collected from recent literature. These are predominantly H I redshifts as described in Table 7. Tifft intervals of $\Delta z = 72$ km s^{-1} are marked. The mean is $\Delta z = +63 \pm 19$ km s^{-1}.

however, are avoided so the result of this particular test is inconclusive.

XI. SUMMARY AND CONCLUSIONS

The first evidence for systematic positive redshifts in companions came about when some companions to M31 and M81 and some companions on the ends of spiral arms were tested and were shown to be systematically redshifted with respect to their central galaxies (Arp 1970*b*). This effect was later confirmed on larger bodies of data by Bottinelli and Gougenheim (1973) and Collin-Souffrin, Pecker, and Tovmassian (1974). Some attempts to criticize the results or explain them were made by Lewis (1971) and Harrison (1974) and discussed in Arp (1971) and Arp (1976). At the Paris Conference in 1976, however, Arp showed that the most accurate redshifts then available established that essentially all the companions of M31 and M81 were positively redshifted with respect to their central galaxy. This result was of such a nature that it was almost impossible to occur by chance.

There was no conventional explanation for this result, and there was no further discussion of the subject. At the present moment the foregoing paper has presented the first new block of evidence, the results of a new and completely independent investigation of this phenomenon. The present investigation strongly confirms the original result. Moreover, in the preceding § X, yet another set of independent and generally very accurate data has been collected from recent publications by a number of different authors. Again, this data independently confirms the systematic redshift for the companions. These two additional confirmations, in addition to the strength of the original results, would seem to observationally establish the phenomenon.

Up until this point in the summary we have been discussing only those companions that are close enough to the redshift of the main galaxy to be conventionally considered physical companions. But there also has been a building amount of evidence that central galaxies can have companions of very large positive redshifts which are nevertheless physically associated.

The history of these larger Δz associations starts with the discovery of distorted spiral arms leading from NGC 772 to companions with highly discordant redshifts (Arp 1970*a*). Then the disturbed Seyfert, NGC 7603, was shown to be linked by a strong, peculiar arm to a companion with $\Delta z = 8{,}200$ km s^{-1} (Arp 1970*c*). Following this, evidence was presented which placed the Stephan's Quintet system at the same distance as the large Sb galaxy, NGC 7331 (Arp 1973*a*). That gave for members of Stephan's Quintet $\Delta z = 4{,}600$ to $5{,}900$ km s^{-1}. Shortly thereafter, it was shown that essentially all known multiple groups which were as interactive as Stephan's Quintet occurred in the near vicinity of large, low redshift galaxies (Arp 1973*b*). It is important to note that the interacting double classification of the present paper is simply a subset of the multiple interesting class. Systems in the present paper such as 19/50, −58/51; 20/01, −60/23; 23/19, −42/46; 23/41, −32/14; 04/36, −47/22; and 06/55, −67/17 represent the cases of very interactive doubles which are companions to much lower redshift galaxies. In addition, there are four very bright interacting groups or pairs in the present paper which all lie in the near vicinity of NGC 253, the low redshift spiral which is at the center of one of the most nearby groups of galaxies, the Sculptor group. These are 00/40, −23/49; 00/49, −27/37; 00/51, −23/50; and 00/58, −31/13 (see Paper I). It is suggested that these unusually bright and strongly interacting objects are companions of NGC 253 and galaxies in the Sculptor group. When the neighborhood of the large, active Seyfert, NGC 4151 was investigated (Arp 1977), it was shown that peculiar companions of considerably higher redshift, some themeselves interacting objects, were apparently associated with the low redshift NGC 4151. Recently one of the companion galaxies to NGC 2859 was shown to have an interactive neighbor of $\Delta z = 5{,}800$ km s^{-1} (Arp 1980*b*). Following this, there were discovered three cases discussed in this paper—20/52, −22/16; 00/12, −60/36; and 00/58, −40/25—where the Δz's are +36,500, +32,800, and +9700 km s^{-1}, respectively. All of these have been discussed in a separate paper (Arp 1980*a*), where it is shown that the evidence for physical association is extremely high. Finally, the two newest cases are discussed only in this paper: 01/45, −53/01 and 02/13, −28/33. They have Δz's = 5400 and 14,000 km s^{-1} and again, extremely strong evidence for association.

The present paper also discusses the general evidence of interaction for these larger Δz's. It shows that the interactive association evidence is particularly strong for the whole group at $4000 < \Delta z < 14{,}000$ km s^{-1} and the whole group at $30{,}000 < \Delta z < 38{,}000$ km s^{-1}. In addition, it shows that the spectra and hence physical conditions in the companions with these large Δz's are conspicuously different from what they would be if they were accidential projections from the background field. Finally, it shows the numbers of these large Δz objects that do not behave with redshift in a way that could be explained by accidental projection of background objects.

In a system such as a companion galaxy which consists of stars and gas and dust, all components whose basic physics is assumed known, it is difficult to accept that there is some intrinsic redshift effect. Nevertheless, if a nonvelocity redshift effect can be proved empirically for Δz's $\lesssim \pm 800$ km s^{-1}, the existence of such an effect must be accepted. Then, there is no reason in principle why the effect cannot exist even more strongly in the companions of higher discrepant redshift. In fact, the closing suggestion of this paper is that as we go toward higher discrepant redshifts, encountering more compact and active objects, that we are proceeding empirically toward a description of that other kind of enigmatic extragalactic phenomenon—the quasars. The same phenomenon of positive, nonvelocity redshifts could occur in even larger amounts in quasars. In fact, a great deal of empirical evidence indicates that quasars are also associated with large nearby galaxies and their companions and therefore have the greatest degree of all of positive, nonvelocity redshift.

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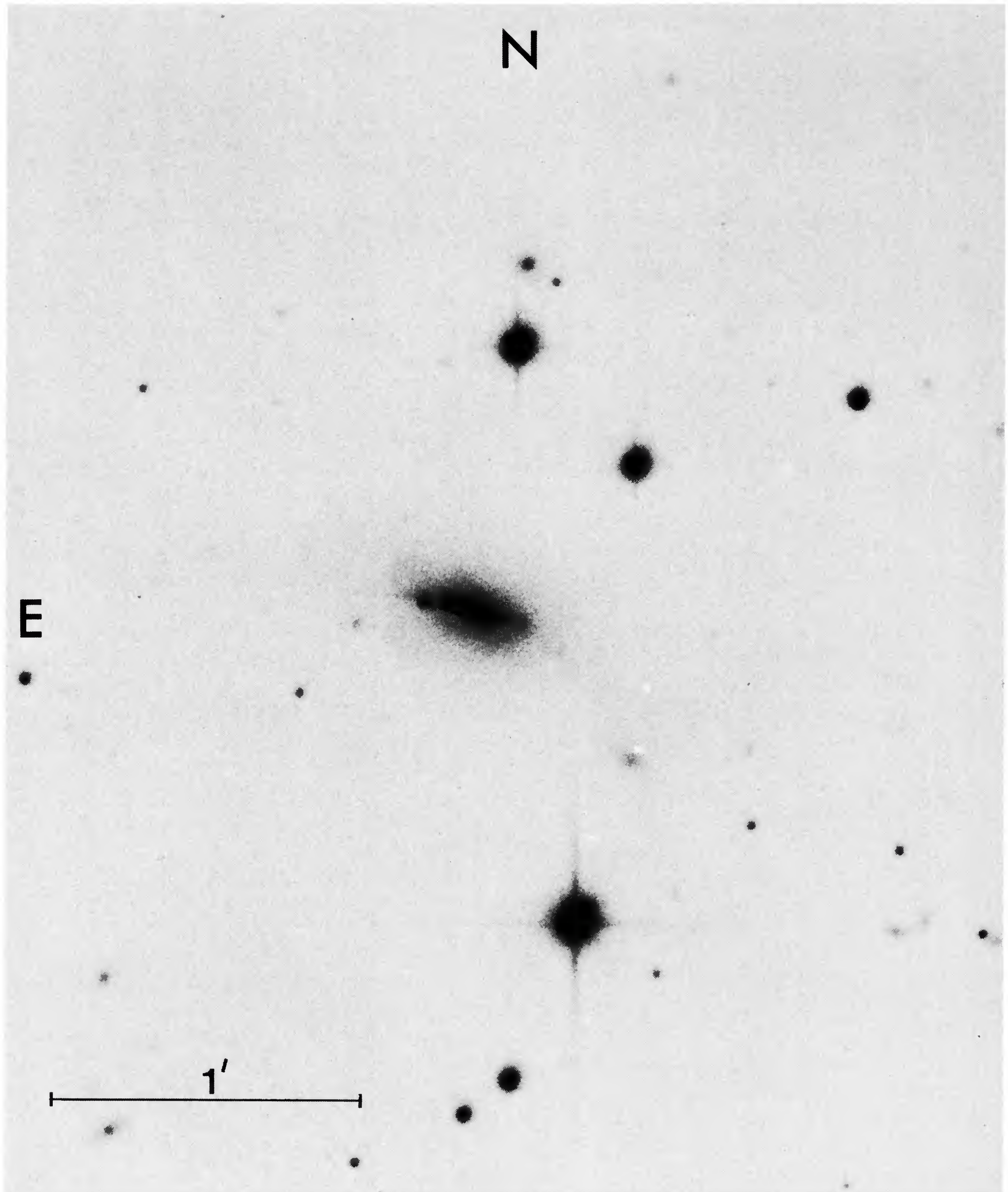

FIG. 10.—Exposure on 124-01 plate with du Pont reflector at Las Campanas Observatory. Object is 00/31, −56/33. Good seeing enables involvement of companion B in NE with dust absorption in central galaxy to be seen. See Paper I, Fig. 26 for UK Schmidt exposure which shows faint surface brightness tail extending to comp A in SW direction.

ARP (*see* page 69)

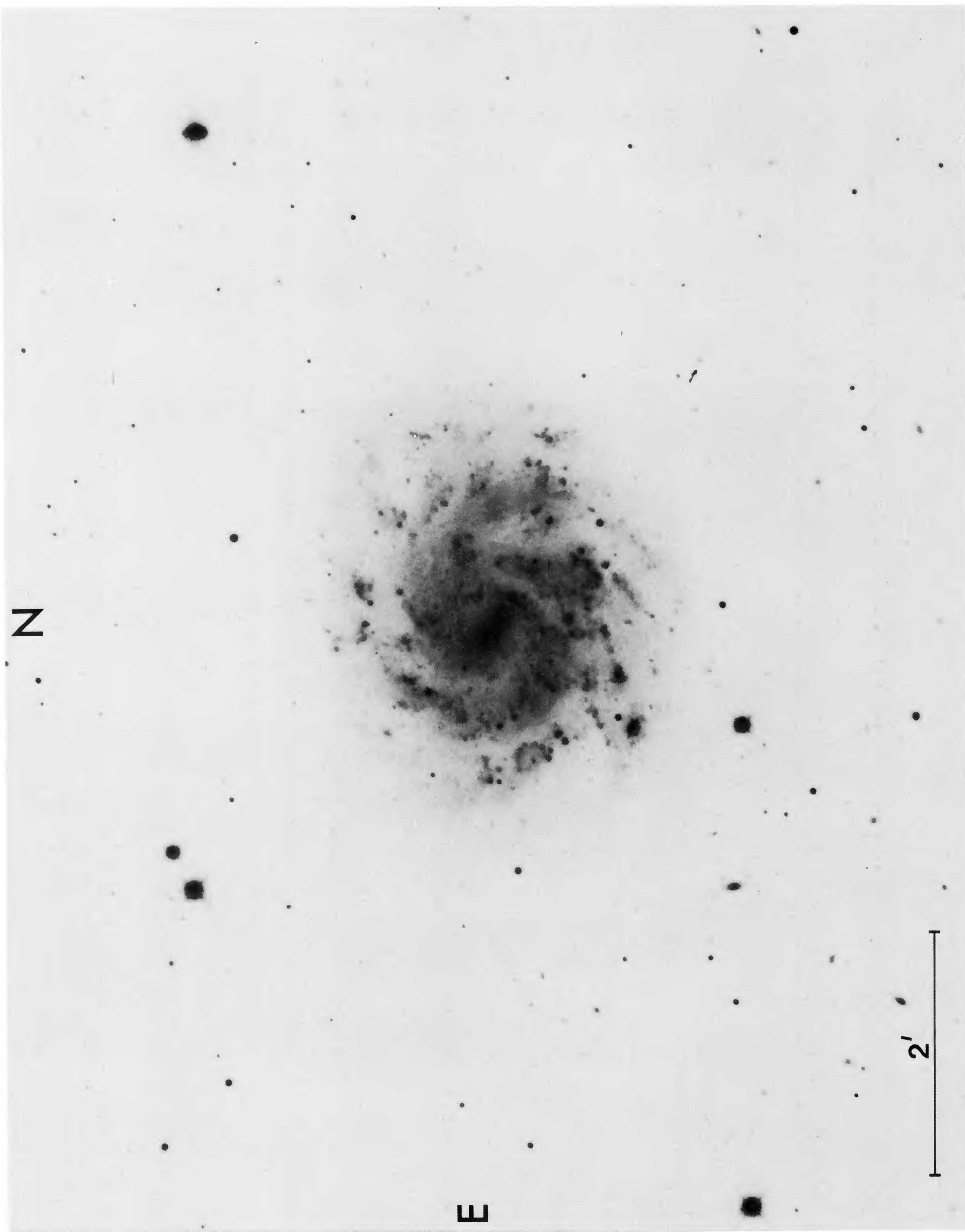

FIG. 11.—The large spiral is NGC 685. Exposure is 55 minutes on sensitized IIIa-J (no filter) at the prime focus of the CTIO 4 m reflector. Companion A is in disk SE and contains three stellar-like condensations in a row. Companion B is to the NW and has two compact condensations on either side of the nucleus. Early absorption spectrum of companion B is shown in Fig. 13.

ARP (*see* page 69)

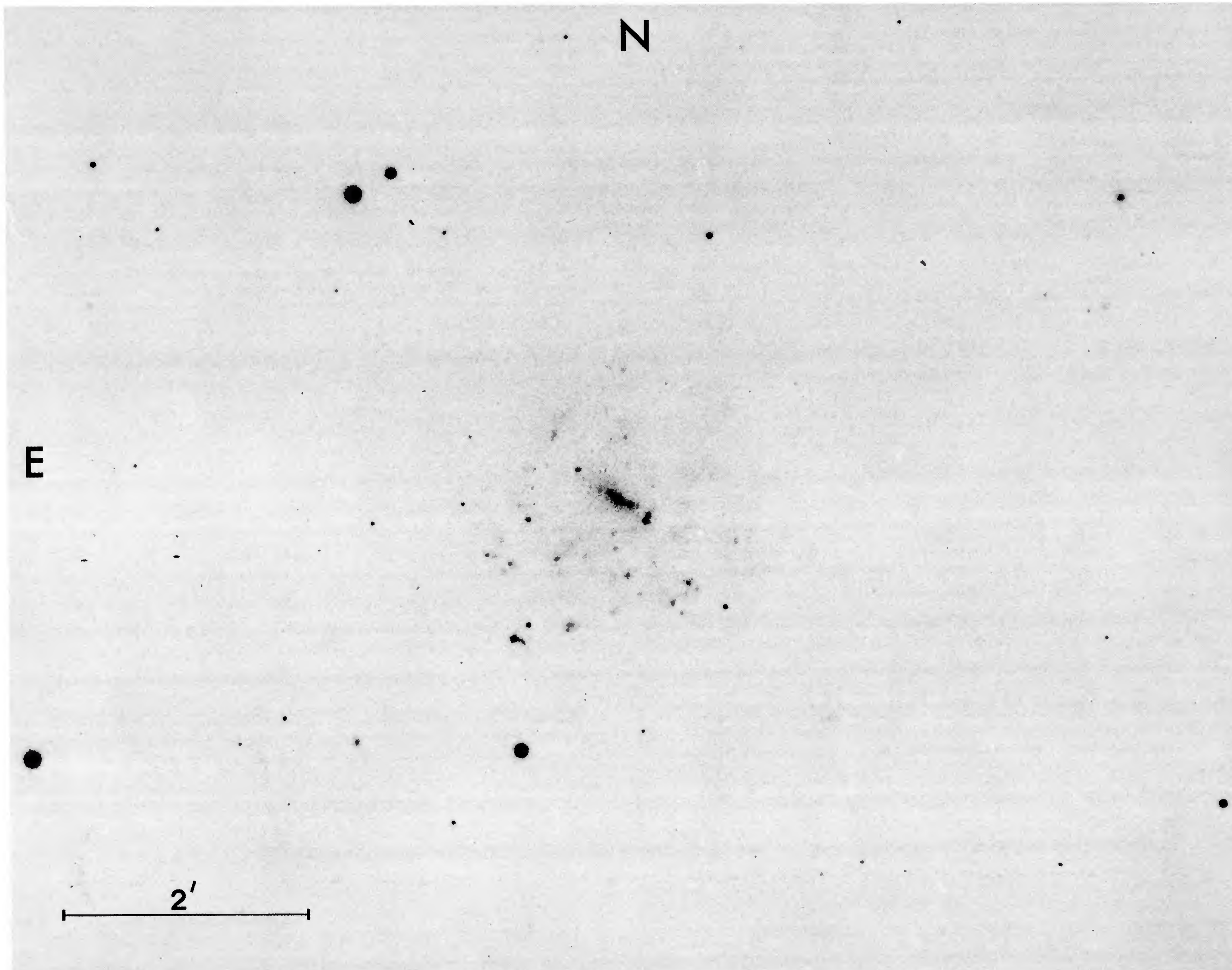

FIG. 12.—This is an Hα interference filter photograph of NGC 685 taken at the prime focus of the CTIO 4 m. The interference filter is about 100 Å wide and registers H II regions in the disk of the spiral. In the half of NGC 685 toward companion A the H II regions are conspicuous; on the half away from companion A, they are totally absent. This effect can be confirmed on lightly printed continuum plates.

ARP (*see* page 69)

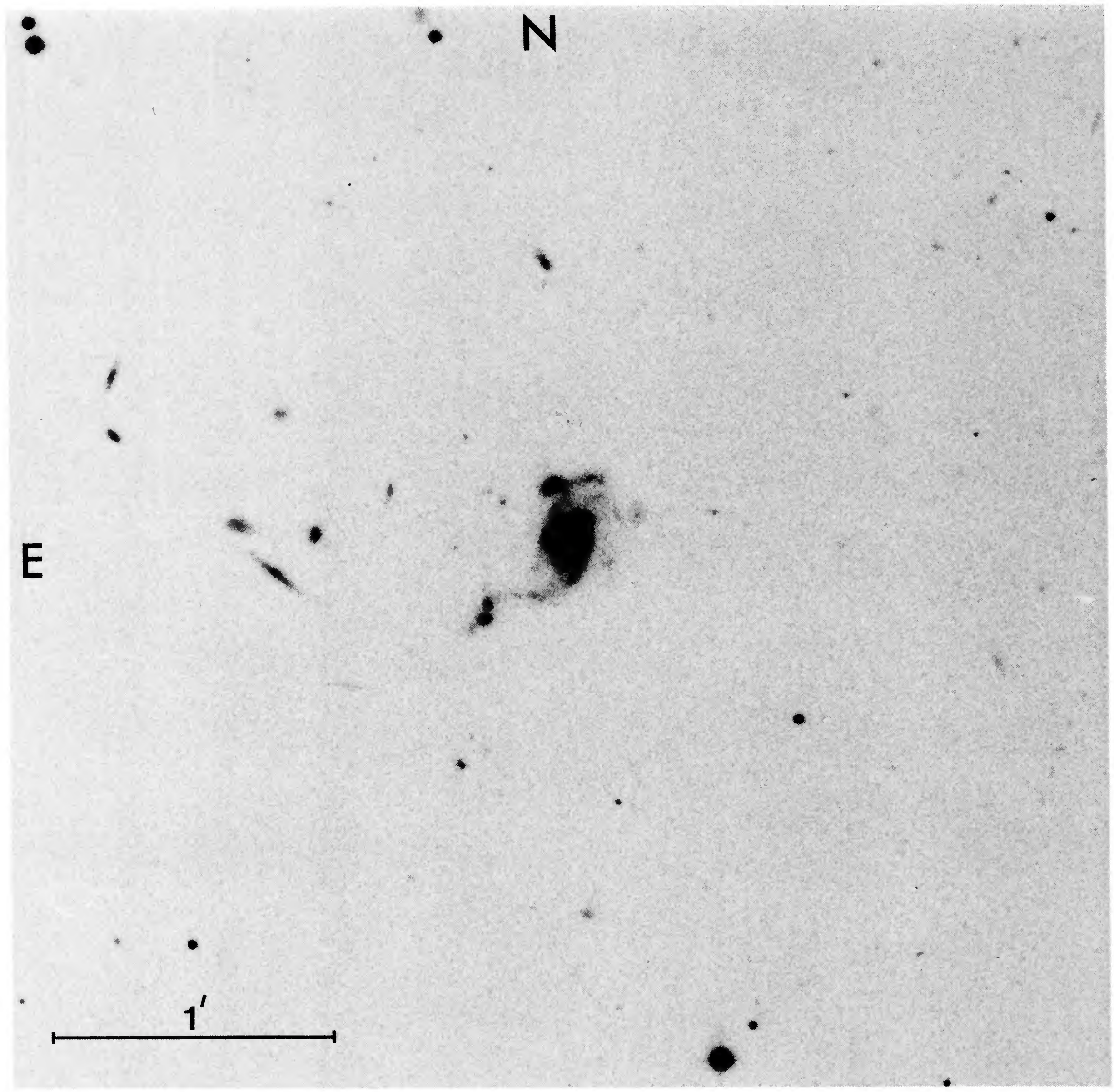

FIG. 14.—Exposure on 124-01 plate with du Pont reflector at Las Campanas Observatory. Object is 02/13, −28/33. Good seeing enables resolution of tail on discordant redshift companion (B) (on north side). Short segments appear to come from center of disturbed spiral to companion B which has $\Delta z = +14{,}021$ km s.

ARP (*see* page 70)

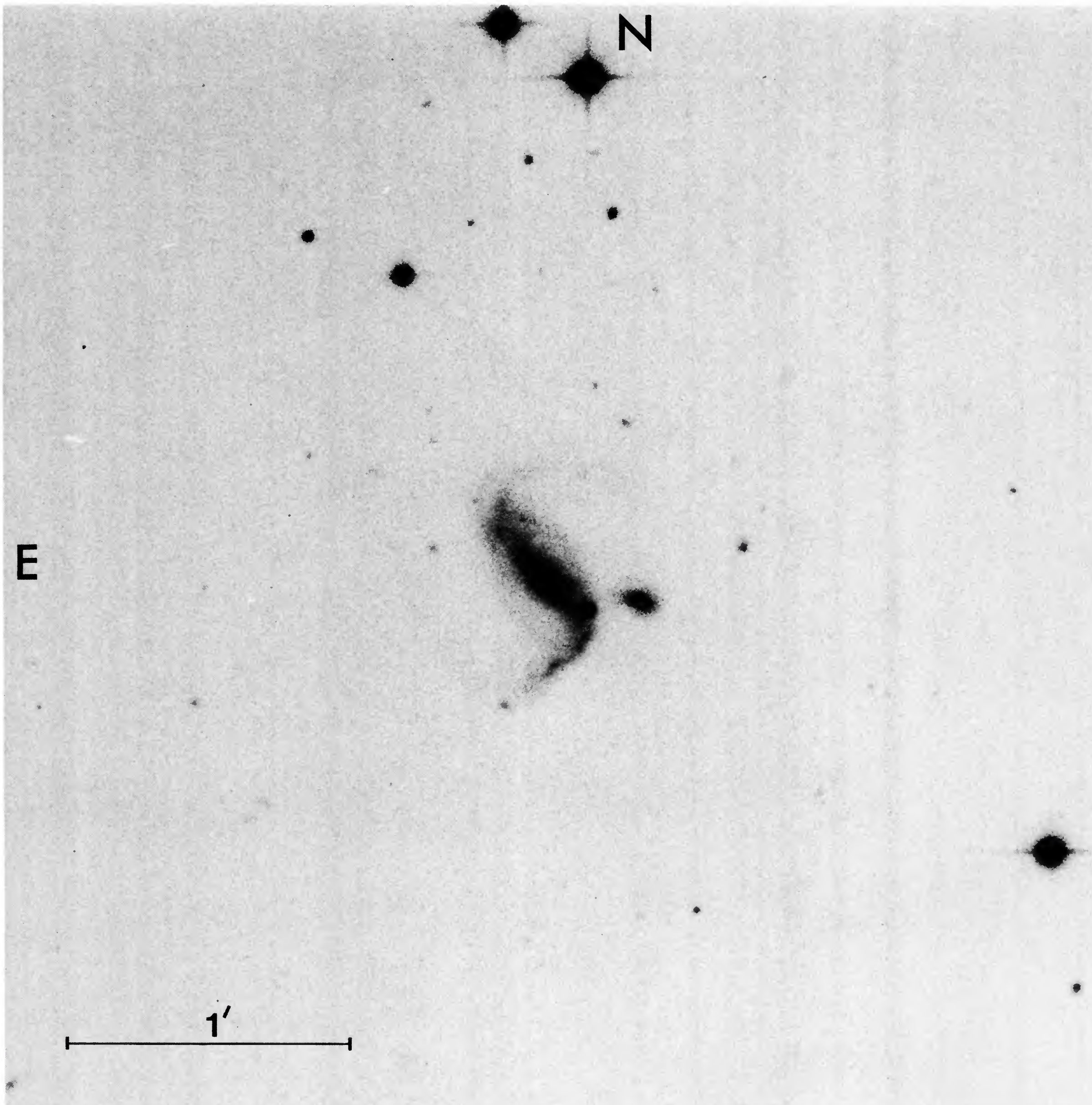

FIG. 15.—Exposure on 124-01 plate with du Pont reflector at Las Campanas Observatory. Object is 02/24, −24/56. Connection of companion back to main spiral is shown on Schmidt photograph of Paper I (Fig. 51). Optically, companion is incipient double. H II regions in central galaxy are strongest on side of interaction.

ARP (*see* page 71)

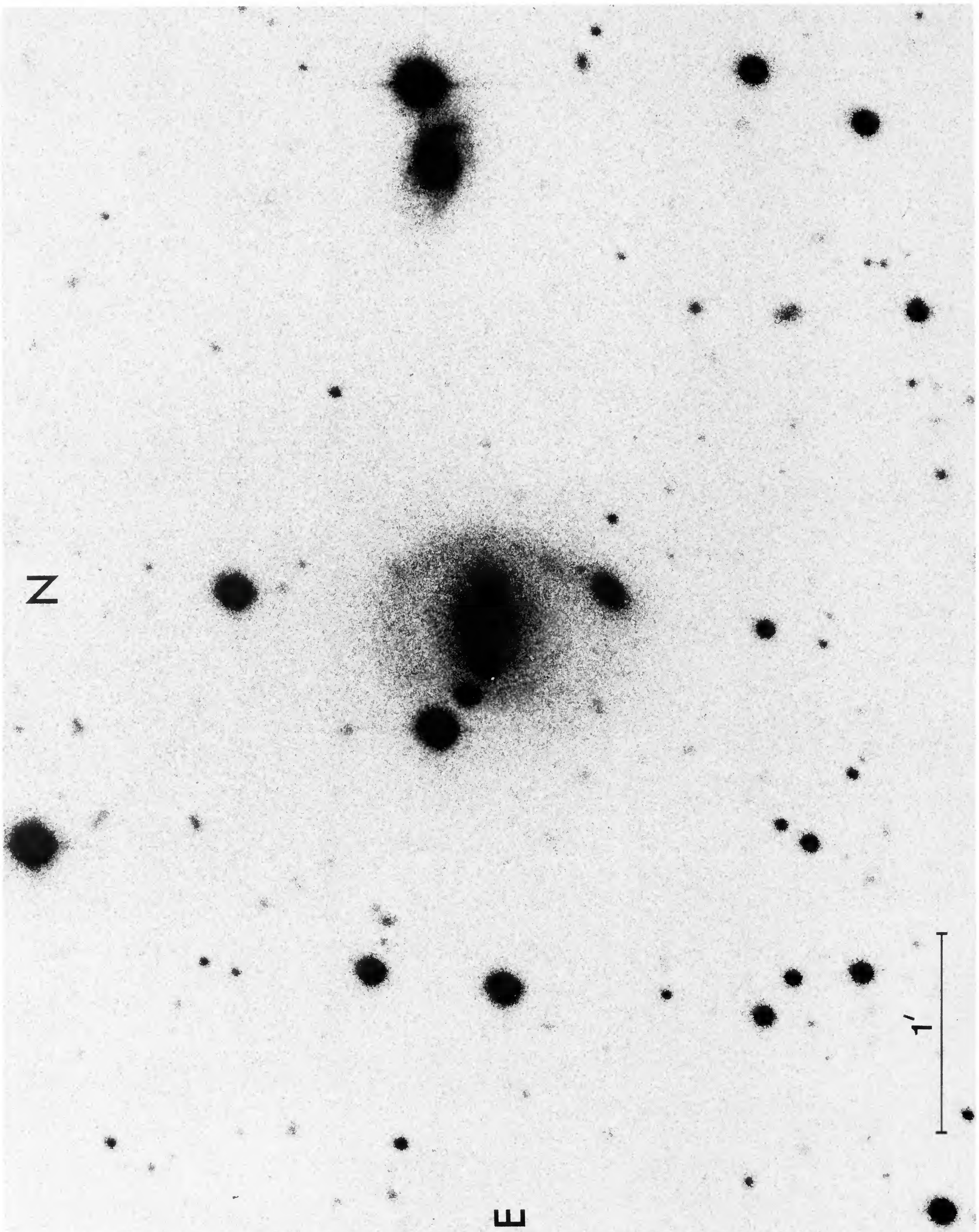

FIG. 16.—Superposition of three 124-01 plates taken with du Pont reflector at Las Campanas (CD 1190, 1191, 1205.) Object is 06/23, −60/52. Companion has $\Delta z = \pm 674$ km s^{-1}.

ARP (*see* page 71)