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SIX GROUPS OF GALAXIES

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ABSTRACT

Six groups of galaxies selected from the catalog of groups by Turner and Gott have been studied in detail. A homogeneous set of new radial velocities for 46 group members is presented, employed to test group membership, and used in analysis of group dynamics. The estimate of interlopers given by Turner and Gott is shown to be accurate. The mean M/L from application of the virial theorem to six subsets of the groups is 204 ± 60. While measuring errors do not dominate the estimate of M/L for these groups, they do preclude dynamical analysis of some small subgroups. Crossing times for the groups average less than one-third of the Hubble time. The mean density of the groups averages 4×10^{-28} g cm^{-3} (about 85 times the closure density). Comparison of group distances derived from radial velocities with the statistical method of Schechter and Press confirms the usefulness of that technique.

Subject headings: galaxies: clusters of — galaxies: redshifts

I. INTRODUCTION

Groups of galaxies are interesting because they constitute a frequent environment for galaxies and because they provide a way to study the dynamical effects of galaxies. Recent investigations (Turner and Sargent 1974; Materne 1974; Materne and Tammann 1974; Rood and Dickel 1976) have focused on the pioneering list of groups selected by de Vaucouleurs (1975).

A second approach to the study of groups is the work of Turner and Gott (1976*a*, hereafter TG I), who examined Zwicky *et al.* (1961–1968, hereafter *CGCG*) in a well-defined and simple way to compile a list of regions where the galaxy surface density is enhanced by a factor of 4.64 or more. They confined their attention to galaxies brighter than $m = 14$, and called the resulting areas "groups." Their list has the advantage that it is well defined and uniform, and the disadvantage that it uses very little information in defining a group.

In an effort to analyze their groups, Turner and Gott depended on published redshifts to derive a luminosity function (Turner and Gott 1976*b*, hereafter TG II) and to perform a virial analysis of the groups (Gott and Turner 1977, hereafter GT I). Because of the scarcity of published redshifts, the set of data used by them is very incomplete and inhomogeneous. A typical group has five members and three measured velocities. They assume that statistically valid inferences can be made about the luminosity function and the mass-to-light ratio, in spite of the handicap imposed by poor data. The purpose of the present investigation is to test the validity of that approach by obtaining a uniform and complete set of velocity data for a few of the groups from TG I.

II. DATA

Image-tube spectra of the galaxies were obtained at the No. 1 0.9 m telescope of the Kitt Peak National Observatory, using the Carnegie image-tube spectrograph at a dispersion of 121 Å mm^{-1}. The spectrograms, on baked IIIa-J emulsion, were measured with the single-axis Grant engine at Kitt Peak. The geocentric velocities obtained are displayed in Table 1, together with an estimated error derived from the disagreement of individual lines in the spectrum. While it is not to be expected that this error represents the total uncertainty in the absolute velocity of a galaxy, it should be a reliable guide to the repeatability of a single measurement using the same equipment and the same reduction techniques. Velocities are corrected for zero point by observations of night-sky lines and corrected to the frame of the Local Group by 300 cos A km s^{-1}, with the solar apex taken as $l = 90°$, $b = 0°$.

Complete data were obtained for five groups, TG 14, TG 46, TG 56, TG 78, and TG 91, and partial data for TG 77. In that case, data from de Vaucouleurs and de Vaucouleurs (1964) have been used to supplement the new measurements and are given in parentheses in Table 1. However, both the incompleteness and the inhomogeneity of the TG 77 data require that conclusions for this group be regarded as less reliable than for the others. The groups observed here were chosen to have several members and few measured velocities. They do not necessarily form a representative sample of the TG I groups.

Table 1 also lists in brackets some galaxies which are not on the lists of TG I, but whose proximity and velocity make them plausible additional members, as

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TABLE 1

VELOCITY DATA USED HERE

TG	Galaxy	V_{meas}	V_{corr}	σ	Subsets
14-1...........	N3016	8844	8701	48	
14-2...........	N3020	1429	1282	22	A
14-3...........	N3024	1506	1364	25	A
46-1...........	Z97–026	6201	6126	35	A
46-2...........	N3768	3301	3217	22	B
46-3...........	N3801	3254	3171	70	B
46-4...........	N3805	6472	6401	35	A
46-5...........	N3816	5548	5476	49	A
46-6...........	N3821	5535	5465	44	A
46-7...........	N3827	3268	3191	20	B
46-8...........	N3842	6111	6040	36	A
46-9...........	N3862	6706	6633	25	A
46-10..........	N3884	6822	6754	30	A
56-1...........	N4081	1312	1451	37	B
56-2...........	N4108	2485	2635	40	A
56-3...........	Z315–022	2641	2780	30	A
56-4...........	N4205	1435	1575	25	B
56-5...........	N4210	2501	2649	25	A
56-6...........	N4221	2816	2965	45	A
56-7...........	N4256	2559	2708	80	A
56-8...........	N4332	2843	2993	46	A
56-9...........	N4391	1337	1484	74	B
56-10..........	N4441	1439	1586	44	B
56-11..........	N4521	2426	2571	40	A
56-12..........	N4545	2703	2847	60	A
	[N4125]	[1365]	[1504]	[40]	B
77-1...........	N5289	2387	2480	65	A
77-2...........	N5290	2518	2612	57	A
77-3...........	N5303	1284	1367	60	
77-4...........	N5311	...	...	...	A
77-5...........	N5313	...	...	...	A
77-6...........	N5320	...	...	...	A
77-7...........	N5326	...	...	...	A
77-8...........	N5336	...	...	...	A
77-9...........	N5337	...	...	...	A
77-10..........	N5351	...	...	...	A
77-11..........	N5350	2356	2450	66	A
77-12..........	N5353	2297	2391	51	A
77-13..........	N5354	2413	2507	50	A
77-14..........	N5355	2368	2462	90	A
77-15..........	N5362	...	...	...	A
77-16..........	N5371	(2583)	(2679)	(31)	A
77-17..........	N5378	2967	3054	100	A
77-18..........	N5380	2848	2934	105	A
77-19..........	N5383	(2264)	(2366)	(50)	A
77-20..........	N5394	(3558)	(3644)	(100)	A
77-21..........	N5395	...	...	...	A
77-22..........	N5406	5151	5244	40	
77-23..........	Z219–056	...	...	...	A
77-24..........	N5515	...	...	...	A
77-25..........	N5541	1763	1869	64	A
78-1...........	N5322	1629	1788	65	A
78-2...........	N5372	1711	1868	25	A
78-3...........	N5376	2077	2237	64	A
78-4...........	N5389	1835	1996	56	A
78-5...........	N5430	2819	2981	74	
	[N5308]	[2039]	[2199]	[46]	A
91-1...........	N5660	2314	2461	42	A
91-2...........	N5673	2140	2289	20	A
91-3...........	I1029	2377	2526	46	A
91-4...........	N5676	2157	2305	20	A
91-5...........	N5689	2028	2176	33	A
	[N5633]	[2346]	[2484]	[38]	A

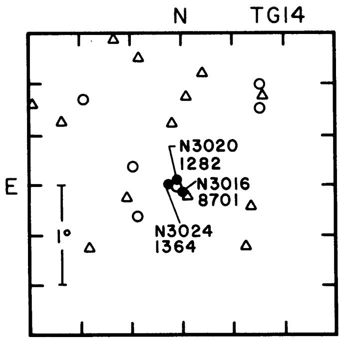

FIG. 1.—TG 14. In all figures, symbols indicate galaxy magnitudes: *filled square with "rays,"* $m_p \leq 11.0$; *filled square,* $11.1 \leq m_p \leq 12.0$; *hollow square,* $12.1 \leq m_p \leq 13.0$; *filled circle,* $13.1 < m_p \leq 14.0$; *hollow circle,* $14.1 \leq m_p \leq 15.0$; *triangle,* $15.1 \leq m_p \leq 15.7$.

discussed below. Velocities for these galaxies are also from de Vaucouleurs and de Vaucouleurs (1964).

Figures 1 through 6 show the distribution of galaxies in each group, in the manner of the *CGCG*. The galaxies designated as group members by TG I are shown, with their velocities. In addition, identification and velocities for neighboring galaxies which were not included by TG I are shown in brackets. Galaxies fainter than the $m = 14.0$ cutoff are also exhibited in the figures.

III. ANALYSIS

Three general aspects of the groups are studied: membership, mass-to-light ratios, and distance estimates.

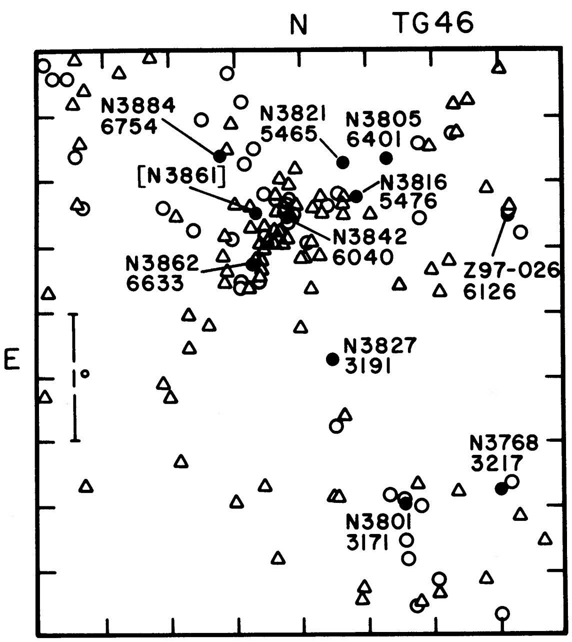

FIG. 2.—TG 46. Note the large number of faint galaxies belonging to A1367.

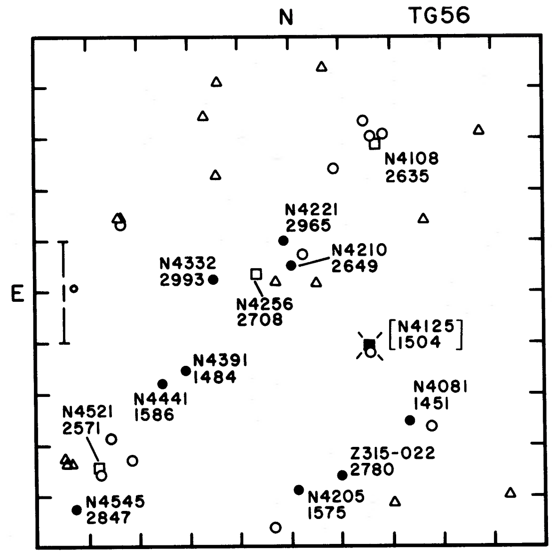

FIG. 3.—TG 56

a) *Membership*

The problem of group membership is one of the most troublesome features of any study of this kind. On the one hand, some of the groups defined by TG I have accidental associations of projected galaxies. On the other, the use of velocity information alone to sort out the foreground and background might prejudice the data toward smaller velocity dispersions. A further complication is that, after the foreground and background have been eliminated, the resulting edited group might fail to satisfy the original surface density criterion used to select the groups.

In order to give a fair idea of the nature of these TG groups, quantitative properties have been calculated both with and without changes in group membership. The details of each subset of a group's membership are given in Table 1, and discussed below.

TG 14.—This very tight trio of galaxies includes NGC 3016 at 8701 km s^{-1} and two others near 1300 km s^{-1}. NGC 3016 is considered a background object and deleted from 14A.

TG 46.—This is the well-studied cluster Abell 1367 (Oemler 1974; Dickens and Moss 1976). The group TG 46 clips out the brightest galaxies in the cluster at $V \approx 6540$ and confuses them with the foreground group to the south and west. Dickens and Moss (1976) quite correctly deleted NGC 3827 from their virial analysis of the cluster, although knowledge of the foreground group makes this procedure even more secure. Here, the bright galaxies of A1367 are called 46A, and the foreground group, 46B.

TG 56.—Group 56 is a rather perverse example of the topological effects produced by the algorithm used in TG I to define groups. In their procedure, the group boundary is defined by the union of the circles that can be drawn around each galaxy such that the surface density within equals f times the mean galaxy

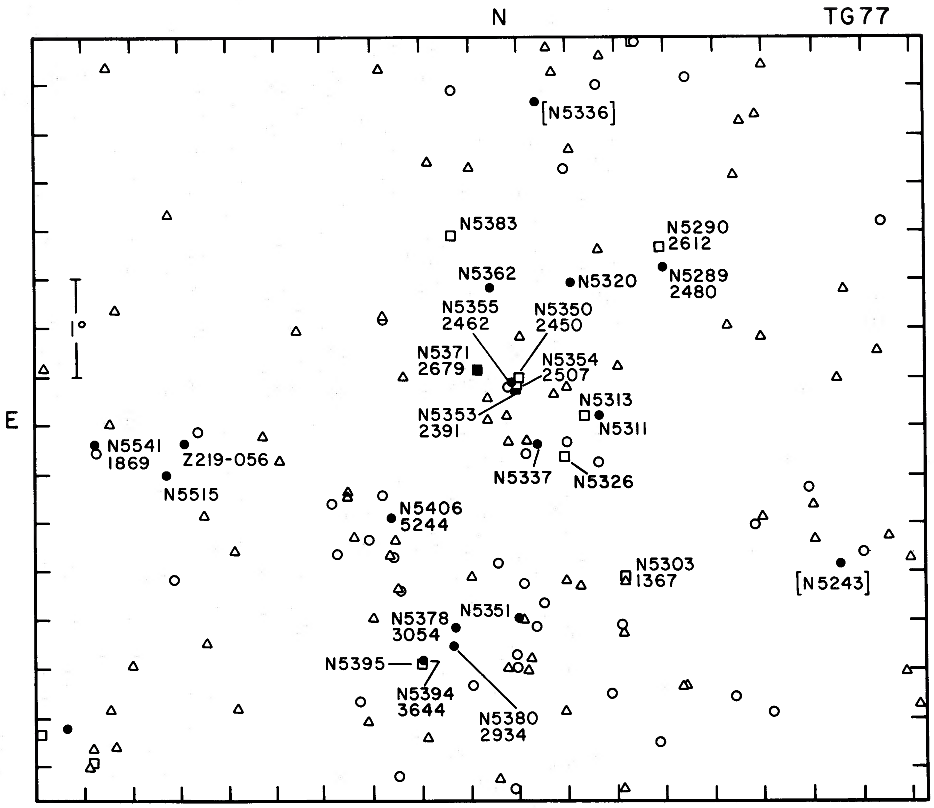

FIG. 4.—TG 77

surface density. In this particular instance, a galaxy *inside* a rough circle of group galaxies is *not* a member of the group! That is, the group boundary forms a torus. NGC 4125, which lies near the center of TG 46, is listed as a field galaxy in TG I. However, with the complete velocity information available, it is apparent that the southwestern portion of TG 56, including NGC 4125, is a cloud at about half the distance of the remaining galaxies. We denote the distant group by 56A, and the nearby one by 56B. Now it is likely that neither of these groups alone satisfies the original density contrast criterion of TG I, although they do not fail by a wide margin. Even so, they are treated here as representatives of the TG I groups.

TG 77.—Because the data are incomplete, only a schematic sorting of the group is possible. The bias is toward leaving galaxies in the group that subsequent data will show should have been discarded. On the basis of velocity difference, which is large compared with the velocity dispersion, 77A does not include NGC 5303 or NGC 5406. The galaxy NGC 5350 is incorrectly listed as 5330 in TG I.

TG 78.—The nearby galaxy NGC 5308 has a velocity very near that of the galaxies of TG 78, while NGC 5430 differs from the mean of the others by more than 3 σ_v. Group 78A includes NGC 5308 and excludes NGC 5430.

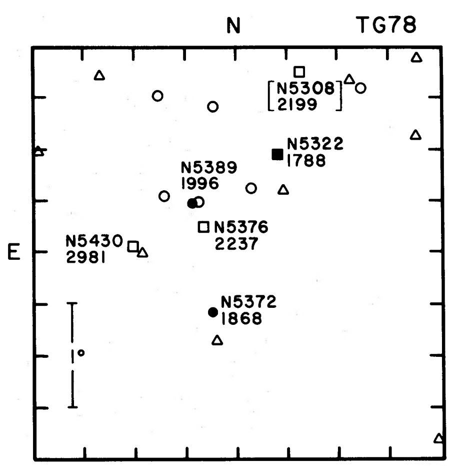

FIG. 5.—TG 78

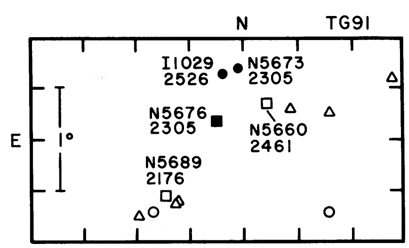

FIG. 6.—TG 91

TABLE 2

GROUP PROPERTIES

Group	No. of Galaxies	R.A. (1950)	Declination (1950)	$\bar{V}$ (km s^{-1})	L_{obs} ($L_{\odot}$)	Comments
14..........	3	$9^h47^m.4$	+12°34′	3374	8.4 + 10	Badly contaminated
14A.........	2	9 47.6	+12 25	1314	9.2 + 9	Binary
46..........	10	11 39.0	+19 41	5080	5.5 + 11	Two groups
46A.........	7	11 39.8	+20 22	6077	5.1 + 11	A1367
46B.........	3	11 37.5	+18 23	3190	7.5 + 10	
56..........	12	12 17.7	+65 27	2453	2.1 + 11	Two groups
56A.........	8	12 18.3	+65 40	2751	2.0 + 11	
56B.........	5	12 08.0	+65 17	1512	8.2 + 10	Includes N4125
77..........	25	13 52.7	+40 14	2615	7.6 + 11	
77A.........	23	13 52.6	+40 21	2553	6.7 + 11	
78..........	5	13 51.2	+60 04	2054	1.4 + 11	
78A.........	5	13 48.9	+60 21	1942	1.3 + 11	N5430 out, N5308 in
91..........	5	14 30.5	+49 39	2340	1.6 + 11	
91A.........	6	14 29.9	+49 14	2357	1.9 + 11	N5633 in

TG 91.—This group is essentially de Vaucouleurs's group 37, except that his G37 includes NGC 5633 where TG 91 does not, and TG 91 includes NGC 5673 where G37 does not. NGC 5633 lies about 2°.5 south of TG 91, and has been included in 91A.

The properties of the groups and their subsets are listed in Table 2. As the length and complexity of this discussion of membership indicate, the groups exactly as listed by TG I contain some interlopers. For a density contrast f, TG I predicts that $1/f$ of the group galaxies will be contaminants. Considering only the five groups with complete data, we find that there are nine probable contaminants out of 35 galaxies, or 0.26. The prediction from TG I, with $f = 4.64$, is 0.22, so the estimate of pollution is statistically correct. However, in any individual case the correct course of action in editing a group is not transparent. It would, of course, be possible to define a volume density enhancement test or a test based on the velocity difference of a galaxy relative to the velocity dispersion of its neighbors, so that the complete velocity information would be employed in defining the group.

b) *Virial Analysis*

These groups represent large surface density enhancements, and correspondingly large true density enhancements. Their crossing times, as described in more detail later, are short compared with the Hubble time; and they can properly be regarded as dynamical systems (Gott, Wrixon, and Wannier 1973). On the assumption that the groups are bound and virialized, we can apply the virial theorem in the manner of Materne (1974) taking into account the effect of measuring errors on the derived M/L. This analysis departs from Materne's method in that velocities are *not* used to derive a separation along the line of sight, since the assumption is that velocity differences among group members have nothing to do with distance differences. Galaxies are weighted according to their luminosity, assuming, after TG II, that $M_{\odot} = +5.48$, $H_0 = 50$ km s^{-1} Mpc^{-1}, and no account is taken of morphological type.

The results are given in Table 3, where a correction for the mass below the magnitude cutoff is also given. This is based on the luminosity function for group

TABLE 3

DYNAMICAL PROPERTIES

Group	No. of Galaxies	M/L_{obs}	L/L_{obs}	M/L	$\sigma(M/L)$	$\langle v^2 \rangle^{1/2}$	$\bar{\rho}$	t_{Ω}	t_l
14..........	3	$2.5E+5$	1.69	$1.5E+5$	2300	5740	$6.3E-26$	0.007	0.006
14A.........	2	287	1.08	266	250	63	$6.8E-30$	0.68	0.21
46..........	10	17400	3.27	5320	250	2460	$1.9E-27$	0.04	0.05
46A.........	7	1550	5.45	284	36	794	$3.1E-28$	0.10	0.11
46B.........	3	< 94	1.60	< 59	≈200	< 72	...	...	...
56..........	12	6280	1.32	4760	70	934	$3.0E-28$	0.10	0.15
56A.........	8	449	1.42	316	162	238	$1.7E-29$	0.43	0.66
56B.........	5	32	1.11	29	75	73	...	...	...
77..........	25	364	1.37	266	22	999	$1.0E-26$	0.02	0.11
77A.........	23	54	1.35	40	12	391	$2.1E-27$	0.04	0.28
78..........	5	4750	1.21	3930	771	727	$2.6E-28$	0.11	0.07
78A.........	5	755	1.19	634	288	320	$8.7E-29$	0.19	0.12
91..........	5	134	1.29	104	53	181	$5.8E-29$	0.24	0.16
91A.........	6	148	1.29	115	61	186	$4.2E-29$	0.28	0.35

galaxies as derived in TG II, and has the form, given in equation (1),

$$L/L_{\rm obs} = \exp\,[(\bar{V}/4666)^2]\,. \quad (1)$$

The only group for which this term is significant is TG 46A (Abell 1367). It is interesting to compare this very rough method of finding M/L with the detailed work of Dickens and Moss (1976). They find $M/L = 295$, based on 35 galaxies in the cluster and Oemler's (1974) photometry, while here the value is 284.

Two of the subgroups, 46B and 56B, have very small velocity dispersions compared with the measuring errors. No reliable estimate of the kinetic energy for these two groups can be made. This introduces a bias in the mean values for M/L, since no small values of M/L can be reliably measured for groups of this size. However, the remaining six subgroups, 14A, 46A, 56A, 77A, 78A, and 91A, all have well-measured velocity dispersions and are not subject to any great revision from radial velocities of higher precision. Groups 46B and 56B have poorly determined M/L because the measuring errors dominate the velocity dispersion. The unedited groups 14, 46, 56, 77, and 78 show how sensitively the determination of M/L depends on elimination of spurious group members.

The mean M/L for these six subgroups is 204 ± 60. There is no observed trend of increasing M/L with group luminosity, and this value is quite consistent with Oemler's data for the rich clusters which give $M/L = 196$ (GT I). This result is not quite in agreement with GT I, who find a mass weighted $M/L = 90$ for their groups using incomplete data; but the relative importance of small samples, incomplete data, and systematic velocity errors have to be carefully considered before the source of this mild discordance will be clear.

The mean density is defined in equation (2),

$$\bar{\rho} = \frac{(L/L_{\rm obs})L_{\rm obs}(M/L)}{R_\Omega^{\,3}}\,. \quad (2)$$

Here R_Ω is the mean harmonic radius, given by equation (3),

$$R_\Omega = M^2\left(\sum_{\rm pairs} m_i m_j/r_{ij}\right)^{-1}. \quad (3)$$

As shown in Table 3, $\bar{\rho} \approx 4 \times 10^{-28}$, or about 85 times the closure density for $H_0 = 50$. If $\Omega < 0.1$, then the groups represent at least a 850-fold density enhancement.

Also shown is the crossing time, in units of the Hubble time. The harmonic crossing time is (Turner and Sargent 1974)

$$\Delta t_\Omega = \left(\frac{3}{5}\right)^{3/2}\frac{R_\Omega}{H\langle \hat{v}^2\rangle^{1/2}}\,. \quad (4)$$

Here, as in Table 3, $\langle \hat{v}^2\rangle^{1/2}$ is the line-of-sight velocity dispersion, after taking the effects of velocity uncertainties into account.

TABLE 4

DISTANCE ESTIMATES

Group	$D_{\rm H} = v/H_0$ (Mpc)	$D_{\rm SP}$ (Mpc)	$(D_{\rm H} - D_{\rm SP})/\sigma_{\rm SP}$
14A......	26	87	−1.36
46A......	122	78	+1.63
46B......	64	98	−0.68
56A......	55	63	−0.36
56B......	30	26	+0.24
77A......	51	44	+0.70
78A......	39	27	+0.67
91A......	47	33	+0.78

A second crossing time has been derived, using the moment-of-inertia radius of Jackson (1975),

$$R_{\rm I}^{\,2} = \left(\frac{3}{2}\right)\left(\sum m_i r_i^{\,2}\right)M^{-1}\,. \quad (5)$$

Here r_i is the distance from the lumicenter to the ith galaxy.

As Table 3 shows, the crossing times for these groups, calculated either way, are generally substantially less than 1, with t_Ω averaging 0.29 and $t_{\rm I}$ averaging 0.29. The crossing time is quite sensitive to contamination, tending toward smaller values as more nonmembers are included among the velocities. The observed crossing time is not really adequate to ensure that the groups are properly virialized (GT I).

c) *Distances*

Schechter and Press (1976) have pointed out that, if there exists a universal luminosity function (Schechter 1976), then the distance to a magnitude-limited group of galaxies can be estimated by comparing the mean apparent magnitude of the group to the apparent magnitude limit of the sample. In TG II, this method is compared with the distance derived from the mean velocity of the group and the Hubble flow. Here, the same comparison is made, but with contamination removed and with mean group velocities improved.

Table 4 shows that this method provides a reliable way to estimate distances to well-defined groups. The difference between the Hubble distance, $D_{\rm H}$, and the Schechter and Press distance, $D_{\rm SP}$, divided by the expected statistical error $\sigma_{\rm SP}$, is of order unity. Of course, the estimates themselves have fairly low precision for groups with relatively few members.

IV. CONCLUSION

The complete and uniform set of data used here provides a reasonable way to eliminate contamination from TG I groups. The resulting estimates of Δt and $\bar{\rho}$ confirm that Turner and Gott did indeed find groups among nearby galaxies, although Δt is rather large for the groups to be virialized at the present time (GT I). Measuring errors do not affect measurements of M/L near 200 for some groups, but prevent a reasonable estimate of M/L for groups of low-velocity dispersion, so that the proper "cosmic" M/L is not available from this study.

Objectively selecting groups and then subjectively editing them introduces real uncertainties into this approach to the mass and kinetic energy of galaxies. A statistical analysis along the lines of Peebles's (1976) cosmic virial theorem may be the ultimate way to derive these quantities. However, because the observational demands of group analysis are so much less taxing, the study of bound groups deserves a thorough examination.

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