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SYSTEMATIC ERRORS IN THE VELOCITIES OF GALAXIES

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SUMMARY

The 21-cm estimate V_{21} of the systemic velocities of 202 galaxies are compared with all available optical estimates for the same objects. The average difference between these measurements is shown to depend on the type of the galaxy. An average estimate V_A of the optical velocity is derived by combining estimates from different observers. The differences $(V_{21} - V_A)$ are normally distributed about zero, showing that despite the difference in precision, both the optical and 21-cm techniques produce statistically equivalent results. There is no dependence of the results on the absolute luminosity of a galaxy and no support is found for the existence of an anomalous redshift.

INTRODUCTION

Interest in the systemic velocities of galaxies, has in the past centred mainly on their relevance to Hubble's (1929) redshift–magnitude relation. As the achieved accuracy of $\pm 100 \text{ km s}^{-1}$ is sufficient for this purpose, many of the nearer galaxies have only been observed once. The primary source of data is still Humason, Mayall & Sandage (1956). More exact values are now wanted to test the recent speculations of Arp (1970), Jaakkola (1971) and Tifft (1972) concerning the possible existence of anomalous redshifts. All existing tests of these hypotheses using optical data, are sensitive to systematic errors in the velocities.

Significant systematic errors may be introduced by the measuring technique adopted (*cf.* Simkin 1972) or by the choice of spectral line available (*cf.* Eilek *et al.* 1973). Roberts (1972) found that a scale error of about 100 km s^{-1} existed in some of the older data, and this has been examined in greater detail by Lewis (1974). A more general search for systematic errors in the optical velocities that were dependent on velocity, nuclear magnitude, morphological type or spectrograph was made by de Vaucouleurs & de Vaucouleurs (1963a), though this did not reveal many significant differences between the velocities obtained by different optical observers. But many possible effects, such as those depending upon varying blends of absorption lines or on changes in the slope of the continuum-intensity level with wavelength, are likely to affect all optical observations to a similar extent.

A more sensitive method of detecting systematic errors, is to compare the optical velocities with the completely independent estimates resulting from 21-cm line-observations. These depend upon the average properties of neutral hydrogen spread throughout the disk, and are measured as a frequency which is easily related to the accurate laboratory determination of the frequency of the transition (Peters & Kartaschoff 1965). There are no adjacent radio-frequency lines to cause blending problems, and if a certain minimum signal-to-noise ratio is obtained, there should be no dependence on the type of the galaxy. Velocities are now available for 202 galaxies ranging in type from S0 to I9.

This paper is mainly concerned with the detection of systematic errors in the optical velocities. Section 1 considers the data, Section 2 the optical measurements of systemic velocity and Section 3 the corresponding 21-cm measurements. A comparison is made in Section 4 between optical and 21-cm velocities with respect to the source of the optical data, the type of the galaxy and the size of the velocity, assuming there are no anomalous redshifts. Evidence for this assumption is presented in Section 5. Finally in Section 6, a search is made for any correlation the differences between the 21-cm and optical velocities may have with the absolute size or luminosity.

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1. SYSTEMIC VELOCITIES

Table I gives 21-cm estimates of the systemic velocities of 202 galaxies, obtained during the last 15 yr, and the corresponding optical estimates for 187 of them, together, with their types, inclinations, luminosities and the sources of the data. Velocities are given in km s^{-1} with respect to the Sun, those derived from studies of the rotation curves being bracketed, and those derived from the velocities of H II regions in the disk being followed by a colon.

Column 1. Usual designation, NGC or IC number, the latter being marked by an asterisk.
Column 2. Simplified de Vaucouleurs type (τ) of the galaxy (from column 7 of *The Reference Catalogue of Bright Galaxies*).
Column 3. Adopted optical velocity (V_A) (see Section 4.8).
Columns 4 and 5. Adopted 21-cm velocity (V_{21}) calculated from the sources cited in column 5. Results of pencil-beam and high resolution studies are given double weight. As far as possible all the values used are consistent with derivation from $V_{21} = c\Delta\lambda/\lambda_0$.
Column 6. Velocity (W) from Table I and II of Humason, Mayall & Sandage (1956). A ' b ' follows those velocities derived from spectra with dispersions greater than 340 Å mm^{-1}.
Column 7. Lick velocity (L) from Table V of Humason *et al.* (1956) or from Mayall & de Vaucouleurs (1962).
Column 8. Emission-line systemic velocities (E). When there are several, they are also listed in column 9. All sources are listed in column 10 with numbers between 49 and 103.
Column 9. Other optical velocities. When these are not based on the measurement of emission lines, they are cited in column 10 by numbers larger than 102.
Column 11. Inclination (i) of the plane of the galaxy to the plane of the sky, from the data of Holmberg (1958).
Column 12. Assumed distance (D) in Mpc from Roberts (1969) or de Vaucouleurs (1965).
Column 13. Absorption-free luminosity in units of $10^9 L_\odot$ (see Section 6.2).

2. OPTICAL ESTIMATES OF THE SYSTEMIC VELOCITY

By far the most frequently used estimate is the velocity of the brightest region near the centre of the galaxy. In most cases, this region coincides with the nucleus, and is the centre of both mass and symmetry. While the velocity of the nucleus is therefore an intrinsically reasonable criterion to adopt, caution is needed if the required accuracy exceeds 100 km s^{-1}. For example in NGC 253, the velocity of the nucleus is about +96 km s^{-1} (Burbidge, Burbidge & Prendergast 1963a) though the systemic velocity appears to be +250 km s^{-1} when estimated from spectra near its minor axis, from its rotation curve and from 21-cm observations (Lewis 1969; Hutchmeier 1972). Other galaxies that are known to show similar large differences between velocities obtained from the nucleus and the whole disk are NGC 3227 (Rubin & Ford 1968), NGC 1068 (Burbidge, Burbidge & Prendergast 1959), NGC 5383 (Burbidge, Burbidge & Prendergast 1963b) and NGC 6574 (Demoulin & Chan 1969). The differences are of the order of 50 to 150 km s^{-1}, but only NGC 6574 shows this difference as an excess redshift in the nucleus. All the velocities in these cases have been estimated from emission lines.

These results may be explained by motions of gas in the nuclear regions. Thus in M82 Lynds & Sandage (1963) find a radial expansion away from the nucleus, whereas Walker (1968) in NGC 1068 finds a number of high velocity clouds that are apparently confined to the nucleus. Only a study of the absorption lines arising from the stellar component in the nucleus, can show whether it has the same systemic velocity as the disk.

Errors of about 50 km s^{-1} occur when the nucleus is not the centre of mass, as in NGC 55 (Robinson & van Damme 1966), NGC 4631 (de Vaucouleurs & de Vaucouleurs 1963b) and in the L.M.C. (McGee & Milton 1966). In some instances, it seems to be partially obscured by dust, and an adjacent bright region is measured instead. This may have occurred in NGC 3310 (Walker & Chincarini 1967), NGC 1808

(Burbidge & Burbidge 1968), NGC 3521 (Burbidge *et al.* 1964) and NGC 4258 (Burbidge, Burbidge & Prendergast 1963c).

When the apparent velocity of the nucleus is taken to be the systemic velocity, all these effects, which were discovered during observations to establish the rotation curve, can introduce significant error. In a list of 44 galaxies studied by the Burbidges and their collaborators, eight have nuclear velocities which require qualification. A 20 per cent frequency for the incidence of these anomalies is probably a lower limit to their true rate of occurrence, and for any source of nuclear velocities, is likely to be a large contributor to the average variance of the series in comparisons with the 21-cm velocities.

The systemic velocities of a few galaxies such as the Sculptor Group members measured by Humason *et al.* (1956) are based solely on the velocity of a bright H II region in the disk. These necessarily contain a large component of the rotational velocity, as well as an additional uncertainty of up to 20 km s^{-1} which is due to the random velocity of H II regions (Gottesman & Davies 1970).

Intrinsic accuracy

The intrinsic accuracy of optical estimates has usually been low and rather variable. Velocities are frequently extracted from low dispersion spectra, which may be underexposed, poorly guided or contaminated by the solar spectrum. Besides errors typical of the night of observation, spectra are subject to emulsion creep, to limitations in the spectrographs and to image-tube distortion or line curvature.

The current state of the art of measuring optical velocities in the external galaxies is best represented in the work of Rubin & Ford (1970). Using a Carnegie image-tube spectrograph with a dispersion of 135 Å mm^{-1} on the H II regions of M31, and measuring only emission lines (usually Hα), they obtain a mean difference of only 23 km s^{-1} from 56 pairs of spectra of bright H II regions. More usually the systemic velocity is derived from spectra of lower dispersion and is dependent in part on the measurement of broad absorption features in the nuclear continuum by visual settings on the line. In an intercomparison of the Mt Wilson and the Lick velocities, A. and G. de Vaucouleurs (1963a) find a probable error for each series of about 50 km s^{-1}. More recent observations with modern spectrographs of cluster galaxies by Kintner (1971) and Tifft (1973) are assigned errors of 100 to 150 km s^{-1}. The techniques used for both new and old observations can easily result in errors in excess of 50 km s^{-1} for a single plate.

Glaspey (1973) offers the hope of a large increase in the precision of optical methods of velocity determination by observing with vidicons and applying numerical analysis to the results. Simkin (1972) has used a micro-densitometer to digitize spectra and then applied numerical techniques. She finds that a classical visual setting on the H and K lines from the S0 galaxy NGC 5866, with a two-coordinate measuring machine, gives a result that differs by 73 km s^{-1} from cross-correlation estimates of the velocity of the same lines on the same plate. Furthermore, if the centroids of the H and K lines are estimated numerically, they are found to differ by 55 km s^{-1} from those obtained after the removal of the slope in the underlying continuum. Systematic effects of this kind can be expected to vary with both the type of the galaxy and the redshift, and are likely to be present in most of the optical data of Table I.

3. 21-CM ESTIMATES OF THE SYSTEMIC VELOCITY

Where the spatial resolution of optical observations poses a problem in finding a reliable general criterion, the 21-cm results benefit from the opposite situation. The early measurements on nearby galaxies with 1° beams gave so little spatial resolution or information on the distribution of the H I within a galaxy, that it had to be assumed that the H I centroid coincided with the centre of mass. Consequently, the velocity of the H I centroid (median velocity of the integrated H I spectrum) was usually adopted as the criterion for measuring the 21-cm systemic velocity V_{21} (Epstein 1964). This criterion is still useful, as current measurements on more distant galaxies using pencil beams have HPBW/H I diameter ratios of similar size to those applying to the early studies of Local Group members. But the availability of pencil beam studies of the closer galaxies has shown that the H I distribution within a few objects is strongly asymmetric, as in NGC 300 (Shobbrook & Robinson 1967), NGC 5236 (Lewis 1968)

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TABLE I

NGC (1)	τ (2)	V_A (3)	V_{21} (4)	Ref. (V_{21}) (5)	W (6)	L (7)	E (8)	Miscellan. (9)	Ref. (8) and (9) (10)	i (11)	D (Mpc) (12)	L ($\times 10^9 L_\odot$) (13)
45	S8	450	464	(1), (8)	450:					55	3·0	1·4
55	S9	147	131	(1), (2), (8)	210:		(110)	165, 233	(51), (52), (53)	85	3·0	49
224	S3	−293	−303	(9)	−266b	−290				77	0·7	80
247	S7	−28	155	(2), (8)	−28:					68	3·0	5·2
253	S5	157	250	(8), (10)	−81:		(250)	−68	(54), (104)	73	3·0	51
300	S7	248	144	(1), (2), (8)	248:					50	3·0	8·4
428	S9	1078	1155	(3), (11)		1078				38	7·9	3·2
520	pec.	2145	2280	(4)		2205				67	16·0	11
598	S6	−178	−179	(2), (12–17)	−189b		−(174)	−195, −167	(55), (105), (106)	57	0·7	6·1
628	S5	561	657	(1), (23)	561					35	7·8	21
672	S6	340	385	(1), (18)		340				68	6·3	3·4
772	S3	2431	2432	(11), (19)	2431					55	16·6	40
925	S7	547	565	(1), (3), (20)	420	587	(580)		(56)	53	6·8	11
1023	L	616	601	(3)	557b	734				71	6·3	7·3
1055	S3	—	1054	(3)						—	—	—
1058	S5	480	517	(4)		80		521, 439	(101), (108)	0	6·3	2·9
1068	S3	1111	1139	(4), (21)	1020b	1121	(1203)	1073, 1079	(57), (109), (109)	37	10·8	51
1073	S5	1239	1218	(5)		1874	1209		(58)	13	12·2	9·9
1097	S3	1292	1251	(3)	1326	1424	(1307)		(59)	50	12·1	83
1140	I9	1544	1528	(11)	1544					62	15·0	9·7
1156	S9	405	380	(11)	405					52	6·3	2·2
1187	S5	1459	1426	(6)		1579				36	15·0	15
1291	S0	906	836	(22)				906	(110)	49	8·0	9·9
1300	S4	1505	1537	(6)		1625				54	13·8	25
1326	L	—	1381	(6)						—	—	—
1332	L	1505	1381	(6)	1609	1573				0	14·0	21
1365	S3	1653	1619	(3)		1750	(1658)	1617, 1790	(59), (111)	66	15·1	229
1507	S9	898	843	(3)			898		(61)	85	2·6	0·32
1518	S8	1027	972	(6)		1027				61	14·0	12
1532	S2	1760	1225	(3)			1760		(53)	86	22·0	90
1560	S7	—	−43	(4)						—	—	—
1569	I9	−4	−93	(1), (11)	−34b	−88				65	2·5	1·1
1637	S5	692	724	(5), (6), (11)	695	528	716		(58)	35	5·6	3·0
1744	S7	676	762	(3)		676				49	10·0	8·8
1784	S5	2301	2316	(5), (6)			2314	2150	(58), (108)	49	23·2	20

1792	S4	1203	1205	(6)			(1215)	1254	(62), (61)	75	13·0	50
1808	So	975	997	(7)		1039	(960)	963	(63), (53)	60	10·5	7·6
1964	S3	1729	1690	(6)		1849				71	15·0	40
2139	S6	1793	1800	(6)		1913				33	15·0	17
2146	S2	866	856	(7)	785	784	(901)		(64)	58	8·7	12
2188	S9	704	762	(3)			(730)	678	(65), (61)	79	3·2	0·79
2217	L	1497	1406	(6)	1585	1573				36	15·0	26
2280	S6	—	1902	(6)						—	—	—
2336	S4	2192	2216	(6)		2252				50	22·2	95
2344	S5	914	962	(6)				914	(108)	—	—	—
2366	I9	169	90	(3)		194	145:		(61)	64	3·3	1·2
2403	S6	119	135	(1), (2), (23–25)	70		(125)		(66)	54	3·3	12
2500	S7	470	531	(3)		470				18	12·0	5·8
2535	S5	4087	4109	(5)	4243		4050	4056	(67), (58)	61	41·0	54
2541	S6	601	571	(3)				601	(108)	62	6·0	2·4
2613	S3	1574	1831	(6)	1710	1555				70	8·7	93
2655	So	1299	1389	(4)	1299					41	13·0	12
2681	So	714	722	(7)	703b	736				0	6·0	3·2
2683	S3	315	260	(5), (11)	336	314	310		(58)	85	5·8	21
2685	L	879	883	(7)	884b	867				50	8·8	2·4
2776	S5	2673	2620	(19)		2673				25	26·2	43
2782	S1	2503	2561	(7)	2517b	2358		2526, 2566	(109), (109)	36	32·7	6·7
2805	S7	1709	1742	(5)		1916	1688		(58)	36	16·0	15
2835	S5	909	882	(3)		909				43	7·6	3·7
2841	S3	624	651	(6), (11)	584	740				67	6·0	18
2903	S4	572	571	(3), (11)	642	645	(589)	540	(68), (69)	70	7·0	33
2997	S5	1030	1049	(6)			1030		(53)	36	7·6	9·8
3027	S7	1079	1061	(6)		1079				58	17·0	11
3031	S2	−52	−40	(2), (26)	−55b	−64	−42	−45	(58), (113)	55	3·3	31
3034	I0	277	280	(2), (3), (18)	263b	275	(284)		(70)	82	3·3	15
3077	I0	−35	11	(4), (26)		−158	−41	−10	(71), (114)	25	3·2	1·7
3079	S9	1170	1124	(3)		1170				83	12·0	34
3109	I9	441	405	(1), (2), (27), (28)		441				90	2·2	1·4
3115	L	648	666	(3), (4)	648b	591		629, 642, 695	(115), (116), (117)	74	4·2	6·0
3169	S1	1237	1093	(6)	1281	1312				34	17·0	29

TABLE I—*continued*

NGC (1)	τ (2)	V_A (3)	V_{21} (4)	Ref. (V_{21}) (5)	*W* (6)	L (7)	E (8)	Miscellan. (9)	Ref. (8) and (9) (10)	*i* (11)	*D* (Mpc) (12)	*L* ($\times 10^9 L_\odot$) (13)
3184	S6	411	588	(4)	443	395				0	9·6	17
3198	S5	649	661	(3), (11)		649				73	9·6	20
3227	S1	1144	1230	(4), (21)	1111b		(1175)		(72)	51	16·5	47
3310	S4	997	981	(6)	1039	998	(986)		(73)	36	14·0	31
3319	S6	826	752	(3), (11)		826				58	9·2	5·4
3344	S4	579	585	(3), (4), (11)	579					14	7·9	11
3359	S5	1008	1008	(1), (11)		1008				51	10·0	13
3368	S2	926	899	(4), (7)	927b	924				46	8·3	22
3379	E	897	857:	(4)	862b	963				32	8·3	15
3395/6	S6/I9	1625	1605	(5)		1697	1614	1622, 1667	(67), (58), (74)	—	—	—
3430/24	S5/S3	1551	1583	(5)		1742:	1504		(58)	—	—	—
3432	S9	650	641	(11)		609		670	(118)	89	9·6	13
3447/A	S7/I9	1052	1062	(5)		990	1067		(58)	—	—	—
3448	I0	1404	1321	(4)			1404		(61)	75	13·2	8·0
3516	L	2620	2503	(7)	2614b	2632				42	35·2	45
3521	S4	788	847	(3)	789b		(815)		(75)	66	6·9	16
3556	S6	692	689	(1), (3), (11)	636	650	(735)		(76)	84	8·2	25
3621	S7	—	722	(3)						—	—	—
3627	S3	707	722	(3)	744b	638				57	7·6	30
3628	S3	842	842	(11)		842				89	7·6	43
3631	S5	1170	1165	(5), (11)		1087	1180		(58)	32	14·5	23
3718	S1	1050	1013	(4), (6), (11)	1050					57	14·5	26
3726	S5	948	762	(11)	948					46	11·5	16
3893/6	S5/—	960	980	(5)	1042:		932		(58)	—	—	—
3938	S5	815	812	(5), (11)		874	742		(58)	28	8·9	9·2
4051	S4	647	728	(4), (21)	627b		658	677	(61), (109)	44	8·0	9·5
4096	S5	—	474	(6)						—	—	—
4144	S6	—	536	(3)						—	—	—
4151	S2	963	989	(4), (6), (21)	960	934	990	952	(69), (109)	50	11·5	28
4157	S3	—	782	(6)						—	—	—
4178	S8	233	329	(4)		233				67	14·8	15
4192	S2	−124	−143	(4)	−124					78	14·8	87
4214	I9	310	288	(1), (2)	295	318				45	3·8	3·3
4216	S3	40	−103	(4)	32b	59				85	14·8	65
4217	S3	—	962	(6)						—	—	—

4236	S8	27	00	(1), (25)		27				74	3·2	5·0
4244	S6	265	242	(1), (2)		265				86	3·8	5·5
4254	S5	2463	2387	(4)	2485	2451				35	14·8	38
4258	S4	473	451	(1)	420b		(510)	472 (505)	(77), (61), (78)	69	3·8	22
4274	S2	767	718	(4)	767					69	9·6	15
4293	S0	750	948	(4)		750				84	14·8	37
4294/9	S6/S7	289	312	(4)				289	(119)	—	—	—
4303	S4	1581	1670	(4), (19)	1671		1560		(69)	47	14·8	58
4321	S4	1617	1600	(4), (6)	1617					25	14·8	49
4374	E1	954	910	(4)	954					11	14·8	32
4429	L	1114	1396:	(4)						53	14·8	14
4449	I9	223	199	(1), (2), (3)	206	309	(204)		(79)	51	3·8	4·3
4472	E2	966	868:	(4)	1013b	876				20	14·8	73
4490	S7	610	572	(1), (3), (4)	625b	528	(590)	631, (655)	(80), (67), (81)	60	8·0	15
4501	S3	2120	2016	(4)	2120					55	14·8	74
4526	L	487	448	(4)	447					88	14·8	40
4535	S5	1948	1942	(4)	1930b	2097	1920		(69)	26	14·8	37
4548	S3	433	495	(4)	433					44	14·8	31
4559	S6	856	792	(3)		856				67	9·6	25
4567/8	S4/S4	2229	2297:	(4)		2349	2199	2266	(67), (109)	—	—	—
4569	S2	−306	−236	(4)	−208		−(310)	−330, (−298)	(82), (69), (83)	62	14·8	83
4579	S3	1752	1808	(4)	1752					49	14·8	54
4631	S7	637	609	(1), (2), (29–30)	591:	665:	(630)	(630), (644):, 646, 692	(84), (85), (86), (109), (109)	85	4·0	12
4651	S5	733	796	(4)				733	(108)	43	14·8	18
4654	S6	1038	1034	(4), (5)			1042	1022	(58), (61)	46	14·8	22
4656	S9	721	632	(2), (3), (29–30)		721		827	(109)	85	4·0	4·8
4698	S2	1032	872	(4)	1032					47	14·8	17
4736	S2	287	240	(1)	282	313	(296)	(259), (278)	(87), (88), (89)	28	3·8	11
4762	L	948	838:	(4)	868	969				88	14·8	24
4826	S2	458	389	(4), (7)	382b		490		(90)	48	3·8	9·2
4861	S9	793	812	(18)		793				73	8·1	2·9
4941	S2	846	648	(7)	846					59	12·0	12
5005	S4	1006	1003	(4)	1013	1041	(1025)		(91)	56	10·8	26
5033	S5	908	913	(11)	924b	861	894		(58)	59	9·5	15
5055	S4	528	511	(1)	500b	538	(560)		(92)	55	4·6	16

Table I—*continued*

NGC (1)	τ (2)	V_A (3)	V_{21} (4)	Ref. (V_{21}) (5)	W (6)	L (7)	E (8)	Miscellan. (9)	Ref. (8) and (9) (10)	i (11)	D (Mpc) (12)	L ($\times 10^9 L_\odot$) (13)
5102	L	523	411	**(6)**				500, 546	**(108), (110)**	69	4·0	1·8
5194	S4	458	465	**(1), (2), (3), (31–32)**	438b	381	(474)	(468), 472, 510	**(93), (94), (69), (112)**	35	4·6	15
5195	I0	570	570	**(32)**	542	508	606	562	**(92), (112)**	38	4·6	34
5204	S9	272	207	**(3), (11)**		272				53	4·6	1·4
5236	S5	488	529	**(2), (3), (33), (34)**	491b		504	418, 495, 497	**(53), (95), (60), (61)**	35	5·0	70
5248	S4	1156	1148	**(4)**	1176	1232	1190		**(96)**	40	11·5	24
5253	I9	390	381	**(4), (35)**	432b		285	396, 404, 383	**(53), (95), (97), (103)**	68	5·0	6·2
5301	S3	1582	1487	**(6)**		1702				77	23·0	30
5457	S6	207	238	**(1), (2), (36–38)**	247b	160				27	4·6	27
5474	S6	247	280	**(3)**		247				20	4·6	1·7
5523	S6	—	762	**(3)**						—	—	—
5585	S7	304	302	**(3), (11)**		304				50	4·6	1·9
5668	S7	1570	1577	**(3), (5), (19), (39)**	1780	1665	1550		**(58)**	20	15·0	12
5676	S4	2184	2196	**(6)**		2244				61	15·0	32
5713	S4	1859	1869	**(6), (11)**	1870	1965	1865		**(58)**	22	13·2	13
5774/5	S7/S5	1562	1689	**(3)**			1562		**(67)**	—	—	—
5866	L	813	758:	**(4)**	740	850				84	13·8	30
5907	S5	533	654	**(3)**	553	522				87	4·6	5·1
5921	S4	1389	1487	**(3)**	1389					32	14·9	28
5962	S5	1993	1932	**(6)**	1993					36	22·0	27
6015	S6	703	852	**(3), (11)**	646	732				67	9·8	7·7
6207	S5	869	852	**(6)**	869					54	13·0	12
6217	S4	1329	1353	**(4), (11)**	1386b	1382				40	16·5	11
6239	S3	964	931	**(6)**		964				50	10·0	6·3
6340	S0	2109	1902	**(6)**	2109					58	17·0	20
6503	S6	30	70	**(3), (11)**		28	(60)		**(98)**	74	4·6	5·8
6643	S5	1539	1492	**(6), (11)**	1494	1682				61	16·5	24
6814	S4	1437	1588	**(6)**	1437					0	25·0	51
6822	I9	−35	−60	**(12), (40)**	−34b	−33				43	4·2	0·22
6835	S1	1720	1568	**(6)**				1720	**(108)**	75	21·0	27

6946	S6	−33	53	(1), (2), (3), (41), (42)	38	−70				22	4·2	13
6951	S4	1224	1396	(6)		1364				38	14·0	20
7013	S0	570	852	(6)				570	(108)	67	11·0	8·4
7137	S5	1395	1568	(6)		1505				25	15·7	6·8
7177	S3	1105	1225	(6)	1105					50	12·3	23
7217	S2	934	842	(3)	911		950		(58)	35	9·1	15
7218	S6	1688	1710	(6)		1808				57	15·0	5·7
7314	S4	1766	1467	(6)	1766					56	20·0	40
7319	S4	6657	6590	(43)	6657					38	65·0	134
7320	S7	768	752	(43), (44)			795		(99)	62	—	—
7331	S4	842	835	(3), (11)	780	900	(850)		(100)	69	7·9	27
7361	S5	1174	1245	(3)			1174		(61)	79	16·0	18
7448	S4	2419	2247	(6)	2419					55	18·0	25
7625	S1	1642	1641	(7)	1706	1828	(1620)		(101)	35	24·5	80
7640	S5	408	371	(1), (3), (11)		423	388		(61)	89	4·4	5·5
7741	S6	799	786	(11)	729		808		(61)	45	10·1	7·0
7793	S8	232	212	(3), (8)	286	177				47	3·0	7·0
10*	I9	−343	−344	(1), (2), (3), (45)	−343b					0	1·2	2·1
342*	S6	9	40	(2), (18), (41)	−10b	34	8		(58)	—	—	—
356*	S1	—	743	(4)						—	—	—
1613*	I9	−238	−230	(2), (18)	−238b					32	0·7	0·11
2574*	S9	28	46	(1), (2)		28				69	3·3	1·9
3576*	S8	—	1080	(46)						—	—	—
4662*	I9	376	295	(47)			377	375	(53), (95)	55	3·8	1·4
A2326	I9	—	−240	(3)						—	—	—
Ho I		—	125	(4)						—	—	—
Ho II	I9	220	157	(1), (2), (3)		220				40	3·3	1·2
Maff II	S4	—	0	(4), (48), (49), (50)						—	—	—
Sex A	I9	414	322	(1), (2)	370	436				36	1·0	0·066
WLM	I9	−78	−130	(1)	−78					—	—	—
LMC	S9	260	276	(2)			(260)		(102)	27	0·1	4·1
SMC	I9	166	160	(2)			(166)		(102)	60	0·1	1·2

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and NGC 5457 (Beale & Davies 1969). These results are strongly confirmed in NGC 5457 by the interferometric observations of Rogstad & Shostak (1971). Thus on occasion, the use of the velocity of the H I centroid may inject a component of the rotational velocity, though its size will be at most in proportion to the departure of the H I distribution from circular symmetry.

As a substitute for this criterion, Roberts (1969) has urged the adoption of the median of the velocity range over which the object is detected. While less sensitive to receiver baseline distortion, this criterion requires the observations to be made to a larger signal-to-noise ratio, in order to define the velocity spread accurately. There is also a tacit assumption of a large-scale symmetry in the rotation curve, a condition which is only approximately satisfied in many cases. In M31 (Roberts 1966) and NGC 5236 (Lewis 1968, 1969b) the departure from symmetry reaches 20 km s^{-1}. Estimation of the systemic velocity by fitting a rotation curve to the whole velocity field, as Lewis (1972) did in the case of NGC 45, also relies on the assumption of symmetry.

The degree of symmetry present acts as the primary limitation on the accuracy of all 21-cm estimates, though errors arising from this factor should not exceed 20 km s^{-1}. This is illustrated by the work of Gottesman & Davies (1970) on M31. They find velocities that range from -297 to -323 km s^{-1}, the particular value being dependent on the method used and the degree to which it is sensitive to asymmetry in the rotation curve.

The large beam-width of most radio-telescopes causes the observation of galaxies with H I within the velocity range covered by our own Galaxy, to be subjected to confusion from local H I. Observers have been very conscious of this, with the result that the average difference $\bar{\Delta} = |V_{21} - V_{\mathrm{Opt.}}|$ for the 25 velocities between -200 and $+200$ km s^{-1} is 45 km s^{-1}. This compares well with $\bar{\Delta} = 43$ km s^{-1} found for the 25 velocities in the next range. Having due regard to the signs

$$\begin{aligned}\bar{\Delta} &= -19 \pm 14\ \mathrm{km\ s^{-1}} \quad (-200 < V_{21} < 0\ \mathrm{km\ s^{-1}})\\ &= +9 \pm 21\ \mathrm{km\ s^{-1}} \quad (0 < V_{21} < +200\ \mathrm{km\ s^{-1}}).\end{aligned}$$

This is consistent with the hypothesis that the velocity spread attributed to each galaxy has been contracted by the presence of local H I, resulting in an error of about 15 km s^{-1}.

A second source of systematic error in V_{21}, is the presence of close double galaxy systems such as NGC 4567/8 within the beam, when both members contain appreciable quantities of H I in much the same velocity range. In most of those cases, when the second galaxy is not an elliptical, the median velocity is adopted as the 21-cm value and is compared with the mean optical velocity of the two systems. The double galaxy NGC 4490/85 is treated differently in Table I, as the median value of V_{21} is close to the optical estimate for NGC 4490, and only one estimate is available for NGC 4485.

The self-consistency and accuracy of the 21-cm results is shown by the small difference between the published estimates of V_{21} referred to in column 5 of Table I and the adopted value of V_{21} listed in column 4. For 25 galaxies with three or more independent estimates, the average difference is $9 \pm 1 (\sigma = 17)$ km s^{-1}, and it is only 11 ± 2 km s^{-1} for the 56 objects for which there are two estimates. The achieved signal-to-noise ratio of any 21-cm measurement is liable to depend on the strength of the signal. This is shown by the 12 galaxies with velocities exceeding 1000 km s^{-1}, which have an average difference of 17 ± 4 km s^{-1}. It is even more clearly shown by the marked type-dependent trend in the size of differences listed in Table II, which follows the variation of H I content with type.

TABLE II

Comparison of the differences (Δ)* *with galaxy type*

Type (τ)	$\tau \leqslant 1$	$\tau \leqslant 2$	3, 4	5	6	$\tau \geqslant 7$	All
$\lvert\bar{\Delta}\rvert$	23	23	13	9	9	6·6	10·2
$\sigma N^{-1/2}$	7	5	3	2	2	1·5	1·1
σ	22	23	18	11	10	12	15
N	9	18	27	27	34	67	173

* $\Delta = V_{21}$ (adopted average) $- V$ (particular source) km s^{-1}.

As almost all 21-cm estimates of the systemic velocity depend upon observations of integral properties of the galaxy, they are both more accurate and more soundly based than the optical values. In all the following comparisons, the V_{21} values are taken as a standard. Their variance (σ^2) never exceeds 14 per cent of the values found in comparisons with the various optical series discussed in Section 4, and is usually about 5 per cent.

4. COMPARISON OF OPTICAL AND 21-CM VELOCITIES

4.1 *Comparison of the Lick* (*L*) *velocities with* V_{21}

(a) *The Roberts' redshift effect.* All velocities determined at the Lick and Mt Wilson observatories (Humason *et al.* 1956) have been determined from spectra taken in the blue region and frequently are based in part on the H and K absorption lines. Roberts (1972) comparing observations from the blue spectral region with V_{21}, noticed that the optical velocities in the range from 1200 to 2400 km s^{-1} were overestimated by about 100 km s^{-1}. Lewis (1974) has shown that this result is confined to the Lick velocities. Fig. 3 of Lewis (1974) shows a plot of the differences $V_{21} - V_L = \Delta_{21-L}$ against V_{21}; the means are tabulated in Table III. Differences from NGC 1058 ($\Delta = +437$), NGC 1073 ($\Delta = -656$) and NGC 2613 ($\Delta = +276$; relative to the mean of the others, $\Delta = +396$) have been excluded.

TABLE III

Dependence of Δ_{21-L}* *upon velocity*

Range	$V < 280$	650	860	1200	1900	> 1900	All
$\bar{\Delta}_{21-L}$	−12	+2	+7	+3	−120	−25	−22
$\sigma N^{-1/2}$	17	17	20	18	17	41	9
σ	77	80	92	82	74	115	95
N	21	21	20	22	20	8	112

* $\Delta_{21-L} = V_{21} - V_L$.

For all types of galaxy in the sample, the systematic error in the range from 1200 to 1900 km s^{-1} is so large at seven standard deviations, that a correction must be applied before making any other comparisons. The optimum adjustment is

$$V_L \rightarrow V_L - 120 \qquad 1200 < V_{21} < 2000$$
$$V_L \rightarrow V_L - 60 \qquad 2000 < V_{21} < 2400$$

This results in the mean residual for the adjusted Lick velocities becoming $+1{\cdot}8$ ($\sigma = 81$) km s^{-1}.

(b) *Comparisons with the adjusted Lick velocities* (L'). The differences Δ_{21-L}' are summarized in Table IV. This table shows the average for groups that are similar enough to be treated together. Average differences for objects with V_{21} less than 1200 km s^{-1} are also listed to show that little significant difference remains between them and the whole sample.

After the application of these type differences as corrections, the adjusted Lick velocities are free of any scale distortion over all velocities up to 2600 km s^{-1} for which comparisons exist. The mean difference is zero and $\sigma = 77$ km s^{-1}.

TABLE IV

Comparison of 21-cm minus adjusted Lick (L′) velocities with galaxy type

Type (τ)	$\tau \leqslant 2$	S3	$4 \leqslant \tau \leqslant 6$	$7 \leqslant \tau \leqslant 9$	I9
All $\langle V_{21} - V_{L'} \rangle$	−8	−36	+24	+8	−70
$\sigma N^{-1/2}$	21	20	11	12	15
σ	107	65	76	56	39
N	26	11	45	23	7
$V < 1200$;					
$\langle V_{21} - V_{L'} \rangle$	−11	−28	+24	+9	−70
$\sigma N^{-1/2}$	23	30	15	13	15
σ	102	79	80	58	39
N	20	7	30	20	7

For the I9, Sb and Sbc to Scd type galaxies, the type corrections in Table IV are all at least twice the standard error, and should be applied in situations requiring a statistical accuracy better than 20 km s^{-1}. It is surprising to find so large a difference for I9 galaxies, as their velocities are wholly determined from emission lines. Negative differences were found in all seven I9 objects, the largest being −14 km s^{-1}. Their irregular structure could make the centre of mass hard to identify, but this should increase the scatter rather than introduce the systematic error, which appears in the results of every observer.

4.2 *Comparison of Mt Wilson (Wa) velocities with V_{21}*

De Vaucouleurs & de Vaucouleurs (1963a) compared the velocities determined at Lick with those measured at Mt Wilson, both at low dispersion (Wa) and high dispersion (Wb), and found significant differences. These will therefore be treated separately. For the 76 Wa velocities listed in Table I, the mean difference $V_{21} - V_{\mathrm{Wa}} = \bar{\Delta}_{21-\mathrm{Wa}} = -14 \pm 13$ (σ = 113) km s^{-1}. Fig. 2 of Lewis (1974) shows these differences plotted against V_{21}. It is particularly noticeable that in the range from 1200 to 1900 km s^{-1}, the Mt Wilson velocities have a much smaller difference than the uncorrected Lick velocities. Table V records the mean difference as a function of velocity, and shows that the variance (σ^2) increases from σ = 86 km s^{-1} for velocities below 200 km s^{-1} to 142 km s^{-1} for velocities above 1200 km s^{-1}. There may be a significant scale error for velocities above 1900 km s^{-1}, but the number of observations is small and this result is more probably a statistical fluctuation.

TABLE V

Comparison of 21-cm minus Mt Wilson (Wa) velocities with velocity

Range	All	$V < 400$	800	1400	1900	> 1900	$1200 < V < 2400$
$\langle V_{21} - V_{\mathrm{Wa}} \rangle$	−14	+2	+18	−13	−28	−111	−35
$\sigma N^{-1/2}$	13	18	21	27	37	23	30
σ	113	111	92	122	132	60	142
N	75	16	19	20	13	7	23

The effect of the type of the galaxy on the differences $\Delta_{21-\mathrm{Wa}}$ is summarized in Table VI. The most significant values are again found in the S8 to I9 group, to which type I9 contributes four differences with a mean value of -31 ± 11 km s^{-1}. Only the Scd group shows a large positive difference, which is shared by all six objects. However, this number is small and the group is not very prominent in any of the other comparisons of Section 4. If the average is formed for all the types from Sb to Sd, $\bar{\Delta}_{21-\mathrm{Wa}} = +12 \pm 18$ km s^{-1}. This is not significant, but it does emphasize the similarity of the pattern of the differences seen in Table VI with those found for the Lick observations in Table IV.

When the mean differences listed in Table VI are applied as corrections to the Wa velocities, the overall mean difference increases from −13 to -5 ± 12 (σ = 107) km s^{-1}. This adjustment has almost no effect on the scale invariance of the series listed in Table V, except that for velocities greater than 1900 km s^{-1}, $\bar{\Delta}$ rises from −111 to −99 km s^{-1}, and over the whole range from 1200 to 2400 km s^{-1}, $\bar{\Delta}$ rises to -17 ± 30 km s^{-1}.

TABLE VI

Comparison of 21-cm minus Mt Wilson (Wa) velocities with type

Type (τ)	$\tau \leqslant 2$	$3 \leqslant \tau \leqslant 5$	$\tau = 6$	$\tau = 7$	$8 \leqslant \tau \leqslant 10$
$\langle V_{21} - V_{\text{Wa}} \rangle$	−48	−6	+90	+8	−33
$\sigma N^{-1/2}$	24	20	29	73	11
σ	115	115	71	163	32
N	23	33	6	5	9

4.3 *Comparison of Mt Wilson (Wb) velocities with* V_{21}

The Mt Wilson (Wb) velocities of Humason *et al.* (1956) which are derived from spectra of higher dispersion are considerably more accurate, though most of the observations refer to the closest galaxies. No significant distortion of the optical velocity scale is evident in the comparisons summarized in Table VII. The dependence of the differences on the type of the galaxy is seen in Table VIII, which shows the same pattern as Tables IV and VI, though all the means are smaller.

TABLE VII

Comparison of 21-cm minus Mt Wilson (Wb) velocities with velocity

Range	$V < 500$	1000	$< V$	All
$\langle V_{21} - V_{\text{Wb}} \rangle$	−10	+2	+25	−2
$\sigma N^{-1/2}$	11	15	31	10
σ	43	57	76	59
N	15	14	6	35

TABLE VIII

Comparison of 21-cm minus Mt Wilson (Wb) velocities with type

Type (τ)	$\tau \leqslant 2$	$3 \leqslant \tau \leqslant 5$	$\tau = 6, 7$	I9
$\langle V_{21} - V_{\text{Wb}} \rangle$	−4	+12	0	−20
$\sigma N^{-1/2}$	18	18	21	15
σ	66	65	43	30
N	14	13	4	4

Spectral types were assigned to all those galaxies observed at Mt Wilson by Humason *et al.* (1956). No clear trend or departure of the mean difference from zero is found when differences are ordered by their spectral type. These are much less useful than the Hubble types for establishing the existence of systematic errors.

4.4 *Comparison of velocities from A. and G. de Vaucouleurs* (1967) *with* V_{21}

Of the 113 galaxies with velocities measured by A. and G. de Vaucouleurs (1967), 20 have known 21-cm velocities. The methods used to reduce the optical results differ from those of Mayall & de Vaucouleurs (1962), in that type-dependent corrections were applied to each spectral line. Table IX summarizes the dependence of the differences (V_{21}–V_{dV}) on both velocity and type. With a variance of

TABLE IX

Comparison of V_{21} *minus the velocities of A. & G. de Vaucouleurs* (1967) *with type and velocity*

Type (τ)	$\tau \leqslant 1$	$4 \leqslant \tau \leqslant 6$	$\tau \geqslant 9$	$V < 600$	900	1600	All
$\langle V_{21} - V_{\text{dV}} \rangle$	−108	+25	−9	−26	+28	0	−2
$\sigma N^{-1/2}$	22	16	46	14	28	29	17
σ	38	59	80	38	62	65	75
N	3	13	3	7	5	5	19

75^2, these results show little improvement on the adjusted Lick (L′) velocities in Section 4.1, which have a variance of 81^2. When compared with earlier and later types, the Sbc to Scd spirals in this sample show the same tendency to have small positive differences, which was noticed in the previous section. The sample shows the usual tendency for the variance to increase rapidly with velocity. The only I9 galaxy has a difference of -55 km s^{-1}.

NGC 7013 of type So has a difference of $+282$ km s^{-1}, and is not included in the calculations of the means listed in Table IX. As the correction of the velocity from the Sun to the outside of the Galaxy is $+287$ km s^{-1} it is probable that the difference is due to a mistake in the observer's reductions. Twelve objects in the sample have velocities determined predominantly from emission lines, and give $\bar{\Delta}_{21-dV} = -3 \pm 16$ ($\sigma = 56$) km s^{-1}. This compares very favourably with the $\sigma = 105$ km s^{-1} found for the four objects relying on absorption-line measures.

4.5 *Comparison of the velocities measured by the Burbidges (B) with V_{21}*

Systemic velocities for 26 of the galaxies listed in Table I have been estimated by the Burbidges and their collaborators during their studies of the optical rotation curve of each object. Consequently errors due to high-velocity motions of the gas in the nucleus or to badly defined centres of mass are minimized in this series. Most of the velocities are based on the measurement of the Hα and N II 6584 Å emission lines from a number of plates. The average difference $\bar{\Delta}_{21-B}$ is -17 ± 8 ($\sigma = 41$) km s^{-1}. The 17 spiral galaxies of types Sb to Sd have the smaller mean of $-27{\cdot}4 \pm 6{\cdot}4$ ($\sigma = 26$) km s^{-1}. As this is four times the standard error and the data have a high weight in the calculation of the average optical velocity (see Section 4.8), it is desirable to apply this difference as a systematic correction, before using the data in other contexts. Table X summarizes these results, and gives in brackets the values which are obtained after adjusting the data. The average adjusted difference is 1 ± 8 ($\sigma = 38$) km s^{-1}.

TABLE X

Comparison of V_{21} minus V_B velocities with velocity and type*

	$\tau \leqslant 2$	$3 \leqslant \tau \leqslant 7$	$V_{21} < 700$	$V_{21} > 700$	All
$\langle V_{21} - V_B \rangle$	−2	−27·4	−20 (−2·6)	−14 (+6)	−17 (+1)
$\sigma N^{-1/2}$	21	6·4	11 (11)	−12 (9)	8 (8)
σ	59	26	44 (44)	38 (31)	41 (38)
N	8	17	15	11	26

* V_B are the velocities measured by the Burbidges and their collaborators that are cited in Table I.

4.6 *Comparison of velocities from Ford et al.* (1971) *with V_{21}*

Ford, Rubin & Roberts (1971) obtained Carnegie Image-tube spectra of 27 galaxies, 19 of which appear in Table I. Rubin & Ford (1968) had previously studied NGC 3227 with the same equipment, so this galaxy has been added to the series. All measurements were made on emission lines with $\lambda \geqslant H\beta$. The results of comparisons with V_{21} are summarized in Table XI.

The nine Sc galaxies show a difference of $+30 \pm 11$ km s^{-1}, which is almost three standard errors. The variance in the high velocity range is notably smaller than that in the low velocity range, until the

TABLE XI*

Comparison of V_{21} minus the velocities of Ford et al. (1971) *with type and velocity*

	$\tau \leqslant 3$	4, 6, 7, 8	5	$V < 1100$	$V > 1100$	All
$\langle V_{21} - V_F \rangle$	−25	+12	+30	+1 (−11)	+25 (+10)	+13 (−½)
$\sigma N^{-1/2}$	35	10	11	16 (14)	11 (12)	10 (9)
σ	70	26	33	50 (43)	33 (37)	43 (40)
N	4	7	9	10	10	20

* Bracketed values are obtained after adding $+30$ km s^{-1} to the velocities of the Sc galaxies.

velocities of the Sc galaxies are adjusted by this difference. This removes any suggestion of a velocity-scale error and causes the mean difference to drop from $+13 \pm 10$ km s^{-1} to $-0 \cdot 5 \pm 9$ ($\sigma = 40$) km s^{-1}. This correction has been applied before using the data in any later section.

Although the results here and in Section 4.5 have been determined from measurements of emission lines, the variance of the late types ($\tau \leqslant 3$) is in both instances twice as large as for the more ordinary spiral galaxies.

4.7 *Comparison of emission line velocities* (E) *with* V_{21}

Data for this section are listed in column 8 of Table I or have numbers between 51 and 102 in column 10. Most of the data are taken from the adjusted values of the Burbidges (Section 4.5) and Ford *et al.* (Section 4.6), or from Carranza (1967) and A. and G. de Vaucouleurs (1967). Only systemic velocity estimates which could be verified as being based predominantly on emission line measures have been included. Fig. 1 shows the dependence of the differences Δ_{21-E} on V_{21}; Table XII lists the means over

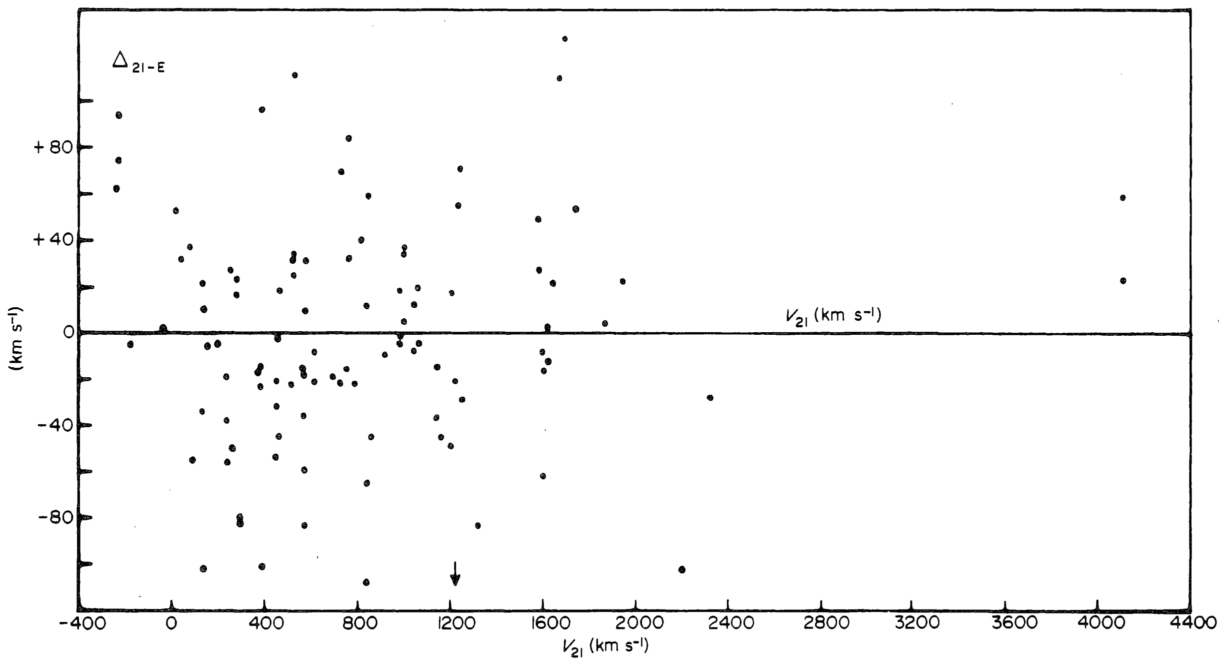

FIG. 1. *Distribution of the residuals* ($V_{21} - V_{Emission}$) *as a function of the 21-cm velocity* V_{21}.

a series of velocity ranges. There is no evidence of any velocity-scale distortion over the range for which comparisons exist. The largest difference is -23 ± 10 km s^{-1}, in the range from $+200$ to 500 km s^{-1}. This result is in contrast with the trend towards positive differences for velocities greater than 1200 km s^{-1} noted by Lewis (1974) in a similar but smaller data sample. This is partly due to the adjustment made in Section 4.6 to the velocities of the Sc galaxies taken from Ford *et al.* (1971). The average of 101 differences is $\bar{\Delta}_{21-E} = -1 \pm 5$ ($\sigma = 48$) km s^{-1}, but for the 56 that are not based on estimates from optical rotation curves, the mean is $+4 \pm 8$ ($\sigma = 57$) km s^{-1}.

Table XIII summarizes the dependence of these differences on the type of the galaxy. In contrast with the results of most of the previous sections, the late type galaxies ($\tau \leqslant 3$) have small mean differences. The overall pattern found in Sections 4.1 to 4.5 persists. The Sc and Scd galaxies have more positive differences than earlier or later types, and the I9 galaxies have large negative differences. When those measured by the Burbidges or by Ford *et al.* (1971) and previously adjusted in Sections 4.5 and 4.6 are not included, the average of the remaining 12 differences for the Sc galaxies is increased to $+24 \pm 12$ ($\sigma = 43$) km s^{-1}.

TABLE XII

Comparison of 21-cm minus emission line velocities (E) with velocity

	$V_{21} < 200$	500	800	1200	2400	$V_{21} > 1200$	All
$\langle V_{21} - V_E \rangle$	+12	−23	+3	−5	+7	+9·5	−1
$\sigma N^{-1/2}$	13	10	10	9	11	11	5
σ	51	45	46	39	56	56	48
N	15	20	22	20	24	24	101

TABLE XIII

Comparison of 21-cm minus emission line velocities (E) with type

Type (τ)	$\tau \leqslant 3$	4	5	6	$7 \leqslant \tau \leqslant 9$	I9
$\langle V_{21} - V_E \rangle$	+1	−3	+16	−7	−11	−46
$\sigma N^{-1/2}$	12	11	8	9	12	17
σ	61	47	38	30	48	38
N	24	18	22	11	17	5

4.8 *Comparison of the adopted optical velocity (A) with V_{21}*

The variance (σ^2) of the majority of the available optical velocities is calculated in Sections 4.1 to 4.7. The adopted velocity has been found by weighting each source with σ^{-2} and weighting the Lick and Mt Wilson velocities in proportion to the number of spectra (up to a limit of four). The adopted optical velocity of column 3 in Table I, is calculated using the values of

σ = 81 Lick
= 113 Mt Wilson (Wa)
= 59 Mt Wilson (Wb)
= 75 de Vaucouleurs (1967)
= 38 the Burbidges (see references to Table I)
= 40 Ford *et al.* (1971)
= 57 Miscellaneous emission (refer references between 51 and 103 to Table I)

The Lick velocities of NGC 1058 and 1073 are known to be greatly in error, and were not used in the calculations for these galaxies. Corrections have been applied to (1) Lick velocities, following procedure of Section 4.1, (2) the Sb to Sd galaxies observed by the Burbidges, following Section 4.5, and (3) to the Sc galaxies of Ford *et al.* (1971) following Section 4.6.

For the 186 differences $\Delta_{21-A} = V_{21} - V_A$ (excluding only the large $\Delta = -535$ km s^{-1} of NGC 1532) the mean is -2 ± 6 ($\sigma = 80$) km s^{-1}. Table XIV shows the mean difference from successive groups of 20 when ordered by their 21 cm velocities. There is no significant deviation of the mean from zero in any velocity range for which comparisons exist, thus showing that the optical velocities have no residual scale-distortion. Fig. 2 shows the dependence of the differences Δ_{21-A} on V_{21}. A steady rise in the variance with increasing velocity is seen in Table XIV. A similar trend occurs in the Mt Wilson data (Sections 4.2 and 4.3) and in the data of A. and G. de Vaucouleurs (Section 4.4).

The type dependence of the differences is shown in Table XV. The large differences from NGC 1532, 2613, 4429 and 7013 have been rejected. All four relate to types later than Sbc. There is a smooth variation in the size of the average difference with type, which is most clearly shown by the means plotted in Fig. 3, but has been displayed in varying degrees by all sources of data with the exception of that measured by the Burbidges (Section 4.5).

As expected from the previous sections, the largest and most significant difference is that for the I9 galaxies, which at $\bar{\Delta}_{21-A} = -37{\cdot}2 \pm 8{\cdot}6$ ($\sigma = 32$) km s^{-1} is 4·5 times the standard error. Similarly, the

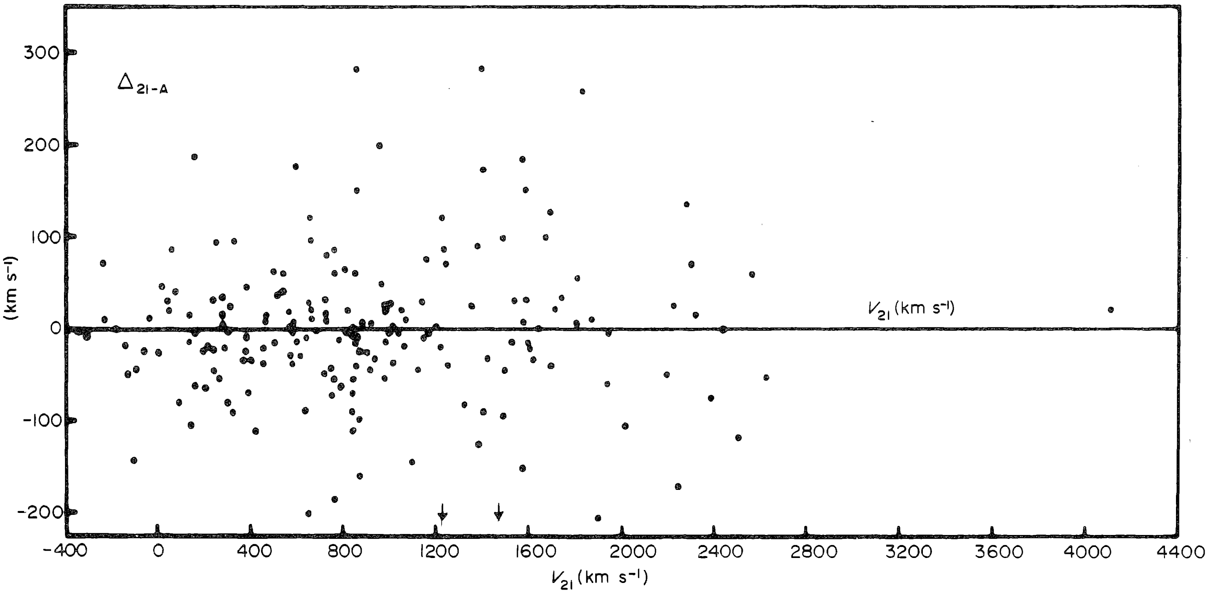

FIG. 2. *Distribution of the residuals* ($V_{21} - V_{Opt.\,Adopt.}$) *as a function of the* 21-*cm velocity* V_{21}.

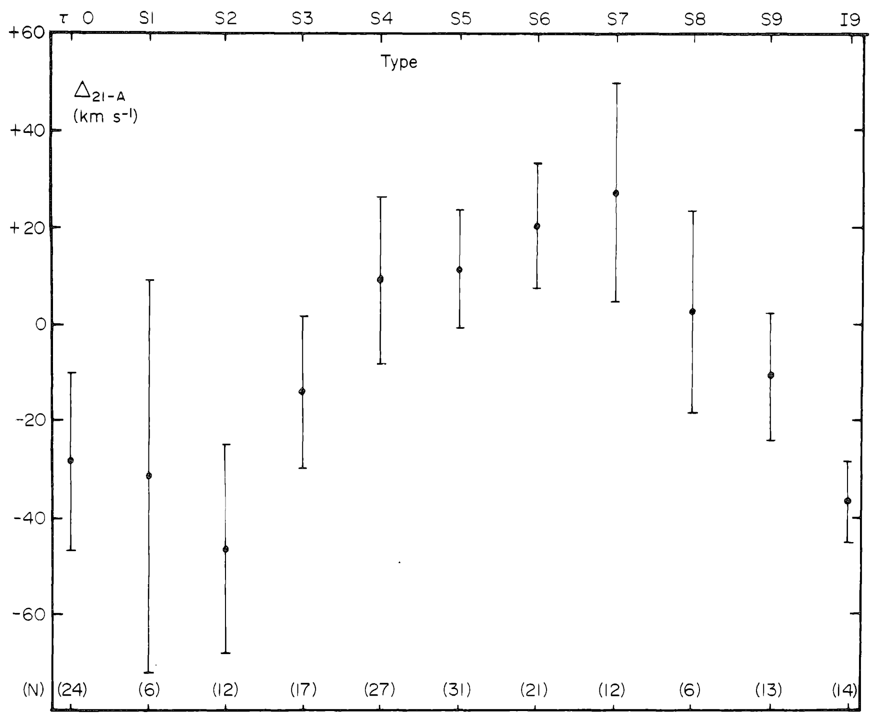

FIG. 3. *Systematic error* $\Delta = (V_{21} - V_{Opt.\,Adopt.})$ *as a function of galaxy type* (τ).

average of all the types with $\tau \leqslant 2$ is -34 ± 13 ($\sigma = 86$) km s^{-1}, which is about 2·5 times the standard error. If all the large differences noted above are included in this mean $\bar{\Delta}_{21-A}$ is equal to -31 ± 19 ($\sigma = 131$) km s^{-1}.

Even with these outliers excluded, the standard error of the velocities of the late-type galaxies is three times as large as that characterizing the I9 class, with a smooth transition between these extremes.

TABLE XIV

Comparison of 21-cm minus adopted optical velocity with velocity

$\bar{V}_{21}$	−64	+241	+458	+652	+807	+928	+1174	+1518	+1977
$\langle V_{21}-V_A \rangle$	−4·6	−10·9	−0·8	+8·2	−17·8	+4·6	−4·7	+12·1	−6·8
$\sigma N^{-1/2}$	11·6	15·0	11·0	17·4	17·2	21·0	14·8	28·9	16·5
σ	51	67	49	78	77	94	66	129	85
N	20	20	20	20	20	20	20	20	26

TABLE XV

Comparison of 21-cm minus adopted optical velocity with type

Type (τ)	$\tau < 1$	1, 2	3	4, 5	6, 7	8, 9	I9
$\langle V_{21}-V_A \rangle$	−28	−42	−14	+10	+23	−6	−37
$\sigma N^{-1/2}$	18	19	16	10	12	11	±9
σ	89	82	65	78	66	48	32
N	24	18	17	58	33	19	14

This trend occurs in every one of the comparisons investigated above, including those that depend entirely on the measurement of emission lines (Section 4.6).

Part of the trend shown in Table XV is due to the variation in the frequency of emission lines with type, and part probably reflects the increased incidence of complex phenomena in the nuclei of late-type galaxies.

The significance of the differences summarized in Table XV can be most simply tested by examining the signs of those in each class. If the null hypothesis is that all types draw their differences from a common population, in which positive and negative differences are equally probable, a nine-category test of the observed distribution of their signs gives $\chi_8^2 = 17{\cdot}54$, or a probability $p \approx 0{\cdot}03$. Thus even this simple test shows the necessity for applying corrections that are a function of type. In general, these are more accurate when applied to data from a single source. The corrections listed in Table XV are only appropriate to optical velocities that are a weighted average of all sources. Miscellaneous sources of emission line velocities for example, are best corrected with the type means of Table XIII.

5. EQUIVALENCE OF THE OPTICAL AND 21-CM VELOCITIES

Though differing considerably in their precision, it has so far been assumed that the 21-cm and the optical methods provide equally valid estimates of the systemic velocity. Evidence for this view comes from the large decrease in the variance of comparisons made between the results of the two techniques, whenever (1) more precise optical methods are used (2) the number of independent observers is increased. A close identity is found in the results obtained from the two techniques.

5.1 *Precision of the optical velocities*

(a) *Emission-line velocities.* The accuracy of the optical estimates of the systemic velocity is greatly increased when derived from emission lines (Humason *et al.* 1956). The average modulus of the differences from the Mt Wilson data is halved if emission lines have been used, and their standard errors decrease from 113 to 80 km s^{-1} for the Wa velocities and from 59 to 30 km s^{-1} for the Wb velocities, when the emission-line spectrum of the H II regions in the disk are observed. A similar result has been noticed in Section 4.4 for the data of A. & G. de Vaucouleurs (1967).

However, Gottesman & Davies (1970) provide some evidence for the existence of systematic errors in emission-line velocities. They compare the velocities inferred from their 21-cm maps of the area with the velocities of H II regions in M31 measured by Rubin & Ford (1970). The mean difference ($V_{21}-V_{H\alpha}$) is equal to $-7{\cdot}1 \pm 5{\cdot}3$ km s^{-1} from 21 regions on the H I ridge. More compelling evidence for the existence of systematic errors comes from the numerous instances in which the velocities measured from adjacent emission lines differ by as much as 100 km s^{-1}. Eilek *et al.* (1973) report such a difference between the results from the emission lines of the Balmer series in the nucleus of NGC 1068 and the other emission lines. Similarly, it is often found that the velocities estimated from N II λ 6584 and the S II lines at $\lambda\lambda$ 6717 and 6732 are very different from those estimated from Hα (e.g. see any Burbidge *et al.* paper cited in Table I).

(b) *The use of several spectra* decreases the influence of random errors due to instrumental effects on the night of observation, emulsion creep and the degree of exposure. The variance of the Mt Wilson data decreases significantly from σ = 95 km s^{-1} (N = 95) for velocities determined from a single spectrum, to σ = 80 km s^{-1} (N = 19) from two plates and a σ = 55 km s^{-1} for the four objects measured on more than two spectra. The low value of the variance achieved by the Burbidges (Section 4.5) is in part due to the use of several spectra.

(c) *The use of a higher dispersion* causes a commensurate decrease in the size of the differences. Thus in the Mt Wilson data, the variance (σ^2) decreases from σ = 113 km s^{-1} for the Wa data to σ = 59 km s^{-1} for the Wb velocities. The excellent results of Ford *et al.* (1971) were not only obtained by restricting their studies to emission lines, and taking care in the correction of the image-tube distortions, but also by using the large dispersion of 135 Å mm^{-1}.

(d) *The number of independent observers* has a marked effect on the variance of the adopted optical velocity. Table XVI summarizes the analysis of the differences Δ_{21-A} from this point of view, and has been calculated using the differences for all velocities numerically less than 250 km s^{-1}.

Predictably the variance decreases rapidly as the number of independent observers increases. Line 5 of Table XVI gives the number of spectra, which would cause it to decrease at the rate shown in the table. Thus the objects with five independent observers have adopted velocities drawn from the equivalent of 17 spectra, each with a standard error of 105 km s^{-1}.

All the devices for obtaining better optical velocities listed above, decrease the variance. This supports the view that the same quantity is being measured by both techniques.

5.2 *Distribution of the differences*

Considered as a set in isolation from the weights attached to the adopted optical velocities, the 182 differences with Δ_{21-A} numerically less than 250 km s^{-1}, are not normally distributed about zero. This result arises from the excess of small differences caused by the fact that some galaxies were observed more than twice. The actual distribution can be approximated by the superposition of five normal distributions, centred on zero and characterized by the variances and numbers listed in lines 3 and 4 of Table XVI. Fig. 4 shows this curve together with the histogram of the observed differences. Comparing these in 16 classes, only two of which have expected frequencies less than five, χ^2_{15} = 18·19. This has a probability of p = 0·244.

Alternatively, the adopted optical velocities can be adjusted using the type differences listed in Table XV. The average difference $\bar{\Delta}_{21-A}$ of the resulting velocities (V_A') is $+1{\cdot}6 \pm 5$ (σ = 68) km s^{-1}. Comparing these differences with the modified normal distribution calculated above in 16 classes, gives a χ^2_{15} = 13·55, or a probability p = 0·56.

Neither set of differences has a mean departing significantly from zero. This is strong evidence that there is no difference between the results of the two techniques, a conclusion supported by the absence of significant scale errors (Table XIV). Roberts (1972) and Gouguenheim (1969) obtained a similar result

TABLE XVI

Comparison of the 21-cm minus adopted optical velocity with the number of independent observers

Nom. observers	1	2	3	4	≥5	All
$\langle V_{21} - V_A \rangle$	−6·5	−9·7	+8·3	+2·4	−4·9	−4·5
$\sigma N^{-1/2}$	9·2	10·6	8·3	8·5	9·1	5·3
σ	83	75	41	34	26	71
N	83	50	25	16	8	182
No. equivalent spectra	1·6	2	6·6	9·5	17	2·2

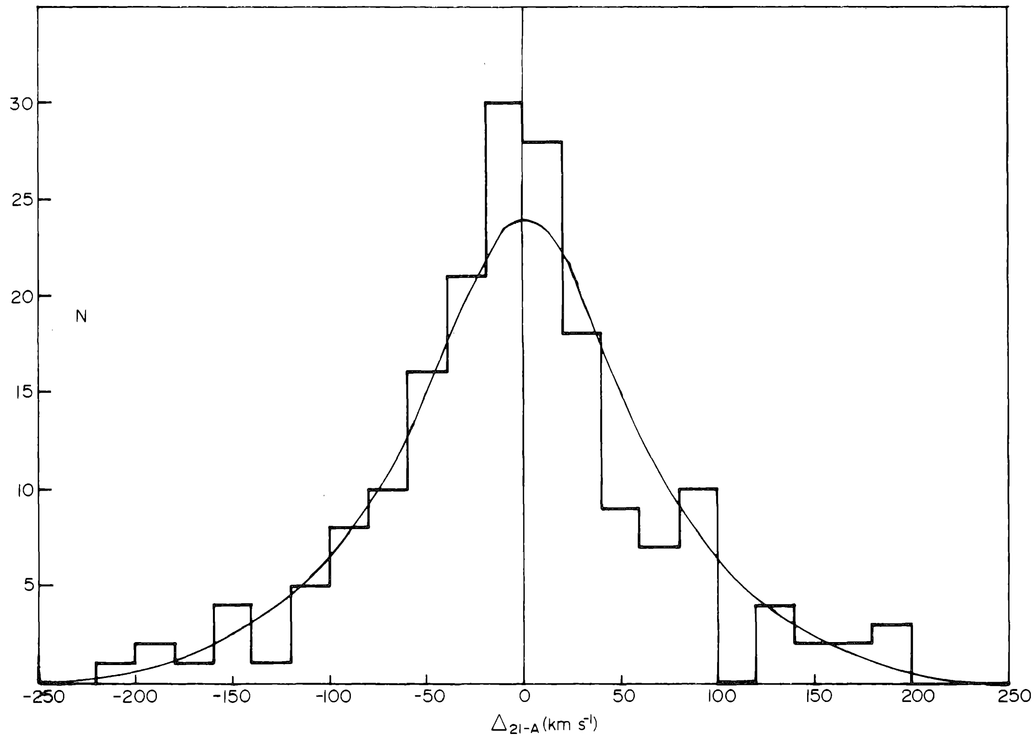

FIG. 4. *Distribution of the residuals expected from a normal distribution, after some allowance for the weight of the optical observations, is shown by the smooth curve. The histogram shows the actual distribution in bins of* 20 *km s*$^{-1}$.

from a regression of V (Optical) against V_{21}. When this is repeated with the present more extensive data, and allowance is made for simultaneous errors in both velocities, the 187 pairs give

$$V\,(\text{Optical}) = V_{21} \times (0{\cdot}9956 \pm 0{\cdot}0059) + (4{\cdot}2 \pm 6{\cdot}0)\ \text{km s}^{-1}.$$

The adopted optical velocities listed in Table I are used in the fit, with a weight in proportion to the square of the individual standard errors of each value of V_A. It can be seen that there is no systematic differences between V_A and V_{21} over the range from -400 to $+6600$ km s^{-1}.

6. ANOMALOUS REDSHIFTS

Section 4 has examined the optical velocities for the existence of systematic measuring errors, in situations where these are both plausible and are not independently suggested by any of the anomalous redshift hypotheses (*cf.* Arp 1970; Pecker, Roberts & Vigier 1973). The assembled set of differences Δ_{21-A} is suited to the investigation of correlations with size and absolute luminosity, where either a systematic error or a redshift anomaly might be predicted, as well as to a search for correlations with colour, inclination or other integral properties of a galaxy, which are unlikely in themselves to be a cause of systematic errors. Sections 6.1 to 6.5 investigate these cases.

If the mechanism for anomalous redshifts in ordinary galaxies is identical with that for quasars, it is *a priori* possible that the associated physics depend on extreme mass and energy densities. The nucleus is the only comparable extended region in most galaxies, and the optical velocity is in general a direct estimate of its redshift. By contrast, the systemic velocities obtained by 21-cm techniques are totally unbiased by the physical regime in the nucleus (Lewis 1971), being determined by the average properties of H I spread through the whole disk. A search for systematic differences between the optical nuclear velocity and the 21-cm systemic velocity should provide a sensitive indication of the existence of any radially dependent anomalies. The close identity found in Section 5.2 between the optical and 21-cm velocities of all measured objects is strong evidence against the existence of any significant radially-dependent effect in the majority of galaxies. This test limits the size of any anomaly, whether produced by established mechanisms such as the gravitational redshift and photon–photon scattering (*cf.* Pecker *et al.* 1973) or by new physics that is largely confined to the nucleus, to less than 5 km s^{-1}.

However, it may be possible to find criteria that will allow the anomalous cases to be identified. The luminosity-class assigned by van den Bergh (1960a) and the absolute luminosity are possibilities that are investigated below. But if the anomalous redshift hypothesis could generate blueshifts as often as redshifts, as with the Doppler mechanism and the hypothesis of Szekeres (1968), it will appear in the present comparison as an extra source of variance. Neither of the existing techniques is sufficiently advanced to allow a test of such hypotheses.

6.1 *Comparison of the differences* (Δ_{21-A}) *with luminosity-class*

Van den Bergh (1960a) found a correlation between the absolute luminosity or size of a galaxy and, the form of its outer spiral structure. He classified the spirals into luminosity-classes. The variation of the differences Δ_{21-A} with luminosity-class, should therefore test their dependence on size without assuming a distance.

Table I lists 97 galaxies with luminosity-classes assigned by van den Bergh (1960b). The distribution of the 75 differences for galaxies of type earlier than Sb is summarized in Table XVII. Those of later type, as might have been expected from the results of Table XV, have a mean of -37 ± 17 km s^{-1}, and are therefore excluded from Table XVII.

TABLE XVII

Comparison of the differences ($V_{21} - V_A$) *with luminosity-class*

Class	I	I–II	II	II–III	III	III–IV	IV	IV–V
$\bar{\Delta}_{21-A}$	+25	+7	0	−10	+14	+14	+9	−21
$\sigma N^{-1/2}$	15	37	15	18	17	22	28	17
σ	60	104	70	37	46	48	79	40
N	15	8	23	4	7	5	8	5

This set has no obvious pattern. The mean difference for the supergiant class I after applying the corrections of Table XV is $+6 \pm 13$ km s^{-1}, and that for the dwarf class IV–V is -3 ± 8 km s^{-1}. These are the only classes of Table XVII that depart by more than a standard error from zero. A test of the distribution of signs give $\chi_4^2 = 3{\cdot}99$ or $p = 0{\cdot}42$. This is not significant and the differences are independent of luminosity-class.

6.2 *Comparison of the differences* (Δ_{21-A}) *with absolute luminosity*

Absolute luminosity is also a function of size, but for this comparison the distances of the individual objects must be known. Here the luminosities have been calculated using distances taken in most instances from de Vaucouleurs (1965). They are based on photographic magnitudes from Holmberg (1958) when possible, or from values of $B(0)$ taken from the *Reference Catalogue of Bright Galaxies*, extrapolated to infinite radius and converted to photographic magnitudes by the relations of Roberts (1968). Corrections for absorption in the object itself and in the Galaxy have been applied, using Holmberg's formulae. The resulting absorption free luminosity is listed in column 13 of Table I. Table XVIII summarizes the results. There is no obvious correlation between the differences and the absolute luminosity and no evidence of significant dependence upon absolute size.

6.3 *Comparison of the differences* (Δ_{21-A}) *with* (B–V)

Section 4 showed a strong correlation between the size of the differences and the type of the galaxy.

TABLE XVIII

Comparison ($V_{21} - V_A$) with absolute luminosity

Range ($\times 10^{11} L_{\odot}$)		$\mathscr{L} < 0{\cdot}01$		0·05		0·1			$0{\cdot}5 < \mathscr{L}$
$\langle V_{21} - V_A \rangle$	−21		−13		+15		−13		+4
$\sigma N^{-1/2}$	26		8		14		8		17
σ	58		45		74		78		75
N	5		30		30		87		19

This trend should also appear as a correlation with colour. Table XIX verifies this and summarizes the results of this comparison between the differences and the $(B-V)$ (O) colours listed in column 19 of the *Reference Catalogue of Bright Galaxies*.

6.4 *Comparison of the differences* ($V_{21} - V_A{}'$) *with inclination* (i)

If photon–photon scattering occurs following Pecker *et al.* (1973), it should be most easily found in galaxies with large inclinations. Table XX summarizes the results that occur when the optical velocities $V_A{}'$ (corrected for the mean type differences of Table XV) are used. Testing the distribution of the signs of the differences ($V_{21} - V_A{}'$) over these classes, gives $\chi_4{}^2 = 1{\cdot}10$ or a probability of random occurrence $p = 0{\cdot}89$. These data place a limit of $15{\cdot}7 \pm 14{\cdot}4$ km s^{-1} on the possible size of Pecker's effect, since for sin i less than 0·8, the mean difference is $+9{\cdot}3 \pm 7{\cdot}2$ km s^{-1} while for sin i greater than 0·8, it is $-6{\cdot}5 \pm 7{\cdot}2$ km s^{-1}.

TABLE XIX

Comparison ($V_{21} - V_A$) with $(B-V)$ (O)

Range		<0·4		0·5		0·6		0·7		0·8		0·9		1·0
$\langle V_{21} - V_A \rangle$	−27		−13		−4		+20		0		−10		−32	
$\sigma N^{-1/2}$	12		14		11		11		14		20		21	
σ	31		54		66		61		65		103		77	
N	7		15		33		32		23		28		14	

TABLE XX

Comparison of the differences ($V_{21} - V_A{}'$) with sin i

Range (sin i)		<0·2		0·4		0·6		0·8		0·94		1·0
$\langle V_{21} - V_A{}' \rangle$	+41		+0		+7		+8		−7		−6	
$\sigma N^{-1/2}$	39		14		11		12		10		11	
σ	95		41		61		73		70		66	
N	6		8		34		40		54		35	

When this test is made with data to which the type difference of Table XV and the velocity adjustment of Section 4.5 have not been applied, there is a significant deviation from a normal distribution among the signs of the differences, with $\chi_4^2 = 9{\cdot}44$, or $p \simeq 0{\cdot}05$. Further, the size of the mean difference then approximates

$$\Delta_{21-A} \simeq 28\text{–}44 \sin i.$$

This false result emphasizes the need for caution when the systemic velocities of galaxies are used to test any of the anomalous redshift hypotheses.

6.5 *Comparison of the differences* ($V_{21} - V_A{}'$) *in barred spirals*

Freeman (1965) predicted that gas would flow out along the bars of spiral galaxies. In the nuclear regions, this flow might have added an extra component to the overall variance of the comparisons.

Table XXI disposes of this suggestion and summarizes the differences ($V_{21} - V_A'$) for the barred, mixed and spiral systems, the classification being taken from the *Reference Catalogue of Bright Galaxies*. There is no trend which depends on this characterization of the structure, and the results from the barred galaxies show both the smallest mean and the lowest variance. The others show surprisingly large departures of their means from zero.

TABLE XXI

Comparison of the differences ($V_{21} - V_A'$) *with barred structure*

Structure	SA	SAB	SB
$\langle V_{21} - V_A' \rangle$	−24	+24	−5
$\sigma N^{-1/2}$	9	11	7
σ	65	78	56
N	47	52	58

CONCLUSION

The comparison of 21-cm and optical velocities from a variety of sources, has shown a well-defined pattern among the differences, as a function of type in every case. This is explicable in terms of systematic measuring errors of both emission and absorption lines, but has no obvious causal relation with any of the current hypotheses which predict an anomalous redshift. These corrections are sufficiently large to require adjustment whenever an accuracy of more than 10 km s^{-1} is needed. Tables IV, VI, VIII–XI, XIII and XV give the corrections for most of the usual sources of optical velocities.

The most significant of the systematic type corrections is for the I9 galaxies, which have velocities determined solely from emission lines. Significant systematic errors occur among the velocities of Sc galaxies measured by Ford *et al.* (1971) (Section 4.6) and among the spiral galaxies measured by the Burbidges (Section 4.5).

A velocity scale error (Robert's effect) occurs among the Lick velocities (Section 4.1), but no significant scale errors are found in any other source. Statistically, the results of 21-cm and optical techniques for measuring the systemic velocity are entirely equivalent, though of rather different precision. The distribution of the residuals is consistent with that expected from a normal distribution centred on zero, after allowance is made for the weights of the adopted optical velocities. This is strong evidence against the existence of any radially dependent anomalous redshifting mechanism in the majority of ordinary galaxies.

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