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SPIN STATISTICS IN BINARY GALAXIES: IMPLICATIONS FOR FORMATION AND EVOLUTION

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ABSTRACT

New data are presented defining unambiguously the spin vectors of spiral galaxies in binaries and small groups. A strong anticorrelation is found, whereby the spins of companion galaxies avoid being parallel and favor being antiparallel. This indicates that the sample contains predominantly true, physically associated pairs. The anticorrelation is stronger for pairs with low indicative mass-to-light ratio: this is taken as additional evidence for the reality of the effect.

Clues to the origin of spin in galaxies are also direct clues to the mechanism of galaxy formation. The evidence so far is clearly against a simple picture where primeval turbulence is the source of spin. But the data are consistent with, and suggestive of, the hypothesis that spins were acquired via tidal torquing; a detailed discussion is given, treating separately the possibility that the effect is primordial and the possibility that it is a result of evolution. Enough data are now becoming available that specific calculations are required to sharpen the predictions for the statistical behavior of spins, especially in binaries.

Subject headings: galaxies: clustering — galaxies: formation — galaxies: internal motions

I. INTRODUCTION

An essential ingredient of any coherent model for galaxy formation is the origin of internal, or spin, angular momentum in the disk component of galaxies. Present epoch data on spin vectors can be used to shed light on conditions and processes at the time of galaxy formation. Pairs and small groups of galaxies are an attractive setting for testing formation theories because of the relative simplicity and abundance of these systems.

This has been recognized for some time, and several different approaches to the problem have been tried (Page 1975; Arigo *et al.* 1978; Gott and Thuan 1978; Noerdlinger 1979; Sharp, Lin, and White 1979). But very little progress has been achieved because only the projected (apparent) images of the galaxies were used, leaving unresolved the ambiguity in the orientation of their spin vectors. Gott and Thuan did resolve this ambiguity, but they studied only the Local Group.

This paper studies a set of binaries and small groups for which kinematic and morphological data are combined to yield a well-defined vector orientation for the spin in each galaxy. The quantity brought under scrutiny is the *physical* angle β formed by the two spin vectors.

Even with an ideal data set, it is clearly impossible to argue back directly from present epoch distributions to primordial conditions; one needs unique and distinguishable predictions associated with various formation theories, to be checked against the observations. These predictions are in somewhat short supply compared to the data now becoming available. In fact, spin acquisition mechanisms may have to be explored in more detail in view of one preliminary finding in this paper, namely that the spin vectors in a pair avoid small angles ($\beta < 60°$) of separation between them.

II. PREVIOUS WORK

a) *Theory*

The two dominant theories for the origin of angular momentum in disk galaxies in the field are the primordial turbulence theory (von Weizsäcker 1951; Gamow 1952; Ozernoy 1974) and the tidal torquing theory (Hoyle 1949; Peebles 1969).

For galaxies in binaries or small groups, the two theories make distinct predictions, provided of course that the group formed as such and not by capture. If, however, binaries are primarily the result of capture, then one expects the spins to have been oriented at random in space at the time the binaries formed, and to have undergone *little* evolution, since capture would have gone on well beyond the epoch of galaxy formation.

In the primordial turbulence picture, the binary or group is thought of as the remnant of a single primordial eddy, and all spins are then expected to be parallel among themselves and to the orbital angular momentum (Ozernoy 1974); this is so already at the level of "primordial conditions," when protogalaxies have just separated. This correlation ought to be preserved up to the present epoch, except for "evolutionary" processes in the recent past.

In the tidal interaction picture, the primordial conditions are arbitrary, and the spin is acquired during the critical phase of the protogalaxies' collapse; whatever correlation between spins is predicted by this theory should be dominant just after the disk galaxies have formed, at the level of the "starting conditions." These conditions will be acted on subsequently by the evolutionary processes. In the context of the hierarchical clustering theory (White and Rees 1978), tidal torques are responsible for spin deposited in the halos which then become the formation sites of disk galaxies. The disk and its halo have parallel spins (Kashlinsky 1982; Jones and Wyse 1983), and a binary system results from neighboring halos, so the discussion (in terms of protogalaxies) in the rest of this paper is exactly applicable to the hierarchical clustering picture.

Gott and Thuan (1978) have suggested that if the spins of the two galaxies in a binary were generated by mutual tidal interactions, and if the protogalaxies collapsed simultaneously *and* instantaneously (compared to the orbital time scale), then the spins would both be perpendicular to the line joining the two galaxies at collapse; this would lead to the spins in a binary being oriented at random *in a plane*, thus defining a set of "starting conditions" quite distinct from those mentioned above.

It has also been suggested that shocks propagating through the pregalactic medium could generate vorticity in an initially irrotational velocity field; the vorticity is derived either from the suppression of the velocity component normal to the shock wave (Doroshkevich 1973), or from the curvature of the shock front (Binney 1974). This mechanism is evoked within the framework of the "pancake theory" of galaxy formation, where the largest structures form first as a result of an adiabatic spectrum of primordial fluctuations (Sunyaev and Zel'dovich 1972; Doroshkevich *et al.* 1980; Jones, Palmer, and Wyse 1981).

Several processes could presumably affect the spin distribution defined by the "starting conditions": The first three mentioned below (all involving external disruption of the binary system) are unimportant compared to merging within the binary, discussed in more detail.

Further *tidal torquing* on the disks is negligible in magnitude, and the disk would be severely disrupted before the spin vector could be reoriented appreciably (Farouki and Shapiro 1981; Thompson 1976).

Whereas spin remains basically fixed, the *orbit* may be substantially altered by distant encounters and soft collisions with other field galaxies.

Member exchange.—"Spontaneous" breakup of binaries and formation by capture must be quite rare events in the recent past; a pair exchanging one of its galaxies with the field, or a galaxy escaping from a small group (i.e., triplet becomes binary) could be more common, but would most often lead to a merger because the remaining galaxies end up in tighter orbits.

Mergers in fact are probably the dominant evolutionary process, since they are known to occur on short time scales (Toomre 1977), and are a strong function of orbital parameters and spin orientation. When a pair of spirals merge to form an elliptical, the β distribution is altered by the loss of that binary.

Most of the results on disk galaxy mergers come from numerical simulations: White (1978, 1979) was first to show the dependence of merging speed on relative orientation of spin (S_1, S_2) and orbit (L). Farouki and Shapiro (1982) explored in some detail that dependence, and came to the following conclusions:

1. The most important factor determining the time scale (or possibility) of the merger, at constant orbital parameters, is the amount of overlap or interpenetration of the two galaxies at closest approach.
2. When that is held constant, the most important factor is

$$\lambda_j = \frac{|\boldsymbol{L} + \boldsymbol{S}_1 + \boldsymbol{S}_2|}{|\boldsymbol{S}|} ;$$

the relative orientation of spins is not significant by itself, because the main disruptive mechanism is a resonance between spin and orbital motions.

b) Observations

Although ensembles of binary systems have been studied by many authors for dynamical and physical properties (e.g., Holmberg 1958; Noerdlinger 1975; Turner 1976; Peterson 1979; White *et al.* 1983), few authors have addressed the question of relative orientation. Noerdlinger (1979) found only a "weak tendency of the sense of spiraling to match, for the two images to be parallel to each other, and for the most elongated images to point at each other." This may sound as if it implies a tendency for spins to be parallel, but if the first two Noerdlinger "tendencies" are completely independent in a statistical sense, parallelism of spins is *not* required.

Sharp, Lin, and White (1979) tested directly for the distribution of spin vectors predicted by Gott and Thuan (1978) within the tidal torquing theory; they found their data incompatible with the expected distribution at the 0.998 level, but consistent with no correlations between the spins of the member galaxies in a pair.

Both of those studies used apparent orientations, and resolved neither of the two projection ambiguities (rotation sense and inclination sign). As a result, the angle formed by the two spins could have any one of four possible values, all of which are compatible with the observed (projected) images.

Another relevant set of results concerns a positive correlation between the physical properties of the two members in a pair:

Type (S or E) (Noerdlinger 1979) is so tightly correlated that mixed type binaries seem to be mostly optical pairs.

Integrated color index and surface brightness (Holmberg 1958) imply similar stellar content and mass distributions.

The similarity between total mass-to-light ratios points in the same direction (Dickel and Rood 1979; Helou, Salpeter, and Terzian 1982, hereafter Paper I).

III. THE DATA

The data base is a set of spiral galaxies, occurring in pairs and small groups, for each of which the orientation of the spin vector is completely determined. To determine this orientation from the projected image of the galaxy, 2 bits of information are needed to resolve the fourfold ambiguity. These could be any two of the following three bits: (1) sense of rotation of major axis (+ or − on minor axis); (2) which side of minor axis is closer to observer; (3) sense of rotation of disk projected on sky (clockwise or reverse). Bit 1 must be obtained from detailed spectral line observations of the galaxy, either at 21 cm or in the optical. Bit 2 can be determined from features of obscuration by dust on the optical image. Bit 3 can be derived from a well traced spiral pattern, by assuming the arms to trail. See Paper I for more detail, or Helou *et al.* (1981).

From the orientation of the spins the angle between them, $\beta = (\boldsymbol{S}_1, \boldsymbol{S}_2)$, is determined. This paper gives β for 31 pairs of galaxies; 22 of them are relatively isolated binaries, and nine are in small groups. This is not a complete sample, but a collection of available data that constitute a homogeneous set, in the sense that all pairs in the set do satisfy the following selection criteria: (1) Δ mag < 2.5; (2) separation < 6 × diameter of larger galaxy; (3) $\delta V \lesssim 250$ km s^{-1}.[1]

Initially, the data set consisted of cases described in Paper I (Arecibo data); but it has been considerably expanded with the largest addition coming from Westerbork observations reported in G. A. van Moorsel's thesis (1982). Table 1 lists all the galaxies involved and their individual parameters; Table 2 lists the pairs considered and their parameters.

Column (1) of Table 1 gives the name of the galaxy, as an NGC number or an IC number if preceeded by I. Column (2)

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[1] The pair NGC 5560/5577 with $\delta V = 252$ km s^{-1} is included because the uncertainty on δV is definitely larger than 2 km s^{-1}.

TABLE 1

THE GALAXIES STUDIED

Galaxy (NGC) (1)	Type (Rev. Hubble) (2)	Size (Holmberg) (3)	B_T (RC2) (4)	V_0 (km s^{-1}) (5)	Spin P.A. (degrees) (6)	Spin Inclination (degrees) (7)	Sources (8)
672	SB(s)cd	$11'.3 \times 4'.1$	11.35	428	155	111	KS, H
I1727	SB(s)m	10.2 × 3.4	12.10	343	−120	116	KS, H
797	SAB(s)a^{a}	3.2 × 2.5^{b}	13.0^{c}	5666	155	157	vM
801	Sc^{d}	4.7 × 1.4^{b}	13.3^{c}	5762	40	57	vM
1134		3.8 × 1.7^{b}	13.0^{c}	3684	58	111	SHST
I267	(R′)SB(s)b	3.4 × 2.4	13.5^{c}	3577	105	140	SHST
2336	SAB(r)bc	10.4 × 6.1	11.15	2199	88	57	vM
I467	SAB(s)c:	5.0 × 2.4^{b}	12.7^{c}	2040	170	113	vM
2805	SAB(rs)d	8.0 × 6.0	11.78	1726	35	38	R
2820	SB(s)cP, sp	4.7 × 1.4	13.29	1692	149	90	R
3003	Sbc?	7.5 × 3.3	12.15	1481	−11	77	RG
3021	SA(rs)bc:	2.6 × 1.7^{b}	13.0^{c}	1540	−160	127	SHST
3501	Sc^{d}	5.3 × 1.1^{b}	13.46	1134	−63	90	HST
3507	SB(s)b	5.0 × 4.1^{b}	11.44	980	−160	148	HST
3504	(R)SAB(s)ab	4.0 × 3.8^{b}	11.8	1543	65	144	vM
3512	SAB(rs)c	2.8 × 2.6^{b}	13.0	1376	−130	25	vM
3623	SAB(rs)a	11.9 × 4.5	10.17	813	−96	74	H
3627	SAB(s)b	13.8 × 6.5	9.70	736	83	62	H
3628	SbP, sp	18. × 4.3	10.15	849	−166	98	H
3681	SAB(r)bc	4.0 × 3.9^{b}	12.40	1237	−149	162	HST
3684	SA(rs)bc	5.0 × 3.6^{b}	12.3	1158	40	135	HST
3686	SB(rs)bc	4.6 × 3.7^{b}	12.0	1156	105	38	HST
3691	SBb?	2.0 × 1.7^{b}	13.4^{c}	1067	−75	140	HST
4016	SBc–Irr^{d}	2.5 × 1.5^{b}	14.3^{c}	3432	85	123	vM
4017	SAB(s)bc	2.9 × 0.7^{b}	13.3^{c}	3452	36	33	vM
4085	SAB(s)c:?	3.7 × 1.5	12.91	752	−12	74	vM
4088	SAB(rs)bc	6.5 × 2.8	11.10	760	133	67	vM
4298	SA(rs)c	5.2 × 4.4	12.07	1136	50	54	HST
4302	Sc:sp	7.7 × 2.5	12.53	1150	−92	90	HST
4411A	SB(rs)dm	3.3 × 3.3	13.55	1282	?	25	H
4411B	SAB(rs)dm	3.6 × 3.6	13.02	1271		180	H
4527	SAB(s)bc	7.5 × 3.5	11.30	1736	157	72	HST
4536	SAB(rs)bc	8.9 × 4.4	10.99	1806	40	116	HST
4567	SA(rs)bc	5.4 × 3.7	12.08	2277	175	135	HST
4568	SA(rs)bc	6.8 × 3.5	11.67	2255	113	116	HST
4618	SB(rs)m	6.0 × 5.6	11.27	537	−65	150	vM
4625	SAB(rs)mP	3.5 × 2.5	12.90	611	45	32	vM
4631	SB(s)d, sp	19. × 4.4	9.75	610	176	95	WSG, KS
4656	SB(s)mP	14.5 × 4.1	10.75	650	−57	98	WSG, KS
5005	SAB(rs)bc	8.1 × 4.7	10.64	945	155	62	HST
5033	SA(s)c	12.3 × 5.8	10.60	876	80	59	HST
5289	(R)SABab:sp	3.2 × 1.2^{b}	13.6^{c}	2525	10	73	vM
5290	Sb:sp	5.2 × 1.7^{b}	12.9^{c}	2571	−175	103	vM
5426	SA(s)cP	4.0 × 2.2	12.75	2516	−90	122	B
5427	SA(s)cP	3.9 × 3.8	12.05	2703	158	158	B
5560	SB(s)bP	5.6 × 1.7^{b}	13.2	1741	25	97	HST
5566	SB(r)ab	8.2 × 3.6^{b}	11.35	1492	−55	109	HST
5569	SAB(rs)cd:	3.1 × 2.7^{b}	14.0^{c}	1772	90	22	HST
5577	SA(rs)bc:	4.7 × 1.7^{b}	13.1^{c}	1490	146	74	HST
5713	SAB(rs)bcP	4.6 × 3.7^{b}	12.00	1900	−80	152	SHST
5719	SAB(s)abP	4.8 × 2.2^{b}	13.1^{c}	1737	17	69	SHST
5740	SAB(rs)b	4.8 × 2.6	12.60	1575	70	58	SHST
5746	SAB(rs)b?sp	9.0 × 2.4	11.40	1724	80	105	RG
5905	SB(r)b	6.3 × 4.9^{b}	12.1^{c}	3390	−135	128	vM
5908	SA(s)b:sp	4.5 × 2.2^{b}	13.2^{c}	3310	64	70	vM

[a] This revised Hubble type comes from the UGC.

[b] These are "deduced" Holmberg diameters, obtained from the UGC and RC2 diameters as explained in Paper I.

[c] This is a "deduced B_T magnitude," obtained from the Zwicky magnitude in UGC using the prescription in Auman *et al.* (1982).

[d] This Hubble type comes from the UGC.

SOURCES.—B, Blackman 1982. H, Haynes 1981. HST, Helou, Salpeter, and Terzian 1982. KS, Krumm and Salpeter 1979. R, Reakes 1979. RG, Riccardo Giovanelli, private communication 1983. SHST, Schneider *et al.* 1984. vM, van Moorsel 1982. WSG, Weliachew, Sancisi, and Guélin 1978.

TABLE 2

GALAXY PAIRS

PAIR NGC (1)	NGC (2)	V_{LG} (km s^{-1}) (3)	δR (arcmin) (4)	δV (km s^{-1}) (5)	β (degrees) (6)	cos β (7)	cos ψ_1 (8)	cos ψ_2 (9)
A. Pairs in Isolated Binaries								
672	I1727	620	8.0	85	77	0.230	0.899	−0.358
797	801	5867	9.1	96	130	−0.640	0.602	0.469
1134	I267	3759	10.3	107	47	0.684	0.946	0.883
2236	I467	2054	20.2	41	96	−0.105	0.914	−0.276
2805	2820	1850	13.2	34	105	−0.250	0.174	−0.970
3003	3021	1492	30.5	59	143	−0.802	−0.998	0.819
3501	3507	951	12.7	153	94	−0.065	−0.292	−0.914
3504	3512	1405	12.0	167	167	−0.973	0.105	−0.358
4016	4017	3391	5.8	20	99	−0.157	−0.839	−0.961
4085	4088	827	11.5	8	128	−0.617	...	...
4298	4302	1033	2.4	14	130	−0.638	−0.743	0.174
4411A	4411B	1141	4.6	11	155	−0.906	...	...
4527	4536	1609	28.3	69	122	−0.524	−0.242	−0.755
4567	4568	2145	1.3	22	53	0.608	−0.259	0.731
4618	4625	606	8.3	74	146	−0.825	0.616	−0.951
4631	4656	617	32.1	41	126	−0.582	0.682	0.174
5005	5033	930	41.2	69	64	0.438	−0.375	0.799
5289	5290	2605	12.7	46	174	−0.994	0.017	0.070
5426	5427	2456	2.3	187	68	0.372	−0.993	0.485
5713	5719	1713	11.4	163	112	−0.370	0.035	0.988
5740	5746	1556	18.3	149	48	0.670	0.809	0.695
5905	5908	3505	13.1	80	156	−0.911	−0.970	0.829
B. Pairs in Small Groups								
3623	3627	670	20.2	77	136	−0.719	...	...
3627	3628	670	35.7	116	112	−0.379	...	...
3623	3628	670	35.7	39	73	0.287	...	...
3681	3684	1074	14.1	78	63	0.457	−0.208	0.052
3681	3686	1074	28.0	79	143	−0.802	0.052	−0.883
3684	3686	1074	14.0	1	112	−0.373	...	...
5560	5566	1472	5.3	249	78	0.203	0.951	−0.139
5560	5577	1472	37.5	252	122	−0.525	...	...
5566	5577	1472	32.6	3	160	−0.938	...	...

gives the revised Hubble type as in RC2 (de Vaucouleurs, de Vaucouleurs, and Corwin 1976) whenever available, or a Hubble type as in UGC (Nilson 1973), as indicated in the notes. Column (3) gives major and minor diameters in the Holmberg system. Column (4) gives the total blue magnitude as defined in RC2. Column (5) gives systemic heliocentric redshift; most of these redshifts are from H I 21 cm data, and have a mean error on the order of 10 km s^{-1}. Column (6) gives the position angle of the spin vector, measured east of north. Column (7) gives the inclination of the spin vector to the line of sight, taken to be 0° if the spin points at the observer, and 180° if it points away. Column (8) gives the source of the spectral line data allowing a determination of the spin P.A.

Table 2 is divided in two sections, the first of which is for "isolated pairs," i.e., pairs where neither of the galaxies is linked to a third member via the pair selection criteria enumerated above. The second section is for pairs which are drawn from a small group; all three groups are dominated by three members, which combine in three pairs all of which are included in Table 2B. Columns (1) and (2) give the names of the two galaxies making up the pair. Column (3) gives the mean redshift of the pair (or the group in Table 2B), corrected for the motion of the Local Group as in the RSA (Sandage and Tammann 1981). Column (4) gives the separation on the sky of the two galaxies in arcmin. Column (5) gives the difference between the systemic redshifts of the two galaxies in the pair. Columns (6) and (7) give the angle $\beta = (\boldsymbol{S}_1, \boldsymbol{S}_2)$ between the two spin vectors in the pair, and the cosine of that angle. Columns (8) and (9) give the observable portion of the relative orientation of spin vector and orbital angular momentum vector. For each member of a pair, $\psi = |\mathrm{OPA} - \mathrm{SPA}|$ is given, where SPA is the spin vector position angle (P.A.) as in column (6) of Table 1, and OPA is an orbital P.A. defined as follows: the direction normal to the line joining the two galaxies is oriented according to which of the galaxies is blueshifted with respect to the other (using the right-hand rule again); OPA is the position angle of that orientation on the sky, defined in the same system as SPA.

As indicated in column (8) of Table 1, a variety of sources were used for the sense of rotation of the program galaxies. In contrast, the optical image information came exclusively from the Palomar Observatory Sky Survey (POSS) Plates. Other published plates were consulted whenever available, and they always agreed with the POSS results.

For the sake of uniformity, all spin position angles (Col. [6] of Table 1) are based on Uppsala General Catalog (UGC) position angles if the latter are available; otherwise, they are based on a kinematic determination of the axis from the redshift map. The mean error on the UGC determination of the P.A. is probably about 10° (Arigo *et al.* 1978; MacGillivray *et*

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al. 1982), but it is clearly a function of axial ratio: the measurement is more uncertain for nearly face-on objects.

Similarly, all inclinations (col. [5] of Table 1) are based on R_{25}, the axial ratio as given in RC2, using the Holmberg formula $\cos^2 i = (R_{25}{}^{-2} - 0.04)/0.96$. RC2 lists mean errors on log R_{25} mostly in the range 0.02–0.05; this would correspond to about 3°–7° at an inclination of 45°.

This uncertainty on β depends in a complicated fashion on the inclination of the two galaxies. The mean errors mentioned above propagate (roughly) to 15° or less on β.

IV. ANALYSIS

The data analysis centers on the angle β between spin vectors, which is a relatively well determined *physical* quantity. Table 3 shows the distribution of $\cos \beta$, binned into four equal intervals for each of three intervals in δV: entries from Tables 2A and 2B are shown independently, separated by the plus sign.

Figure 1*a* shows the distribution of $\cos \beta$ for the sample. In the absence of correlation between the two spins, one expects $f(\cos \beta) d \cos \beta = \text{constant} \times d \cos \beta$. The data disagree with this possibility with a significance of about 99% (see the first line of Table 4).

Figure 1*b* shows the distribution of β. Uniformity in β is not the simplest null hypothesis, but it has been proposed as a possible result of tidal torques (of § II*a* above). The data, however, disagree with this possibility too (see the second row of Table 4).

Table 4 tests each hypothesis entered in column (1), using the technique described in column (2), on four different samples; the results are entered in column (3), for the subsample of pairs with the more restrictive selection criterion $\delta V < 100$ km s^{-1} (the first entry is for all pairs, both isolated and in groups; the second entry, in parentheses, is for isolated pairs only); and in column (4), for the full sample $\delta V \leq 250$ km s^{-1} (the two entries refer again to all pairs and isolated pairs only [in parentheses]).

The tests above are only against the uniformity of the distribution as a whole. But in fact, the salient feature of the distribution in Figure 1 is the asymmetry about $\beta = 90°$. This stands in direct conflict with the simplest *a priori* expectation that β and $180° - \beta$ are equally probable. Indeed, if the vector orientations were not completely resolved, β would have four possible values for each pair of galaxies, namely two pairs of supplementary angles. If all these values are considered equally probable, one could generate a "degraded" distribution, shown in Figure 1 as the broken line. All previous work discussed in § II*b* concentrated on this "degraded" distribution, and restricted itself to $0° < \beta < 90°$ because of the obvious symmetry. The asymmetry is therefore a new result which could not have been detected in previous studies.

The degraded distribution for the data set is quite uniform in $\cos \beta$, indicating that no geometric preselection has taken place, and agreeing with the result by Sharp, Lin, and White (1979). A slight dip near $\cos \beta = 0$ was already suggested by Noerdlinger's (1979) observation that the two images tend to be parallel (cf. § II*b*).

In the absence of geometric preselection, it is extremely difficult to produce this particular asymmetry in $\cos \beta$ with any selection effects. Furthermore, errors and uncertainties on the spin orientations would tend to *fill up* any holes in the distribution of β rather than create them. It is also clear that if the selection criteria allow too many line-of-sight pairs into the sample, that will only *dilute* any true asymmetries: for pairs of vectors selected at random will follow the null hypothesis of $f(\cos \beta) d \cos \beta = \text{constant} \times d \cos \beta$. In fact, one does observe a steeper asymmetry in $f(\cos \beta)$ if the δV selection criterion is tightened: this is illustrated in Table 3, and more clearly in Table 4, where the probabilities in column (3) (lines 3, 4, 5) are smaller than those in column (4).

The imbalance between $\cos \beta < 0$ and $\cos \beta > 0$ for the whole sample is 22 to 9 (or 16 to 6 for the isolated pairs). Figure 1*a* indicates that the imbalance is restricted to the intervals $|\cos \beta| > 0.5$, where it is 15 to 3 (or 11 to 3). For the null hypothesis of symmetry, Table 4 gives the probability of this configuration as less than 0.8% (or 6%). On Figure 1*b*, the imbalance between $\beta < 45°$ and $\beta > 135°$ is 9 to 0 (or 6 to 0). The probability of this against the hypothesis of symmetry is about 0.4% (or 3%).

TABLE 3

DEPENDENCE OF COS β ON δV

δV Range	$-1 < \cos \beta < -0.5$	$-0.5 < \cos \beta < 0$	$0 < \cos \beta < 0.5$	$0.5 < \cos \beta < 1$
$0 < \delta V \leq 50$	5 + 1	3 + 1	0 + 1	1 + 0
$50 < \delta V \leq 100$	5 + 2	0 + 0	2 + 1	0 + 0
$100 < \delta V \leq 250$	1 + 1	2 + 1	1 + 1	2 + 0

TABLE 4

STATISTICAL TESTS

		PROBABILITY OF HYPOTHESIS (%)	
HYPOTHESIS TESTED (1)	TECHNIQUE (2)	Only $\delta V < 100$ km s^{-1} $n = 22$ (16) (3)	All: $\delta V \lesssim 250$ km s^{-1} $n = 31$ (22) (4)
$f(\cos \beta)$ uniform	χ^2 test, 4 bins	0.2 (0.6)	2 (5)
$f(\beta)$ uniform	χ^2 test; 4 bins	3 (4)	0.8 (3)
$\langle \cos \beta \rangle = 0$	t test, 2 sided	0.1 (0.4)	0.5 (3)
$\langle \beta \rangle = 90°$	t test, 2 sided	0.1 (0.4)	0.3 (2)
Symmetry for $\lvert \cos \beta \rvert > 0.5$	binomial, 2 sided	0.2 (1)	0.8 (6)
Symmetry for $\lvert \beta - 90° \rvert > 45°$	binomial, 2 sided	0.8 (6)	0.4 (3)

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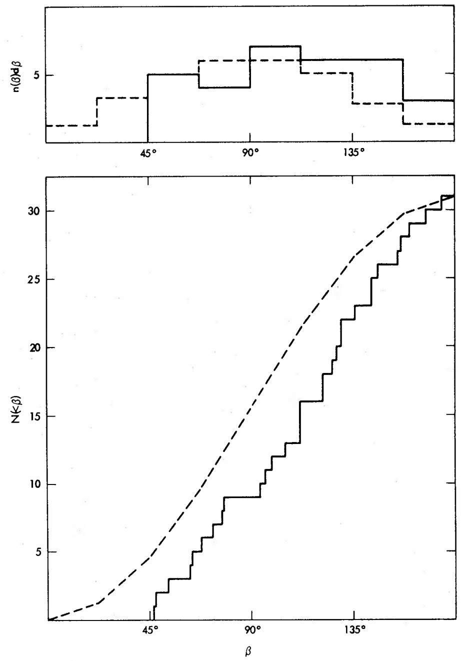

FIG. 1*a*

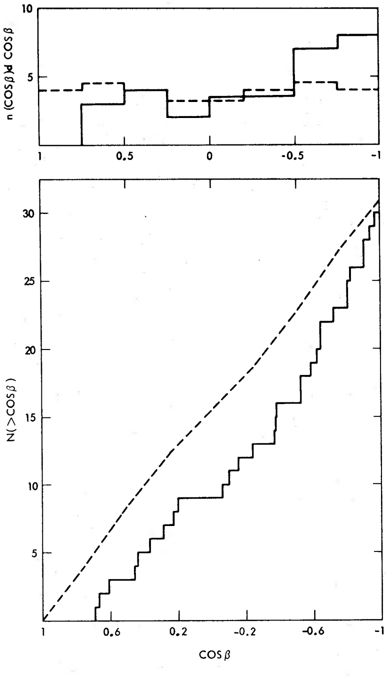

FIG. 1*b*

FIG. 1.—(*a*, *b*) The distribution of β (*solid lines*) in both cumulative (*lower frame*) and differential (*upper frame*) forms, and both as a function of cos β (Fig. 1*a*) and β (Fig. 1*b*). If the spins had been completely uncorrelated, cos β would have been uniformly distributed. Clearly, the two spins in a binary avoid being parallel, and favor being antiparallel. In the bins $|\cos \beta| < 0.5$, the asymmetry is 15 to 3 whereas symmetry is expected *a priori*.

If the data were "degraded" back to full ambiguity, then β is fourfold degenerate for each pair of galaxies. The distribution of all these possible "shadow" values of β is given by the broken line. It shows that the sample has no geometric preselection.

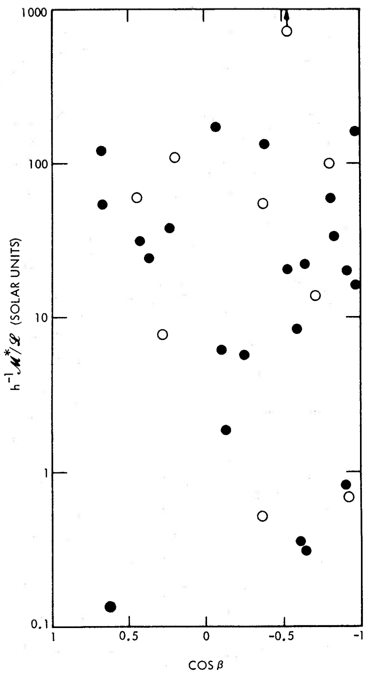

FIG. 2.—For each pair of galaxies one point is shown whose ordinate is the indicative mass-to-light ratio of the pair, and whose abscissa is the angle β between the spins in the pair. Filled circles are for isolated pairs; open circles, for pairs in small groups. The smaller the mass-to-light ratio, the stronger the asymmetry in β: this is taken as evidence that the asymmetry arises in true binaries, and is diluted by the inclusion of optical pairs in the sample.

Table 4 also looks for asymmetry by testing the mean values of β and cos β in the sample (and subsamples). Symmetry is again found improbable, at the level of a few per thousand.

For further assessment of the "reality" of the observed avoidance of parallel spins, let us make use of a more elaborate discriminator of "physical" binaries, the mass to light ratio in the pair. Figure 2 plots $\mathcal{M}^*/\mathcal{L}$ versus cos β, where $\mathcal{M}^*$ is an estimate of the dynamical mass in the pair, and $\mathcal{L}$ is the total blue luminosity in the pair corresponding to B_T (as in col. [4] of Table 1). The indicative mass is computed roughly as in Paper I using the Peterson (1979) formula:

$$\mathcal{M}^* = \frac{1}{0.261}\frac{\delta R^* \delta V^2}{G} ;$$

δR^* is scaled from the apparent separation δR (col. [4] of Table 2) by V_{LG} (col. [3] of Table 2), assuming $H_0 = h \times 100$ km s^{-1} Mpc^{-1}. The constant in $\mathcal{M}^*$ is a mean projection correction averaged over all orientations.

The significance of Figure 2 is in the following interpretation: the smaller $\mathcal{M}^*/\mathcal{L}$, the greater the probability that the pair is a physical entity. It is remarkable that pairs with $\mathcal{M}^*/\mathcal{L} < 20h$ (roughly) favor overwhelmingly (14 to 2) values of $\beta > 90°$. This indicates that the preference of antiparallel spins to parallel ones is a property of true pairs of galaxies, and is diluted by line-of-sight binaries which contaminate the present sample.

Another point that is well illustrated by both Table 3 and Figure 2 is that it is impossible to distinguish statistically between the subsets in Tables 2A and 2B—namely, between isolated pairs and pairs within small groups.

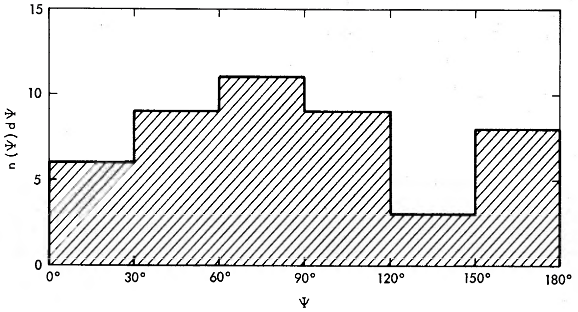

FIG. 3.—ψ is the angle $|\mathrm{SPA{-}OPA}|$, where SPA is the position angle of a galaxy's spin, and OPA is the position angle of the apparent orbital motion. In the absence of correlation between spin and orbit, ψ is uniformly distributed, which is apparently the case. It should be emphasized that ψ is not a physical angle like β, and is strongly affected by projection ambiguities.

Finally, Figure 3 shows the distribution of ψ, which is a *weak* measure of correlation between spin and orbit (cols. [8] and [9] of Table 2). No departure from randomness is indicated; there is no evidence for the existence of correlation between spin and orbit.

V. DISCUSSION

The first point to be made is that the null hypothesis of randomly oriented spins is ruled out. It follows that:

i) The data set is dominated by "real binaries," which provide the bulk of the asymmetry in $f(\beta)$.

ii) The β distribution must contain information about the epoch of galaxy formation, since spin orientations are fossilized at that epoch (Farouki and Shapiro 1981). The observed correlations between physical parameters of the galaxies in a pair (cf. § II*b*) oppose quite strongly the hypothesis that most binaries are formed by capture at times extending long after galaxy formation.

The second point is that when the shape of the β distribution is considered, direct statements can be made about specific models:

iii) The lack of parallel spins is exactly the opposite of what primordial turbulence would have entailed. The data therefore argue directly against primordial turbulence as a source of angular momentum. A similar argument has been made earlier (Helou and Salpeter 1982), and the evidence at this point opposes this theory quite strongly.

iv) The Gott and Thuan (1978) prediction that $f(\beta)d\beta = \text{constant} \times d\beta$ is certainly not borne out. But the failure of that prediction is *not* a direct argument against the hypothesis of tidal torquing, since the prediction is not a *necessary* result of the theory, but is contingent upon other assumptions (rapidity and simultaneity of collapse). The failure of these assumptions is no surprise, for collapse and orbital motion have comparable time scales.

v) But even in the absence of predictions from particular theories, it is still possible to extract information from the β distribution using general principle arguments. To simplify the discussion, two cases will be treated separately:

a) *The steady state case*, where $f(\beta)$ is time independent; the observed anticorrelation in binary spins reflects the "starting conditions,"

Because anticorrelation is not a transitive relation, it cannot be the reflection of a property describing a set containing all the spin vectors. It follows that spin acquisition must have been a local, not a global mechanism; point (iii) above is a special case of this. One other example: if shock waves are the origin of spin, the critical parameters must be local properties of the shock front or the shocked medium, not the large-scale character of the pancake; this would then favor the Binney (1974) mechanism over the Doroshkevich (1973) mechanism (cf. § II*a*).

If the anticorrelation is acquired at the time of galaxy formation, a coupling mechanism between the two protogalaxies is then *certainly* needed. Tidal torques are the most natural if not the only candidate for such a mechanism.

b) *The evolutionary case*, where $f(\beta)$ is altered by galaxy merging (cf. § II*a*), which eliminates binaries from the population. The contention is that binaries with parallel spins would merge faster, depleting at low β an arbitrary, starting-point distribution. This picture is suggested by Figure 2: the isolated point at low β *and* low $\mathscr{M}^*/\mathscr{L}$ is the pair NGC 4567/68, which is the only pair in this sample that seems to be interacting substantially! But this picture is compatible with the Farouki and Shapiro (1982) results *only if* other correlations are postulated, since parallelism of spins is not equivalent to maximizing λ_j, nor does it enhance overlap between the two galaxies (cf. § II*a*). But then the existence of these hidden correlations between orbit and spin again entails the necessity of a coupling mechanism; tidal torques are again strongly suggested.

But apart from any hidden correlations, an important numerical constraint obtains from the assumption that the asymmetry in $\cos\beta$ is solely due to preferential merging. Farouki and Shapiro (1982, Fig. 4) find that, all else equal, the enhancement in merging rates due to a reorientation of spins and orbit cannot exceed a factor of 2. The two bins $|\cos\beta| > 0.5$ hold presently 3 and 15 pairs; if they held x pairs each at the time of "starting conditions," then the differential merging rate would be $(\ln x - \ln 3)/(\ln x - \ln 15)$. If this is less than 2, then $x > 75$. Integrating over $\cos\beta$, one finds that at least 90% of the starting population of pairs must have already merged by now to form elliptical galaxies. The dependence of the total merging rate on the differential rate is clearly steep: if the differential rate called Δ, then the ratio of the initial to the present day numbers of binaries is roughly $R_m = 1 + \frac{3}{8} \cdot 5^{\Delta/\Delta - 1}$; for $\Delta = 1.5$, $R_m = 48$.

These values of R_m are unacceptably large, even if all ellipticals were to be formed from these merger events (Toomre 1977). If the selection criteria for the present sample of pairs were applied to the UGC, a conservative estimate is that *at least* 10% of all galaxies will belong to binaries and small groups of three or four. It follows that, for $\Delta = 2$, about 50% of present day galaxies are expected to be merger remnants. But then *all types* earlier than Sa account for less than 30% of the entries in the RSA! If the observed asymmetry in the β distribution is to be interpreted as a result of evolution, it is necessary to invoke larger values of Δ; this may be achieved by conjecturing, for instance, that low β values occur preferentially in systems with a low content of orbital angular momentum, which will tend to merge faster because of larger overlap at closest approach (Jones and Efstathiou 1979). This exemplifies precisely the resource to "hidden correlations" mentioned above.

In view of (iv) and (v), it seems unavoidable to go beyond the Gott and Thuan picture, and attempt numerical simulations of the collapse phase of protobinaries. Such simulations should help answer, at least in part, the questions posed by the present data: Will the model reproduce the observed β distribution? Will this distribution appear from the outset (case A), or is it the result of evolution guided by the "starting" condition (case B)? What is the true shape of $f(\beta)$?

I would speculate that where β is concerned, an essential ingredient of the collapse process is the conservation of total angular momentum in the protobinary system. If the tidal interaction remains "soft" with no substantial ejections, then the orbital motion could be substantially affected by the extraction of spin from orbital angular momentum, since the magnitudes of these components are comparable. This may be the source of the "hidden correlations" that guide the evolution of $f(\beta)$.

VI. CONCLUSION

Data on the true orientation of spins in binaries and small groups of galaxies are presented for the first time. It is found that spins of galaxies in pairs avoid being parallel and favor being antiparallel; the asymmetry is strongest between $\beta < 60°$ which holds 9% of the sample, and $\beta > 120°$ with 47% of the sample. No significant correlation is found between the spin and orbital (projected) orientations.

This result argues directly against a primordial origin for turbulence. It is also incompatible with the prediction that $f(\beta)d\beta = \text{constant} \times d\beta$, based on the tidal torques theory; but the latter is not itself threatened by the failure of that prediction. Actually, if one assumes the β distribution to have been invariant since galaxy formation, tidal torques are a necessary ingredient of the formation epoch. Alternatively, even if $f(\beta)$ has evolved by galaxy mergers, the assumption that tidal torques were active at the time of galaxy formation is needed to avoid producing too many mergers over the lifetime of the universe.

Two more conclusions can be reached independent of any models or theories, simply because the null hypothesis of a random distribution is ruled out (§ IV); both of these conclusions are bolstered by the positive correlations observed between physical parameters of the galaxies in a pair (§ II*b*): first, that the data set at hand is composed mostly of true, physically associated binaries, with some contamination by "optical" pairs; second, that capture is ruled out as the prevalent origin of these pairs; these galaxies have been companions since their formation.

Finally, these results should motivate a more detailed exploration (e.g., through numerical simulations) of the collapse and formation of binary galaxies. Similarly, more data are needed to improve the statistics and define better the shape of $f(\beta)$.

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