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Binary galaxy spin correlations arising from mergers of galaxies

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Abstract. Statistics of spin orientations in binary galaxies may be used as a tool to study the formation process of galaxies. Helou found that the spins of spiral galaxies in binary systems are anticorrelated, and he suggested that it may have to do with the inclination dependence of the galaxy merger process. We study this dependence in small groups of galaxies. An N-body code is developed which uses an inclination dependent dynamical friction law to affect mergers of galaxies. It is found that some correlation results in this way in groups which have initially random spin orientations.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: interactions

1. Introduction

The spins of galaxies may contain important information on the formation of galaxies since it is hard to change the spins in subsequent encounters. Only in a merger of two comparable galaxies do we expect the original spin to change completely. Galaxies with thin disks have probably not suffered a major merger for a long time; thus the study of galaxies with thin disks, i.e. spiral galaxies, may prove fruitful in trying to understand galaxy formation.

Helou (1984) collected data on the spin vectors of 62 spiral galaxies in binary pairs, and found that the spins tend to be antiparallel. The same is also true for the Galaxy/Andromeda galaxy pair (Gott and Thuan 1978). Helou (1984) considered various alternatives for the origin of this correlation and suggested merger evolution. He recommended numerical simulations of the formation of binary galaxies. Subsequently Keel (1991) studied the correlation of the spin of the primary galaxy with the orbital angular momentum and found a significant correlation between the nature of the encounter (direct/retrograde) with the relative orbital speed at the encounter. He also assigned the difference to a different dynamical evolution.

The purpose of this work is to explore one possible avenue of evolution to a binary state, and to study the spin correlations within this framework. The work is a continuation of the studies of merger evolution in small groups of galaxies which have been previously carried out (Valtonen et al. 1993, Zheng et al. 1993, Byrd et al. 1994, Valtonen & Wirén 1994, Wirén et al. 1996). In those studies the merger evolution was obtained in N-body simulations by using the Chandrasekhar approximation of dynamical friction. The galaxies were assumed to be perfectly spherical and the friction therefore was independent of the orientation of the orbit relative to the galaxy. In this work the same approximation is used, except that the frictional force is spin-dependent. We first describe the structure of the new code, and then give results of some merger evolution experiments.

2. Numerical method

The computer code is based on a “standard” version of the N-body code (Aarseth 1985, see Binney & Tremaine 1987). Each galaxy is represented by a single particle, and the force law is basically Newtonian. However, the interaction between two particles is modified at close range. Each particle has a mass m_i and the associated radius r_i. If the separation between particles i and j, r_{ij}, is less than $r_i + r_j$, the Newtonian force law is modified by an additional frictional force.

We use the Chandrasekhar friction (see e.g. Binney & Tremaine 1987, Eqs. 7-17):

$$\frac{d\mathbf{v}_M}{dt} = -\frac{4\pi ln\Lambda G^2 m_j \rho C(X)}{v_M^3}\mathbf{v}_M \qquad (1)$$

where $\mathbf{v}_M$ is the relative velocity between the two galaxies, t is time, G is the gravitational constant, m_j is the mass of the smaller galaxy, ρ is the stellar density of the larger galaxy (at the position of the smaller galaxy), $C(X)$ is a function which can be adequately approximated by

$$\begin{aligned} C(X) &= 0.625X^3, X < 0.55 \\ &= 0.7(X-0.4), 0.55 \leq X \leq 1.83 \\ &= 1.0, X > 1.83, \end{aligned}$$

where

$$X = v_M/(\sqrt{2}\sigma),$$

and σ is the velocity dispersion in the larger galaxy. $\Lambda = b_{max}/b_{min}$ is the ratio of the maximum impact parameter to the minimum impact parameter in the scattering of the smaller

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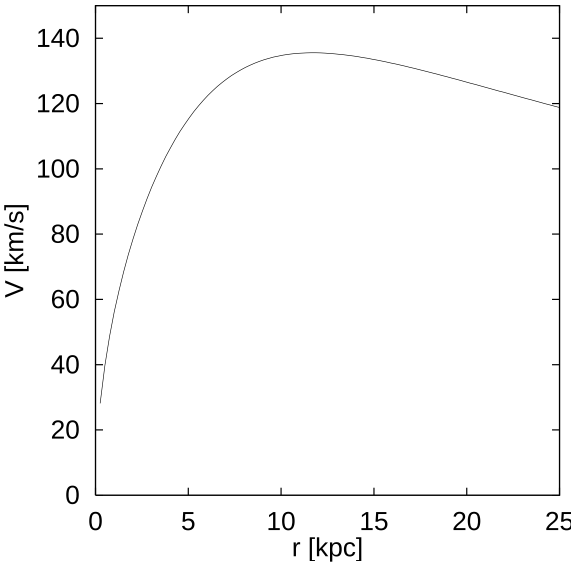

Fig. 1. The circular rotation velocity V as a function of radial distance r for $m_i = 10^{11} M_\odot$

galaxy from the stars of the bigger galaxy. In the units of our calculation ($G = 1$, time in $10^6 yr$, v_M and σ in 1000 km/s, ρ in $M_\odot/pc^3$, m_j in $2.3 \cdot 10^{11} M_\odot$) and considering that $b_{max} \approx 2r_{ij}$ and that the tidal radius of the smaller galaxy $r_t \leq 0.5 r_{ij}$, we may adopt $b_{max} \simeq 2.5 r_t$, $b_{min} \simeq 0.2 r_t$ (White 1976) and obtain $ln\Lambda \simeq 2.5$ which leads to

$$\frac{d\mathbf{v}_M}{dt} = -0.138 C(X) m_j \rho \mathbf{v}_M v_M^{-3}. \tag{2}$$

At the same time, the central attractive force is reduced by considering only the effective mass $m_i(r_{ij})$ in Newton's force law. Here $m_i(r_{ij})$ is the mass within the radial distance r_{ij} inside the main (more massive) galaxy i. The spherically symmetric mass distribution m_r is the same as in our previous studies (Wirén et al. 1996 and reference therein), i.e. the circular rotation velocity V at the radial distance r is

$$V = \sqrt{(Gm_i/r_i)(r_i/r)\left[1 + (r_i/2r)^2\right]^{-1}} \tag{3}$$

where m_i is the total mass of the galaxy and r_i is its radius. The rotation curve is illustrated in Fig. 1.

The initial values for the orbital integration of a system of galaxies are (1) the masses, (2) positions, (3) velocities and (4) spin directions of the galaxies. The magnitudes of the spins as well as the radii of the galaxies are taken to be functions of the galaxy mass m_i. The functions which we use are

$$\begin{aligned} r_i &= 23.4\sqrt{m_i/10^{11} M_\odot}\ kpc \\ s_i &= 410 (m_i/10^{11} M_\odot)^{3/2}\ 10^{11} M_\odot kpc\ km\ s^{-1} \end{aligned} \tag{4}$$

Our model galaxy is adopted from Quinn & Goodman (1986), and we refer to this work for the details of the model. Consequently we also make use of Quinn & Goodman (1986) simulation of the sinking rates of the satellite galaxies in order to adjust the dynamical friction for different inclinations. Careful studies by Donner & Sundelius (1993), Wahde et al. (1996) and Cora et al. (1997) have confirmed that it is possible to describe approximately the infall of a satellite in a disk galaxy by dynamical friction. One should note that the rates are a function of the halo/disk mass ratio of the model (Valtonen et al. 1990) .

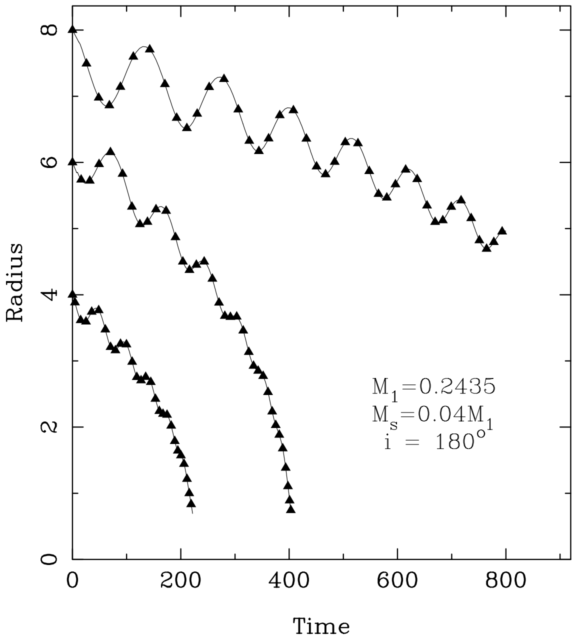

Fig. 2. The evolution of the radial distance between the primary galaxy and a satellite galaxy. The primary galaxy has the disk mass $M_1 = 0.2435$, in units of $2.3 \cdot 10^{11} M_\odot$, and the satellite mass is $0.04 M_1$. The initial orbit is circular and retrograde. The distance unit is 3.5 kpc and the time unit $1.3 \cdot 10^7$ yr, in accordance with Quinn & Goodman (1986)

After trying several functional forms we adopted the following coefficient:

$$\begin{aligned} C_1(i) &= \quad (1 - 2i/\pi)^3 + 0.01,\ i \leq \pi/2 \\ C_1(i) &= 0.1 \cdot (2i/\pi - 1)^3 + 0.01, i \geq \pi/2 \end{aligned} \tag{5}$$

The Chandrasekhar dynamical friction is multiplied by $C_1(i)$ (for details of the calculation, see Valtonen & Wirén 1994). The resulting sinking rates are illustrated in Figs. 2 and 3 which correspond to Fig. 9 and Fig. 6 of Quinn & Goodman (1986), respectively. The system of units in Figs. 2 and 3 is also the same as in the latter paper.

3. Spin correlations in groups with mergers

We have simulated the evolution of a bound small galaxy system until only one binary system is left. We study the remaining two-galaxy configurations and note the main properties of the pairs. The initial group is characterized by the maximum size R_{max} and the virial coefficient C_V (see Wirén et al. 1996), and the initial masses of the galaxies. The latter are randomly distributed

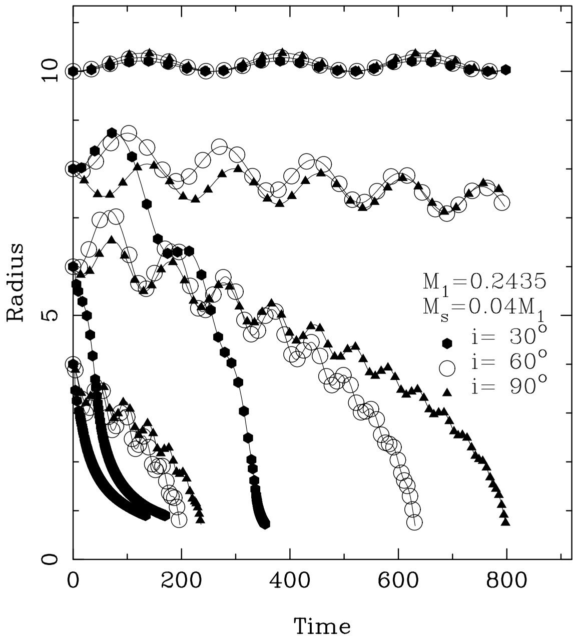

Fig. 3. As Fig. 2, except that initial orbital inclination is $i = 30°$ (hexagons), $i = 60°$ (open circles) and $i = 90°$ (triangles)

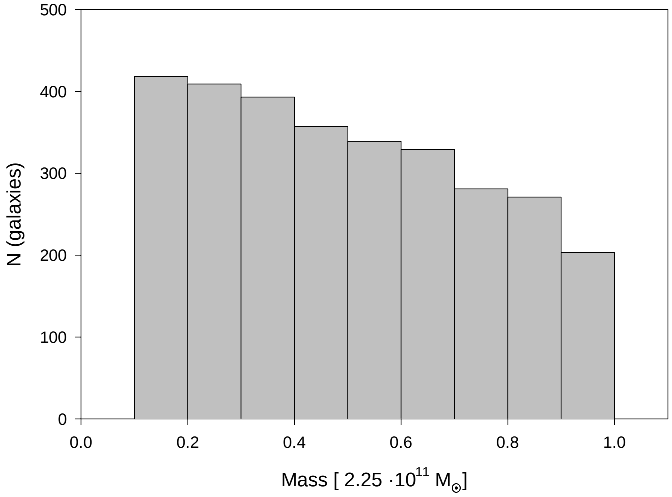

Fig. 4. The initial mass distribution for 500 six-galaxy groups

Table 1. Simulation results with different initial parameters

Set	N_{gal}	C_v	R_{max}	M_{min}	M_{max}	N_{dir}/N_{ret}	$N{<}20/N{>}160$
1	3	0.2	300	0.1	1.0	256/244	12/15
2	3	0.3	300	0.1	1.0	252/248	15/11
3	3	0.4	300	0.1	1.0	262/238	14/8
4	3	0.5	300	0.1	1.0	238/262	22/21
5	3	0.5	300	0.01	1.5	244/256	19/17
6	3	0.5	300	0.1	1.4	256/244	18/20
7	3	0.5	300	0.1	1.9	239/261	14/21
8	3	0.5	300	0.2	1.0	247/253	23/22
9	3	0.5	300	0.3	1.0	242/258	22/18
10	3	0.5	300	0.9	1.0	261/239	17/13
11	3	0.5	300	1.0	1.5	269/231	22/17
12	3	0.6	300	0.1	1.0	242/258	17/23
13	3	0.7	300	0.1	1.0	242/258	15/14
14	4	0.2	300	0.1	1.0	293/207	35/16
15	4	0.3	300	0.1	1.0	284/216	33/21
16	4	0.4	300	0.1	1.0	299/201	61/14
17	4	0.5	300	0.1	1.0	280/220	54/18
18	4	0.6	300	0.1	1.0	282/218	64/16
19	5	0.2	300	0.1	1.0	294/206	47/20
20	5	0.3	300	0.1	1.0	305/195	58/15
21	5	0.4	300	0.1	1.0	287/213	69/13
22	5	0.5	300	0.1	1.0	312/188	72/21
23	5	0.6	300	0.1	1.0	278/222	67/24
24	6	0.2	300	0.1	1.0	275/225	42/23
25	6	0.3	300	0.1	1.0	275/225	53/23
26	6	0.4	300	0.1	1.0	279/220	56/21
27	6	0.5	145	0.1	1.0	268/232	67/22
28	6	0.5	175	0.1	1.0	300/200	83/19
29	6	0.5	200	0.1	1.0	293/207	68/11
30	6	0.5	250	0.1	1.0	309/191	90/19
31	6	0.5	300	0.1	1.0	284/216	64/17
32	6	0.5	300	0.1	1.0	896/604	222/61
33	6	0.5	350	0.1	1.0	304/196	74/22
34	6	0.5	390	0.1	1.0	293/207	79/18
35	7	0.5	300	0.1	1.0	301/199	58/17
36	8	0.5	300	0.1	1.0	312/188	74/26
37[1]	3	0.5	300	0.1	1.0	239/261	22/18
38	4	0.5	300	0.1	1.0	279/221	54/21
39	5	0.5	300	0.1	1.0	285/215	73/13
40	6	0.5	300	0.1	1.0	309/191	83/16

between M_{min} and M_{max}[1]. An example of the initial mass distribution is given in Fig. 4. The range is typically a factor of ten which corresponds to a magnitude difference of 2.5. This range is valid for all Helou's pairs. In the sample of close binary galaxies by Karachentsev (1987), the magnitude differences are within our range in 552 out of 575 binaries. We also require that initially the distances between galaxies are at least three times the sum of their radii in order to avoid instant mergers.

The initial number of galaxies in a group is varied. The experiments with different values of parameters are listed in Table 1, where N_{gal} = initial number of galaxies in the group, R_{max} = maximum group size, C_V = virial coefficient, M_{min}, M_{max} = limits of the initial galaxy mass distribution in units of $2.3 \cdot 10^{12} M_\odot$, N_{dir}/N_{ret} = number of binaries at the end with the spin difference angle β from 0° to 90°/90° to 180°, respectively. The last column gives the corresponding numbers for the β-intervals 0° to 20° and 160° to 180°, respectively. The total number of experiments in each set is 500, except in set 32, where it is 1500. After a binary system has formed, we continue the simulation until the final galaxy merger or until 10 billion yr, whichever happens first. An example of the distribution of the time scales is shown in Fig. 5. The average time of evolution from six galaxies to one galaxy is about 8 Gy and the evolution from a binary to a single galaxy is typically less than 2 Gy.

An example of the distribution of the separations of the galaxy pairs at the time of the origin of the binary system is

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[1] from set 37 on a different, uniform distribution for initial masses was used

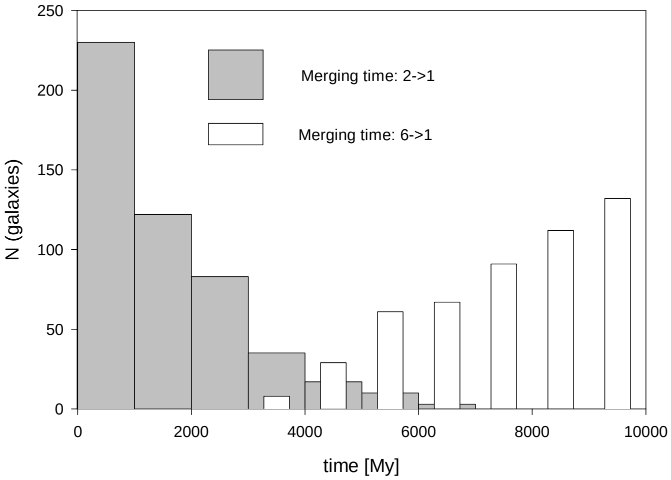

Fig. 5. The distribution of the time scale for the last merging of the binary to a single galaxy (shaded histogram). Initially there were six galaxies in each of the 500 groups. The total evolution time from six galaxies to one galaxy is shown with white bars

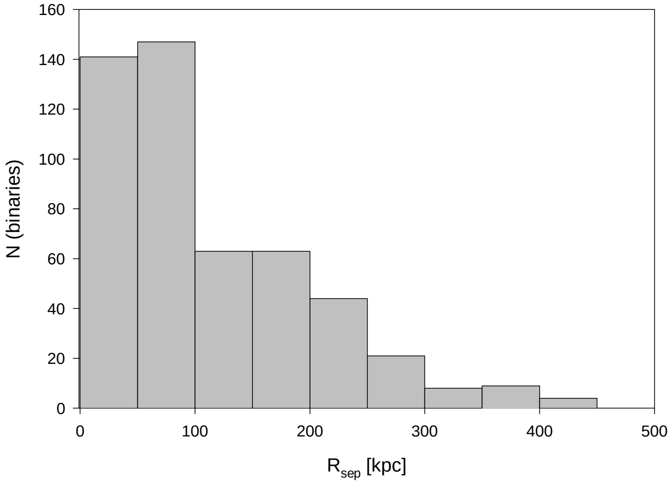

Fig. 6. The distribution of the separations for 500 galaxy pairs after the last merger in six-galaxy groups

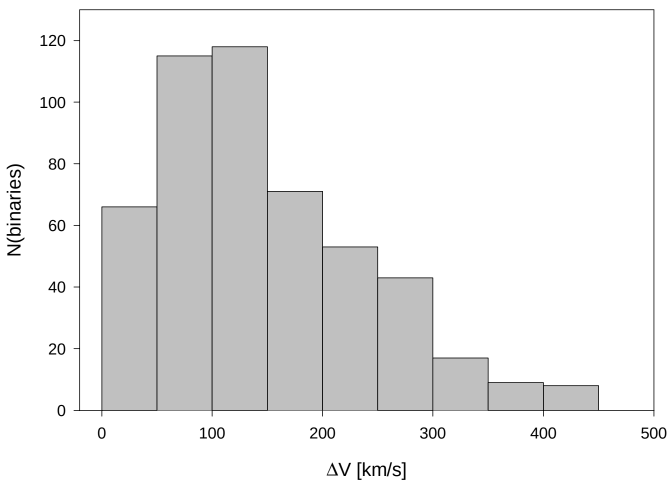

Fig. 7. The same as Fig. 6 but for relative velocities

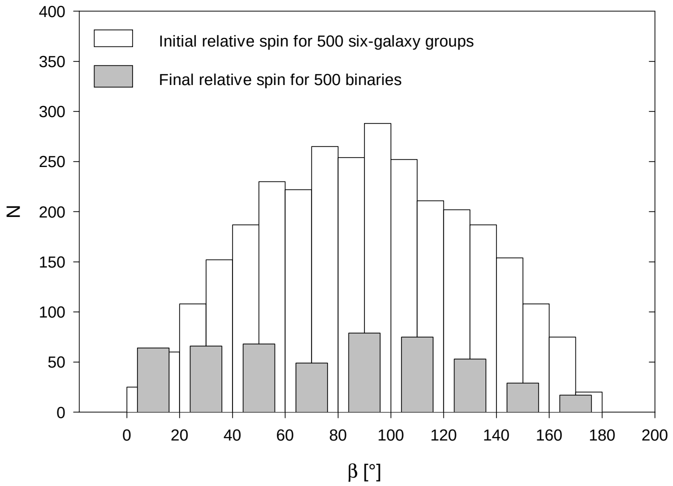

Fig. 8. The distribution of relative spins β of the groups after mergings into binaries (shaded bars). Initial relative spins between any two pairs of the six-galaxy groups are also shown (unshaded histogram).$C_V = 0.5$

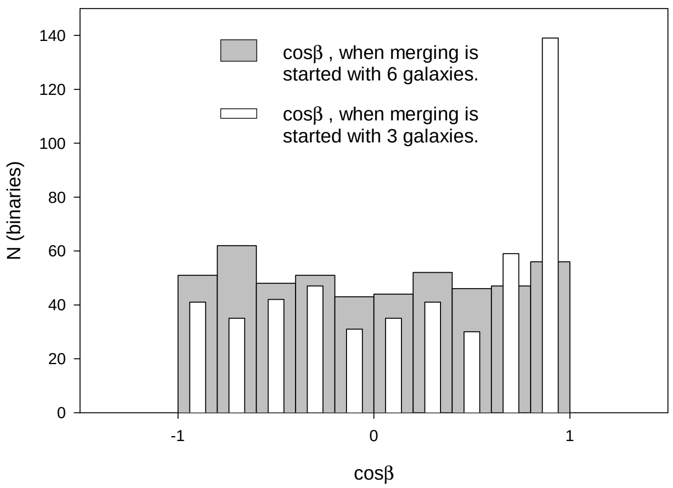

Fig. 9. The distribution of relative spin orientations β of binary galaxies resulting from mergers of six or three galaxy groups. In a random situation the distribution of cosβ is uniform. This is true for three galaxy groups, but in initially six galaxy groups there is an excess at cos$\beta > 0.8$, corresponding to an excess of parallel spins

shown in Fig. 6. The corresponding distribution of relative velocities is given in Fig. 7. These are similar to the distributions in the observed samples of binary galaxies by Karachentsev (see Wirén et al., 1996, for the distributions and references to the original work). An example of the distribution of the spin angles between the two galaxies, β is given by the shaded bars in Fig. 8. There is an excess of small angles β which becomes more obvious when we plot the data as a function of $\cos(\beta)$ (Fig. 9). For random spin orientations the distribution should be uniform. The spin of the merged galaxy is calculated as the vector sum of the original spins of the two components plus the orbital angular momentum which is calculated before the merging begins.

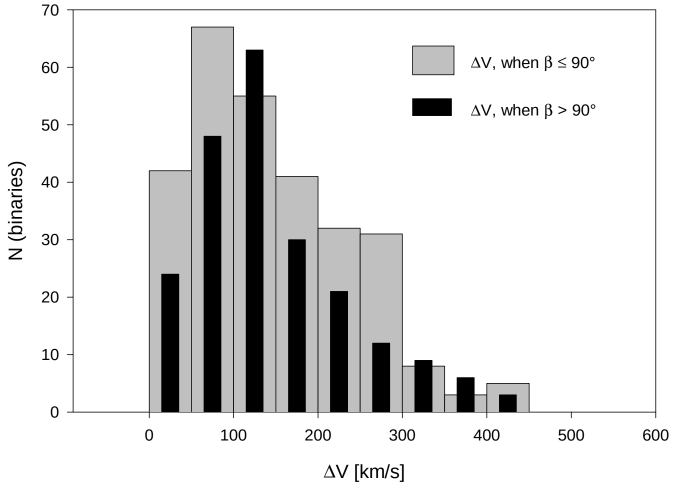

Fig. 10. Histograms of relative velocities between binary galaxies arranged according to the spin difference. Each integration was started with six galaxies. In the simulation 500 groups were involved. Initial minimum mass $M_{min} = 0.1$ (in units of $2.25 \cdot 10^{11} M_\odot$) and $C_V = 0.5$

The β-distribution arising from our simulation is quite contrary to the observations of Helou (1984, Fig. 1a). In retrospect, this is not surprising since the sample of Helou consists of spiral galaxies while many of the galaxies in our calculated sample may have lost their spiral characteristics after the mergers. There are no corresponding observational statistics for elliptical galaxies for comparison with our numerical simulations. The original spin directions are chosen to be random and therefore the spin difference angle β between any two pairs in the original six-galaxy system follows a sinβ -distribution (unshaded histogram in Fig. 8). After the mergers the distribution of β has shifted towards lower values. The asymmetry which Helou (1984) finds is 22:9 in favour of $\beta > 90^\circ$, i.e. antiparallel spin. In our simulations the same ratio in favour of *parallel* spins is 3:2. For extreme spin values, i.e. between $\beta < 20^\circ$ and $\beta > 160^\circ$ the asymmetry becomes 15:4. The degree of asymmetry clearly increases with the initial number of galaxies in the group. At the end of the simulations of the six galaxy groups the peak at the lowest values of β is very prominent whereas the same peak is missing when we start the simulation with three galaxies.

We have also looked at the distribution of the angle ψ between the orbital angular momentum and the spin. We find no significant deviation from the sinψ-shape, in accordance with Helou (1984, Fig. 3).

When we divide the velocity distribution of Fig. 7 in two parts, retrograde contra direct motion of the secondary relative to the primary, we find no significant difference among all of our 500 binaries (Fig. 10). However, if we take only those pairs that had spin differences less than 15 degrees or greater than 165 degrees, we find a shortage of relative retrograde velocities above 200 km/s (Fig. 11). This has also been noticed by Keel (1991) in observations. He had restricted his sample by taking only those pairs of the Karachentsev (1987) binaries that are seen within 30 degree of the disk plane. This restriction is somewhat similar to ours in that it tends to pick pairs which have spins either parallel or antiparallel.

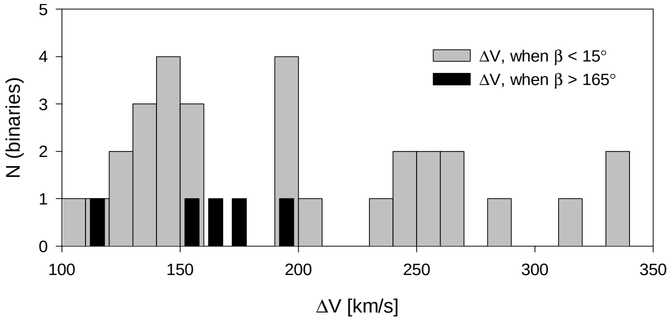

Fig. 11. The same as Fig. 10 but for restricted samples corresponding to Keel's Fig. 2 (Keel, 1991). Only pairs with $\beta < 15$ degrees (shaded histogram) and $\beta >$165 degrees (black bars) are included

4. Discussion

We have found that the dynamical evolution in a small merging group of galaxies tends to produce binaries with an excess of parallel spins. This is opposite to the observations of Helou (1984) and therefore we can say that the origin of the phenomenon observed by Helou is unlikely to be the merger evolution of galaxies. Instead we have found support for the phenomenon observed by Keel (1991), namely that the relative velocities between the two galaxies tend to be higher when the spins are parallel rather than when they are antiparallel. It is not clear to us why the end products of merger evolution should have these features. Anyhow it is obvious that multiple mergers are required since the phenomena are not observed in the merger of three galaxies: at least four galaxies are required initially to produce the parallel spin excess.

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