1993AJ....105..886V

THE ASTRONOMICAL JOURNAL VOLUME 105, NUMBER 3 MARCH 1993

A REVISED HISTORY OF THE LOCAL GROUP AND A GENERALIZED METHOD OF TIMING

MAURI J. VALTONEN
Tuorla Observatory, University of Turku, 21500 Piikkiö, Finland

GENE G. BYRD
Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama 35487

MARSHALL L. MCCALL AND KIMMO A. INNANEN
Department of Physics and Astronomy, York University, 4700 Keele Street, North York, Ontario M3J IP3, Canada
Received 17 August 1992; revised 21 October 1992

ABSTRACT

Recent measurements suggest that the giant galaxies IC 342 and Maffei 1 are moving so rapidly for their distances that they were close to M31 only 4 billion years ago. If correct, the two-body approximation of Local Group Timing would not be valid. *N*-body simulations have been carried out to explore how the indicated configuration of four massive bodies might arise, and to study the implications for the mass of local dark matter and the age of the universe. Provided that the total systematic mass is close to 3×10^{12} solar masses, the high speed of IC 342 and Maffei 1 and the turn around of the motion of M31 with respect to the Milky Way could be explained if IC 342 and Maffei 1 were each members of binaries which successively fell past M31, interacting with M31 strongly and ejecting one component. Because ejection speed depends upon each galaxy's rotational velocity at its edge, observations rule out masses much greater than 2×10^{12} solar masses. Generalizing conventional Kahn–Woltjer timing to account for the ejections, the age of the universe consistent with a systemic mass of 3×10^{12} solar masses is 19 ± 4 billion years.

1. INTRODUCTION

Kahn & Woltjer (1959) devised an elegantly simple method to calculate the mass of the M31-Milky Way pair, known as "Local Group Timing," that has since stood the test of time as one of the strongest nearby pieces of evidence for the existence of massive halos around spiral galaxies. More sophisticated calculations, considering M31 and the Milky Way as "seeds" into which matter falls after the origin of the universe, give results within 10% of those of Kahn and Woltjer (Fich & Tremaine 1991; Peebles *et al.* 1989). With the aid of Local Group dwarfs, the method can be extended to simultaneously constrain the age of the universe (Lynden–Bell 1981).

In conventional Local Group Timing, the Local Group is assumed to be an isolated system of two point masses (the Milky Way and M31) that form together and initially move away from one another as the universe expands (i.e., radial motion only). Companion galaxies are assumed to be (and probably are) inconsequential in mass. As the Milky Way and M31 move apart, their mutual gravitation eventually halts the expansion (about 4 billion years ago), and the two galaxies begin moving toward one another, until they reach their present separation (708 kpc and relative radial velocity -121 km s^{-1} if the circular velocity at the solar radius is 220 km s^{-1}). If the age of the universe is 10–20 Gyr, then the mass of the Local Group is 5.6×10^{12} to 3.3×10^{12} $\mathcal{M}_\odot$, which demonstrates that rather massive halos must exist (Fich & Tremaine 1991).

Given the strong observational foundations, and the relevance of the conclusions to cosmology, further study of the validity of Local Group Timing is important. Motivated by recent revelations concerning IC 342 and Maffei 1 (McCall 1989), the method of timing is reevaluated. Through *N*-body simulations, it is found that Local Group Timing must be modified if IC 342 and Maffei 1 are as close as suggested. A "Generalized Timing Method" is proposed, and revised values for the mass of the Local Group and the age of the universe are estimated. A number of simulations of the past history of the Local Group are constructed to account for the contemporary situation.

2. THE CURRENT MEMBERSHIP OF THE LOCAL GROUP

The important question here is whether there are other galaxies near enough and massive enough to significantly perturb the two-body motion of M31 and the Milky Way. Raychaudhury and Lynden-Bell (1989) concluded that this is not the case and that the two-body assumption is correct. However, Buta & McCall (1983) and McCall (1989) have made estimates of the distances of the low-latitude galaxies Maffei 1 and IC 342 based upon new direct measurements of extinction by intervening dust. The distances and radial velocities indicate that the two galaxies were in the past close enough to strongly perturb the motion of M31 relative to the Milky Way (McCall 1989; Zheng *et al.* 1991).

Figure 1 shows the positions of Maffei 1 and IC 342 relative to M31 and the Milky Way, projected on to the supergalactic plane. The four galaxies lie approximately in the supergalactic plane, so the two-dimensional view quite accurately reflects the true configuration in space. The fi-

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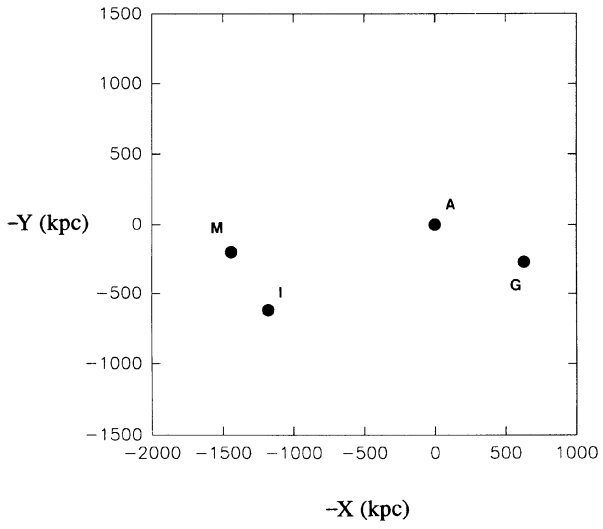

FIG. 1. Present day positions of M31 (*A*), the Milky Way (*G*), Maffei 1 (*M*), and IC 342 (*I*) projected on to the Supergalactic plane. Note that the true supergalactic coordinates are the negatives of those shown.

ducial data for these galaxies are taken to be: for IC 342, a distance of 1800 kpc and a mass 0.23 that of M31; for Maffei 1, a distance of 1900 kpc and a mass 0.20 that of M31. We take the mass of the Milky Way to be 0.74 that of M31, and the distance and radial velocity to be the values mentioned earlier. The radial velocities of Maffei 1 and IC 342 relative to the center of the Milky Way are 145 and 172 km s^{-1}, respectively, assuming the solar circular velocity is 220 km s^{-1}. The distances and masses are from McCall (1989; 1992; see also Valtonen *et al.* 1992).

In conventional two-body timing, M31 has spent most of the last 4 billion years at almost the same distance from us, just reaching the extremum of its motion away from the Milky Way and turning around to approach us. Extrapolating backward at constant radial velocity, we see that the positions of Maffei 1 and IC 342 were, respectively, 600 and 700 kpc closer to us 4 billion years ago, so close to M31 that the assumption of two-body motion has to be questioned. This can be seen using Fig. 1. Indeed, at this time in the past, a major dynamical interaction would have taken place between the two interlopers and M31 while the Milky Way would have been a comparative bystander 700 kpc away. Of course, this result means that the motion is more complicated than can be accounted for by the analytic two-body calculations of the classical timing method. Therefore we proceed to do many-body calculations by numerical means to understand what may have happened prior to the time of strong interaction.

3. SEXTUPLE GALAXY EXPERIMENTS

We have constructed a modification of Aarseth's (1971) *N*-body code which includes gravitational drag and collisions between galaxies. It utilizes a softened force law between two galaxies such that the acceleration of galaxy *i* by galaxy *j* is

$$\ddot{r}_i=\frac{m_j}{r_{ij}^2+(a/2)^2}, \tag{1}$$

where a is the softening parameter and r_{ij} is the radial distance between the centers of the two galaxies. Each galaxy has a mass value m_i, $i=1,...,N$, and a corresponding radius

$$a_i=9.8\sqrt{m_i/10^{11}\mathcal{M}_\odot}\ \text{kpc}. \tag{2}$$

This relation was motivated by Young's (1976) study of standard de Vaucouleurs' law galaxies. The softening parameter $a=\max(a_i,a_j)$.

When the radii of two galaxies touch each other, an extra force of gravitational drag is included. It is calculated using the secondary galaxy as a test particle in the Chandrasekhar (1942) formulation of gravitational friction. The local mass density and velocity dispersion of the primary galaxy are substituted in the standard expression for gravitational friction. The logarithmic term involving the limits of integration, i.e., $\log(b_{\max}/b_{\min})$, was given the value of 2.3. This was considered adequate after comparing gravitational drag in large-N simulations with the Chandrasekhar approximation.

Because of the drag, interpenetrating galaxies gradually lose their orbital energy. A merger was considered to have happened when the drag deceleration became comparable to the central acceleration between the two galaxies. A collision of two galaxies was simulated by combining the masses of the colliding galaxies and by calculating the new radius from Eq. (2). The total momentum of the colliding galaxies was conserved in the process, and transferred to the combined galaxy.

The code has been tested in various situations involving both energy conserving and nonconserving (drag) dynamics. In the latter situation, the performance of the code is monitored via conservation of linear momentum. The number of integration steps is chosen such that the linear momentum is conserved to one part in a thousand.

IC 342 and Maffei 1 possess high speeds relative to M31. The mean value is about 275 km s^{-1}, or even somewhat higher depending on the details of the motion of M31. We attempt to find a past configuration of objects which could ultimately yield two galaxies with positions and speeds comparable to those claimed for IC 342 and Maffei 1.

The most physically reasonable mechanism to impart a high speed to one object is to have a single galaxy and a binary pass near one another. Kinetic energy is given to one member of the binary, which then escapes. The single galaxy is left tightly bound to the other member of the binary, and the two galaxies quickly merge. As a general rule, any high speed ejection involves at least one merger.

The maximum ejection speed is comparable to the orbital speed of the initial binary (Valtonen & Mikkola 1991). There is no dynamical subsystem in the present day Local Group of galaxies which could impart such speeds to escaping members. We have to assume that compact binary galaxies have existed previously. After a little experimenting, it became clear to us that at least six major primordial galaxies must have existed in order to eject two at

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high speeds (IC 342 and Maffei 1) and leave two behind (M31 and the Milky Way). The number could have been greater, but we prefer to study the six galaxy problem as the simplest case.

Various kinds of sextuple groups were studied. Common to all of them was the position of the Milky Way as a bystander. The actual dynamical interaction took place among the five other galaxies. In all, something of the order of 10^4 systems were integrated through about 10^{10} yr. A typical single orbit integration took about 100 s of CPU time on the Sun-4 of the University of Turku Computer Center.

All galaxies out of 3 Mpc from M31 lie close to the supergalactic plane, and probably have motions largely confined to that plane (McCall 1986). This allows us to reduce the initial value space from 42 to 30 dimensions. In practice, however, it is not possible to cover the 30-dimensional space even with a few values per parameter. Thus, of the various ways to set up a quintuple galaxy interaction, we restricted our studies to the following: binary+binary+single galaxy, stable triple+binary, and binary+single galaxy+binary. The last approach proved to be most fruitful in terms of producing high speed ejections of *two* galaxies. It is also a process which is easy to control by adjusting just a few parameters of the 30-dimensional initial value space.

In practice, two binaries (which we call the Maffei binary and the IC 342 binary) were induced to interact with a single galaxy (proto-M31) in succession. The two binaries were given initially circular orbits with semimajor axes which were roughly 10% greater than the minimum value for a stable (no-drag) orbit. The center of mass of each binary was allowed to fall toward the central single galaxy along an elliptical orbit with a selected value of the impact parameter. The two impact parameters constituted two variables to be covered in setting up different systems. The next two parameters covered the orbital phases of the binaries. The fifth parameter was the mass of the binaries relative to the single galaxy, which usually was set to one of two possible values. In addition, the total mass of the system was varied. With this reduction of initial parameter space, it became feasible to explore regions which produced two high speed ejections, and also to get an estimate of the probability of such an occurrence.

Figures 2–7 show six representative cases (in the center-of-mass frame). Note that Maffei 1 and IC 342 fly off at high speed to the left while the more massive M31 recoils with lower speed to the right. The initial parameters of the six representative simulations are listed in Table 1. To avoid confusion, the simulations are designated with numbers which correspond to the figures where they are displayed. Each was picked from about 300 runs in which the impact parameters and orbital phases of the two binaries were varied. The examples given are those where two galaxies escaped with the highest speeds.

We would like to be sure that the initial values are in reasonable accord with the cosmological initial conditions. At the time ~2 Gy after the Big Bang the velocities should have been reasonably small. In our experiments the speed

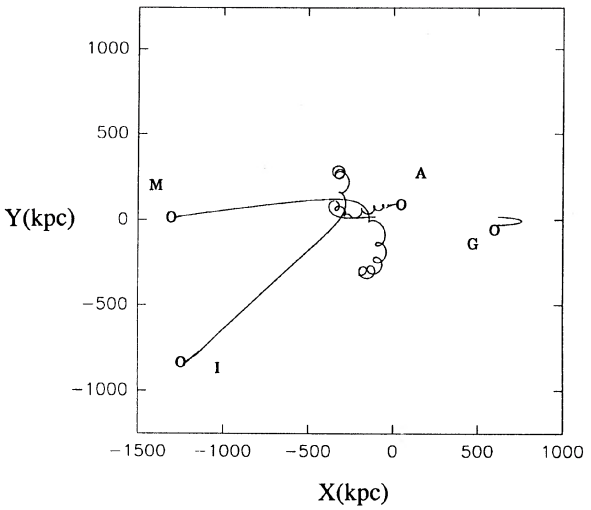

FIG. 2. The orbits of four galaxies in case 2. The circles mark the final positions. The orbits of the two merged binary members are not shown.

of the binaries with respect to the Andromeda galaxy were below 200 km s^{-1}, and remained even smaller until the next strong interaction period. This would seem to be acceptable from what has been deduced otherwise, and is not much different in the models where Maffei 1 and IC 342 do not play a major role in the Local Group dynamics (Peebles 1990).

Column 1 of Table 1 gives the case number. The total time of the model from the Big Bang to the present is given in column 2. We did not actually start the integration from the Big Bang but a few billion years after it. The total time was obtained by adding the time to go backward to a configuration where all galaxies were about 200 kpc from each other (the Big Bang) to the time to go forward to a con-

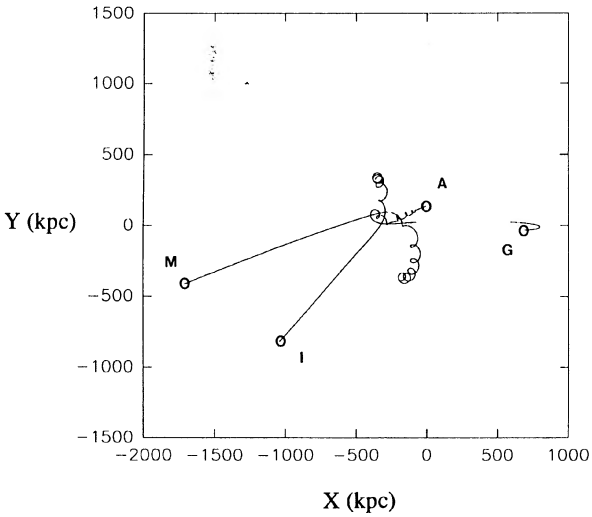

FIG. 3. The orbits of four galaxies in case 3. The circles mark the final positions. The orbits of the two merged binary members are not shown.

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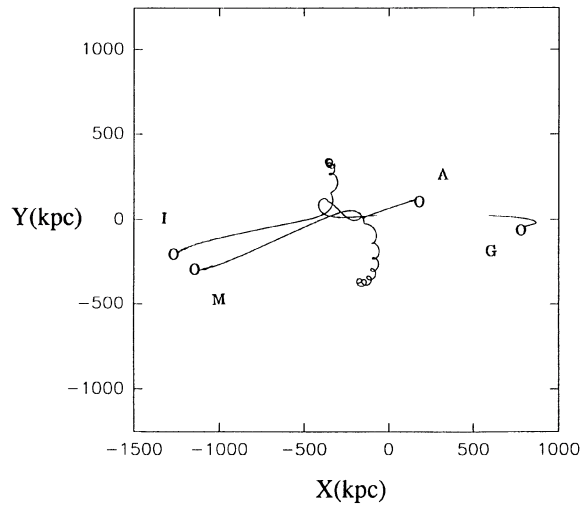

FIG. 4. The orbits of four galaxies in case 4. The circles mark the final positions. The orbits of the two merged binary members are not shown.

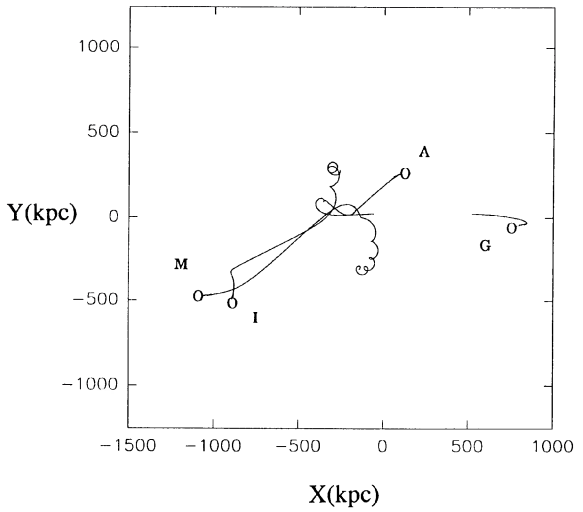

FIG. 6. The orbits of four galaxies in case 6. The circles mark the final positions. The orbits of the two merged binary members are not shown.

figuration resembling that observed today. It is difficult, time consuming, and probably futile to adjust the initial conditions such that an exact match is produced. Columns 3–8 list the masses of the six galaxies (A=M31; G=Milky Way; $I1$ and $I2$=the two components of the initial IC 342 binary, $I=I1+I2$; M1 and M2=the two components of the initial Maffei 1 binary, M=M1+M2). The semimajor axes of the two binaries are given in columns 9 and 10, and the starting distances of the binaries and the Milky Way from M31 are given in columns 11–13. Column 14 gives the initial speed of the Milky Way directly away from M31, in units of the circular orbital speed around the center of mass of the system at that distance. The total mass of the system is given in column 15.

Table 2 summarizes the final configurations. Column 1 is again the case number. The masses at the end of the calculation are given in columns 2–5 (A=M31; G=Milky Way; I=IC 342; M=Maffei 1). Our representative cases are selected such that the final configuration has four galaxies, and M31 has resulted from a merger of three galaxies. Column 6 gives the mass ratio M31/(IC 342+Maffei 1), which is a result of both the type of initial conditions used and the dynamical processes involved. The fiducial value is 2.3. The final distances between the Milky Way and the three other galaxies are given in columns 7–9. The corresponding radial velocities are given in columns 10–14. Columns 10–12 list velocities relative to the center of the

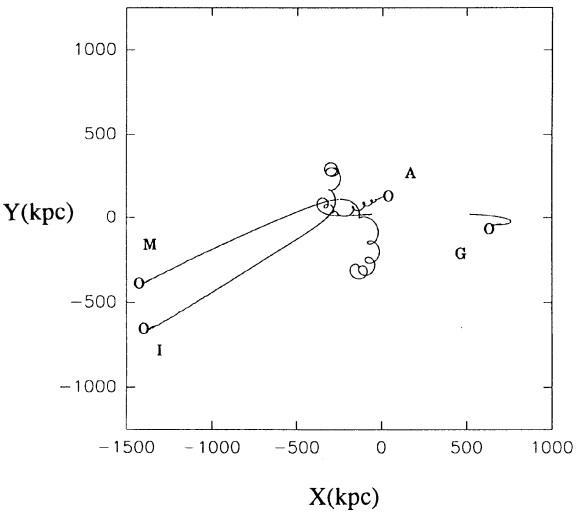

FIG. 5. The orbits of four galaxies in case 5. The circles mark the final positions. The orbits of the two merged binary members are not shown.

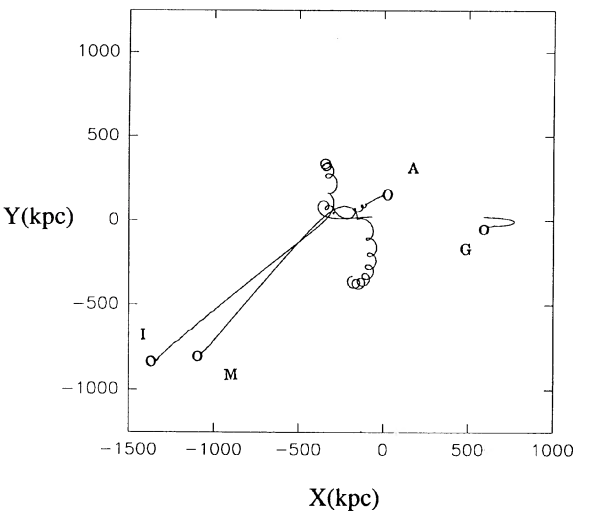

FIG. 7. The orbits of four galaxies in case 7. The circles mark the final positions. The orbits of the two merged binary members are not shown.

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TABLE 1. Initial parameters in sextuple galaxy experiments.

Case no.	Time (10^6yr)	Masses (10^{11} $M_\odot$)						Semi-major axes (kpc)		Starting distances (kpc)			Milky Way Speed	Total mass $10^{11}M_\odot$
		A	G	I1	I2	M1	M2	M	I	M	I	G		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
2	12 200	8.4	8.4	6.3	2.1	6.3	2.1	42.5	42.5	318	330	720	0.93	33.6
3	14 200	8.4	8.4	6.3	2.1	6.3	2.1	42.5	42.5	390	400	658	0.91	33.6
4	14 700	6.7	6.7	3.3	3.3	3.3	3.3	40.0	40.0	390	400	658	1.085	26.8
5	11 300	10.1	10.1	7.5	2.5	7.5	2.5	46.5	46.5	330	340	580	1.2	40.3
6	11 100	9.8	9.8	5.8	4.7	5.8	4.2	48.0	49.5	330	340	580	1.4	40.1
7	14 700	6.3	4.7	4.7	1.6	4.7	1.6	37.0	37.0	390	400	658	0.85	25.0

Milky Way. However, in evaluating a model, we take the most crucial factors to be the heliocentric radial velocities of the ejected galaxies minus the heliocentric radial velocity of M31. These are given in columns 13 and 14, assuming the circular velocity of the Sun is 220 km s^{-1}. The observed differences are 324 and 289 km s^{-1} for IC 342 and Maffei 1, respectively.

Only in case 5 does the mean of the radial velocities of IC 342 and Maffei 1 relative to M31 reach the observed value, but case 3 comes close to the observed value. Cases 4 and 6 produce radial velocities which are too small. Cases 2, 3, 5, and 7 are models for which the mass ratio M31/(IC 342+Maffei)$\geqslant$5. For these, the total mass of the Local Group$\geqslant 33\times 10^{11}$ $\mathcal{M}_\odot$. A high mass ratio (inconsistent with the fiducial value) and a large total mass appear to be the two main requirements for an acceptable model.

4. ROTATION CURVE LIMITATIONS

We have found in the previous section that the requirement of high speed ejection of two galaxies puts a clear lower limit on the total masses of the galaxies. We now compare how this limit agrees with what we know of the masses on the basis of rotation curves. What is essential to explain the observations with the proposed model is a high rotation speed at the edge of the galaxies. This allows a lot of mass to be contained in a tight binary, thus maximizing the orbital (and ejection) velocities. Merely raising the masses of galaxies by adding mass to the outer layers while keeping the rotation curves flat does not improve chances of high speed ejections, because the initial semimajor axis of the binaries must be increased to prevent merging. As the mass of the system rises, so must the edge value of the rotation speed for each galaxy.

The circular rotation speed at the edge of the model galaxy i is

$$V_i = 190\ (m_i/10^{11}\mathcal{M}_\odot)^{1/4}\ \text{km s}^{-1}, \quad (3)$$

for our assumed potential. For IC 342, using $m_i=2.1\times 10^{11}$ $\mathcal{M}_\odot$ from column 4 of Table 2, leads to $V_i\cong 230$ km s^{-1}, in contrast to the observed $V_i\cong 190$ km s^{-1}. Figure 8 shows the observed rotation curve (filled circles) for IC 342 (Newton 1980). The filled triangle corresponds to the edge velocity and radius. The model could be made to agree with extrapolated observations by lowering the mass of IC 342 to about half of the model value. Alternatively, one could postulate the existence of an additional massive component outside the last observed point in the rotation curve. The former is probably more reasonable. If the mass of Maffei 1 is reduced by the same factor, then the M31/(IC 342+Maffei 1) mass ratio is raised to about 10. There is no objection to this on dynamical grounds, but the mass ratio is about four times larger than the fiducial value.

In our model, M31 is a multiple merger, and we have no reason to expect that its observed maximum rotational velocity would come from Eq. (3), i.e., the rotation curve may not be primordial. The only pristine galaxy, according to our simulations, is the Milky Way. Thus, the presently observed rotation curve should be close to the original. Therefore, it is worth examining the Milky Way in greater detail.

Our objective is it constrain the mass of the Milky Way by producing a simple galactic mass distribution which

TABLE 2. Final results in sextuple galaxy experiments.

Case no.	Masses (10^{11} $M_\odot$)				Mass ratio	Distances (kpc)			Radial speeds (km s^{-1})				
	A	G	I	M	A/(I+M)	A-G	I-G	M-G	A-G	I-G	M-G	I-A	M-A
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
2	21.0	8.4	2.1	2.1	5	671	1935	2000	-116	197	109	313	225
3	21.0	8.4	2.1	2.1	5	712	2429	1897	-109	280	71	389	180
4	13.4	6.7	3.3	3.3	2	710	1949	2046	-103	217	39	320	142
5	25.2	10.1	2.5	2.5	5	705	2095	2126	-110	275	123	385	233
6	20.3	9.8	5.8	4.2	2	803	1903	1769	- 72	184	79	256	151
7	15.6	4.7	1.6	1.6	5	703	1865	2184	- 90	195	119	285	209

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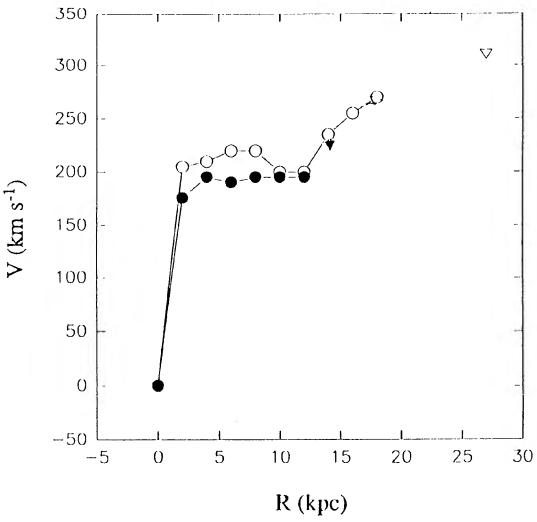

FIG. 8. The rotation curves of the Milky Way (open circles, Fich & Tremaine 1991) and IC 342 (filled circles, Newton 1980). Triangles mark the rotation speed at the edge of each galaxy which is required by the models. The position of the open triangle corresponds to a mass for the Milky Way of $7.5\times10^{11}\,\mathcal{M}_\odot$. The position of the solid triangle corresponds to a mass for IC 342 of $2.1\times10^{11}\,\mathcal{M}_\odot$.

approximately mimics the rotational behavior described by Fich & Tremaine [1991, Fig. 2(b)]. The outstanding feature of the rotation curve is a dramatic rise in rotation speed from $\sim$210 km s^{-1} somewhat beyond the solar circle to $\sim$300 km s^{-1} at a galactocentric distance of $\sim$20 kpc (see Figs. 8 and 9). For simplicity, it turns out to be adequate to work with a massive, spherical halo, a pure disklike component, and a compact spherical nucleus (no "bulge" is necessary, and the spherical nucleus is only cosmetic in the sense that it produces the sharp central peak of 250 km s^{-1} at 0.5 kpc).

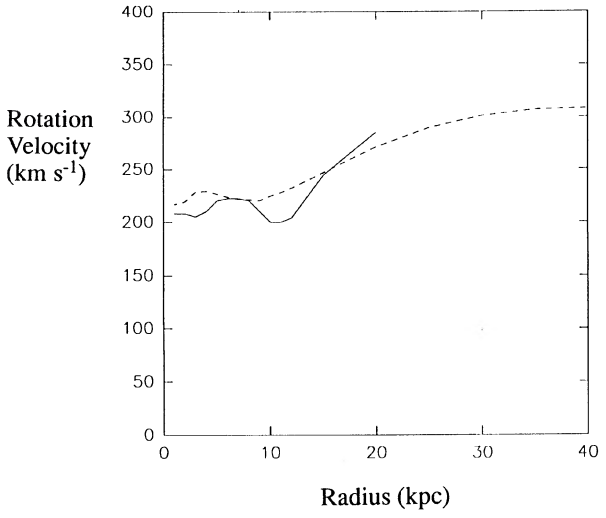

FIG. 9. A model (dashed line) fit to the observed rotation curve (solid line) of the Milky Way. Observations: Fich & Tremaine (1991); theory: see the text.

The spherical halo we use is completely equivalent to a Plummer potential (Spitzer 1987, p. 13). The required total mass and scale size are, respectively, $1.6\times10^{12}\,\mathcal{M}_\odot$ and 30 kpc. Approximately 35% of the mass is inside a sphere of radius 30 kpc. In fact, the halo is so massive that it contributes about 35 km s^{-1} to the rotational speed of 221 km s^{-1} near the Sun at 8.0 kpc. Therefore the pure disk component (scale size 2.6 kpc, mass $0.65\times10^{11}\,\mathcal{M}_\odot$) has been reduced in mass somewhat to compensate for the presence of the halo. The disk potential is of the same family used, e.g., in Carlberg & Innanen (1987).

The fitted rotation curve, together with the mean Fich and Tremaine curve, are shown in Fig. 9. The 15 km s^{-1} dip in the rotational data of Fich & Tremaine just beyond the solar circle, if real, seems difficult to replicate with the demands of the massive halo. Whether the dip is real or not, however, has no significant effect on the outcome of the present work.

The comparison of the fit with the model of Sec. 3 has to be done in terms of rotation velocity at the edge of the galaxy. Using Eq. (3) and Table 2, the model rotation speed should be at least 320 km s^{-1}, while the fit to the rotation curve only allows about 300 km s^{-1}. Therefore the mass values of Table 2 for the Milky Way have to be considered to be upper limits.

One could also modify the models of Sec. 3 by lowering the mass of the Milky Way by a factor of 1.3, for example. The Milky Way plays no role in the ejection of IC 342 and Maffei 1, and its total mass is thus of secondary importance. The drawback of this modification would be a commensurate increase in the mass ratio M31/Milky Way, which we have kept in the range 2–3. The resulting ratio would be even farther from the fiducial value, which is 1.4.

Overall, it would seem that rotation curves point toward a systemic mass less than $3\times10^{12}\,\mathcal{M}_\odot$. Combining this with the lower limit from the simulations, a mass value not far from $3\times10^{12}\,\mathcal{M}_\odot$ may provide self-consistency for the overall properties of the four galaxies. Note that this result is not sensitive to the age of the universe.

5. GENERALIZED TIMING

Given the nature of the models, it is possible to time the four-body system by applying the principles of conventional timing in two stages. It is possible to regard the Milky Way and the progenitor of M31 as being initially in bound radial orbits with respect to one another. The binary encounters about 5 billion years ago can be represented as a sudden addition of mass to M31 with concomitant ejection of another body, namely, the center of mass of IC 342 and Maffei 1. Thus, the two-body timing problem considered by Kahn & Woltjer (1959) is most simply generalized as a combination of two-body and three-body timing problems.

In practice, we solve the reverse problem. The three-body system is integrated backwards in time from the observed present configuration until the center of mass of Maffei 1 and IC 342 collides with M31. This moment corresponds to the dynamical ejection of Maffei 1 and IC 342,

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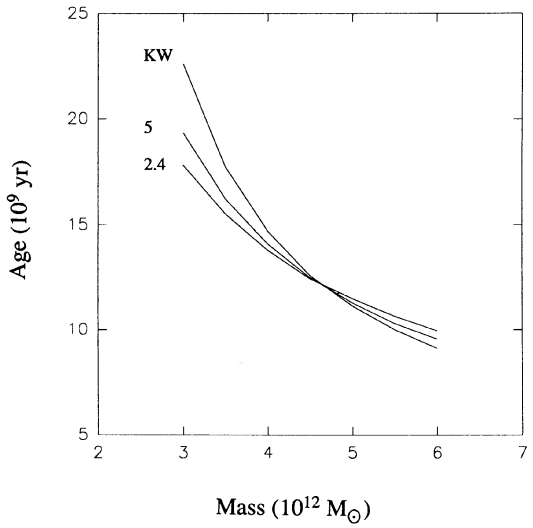

FIG. 10. The Kahn–Woltjer (conventional timing) relation between the age of the universe and the mass of the Local Group (KW), as well as the relations for generalized timing with the M31/(IC 342+Maffei 1) mass ratio set to 5 and 2.4. As the mass ratio increases, the solution goes towards the KW line. For the computations, the distance to the center of mass of IC 342 and Maffei 1 was set to be 2.0 Mpc, and the circular velocity at the Sun was adopted to be 220 km s^{-1}.

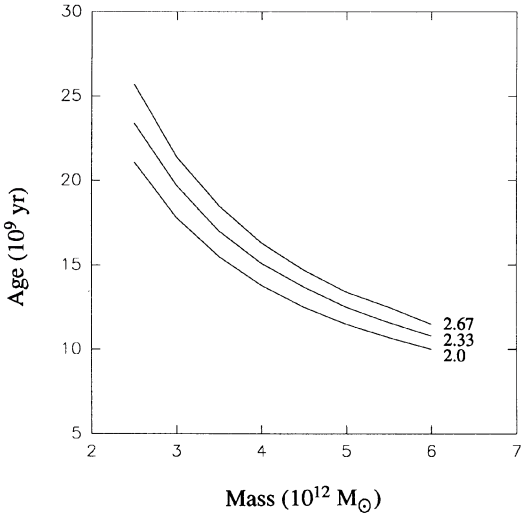

FIG. 11. The age of the universe vs systemic mass for three values of the present distance to the center of mass of IC 342 and Maffei 1. The distances (in Mpc) are given next to the curves. For the computations, the M31/(IC 342+Maffei 1) mass ratio was fixed at 2.4, and the circular velocity at the Sun was set at 220 km s^{-1}.

time reversed. From there, the orbits of the Milky Way and the progenitor of M31 are integrated backwards until the two bodies collide at the time of the Big Bang. The moment of collision gives the age of the universe, which can be calculated as a function of various parameters: the mass of the system, the relative masses of the galaxies, the local solar orbital speed (which sets present relative velocities), and the present separations of the galaxies. The transverse speed of the center of mass of Maffei 1 and IC 342 is constrained by the requirement that the center of mass and M31 go back to the same point.

In Figs. 10–12, we provide examples of how the relationship between the age of the universe and the systemic mass changes with different choices for the key parameters. Figure 10 shows the effect of varying the mass ratio M31/(IC 342+Maffei 1). Also shown is the Kahn–Woltjer (i.e., conventional timing) relation which is equivalent to that for the ejection of a galaxy of zero mass from M31 (KW in Fig. 10). The present distance of the IC 342-Maffei 1 center of mass was taken to be 2.0 Mpc, and the local circular rotation speed in the Milky Way was adopted to be 220 km s^{-1}. Figures 11 and 12 show the effect of varying the center-of-mass distance and the solar velocity, respectively, when the mass ratio is 2.4. In all three figures, the value of the varying parameter is given next to each curve.

The Kahn–Woltjer relation is modified by the inclusion of mass ejection. With a systemic mass of 3×10^{12} $\mathcal{M}_\odot$, the age of the universe is reduced from 23 billion years to about 19 billion years by allowing an ejection of one-fifth of the present Andromeda mass. Figure 11 shows that an increase of the center-of-mass distance by 30% would increase the age of the universe back to about 23 billion years, keeping other parameters constant. Figure 12 demonstrates that an increase of the local circular velocity to 250 km s^{-1} would bring the age down to about 14 billion years.

In all of the above calculations we used the Andromeda/Galaxy mass ratio of 1.87. As mentioned in Sec. 2, the best value at present may be only 1.36. The effect of lowering the mass ratio is to increase the age of the universe. For example, in Fig. 10 the curve labeled 2.4

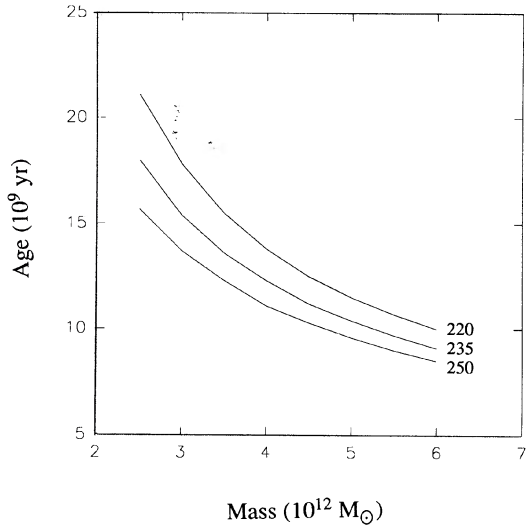

FIG. 12. The age of the universe vs systemic mass for three choices of the rotation speed of the Milky Way at the solar radius (in km s^{-1}). For the computations, the M31/(IC 342+Maffei 1) mass ratio was fixed at 2.4 and the distance to the center of mass of IC 342 and Maffei 1 was set to 2.0 Mpc.

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would be raised to the level of the curve labeled 5.

If we take the best fiducial values available at present (see Sec. 2) as well as the total mass of $3\times10^{12}\ \mathcal{M}_\odot$, we obtain an age of 19×10^9 yr. The greatest uncertainty in this value comes from the uncertainty in the total mass of the Local Group. If it is in the range $2.5\text{–}3.5\times10^{12}\ \mathcal{M}_\odot$, then the age of the universe is likely to be in the range $16\text{–}25\times10^9$ yr. The result agrees nicely with the age derived from globular clusters (Catelan & de Freitas Pacheco 1992).

6. CONCLUSIONS

Using *N*-body integrations, we find that there do exist scenarios which can explain the high velocities of IC 342 and Maffei 1 relative to the Local Group. The main requirement is that the mass of the four-body system (M31, Milky Way, IC 342, and Maffei 1) exceed about $3\times10^{12}\ \mathcal{M}_\odot$. In addition, the galaxies involved in the dynamical ejection of IC 342 and Maffei 1 need to have high rotational velocities at their edges. Reasonable extrapolations from the known rotation curves of IC 342 and the Milky Way make it difficult to raise the systemic mass above $3\times10^{12}\ \mathcal{M}_\odot$. Thus, a self-consistent solution appears to be possible only if the total mass is about $3\times10^{12}\ \mathcal{M}_\odot$. The total amount of blue light in the galaxies is $0.9\times10^{11}\ L_\odot$, which gives an average mass-to-light ratio of $33\ \mathcal{M}_\odot/L_\odot$. These results are not particularly sensitive to the age of the universe, but on the other hand they are not that different from the results of conventional timing.

Accordingly, we reverse the problem and use our new understanding of the history of the Local Group to study the age of the universe. We modify the Kahn–Woltjer timing argument to suit the more complex dynamical evolution, but results are not very much different from the original ones. The most likely value for the age of the universe is about 19 billion years. However, this could be varied either way by ~25% because of the uncertainties in the total mass of the Local Group, in the distances and masses of IC 342 and Maffei 1, and in the local circular velocity at the solar radius.

The biggest problem of the proposed evolutionary scenario is that the ratio of the mass of M31 relative to (IC 342+Maffei 1) seems to be required to be significantly higher than expected from observations. Consequently, this may force the sizes of the galaxies to be comparable to the semimajor axes of the binaries from which they were ejected. If the fiducial mass ratios are correct, and if rotation curves do not rise at large radii, then an alternative model would have to be found.

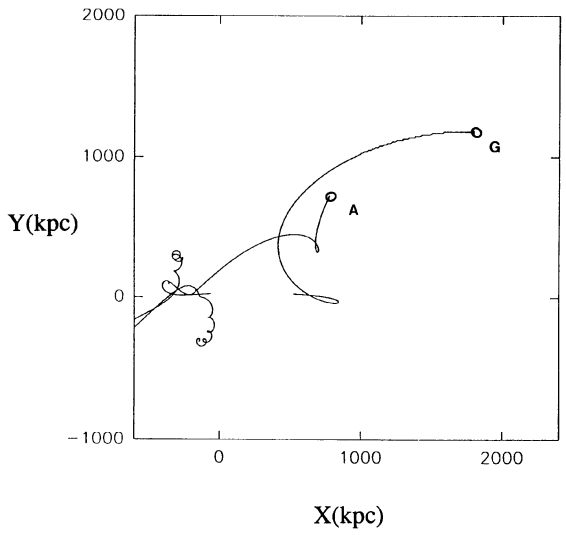

FIG. 13. The future orbits of M31 and the Milky Way in case 7. The positions 20 billion years from now are marked by circles.

In view of the violent history of the Local Group, it is interesting to ask what lies ahead. Consequently, we have run case 7 forward in time another 20 billion years. The orbits are shown in Fig. 13. Due to the transverse momentum of M31 imparted by the ejections, the Milky Way will not have a very close encounter with M31. Instead, the two galaxies will form a wide binary. The distance at closest approach in this scenario is about 250 kpc, a distance which does not much disturb the disks (Byrd & Howard 1992).

Since we propose that at least two galaxies have merged with M31, it is reasonable to ask whether or not observational evidence of the events remains. This question will be addressed in another paper (Valtonen *et al.* 1992).

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