PART III

DYNAMICS AND EVOLUTION

https://doi.org/10.1017/S0074180900242940 Published online by Cambridge University Press

Local organizers Willy Bosman (standing) of Groningen University Congress Office and Jan de Boer, between secretary Ineke Rouwé and Eli Brinks (left). Behind De Boer: LOC Chairman Allen, between Lin (left) and Paul; continuing around the table: Rydbeck, Johansson, D.M. and B.G. Elmegreen.
LZ

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SECTION III.1

MILKY WAY, MAGELLANIC SYSTEM AND LOCAL GROUP

Thursday 2 June, 1220 - 1320

Chairman: T.S. van Albada

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.bove: Oort and Van Albada. In background, to their left: D.B. Sanders, unidentified, Liszt, Lub and Higgs; at right: Terzides and Alladin. Foreground, from left: Van Driel, Mrs. Oort, Kormendy, Fujimoto, Okuda, Seiden, Brink, Carignan. LZ
Below: Mieke Oort (right) and Anneke van Albada LZ

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SLIPPERY EVIDENCE ON MASSES IN THE LOCAL GROUP

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Once it is agreed that not all mass gives a significant contribution to light or any other emission, then one must rely on the dynamics of the visible objects to determine the total gravity field. It is clearly impossible to do this without subsidiary hypotheses. Here we shall assume that all members of the Local Group began together in the Big Bang, and that their dynamics have been governed by their mutual gravitational interactions since the system first achieved a size of some 200 kpc. This must have been some 10^9 years after the Big Bang.

The light of the Local Group is dominated by that of M31 and the Milky Way, so we shall assume that they and their haloes dominate and these masses will in turn determine the dynamics of the Group. Our aim will be to determine their masses.

Objects close to either of the big two will typically have orbits with periods much less than 10^{10} years, so that they will have been in and out more than once. There are nine satellites of the Milky Way that fall into this category and at least seven satellites of M31. One may use their separations from their primary galaxy and their velocities to determine the masses of the two primary galaxies as far out as the satellite systems extend. Such estimates assume the satellites are randomly phased in their orbits which are randomly oriented to the line of sight (Lynden-Bell 1983). Some subsidiary data come from satellites whose light distributions show evidence of tidal limitation by the primary. As we shall see in the next section, the data are not yet sufficient to do a good job on M31, while our special observing position leads to an ambiguous result for our satellites.

However, of greater interest than the discussion of the short-period orbits is the discussion of those with periods greater than the current age of the Universe. For these orbits we are not only interested in the amplitudes of the motions but also in their phases, because we have the boundary condition that all the objects must have been together at the Big Bang. The simplest example of this constraint was given in the timing argument of Kahn & Woltjer (1959). They assume that the present

H. van Woerden et al. (eds.), The Milky Way Galaxy, 461–469.

https://doi.org/10.1017/S0074180900242940 Published online by Cambridge University Press

velocity of approach of M31 has been caused by our mutual attraction, which first slowed our relative expansion in the Big Bang and then reversed it. This picture gives us a relationship between the sum of the masses M, the time since the Big Bang t, the relative velocity of the two galaxies v and their separation r. To sufficient accuracy (3%) this relationship is

$$\left(\frac{GM}{r^3}\right)^{\frac{1}{2}} t + 0.85\ vt/r = 2^{-2/3}\pi = 1.11\ . \qquad (1)$$

For r = 700 kpc, t = $(1.5\pm0.5)\times10^{10}$ yr, and v = −123 km/s we have M = $(4.3\mp1.0)\times10^{12}$ $M_\odot$. This result is increased if significant transverse motion exists in the Milky Way - M31 binary. Such a transverse motion was formerly found, but with Sandage's new determination of Local Group members we find that our Galaxy's motion through them is towards Andromeda to within better than the accuracy of determination. v depends on the heliocentric velocity of Andromeda, for which we used −301 km/s, and the circular velocity of the LSR for which we used 220 km/s. Recent radio data may favour −310 km/s for M31 which would require even more mass. Alternatively, if our circular velocity is 250 km/s, then M is reduced to $(3.4\mp0.9)\times10^{12}$ $M_\odot$.

The largest uncertainty is in the time since the Big Bang. If we knew the distances to more distant members of the Local Group more accurately, we could in fact determine that time as well, because the distance and velocity of the third member from the barycentre also obeys relation 1 in the approximation in which M31 and the Galaxy are treated as a single heavy mass. With two equations like (1) both M and t may be solved for. My attempts to do this using the small galaxy Wolf-Lundmark-Melotte have yielded ages between 16 and 10 billion years, depending on whether WLM is at 1.6 Mpc or 1.3 Mpc distance (Lynden-Bell 1981).

A crucial assumption of all methods based on Local Group dynamics is that M31 and the Galaxy are truly dynamically related. If the masses are insufficient to bind us, then as we proceed into the past, M31 will continue to recede and other galaxies will come between us. Eventually there will be such a mass between that we will all be dragged back together into the Big Bang. It is not obvious that the relative motion of M31 and the Galaxy must have been reversed by our gravity rather than by the intervention of others.

THE M31 SUBGROUP

M31, M32, NGC205, 185, 147, and the dwarfs I, II & III are members. Other more doubtful candidates are M33, IC10, Pisces and IC1613 - the last is 40° away from M31 but at a similar distance. Figure 1 shows log $3(\Delta v_r)^2$ plotted against distance from M31. The former should equal log V_c^2 on average because of the theorem that in time average around any orbit $\langle \underline{v}^2 \rangle = -\langle \underline{r}.\underline{\nabla}\psi \rangle = \langle V_c^2 \rangle$. For this reason the rotation curve

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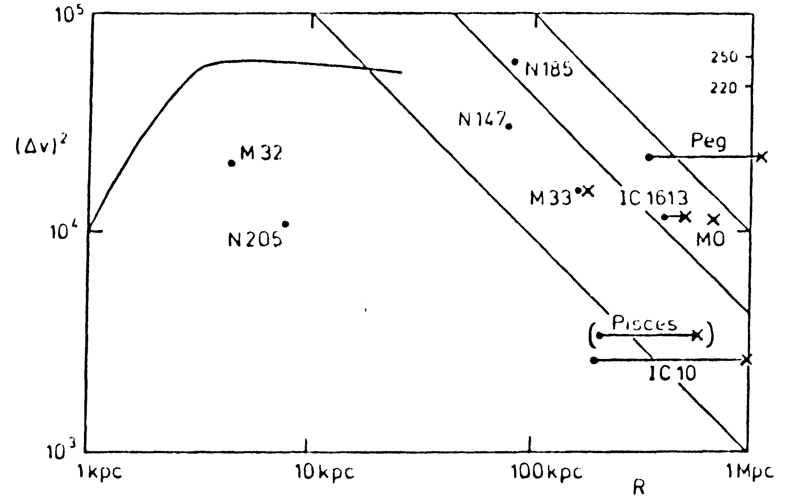

FIGURE 1: Possible Andromeda Satellites. Sloping lines are 2.3, 10 and 23 x 10^{11} $M_{\odot}$.

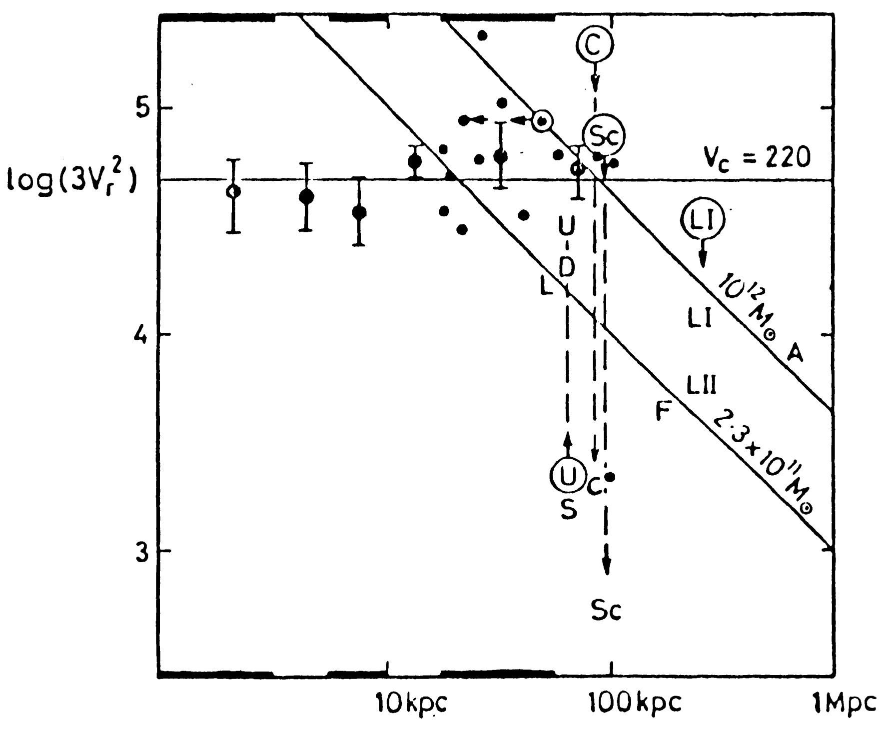

FIGURE 2: Satellites of the Galaxy (obsolete values ringed) and means of globular clusters (with error bars); distant globulars are also plotted individually.

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of M31 taken from Newton & Emerson is also plotted. It looks as though the rotation curve probably stays high out to nearly 100 kpc and that a total mass appropriate for M31 is of the order of 1 or 2 x 10^{12} $M_\odot$.

THE MILKY WAY SUBGROUP

Large masses have been obtained by several workers trying to get precise gravitational models for the Magellanic Stream, but such modelling depends crucially on the idea that only gravitational forces are involved. Relaxing this constraint would probably allow too many new parameters to give any definitive result. Davies & Wright (1977) early showed that even within gravitational models a heavy mass for the Galaxy was not the only possible way of getting the high velocities in the Magellanic Stream. If we want more definite assurance that the Galaxy is heavy, we should turn to the observations of globular clusters and satellite galaxies, Figure 2. At first glance it appears that the flat rotation curve of the Galaxy must continue out to 100 kpc. However, there are disturbing reasons to treat this result with caution. Firstly, not all the globular-cluster data are accurate and some clusters still have their distances changed by factors of 2 or 3! In our problem clusters of large $v^2 r$ are important. The majority lie below a line corresponding to 2.3 x 10^{11} $M_\odot$. The scatter of points above and to the right of that could be sent there by poor velocities, poor distances or a suitable orientation of the velocity vector so that $v^2 \cong v_r{}^2$ rather than being three times as large. Note it is the distant, faint halo globulars with low metal abundance and weak lines in their spectra that determine the outer extension of the Galaxy. It is these that will have the greatest distance and velocity errors. A hint that this may indeed be so comes from the dwarf-spheroidal galaxies, where the method of measuring the velocities off Carbon-star band heads has greatly improved the data over the last two years, particularly by the hands of Richer & Westerlund (1983), and Aaronson, Olszewski & Hodge (1983). Whereas Draco has remained with the velocity as determined off red giants by Hartwick and Sargent (1978), there have been large changes in the velocities of Sculptor and Ursa Minor. Very recently Lynden-Bell, Cannon and Godwin (1983) redetermined Carina's velocity and showed that, far from being the Galaxy's fastest-moving satellite, it was in fact one of the slowest. The heliocentric velocity is not 450±100 but 240±10 km/s, and this changes the Galactocentric velocity from 235 to 24! Of our 9 satellites, 7 now have well-determined velocities: LMC, SMC, Draco, Ursa Minor, Sculptor, Carina and Fornax. The velocities of Leo I and Leo II are currently less secure, mainly because the Carbon stars are so faint in these distant systems.

On the hypothesis that the motions are randomly oriented to the line of sight, we can determine the rms circular velocity at the distance of these satellites (52 to 220 kpc) to be

$$V_c = \langle 3v_r{}^2 \rangle^{\frac{1}{2}} = 106 \pm 19 \text{ km/s}.$$

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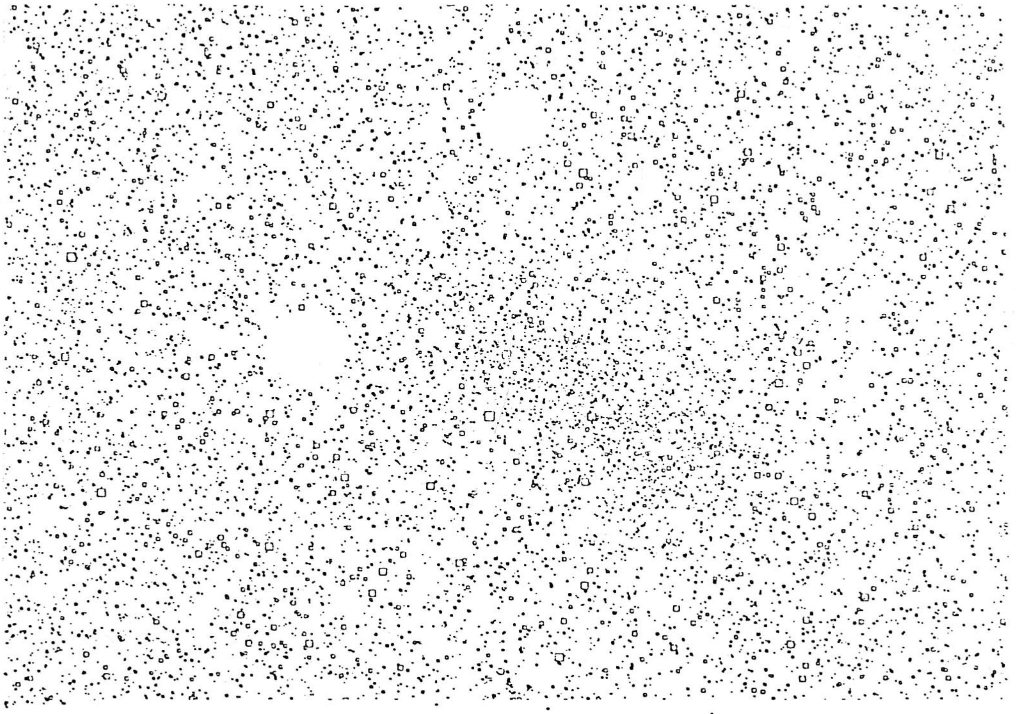

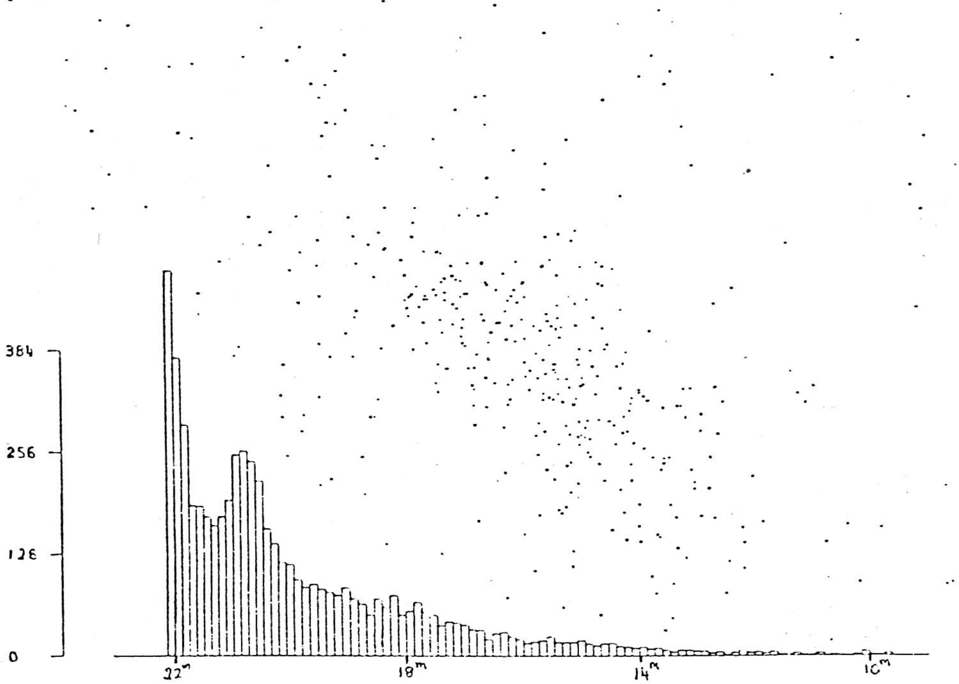

FIGURES 3 & 4: Ursa Minor dwarf. Processed by Kibblewhite's A.P.M. Group, Cambridge.

This low value suggests that a point-mass approximation to the orbits might be appropriate. For such orbits the radial velocity is given by

$$v_r^2 r = GM\, e^2 \sin^2\phi \,/(1+e \cos\phi),$$

or time-averaging over the orbits

$$\langle v_r^2 r\rangle = \tfrac{1}{2}\, GM \langle e^2\rangle .$$

Now Jeans (1928) showed that, if the velocities are isotropically distributed, then e is distributed like 2e de between 0 and 1. We therefore expect $\langle e^2\rangle = \frac{1}{2}$ and

$$GM = 4 \langle (v_r^2 - \varepsilon^2) r\rangle .$$

We have replaced v_r^2 by $v_r^2-\varepsilon^2$ to allow for measurement errors in velocities, ε, which are significant for Leo I and Leo II. Applying this formula to the nine satellites of the Galaxy (which lie between 52 and 220 kpc from the centre) we find

$$M = (2.6 \pm 0.8)\times 10^{11}\ M_\odot$$

A result which, if taken at face value, implies no heavy halo. As implied by our title, this result should not be taken uncritically. $\langle e^2\rangle = \frac{1}{2}$ implies a typical e $\sim$ 0.7 or a typical radial excursion by a factor 6. Most of the satellite galaxies could not withstand the tide of the Galaxy if they were brought 6 times closer. Thus it is not unlikely that the orbits of our distant satellites are just those that allow those satellites to survive. The more nearby circular orbits ($e<\frac{1}{2}$) will never have subjected them to tides capable of tearing them apart. If in place of Jeans's distribution we say that the eccentricity distribution is truncated at $e = \frac{1}{2}$, then we have a distribution 8e de and a $\langle e^2\rangle$ of 1/8 in place of $\frac{1}{2}$. This gives a mass of four times our former estimate, consistent with a heavy halo which extends to 100 kpc.

The great importance of tides in the above argument has led us to look more carefully at the distribution of faint stars in Ursa Minor on a deep IIIaJ Schmidt plate, kindly provided by the Palomar Observatory. Although Ursa Minor is never easy to see on an original plate, it shows up well on a plot of all faint stars on the plate, Figure 3. We may study its extent by taking only the blue horizontal-branch stars which give a remarkably clean picture, Figure 4. At the bottom we superpose the luminosity function. All this work is the product of the A.P.M. unit at Cambridge. In Figure 3 Ursa Minor has a sharp NW edge and is elongated at $53^\circ \pm 3^\circ$ with b/a = 0.47, values in good agreement with those of Hodge (1964). The orientation is almost precisely along the Magellanic Stream, and it lies as accurately in the stream as the SMC, to which it is antipodal in the galactocentric sky. Since Draco is also antipodal to the LMC and oriented along the Magellanic Stream, the idea of a tidal origin of all dwarf spheroidal galaxies should be taken seriously. Sculptor, Leo I, Leo II and Fornax lie too precisely in a galactocentric great circle for chance alignment. If they were made from debris torn off Fornax in some long-dead Fornax stream, we have a natural explanation of this great circle.

DWARF SPHEROIDALS AND MISSING MASS

If the missing mass were heavy neutrinos with a rest mass of 10-30 eV/c^2, then they will have moved collisionlessly since they were created in the Big Bang. Their phase-space density will be the same as it was initially, but on coarse graining it may decrease. Such arguments show that it is difficult to account for galaxies' heavy haloes with such particles, and it would be impossible to account for missing mass in the weakly bound dwarf spheroidals. Aaronson's work on Draco (Aaronson 1983) is especially interesting in this regard, as it may indicate the need for missing mass there, in which case we would have an example of abundant dark matter that is not neutrinos. However, the reliability of Aaronson's result can be called in question, because different Carbon stars have dredged up different amounts of Carbon from their interiors. Thus correlation techniques may give slightly different velocities for Carbon stars whose spectra differ, even if the true velocities are the same. It is possible that Aaronson's apparent velocity dispersion arises from such a situation, in which case the estimate of the mass and missing mass of Draco would be meaningless. An easier test may be made with Fornax, where the one planetary nebula and the five globular clusters have velocity differences within their errors (Cohen 1983). There is no case for Fornax having a mass-to-light ratio greater than that of a normal stellar population. This must cast some doubt on the Draco result.

ENHANCED TIDES AND HEAVY HALOES

By giving galaxies more mass the heavy-halo hypothesis clearly enhances tides between them, but there is also an indirect effect that makes tides about three times greater still. For example, the tide of M31 will distort our halo, and our distorted halo then helps to distort our disk. Thus the tide imposed by M31 and its halo will be magnified by the distortion of our halo. To be definite, we take a static model with an initially spherical halo with density $\rho = A\, r^{-\alpha}$ and a free boundary at r_h. We shall assume that the halo is a polytrope of index n with $\alpha = 2n/(n-1)$ and follows the same equation of state during perturbation. Let the tide-producing body be of mass M and at distance R. The hydrostatic equation for the perturbed potential ψ reads

$$\nabla(\psi - \frac{dp}{d\rho}\frac{\delta\rho}{\rho}) = 0 \; ,$$

from which one deduces that $\delta\rho = \rho \dfrac{d\rho}{dp}\, \psi$.

Inserting this perturbation in Poisson's equation and taking ψ and ρ to have the P_2 tidal form, we have

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$$\nabla^2\psi = r^{-2}\, d/dr(r^2 d\psi/dr) - 6\psi/r^2 = -4\pi G\rho\, d\rho/dp\ \psi$$

If we write $\psi_\ell = d\psi/d\ln r$ and evaluate $G\rho\, d\rho/dp$ from the unperturbed state, this equation becomes

$$\psi_{\ell\ell} + \psi_\ell - [6 - N]\psi = 0 \quad \text{where } N = \alpha(3-\alpha)$$

hence $\psi = C(r/r_h)^\beta P_2$,

where β is the positive root of $\beta^2 + \beta - (6 - N) = 0$

which is $\beta = -\frac{1}{2} + (\frac{25}{4} - N)^{\frac{1}{2}}$.

Outside the halo $\psi = [C_1(r_h/r)^{-3} + GM\, r^2/R^3]\, P_2$.

To evaluate C we must use the boundary conditions at $r = r_h$. Continuity of ψ gives $C = C_1 + GM\, r_h^{\,2}/R^3$ (2). The free boundary condition becomes

$$\beta C/r_h = -3C_1/r_h + 2GM\, r_h/R^3 + 4\pi G\rho\xi_r/P_2. \qquad (3)$$

Here ξ_r is the radial displacement at the boundary. ξ_r can be evaluated from the condition that on the displaced boundary there is no pressure change, which gives on the unperturbed boundary $r = r_h$ the condition

$$\delta p = -\rho\ \underline{\xi}\cdot\underline{g}\ ,$$

where $\underline{g}$ is the acceleration due to gravity at r_h. Evaluating these expressions we find

$$4\pi\ G_\rho\ \ \xi_r = (3-\alpha)\ \psi/r_h.$$

Hence from (2) and (3) $\quad C = [5/(\alpha+\beta)]\ GM\ r_h^{\,2}/R^3$.

Thus

$$E = \frac{\text{Total potential change}}{\text{imposed potential}} = \frac{\psi}{GM\ r^2\ P_2/R^3} = \frac{5}{(\alpha+\beta)}\left(\frac{r}{r_h}\right)^{\beta-2},$$

where the halo density is $Ar^{-\alpha}$ and $\beta = -\frac{1}{2} + [\frac{25}{4} - \alpha(3-\alpha)]^{\frac{1}{2}}$.

For $\alpha = 2$, $\beta = 1.56$ and $E = 1.4(\frac{r}{r_h})^{-0.44}$. For $r_h/r \sim 10$ this enhancement factor is 3.9. However, even with such a factor, Andromeda's tide remains a negligible effect out to well beyond the observed warp. The above calculation cannot describe the dynamic tide of the Magellanic Clouds which orbit within our dark halo.

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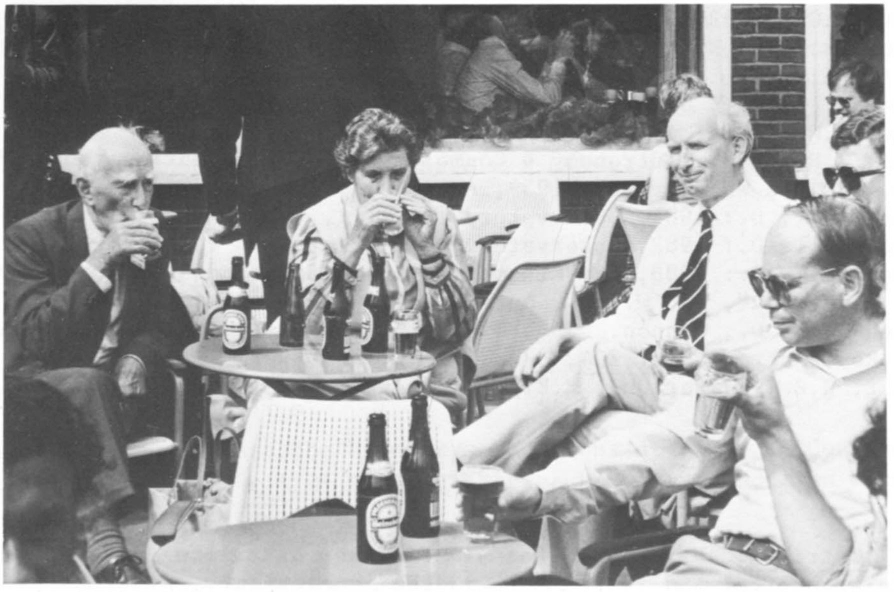
DISCUSSION

J.P. Ostriker: Have you reanalyzed the satellite data, assuming circular orbits? And if so, what is the conclusion?

Lynden-Bell: I know the exact answer to that: the mass of the Galaxy, assuming circular orbits, is infinite since we do discover actual velocity shifts.

Ostriker: It would be infinite anyway, because we are on an other side of the Galaxy.

Lynden-Bell: Yes, I agree, but the velocities do not correlate with position on the sky in the way one would like them to.



Above: Oort, Mrs. Oort, Lynden-Bell, Van der Laan and Hartwick. LZ
Below: Mrs. Blaauw and Alladin enjoy University President's supper, while Schmidt and Ostriker have another debate. CFD

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