THE ORIGIN OF DWARF SPHEROIDAL GALAXIES

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ABSTRACT

Two dwarf spheroidal galaxies are associated with the Magellanic Stream with their major axes oriented along it. Evidence suggests that all the dwarf spheroidal satellites of the Galaxy belong to one or other of two streams of tidal debris. If this is true the orbits will give the first reliable determination of the total mass of the Galaxy out to 120 kpc.

In order to measure the mass of our Galaxy's halo we need good data on well determined orbits far from the galactic centre. Can we get such information?

After taking account of the parallax due to our offset from the galactic centre Ursa Minor and Draco lie opposite the SMC and LMC in the Galacto-centric sky. They therefore lie in the great circle of the Magellanic stream. When a satellite is tidally torn, the main shearing is in the plane of the orbit - the part of the satellite closest to the Galaxy is pulled down towards it and runs forward in the orbital plane by angular momentum conservation, while the tidal tail is left behind in the orbit beyond the remnant of the satellite. Thus, from the Galactic centre a satellite that is being torn will appear as a streak elongated along the orientation of the orbit. Likewise, the pieces that are being torn away are likely to be shearing in the plane of the orbit. If pieces manage to hold themselves together their final spins are likely to be oriented with axes perpendicular to the orbital plane. Thus their major axes will be oriented in the orbital plane. In the figure the tick marks show the orientations of the major axes. Both Ursa Minor and Draco are oriented along the Magellanic Stream. This strongly suggests that they were once part of the Greater Magellanic Galaxy that has been torn up by successive passages. One might suspect that both objects were torn off long ago when still gaseous, and made

E. Athanassoula (ed.), Internal Kinematics and Dynamics of Galaxies, 89–92.

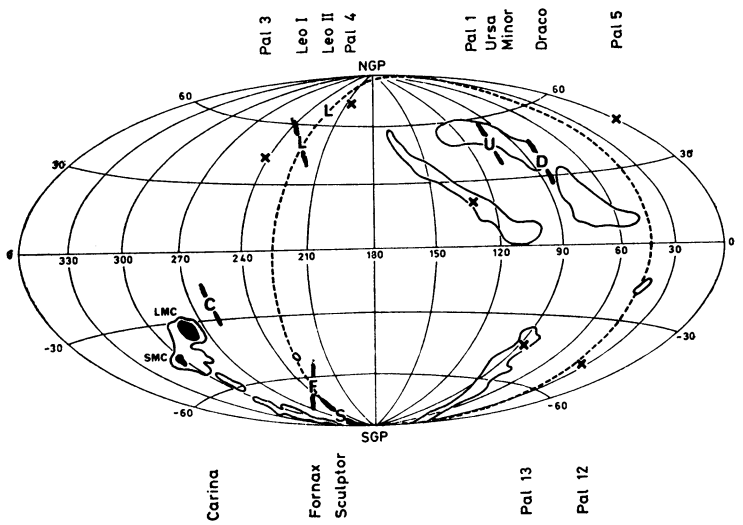

Figure 1. The Fornax-Leo-Sculptor great circle plotted on a map of high-velocity clouds with the dwarf spheroidal galaxies and diffuse globular clusters. The plot is in Galactic coordinates as observed from the Sun. Correction to the Galactocentric coordinates are minor.

stars through the shocks that accompanied the encounter. Hodge & Michie showed that both objects are at or close to their tidal limits even for a Galaxy without a halo.

The fact that two of our dwarf spheroidals were probably made from "tidal debris" suggests that all of them might have that origin. Carina lies near the Magellanic Clouds and although its orientation is 20° out of true, this is no more than is seen in some of the hydrogen clouds that form part of the Magellanic Stream. There may be a real association here but the case is not proven. There remain 4 other dwarf spheroidal satellites, Sculptor, Fornax, Leo I and Leo II. Of these, Sculptor lies very close to the Magellanic Stream but, although close to its tidal limit, it has the wrong orientation some 45° off that of the stream. More interestingly, all four of these systems lie accurately in a great circle in the galactocentric sky and Sculptor, the one closest to its tidal limit, is oriented along that great circle. The largest of these systems is Fornax which has four of its own globular clusters. This suggests the existence of a Fornax-Leo-Sculptor stream caused by the tidal break-up of a greater Fornax.

It will be interesting to search both this great circle and the Magellanic Stream circle for small faint dwarf spheroidals which may have been missed.

If we assume that Leo I, Leo II and Sculptor were torn off Fornax, then each should have approximately the same specific energy and specific

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angular momentum in its orbit about the Galaxy. Accurate tests of this can only be made when velocities for the Leo systems are available, but guessing that they will be small galactocentrically, one deduces a mass for the Galaxy out to 120 kpc of $(5 \overset{\times}{\div} 2) \times 10^{11}$ $M_\odot$. Most of the uncertainty comes from our imprecise knowledge of the velocity of Fornax. More work on the dwarf spheroidals will provide the best data on the mass of our Galaxy's halo however the orientations of Leo I, Leo II and Fornax do not lie along the F.L.S. stream. This might be because they are not close to their current tidal limits, but it could be that the great positional accuracy (the centres lie off 'the great' circle by only 0.5°, 1.4°, 0.6°, 0.6° while Sculptor agrees in orientation to 3°±3°) is after all due to a chance coincidence!

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DISCUSSION

WHITE: Under what conditions do you suspect that debris torn from a satellite galaxy will be able to overcome the tidal field of the parent and recollapse to form stellar systems such as Fornax or Sculptor?

LYNDEN-BELL: I do not believe that the tidal field of the parent has to be overcome as the debris may be a considerable distance from its parent before forming a true body. I envisage that the stream of debris may consist of two parts that try to cross each other and the resulting shocked region both loses energy and provides the conditions necessary for star formation. The resulting stellar system would then be weakly bound and therefore diffuse. This may well be the case for Ursa Minor and Draco in the Magellanic orbit and for Sculptor and the Leo systems in the other. Currently I regard Fornax as the most probable parent of this second suggested stream, in which case Fornax may not have been made by a much larger parent but merely shaken up as its outer parts were torn off.

INAGAKI: Do you think that the stellar debris and the gaseous debris were torn from the Magellanic Clouds at different epochs? If so have you a reason why?

LYNDEN-BELL: Unlike some astronomers, my familiarity with epochs long ago is much less than it is with the current one. We see gas currently leaving the surroundings of the Magellanic Clouds and being drawn out into the Magellanic Stream. It would not amaze me if one of

the larger condensations eventually formed stars and became a dwarf spheroidal galaxy. It would be diffuse for lack of binding and oriented along the orbit as indeed the clouds of the stream are. Since all this may be happening now, it seems natural to suppose that it may have happened before, both to the Magellanic Cloud system and to a probably gaseous proto-Fornax. There are examples in the sky of stellar systems being tidally torn but I get the impression that the smoother streams left behind by them will disperse. Draco and Ursa Minor were probably torn off the very outer parts of the Greater Magellanic Galaxy in gaseous form. I suspect old gaseous debris that does not condense gets too dispersed to be detected. Thus all that is needed is that the present epoch is none too particular but that the Magellanic Clouds have suffered repeated disruption due to tides. Magellanic Streams form whenever the spin orientations at closest approach are most favourable to disruption.

(The Figure is adapted from Ref. 5, with permission).

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