To appear in "The Formation of the Galactic Halo – Inside and Out", eds. H. Morrison & A. Sarajedini, (ASP, San Francisco).

Models of Dwarf Galaxy Destruction

C. Pryor

Dept. of Physics, Rutgers, the State University of New Jersey, P.O. Box 849, Piscataway, NJ, 08855–0849

Abstract. Dwarf galaxies might be destroyed either by internal processes, such as gas loss induced by star formation, or external processes, such as tidal disruption. It is hard to see how gas loss or stellar mass loss can disrupt a galaxy dominated by dark matter. Recent modeling of the tidal destruction of dwarf spheroidal galaxies around the Milky Way has concentrated on what the dwarf would look like during the destruction. A velocity gradient across the galaxy that is larger than the velocity dispersion is the clearest signature. The lack of such gradients in all of the local dwarf spheroidal galaxies except Sagittarius means that these galaxies are not being significantly affected by tides and that tides cannot explain their large measured mass-to-light ratios. Sagittarius probably is being destroyed by tides today and models of tidal destruction are being applied to interpret the observations of this galaxy.

1. Destruction Mechanisms

The small masses and shallow potential wells of dwarf galaxies makes their destruction seem more plausible than that of larger galaxies, which may merge, but are probably never dispersed. This article focuses on the nine dwarf spheroidal (dSph) galaxies orbiting the Milky Way, since their low masses, low densities, and/or closeness to our galaxy make them the best candidates for destruction.

The destruction of a gravitationally bound dwarf galaxy requires the input of energy from either internal or external processes. Internally driven gas loss, stellar mass loss, or ram pressure stripping of gas could remove mass from a dwarf galaxy, perhaps making it unbound. Alternatively, the tidal force of a larger galaxy could also destroy a dwarf.

The observation that large HI shells are common in dwarf galaxies (Puche & Westphal 1994, see also Marlowe *et al.* 1995 for the ionized gas) make it plausible that the radiation pressure, stellar winds, and supernovae from a young stellar population can at least push the interstellar medium to large radii and perhaps expel it completely. A similar process is the loss of stellar mass caused by supernovae and, more slowly, by stellar winds. Both of these are probably important for the early evolution of open and globular clusters (Hills 1980, Mathieu 1983, Angeletti & Giannone 1977, Chernoff & Weinberg 1990). The hot gas in clusters of galaxies may lead to the removal of gas from even massive galaxies (see the review by Sarazin 1986). Of more relevance to the local dSphs is that one of the mechanisms proposed to create the Magellanic Stream is the ram pressure stripping of gas from the Magellanic Clouds by a hot gaseous halo of our own galaxy (*e.g.*, Wayte 1991). While there is evidence for such halos from quasar absorption lines (Lanzetta *et al.* 1995) and from ram pressure heating of clouds in the Stream (Weiner & Williams 1996), such halos do not seem dense enough to strip dense gas clouds by ram pressure and so remove all of the interstellar medium.

The big problem with destroying even dwarf galaxies with gas loss or stellar mass loss is that it is very difficult to see how they can unbind a galaxy dominated by dark matter, as the visible matter is a small fraction of the total mass. The rotation curves of dwarf galaxies (*e.g.*, Carignan & Beaulieu 1989, Lake *et al.* 1990) and the velocity dispersions of the dSphs (*e.g.*, Mateo 1994, Armandroff *et al.* 1995) argue strongly that dwarf galaxies do contain dark matter (also see the discussion in section 3). Indeed, models of galaxy formation invoke the expulsion of gas in an early burst of star formation to explain the low surface brightnesses and metal abundances of the dSphs (Dekel & Silk 1986) or their star-formation histories (*e.g.*, Silk *et al.* 1987), rather than their destruction.

2. Tidal Disruption

Tides seem to be the most plausible dwarf galaxy destruction mechanism. A discussion of tides will take up the remainder of this paper. This mechanism received a considerable boost recently with the discovery of the Sagittarius (Sgr) dSph, which is very likely being tidally disrupted (Ibata *et al.* 1994; see also the discussion in section 5). However, I will argue in this paper that most of the local dSphs that we see today have not been significantly affected by tides.

A simple definition of the "tidal radius" (r_{tid}), outside of which tidal forces are important, is the radius at which the magnitude of the internal gravitational force equals that of the tidal force along the line connecting the centers of the dSph and Milky Way at closest approach (King 1962). Treating both bodies as point masses then leads to the criterion that tides will be important when the average density of the dSph approximately equals the average density of the Milky Way inside of the galactocentric radius of the dSph. The low central densities of stellar matter in the dSphs, about 0.01 $M_{\odot}$ pc^{-3}, led Hodge (1971; Hodge & Michie 1969) to suggest that some of the observed dSphs extended beyond their tidal radii and would soon be destroyed by tidal forces.

The luminosity profiles of the local dSphs fall steeply outside of the core. Mass probably does not follow light, but let us start by taking this as a first approximation. Then a dSph should be either completely disrupted or experience little tidal damage since there is no extended low-density envelope which could be more easily tidally stripped than the denser inner regions (see the discussion in Oh *et al.* 1995, OLA hereafter). Most of the dSphs have a central concentration index $\log(r_{lim}/r_c) \lesssim 1$ (see the summary in Piatek & Pryor 1995, PP hereafter), where r_{lim} is the limiting radius at which the projected density goes to zero and r_c is the core radius at which the projected density is half of the central value. Both of these radii are usually estimated by fitting King (1966) models to the projected density profiles. These central concentrations are as low as the lowest found for globular clusters (see the compilation in Trager *et al.* 1993). The simulations of OLA, discussed in more detail below, show that galaxies with such profiles will be strongly affected by tides if $r_{lim}/r_{tid} \gtrsim 1.5$ and will be essentially unaffected if $r_{lim}/r_{tid} \lesssim 1.0$.

Figure 1 shows the susceptibility of the local dSphs to tidal disruption by plotting r_{lim}/r_{tid} *vs.* galactocentric radius, R_{gc}. The plot assumes a flat rotation curve for our galaxy with velocity $v_c = 220$ km s^{-1} and circular orbits for the dSphs at their observed radii. These assumptions yield (*e.g.*, OLA)

$$\begin{aligned} r_{tid} &= \left(\frac{1}{2}\frac{\mathcal{M}_{dSph}}{\mathcal{M}_{gal}(R_{gc})}\right)^{1/3} R_{gc} = \left(\frac{G\mathcal{M}_{dSph}}{2v_c^2 R_{gc}}\right)^{1/3} R_{gc} \\ &= (740 \text{ pc}) \left(\frac{\mathcal{M}_{dSph}}{10^7\,\mathcal{M}_\odot}\right)^{1/3} \left(\frac{R_{gc}}{30 \text{ kpc}}\right)^{2/3}. \end{aligned} \quad (1)$$

The data for all of the dSphs except Sgr are taken from PP. The dSph masses are calculated from the absolute magnitudes assuming a mass-to-light ratio of either $\mathcal{M}/\mathcal{L}_V = 2.3$ (the upper panel) or 30 (the lower panel). The smaller $\mathcal{M}/\mathcal{L}_V$ is the average value for globular clusters (Pryor & Meylan 1993) and the larger is a typical value calculated from dSph galaxy velocity dispersions assuming that mass follows light (*e.g.*, Mateo 1994). For Sgr, I adopted an absolute V magnitude of –14, an R_{gc} of 16 kpc (Ibata *et al.* 1994), and an r_{lim} of 4.0 kpc (Mateo *et al.* 1996; Alard 1996; Irwin *et al.*, this volume).

If $\mathcal{M}/\mathcal{L}_V = 2.3$, equivalent to assuming that no dark matter is present, then Sextans (Sex) and Sgr have $r_{lim}/r_{tid} > 1.5$, Sculptor (Scl) has $r_{lim}/r_{tid} = 1.5$, and Ursa Minor (UMi), Draco (Dra), and Carina (Car) have $0.9 < r_{lim}/r_{tid} < 1.5$. The large r_{lim}/r_{tid} for Sex reflects its low stellar density for its luminosity. The Sex r_{lim} is uncertain because of the low galactic latitude of this dSph, but its core radius is also somewhat large for its luminosity.

If $\mathcal{M}/\mathcal{L}_V = 30$, then the r_{lim}/r_{tid} values decrease by a factor of 2.4 and only Sex and Sgr seem likely to be strongly affected by tides. However, this calculation assumes that the dark and luminous matter have the same spatial distribution, which seems unlikely. This point will be taken up again after first discussing tidal models with no dark matter in the dSph.

3. Can Tides Eliminate the Need For Dark Matter In DSph Galaxies?

Plots like the upper panel of Fig. 1 have given rise to the suggestion that the larger than expected velocity dispersions measured for some dSphs (Aaronson 1983, see Mateo 1994 for a recent summary) are due to a lack of virial equilibrium caused by tidal forces (Aaronson 1983, Kuhn & Miller 1989). Two of the most tidally stable dSphs, Fornax (For) and Leo II, have $\mathcal{M}/\mathcal{L}_V = 12$ and 11, respectively (Mateo *et al.* 1991, Vogt *et al.* 1995). These are larger than the values found for globular clusters, whereas smaller values might have been expected because of the somewhat younger stellar populations in the dSphs. This suggests that dSphs do contain dark matter, but For and Leo II have some of the lower $\mathcal{M}/\mathcal{L}$ values measured for dSphs and so the presence of dark matter remained controversial. However, recent theoretical and observational work has

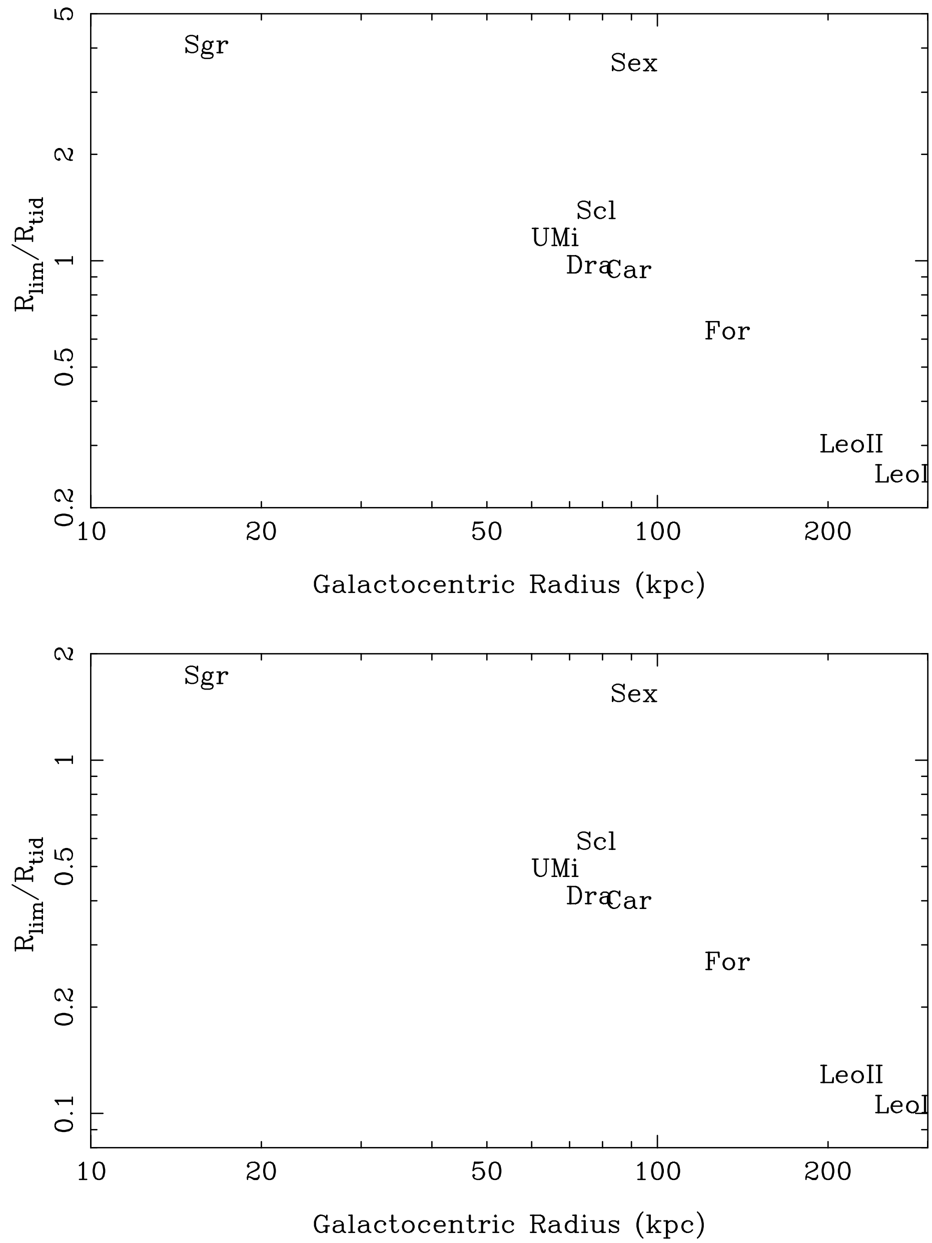

Figure 1. Ratio of limiting to tidal radii for the dSph galaxies around the Milky Way. The plots assume a flat rotation curve with an amplitude of 250 km s^{-1} for the Milky Way and that the dSph galaxy masses are proportional to their luminosities. The top panel adopts a mass-to-light ratio for the dSphs is 2.3 and the bottom panel adopts a value of 30. The simulations of OLA show that galaxies with $r_{lim}/r_{tid} \gtrsim 1.5$ will be strongly affected by tides and that galaxies with $r_{lim}/r_{tid} \lesssim 1.0$ will be essentially unaffected.

demonstrated that at least some, and probably all, of the large measured $\mathcal{M}/\mathcal{L}$ values are NOT due to departures from virial equilibrium.

3.1. Models of Strong and Weak Tidal Encounters

PP modeled the destruction of a dSph galaxy containing no dark matter by a single strong tidal encounter using N-body simulations. They found that tides never significantly increase the central velocity dispersion, which is what is measured by most studies. Tidal forces vary smoothly with location and thus produce ordered rather than random velocities. The clearest signature of a dSph disrupted by tides is a velocity gradient across the galaxy in the unbound stars. These unbound stars disperse to surface densities much lower than those observed for the dSphs in about one period of the dSph orbit about the galaxy.

Increasingly large velocity samples for the dSphs have not found velocity gradients larger than the velocity dispersion, except for Sgr, which is discussed in the final section of this paper. It is worth emphasizing that the large velocity dispersions of the dSphs are not due to a few extreme stars. For example, the dispersions calculated with the biweight estimator (see Beers *et al.* 1990), which is insensitive to a few outlying velocities, are the same as those calculated using the traditional estimator (Mateo 1994). Thus the velocity gradient should be visible if it has significantly increased the measured dispersion.

Hargreaves *et al.* (1994b) reported a velocity gradient in UMi, which was confirmed by the data of Armandroff *et al.* (1995). This gradient is peculiar because it is most nearly along the minor axis, rather than along the major axis as expected for the stretching induced by tides. Removing the gradient from the data decreases the dispersion by only 0.2 km s^{-1} (Pryor *et al.* 1996), so the gradient is not significantly affecting the measured dispersion. Gerhard (1994) suggested that the Suntzeff *et al.* (1993) velocities for Sex showed a velocity gradient, though, again, this was smaller than the dispersion. The more precise Sex velocities from Hargreaves *et al.* (1994a) do not show any gradient, nor does the combined data set if it is restricted to velocities with uncertainties smaller than 7 km s^{-1} (PP).

OLA modeled the destruction of dSph galaxies by weaker tidal encounters at multiple pericenter passages using N-body and restricted N-body simulations. They found that the velocity dispersion was always that given by the virial theorem until the system was disrupted and that unbound material dispersed in about one period of the dSph orbit. Like PP, they concluded that tides were not responsible for the large $\mathcal{M}/\mathcal{L}$ values measured.

3.2. The Tidal Resonance Destruction Mechanism

Still weaker tidal forces are invoked in the tidal resonance model of Kuhn & Miller (1989; see also Kuhn 1993). The basic idea is that the dSph is destroyed by energy pumped in through a resonance between collective radial oscillations and the changing tidal force of a slightly elliptical orbit. That such a resonance might exist is suggested by the approximate equality for many dSphs of the galactic orbital period and $(G\rho)^{-1/2}$, where ρ is some average density for the dSph. Note that this is approximately the same as saying $r_{lim}/r_{tid} \approx 1$ and, thus, the Kuhn & Miller (1989; KM hereafter) mechanism works in a regime not too different from that studied by OLA. The resonant simulation presented in KM had $r_{lim}/r_{tid} \approx 1$.

There are two questions here. The first is whether the KM mechanism can disrupt a dSph and the second is whether it can produce the large $\mathcal{M}/\mathcal{L}$ values observed. I will argue that the first question is still open, but that the answer to the second question is no.

The two key issues for the first question are whether sufficiently weakly damped collective oscillation modes exist and how much fine tuning the resonance requires. Weinberg (1994) has found weakly damped collective modes in stellar systems resembling dSphs, however, these are "sloshing" modes in which the center moves with respect to the outer parts of the galaxy. It is not clear that such modes can be excited by symmetric tidal forces. No definitive N-body simulations of the KM model have been made. The calculations are not easy because following the resonance requires accurate integration of the internal motions. The simple N-body models presented in KM suggest that the mechanism can disrupt a dwarf and that the mismatch between the orbital and internal frequencies can be up to 25%. Few details of these models are presented, but it is stated that the rms radius of the initial dSph was 3.9 grid units and so the treatment of the internal dSph dynamics was probably rather approximate.

If the KM mechanism is able to destroy dSphs on a wide variety of orbits it is somewhat surprising that the OLA study did not encounter it. However, that study used only circular orbits and orbits with $e = 0.5$. Thus, a survey of a modest number of dSph orbits with a numerical technique tailored for this problem may be worthwhile to determine if the OLA tidal disruption criterion needs modification. Note, however, that Sgr, the one dSph that shows clear evidence for tidal disruption, does satisfy the OLA criterion.

A less ambiguous answer can be given to the question of whether the KM mechanism can produce the large $\mathcal{M}/\mathcal{L}$ values observed. Figure 2 of KM shows the dynamical mass of the simulated dSph increasing to 10–20 times its original value after 12 orbits. This dynamical mass is calculated from the mean $v_r^2 r_p$, where v_r is the radial velocity of a star with respect to the mean dSph velocity and r_p is the projected distance of the star from the dSph center. Energy can only be fed into an oscillator until the spring breaks, which in this case means the system becoming unbound. The virial theorem says that this happens when the velocity dispersion has doubled, implying an approximate doubling of the dynamical mass, not an increase by a factor of more than ten. The size of the system will also increase, but, during the slow pumping of the system by the resonance, one might expect the system to stay near virial equilibrium and thus to have no increase in the inferred dynamical mass at all (as in OLA).

It thus seems clear that the large increase in the dynamical mass seen in Fig. 2 of KM must occur because of the inclusion of unbound stars far from the dSph in the mass estimate. Of course, this is allowed if such stars are also in the observed samples. The radial velocity samples generally consist of stars projected close to the center of the dSph and the dSph luminosity profiles require that these stars be spatially close as well. However, the unbound stars in the KM model are spread over a much larger volume of space than the observed dSphs. One simple way to see this is to treat the unbound cloud of stars with epicyclic motions. The tidal forces are assumed to pump energy into the epicyclic motions until the maximum epicyclic velocities perpendicular to the epicycle guiding center (*i.e.*, the dSph) orbit, v_r, are equal to the observed dSph dispersion. Assuming a flat rotation curve with velocity $v_c = 220$ km s^{-1} and approximating the initial orbit as circular with radius R_{gc}, the diameter of the long axis of the epicycle, which is along the original orbit, is

$$d = R_{gc}\frac{v_r}{v_c} = (2.9 \text{ kpc}) \left(\frac{R_{gc}}{70 \text{ kpc}}\right) \left(\frac{v_r}{9 \text{ km s}^{-1}}\right). \quad (2)$$

The numbers are appropriate for Dra and UMi. There is an epicycle extending to either side of the center of the dSph, so the actual cloud of stars would be more than 5 kpc across. This is much larger than the $r_c \approx 100$ pc and the $r_{lim} \approx 600$ pc observed for Dra and UMi.

The stars might be arranged on the epicycles to produce a more compact configuration. However, the epicycle and orbital periods are not commensurate, so multiple clumps of stars are expected along the epicycle. It is also true that, if the escaping stars have any motion along the orbit, v_t, then their guiding centers will disperse along the orbit with a velocity of about $v_t/2$. For Dra and UMi, this amounts to a motion of 1 kpc per orbital period for $v_t = 1$ km s^{-1}. Kuhn (1993) did some simple modeling of the expected distribution of stars along the epicycles. Even the most compact configuration shown in his Fig. 1, which assumes $v_t = 0$, has a full width at half maximum along the orbit of about 5°. For Draco and UMi, $2r_c$ subtends 0.2°.

Finally, epicycles have a fixed direction of circulation. Thus, the unbound stars will show velocity gradients along the major axis similar to those found by PP and for basically the same reason. These are not observed for any dSph except Sgr.

4. Tides and DSph Galaxies With Dark Matter

With both tides and binary stars (Olszewski *et al.* 1996, Hargreaves *et al.* 1996) eliminated as possible explanations for the large $\mathcal{M}/\mathcal{L}$ values observed for dSphs, it seems likely that these galaxies do contain large amounts of dark matter (though see Milgrom 1995). The bottom panel of Fig. 1 shows that, if $\mathcal{M}/\mathcal{L}_\mathcal{V} = 30$ and mass follows light, then only Sgr and Sex are vulnerable to tidal damage. This is still the case if the pericenters of the dSph orbits are equal to half of their observed radii.

However, the dark matter is more extended than the luminous matter in giant galaxies. If this is the case in the dwarfs, the dark matter might be more susceptible to tidal stripping. The best-determined parameter of the dark matter in the dSphs is the central density, ρ_0, (Kormendy 1987). Though significant uncertainties remain (*e.g.*, Pryor & Kormendy 1990), these densities are typically larger than 0.1 M$_\odot$ pc^{-3} (Mateo 1994).

If the dark matter is distributed like a King (1966) model with $\log(r_{lim}/r_c) = 0.6$, then $r_{lim} = r_{tid}$ at

$$R_{gc} = (59 \text{ kpc}) \left(\frac{0.1\ \mathcal{M}_\odot \text{ pc}^{-3}}{\rho_0}\right)^{1/2}. \quad (3)$$

This argues that all of the dSphs except Sgr are stable against tidal disruption at their present radii, though not by large margins. A more extended spatial distribution for the dark matter would result in the tidal stripping of the outer parts of dark halos of the observed dSphs. One can speculate that this would not observably affect the luminous parts of the galaxies.

In summary, I conclude that the lack of large velocity gradients in any of the observed dSphs except for Sgr argues that only Sgr is strongly affected by tides today. This is consistent with theoretical expectations about which systems are susceptible to tides.

5. Models For the Disruption of Sgr

The nearness of the Sgr dwarf to the Milky Way ($\sim$16 kpc), combined with its large physical extent when compared to its estimated mass and its strong elongation, led Ibata *et al.* (1994) to argue that Sgr was currently undergoing a strong tidal encounter. Later studies showing an even larger physical extent in associated globular clusters (Da Costa & Armandroff 1995; see also Ibata *et al.* 1994) and stars (Mateo *et al.* 1996; Alard 1996) have strengthened this conclusion. Sgr extends for at least 20° along its orbit, implying a major axis diameter of 8 kpc or more. Further support for the idea that Sgr is tidally disrupted is the velocity gradient reported by Irwin *et al.* at this meeting.

The most detailed modeling of the destruction of Sgr has been that of Velásquez & White (1995, VW hereafter). They used the lack of a large radial velocity gradient over the inner 8° to tightly constrain the orbit. N-body simulations of a Fornax-like progenitor were able to reproduce those observations known at the time and to do a reasonable job of predicting the further observations reported at this meeting. The lack of a radial velocity gradient over the inner 8° is explained by a cancellation between the actual gradient and the change in the observed radial velocity due to the changing angle to different parts of the galaxy. The essentially unique orbit that this required and the prediction and observation of a velocity gradient at larger distances from the center (see also the modeling by Johnston *et al.* 1995) argues that this result does not compromise the conclusion of the previous section.

The most uncomfortable aspect of the VW model is that it requires that Sgr have an orbital period of about 7.6×10^8 yrs and to have thus completed many orbits about the galaxy. This raises the question of how Sgr has survived until today. Simple calculations of the dynamical friction time scale for Sgr show that it is of order a Hubble time. Thus, the orbit may have shrunk somewhat. It would also be interesting to check if the orbit could have been significantly altered recently by an encounter with the Magellanic Clouds. Models for the destruction of Sgr by Johnston *et al.* (1995) (particularly model D in their Fig. 2) show that a Sgr-like dwarf could have survived repeated pericenter passages before disrupting. So we are perhaps only left with the discomfort that we are somewhat lucky to be living within about one orbital period of the disruption of Sgr. This occurred during the pericenter preceding the most recent one according to VW.

One currently puzzling aspect of Sgr is the lumpiness displayed in the isopleth map of Ibata *et al.* (1994; their Fig. 11). Such lumpiness is not present in the tidal debris resulting from the simulations of PP and Johnston *et al.* (1995). Fig. 3 of VW does show lumpy debris, but those authors do not provide any discussion of whether this could be due to small number statistics. The isopleths of the RR Lyrae variables associated with Sgr presented in Alard (1996) also suggest a lumpy distribution, but it may be possible to explain this with counting statistics. More observational and theoretical work is needed on this subject.

The continuing observational and theoretical studies of Sgr will be very exciting and should teach us a lot about the tidal disruption of a dwarf. Johnston *et al.* (1995) also raise the possibility that the debris from dwarfs disrupted in the past could still be visible in the halo as moving groups (see also Johnston *et al.* in this volume). It is even possible that such a group has been seen (Majewski 1992). The next decade should be an interesting one for the study of the disruption of dwarf galaxies and the role that this plays in the formation of galaxies.

Acknowledgments. I thank Ed Olszewski and Taft Armandroff for many discussions about the disruption of the local dwarf spheroidal galaxies. I also thank Ed for reading an early draft of this paper. My research on dwarf galaxies was partly supported by NSF Grant AST-9020685.

References

Aaronson, M. 1983, ApJ, 266, L11

Alard, C. 1996, ApJ, in press

Angeletti, L., & Giannone, P. 1977, A&AS, 58, 363

Armandroff, T.E., Olszewski, E.W., & Pryor, C. 1995, AJ, 110, 2131

Beers, T. C., Flynn, K., & Gebhardt, K. 1990, AJ, 100, 32.

Carignan, C., & Beaulieu, S. 1989, ApJ, 347, 760

Chernoff, D. F., & Weinberg, M. D. 1990, ApJ, 351, 121

Da Costa, G. S., & Armandroff, T. E. 1995, AJ, 109, 2533

Dekel, A., & Silk, J. 1986, ApJ, 303, 39

Gerhard, O. E. 1994, in Dwarf Galaxies, edited by G. Meylan & P. Prugniel (ESO, Garching), p. 309

Hargreaves, J.C., Gilmore, G., & Annan, J. D. 1996, MNRAS, in press

Hargreaves, J.C., Gilmore, G., Irwin, M.J., & Carter, D. 1994a, MNRAS, 269, 957

Hargreaves, J.C., Gilmore, G., Irwin, M.J., & Carter, D. 1994b, MNRAS, 271, 693

Hills, J. G. 1980, ApJ, 235, 986

Hodge, P. W. 1971, ARA&A, 9, 35

Hodge, P. W., & Michie, R. W. 1969, AJ, 74, 587

Ibata, R. A., Gilmore, G., & Irwin, M. J. 1994, Nature, 370, 194

Johnston, K. V., Spergel, D. N., & Hernquist, L. 1995, ApJ, 451, 598

King, I. R. 1962, AJ, 67, 471

King, I. R. 1966, AJ, 71, 64

Kormendy, J. 1987, in Dark Matter In the Universe, IAU Symposium No. 117, edited by J. Kormendy & G. R. Knapp (Reidel, Dordrecht), p. 139

Kuhn, J. R. 1993, ApJ, 409, L13

Kuhn, J. R., & Miller, R. H. 1989, ApJ, 341, L41

Lake, G., Schommer, R. A., & van Gorkom, J. H. 1990, AJ, 99, 547

Lanzetta, K. M., Bowen, D. V., Tytler, D. & Webb, J. K. 1995, ApJ, 442, 538

Majewski, S. R. 1992, ApJS, 78, 87

Marlowe, A. T., Heckman, T. M., Wyse, R. F. G., & Schommer, R. 1995, ApJ, 438, 563

Mateo, M. 1994, in Dwarf Galaxies, edited by G. Meylan & P. Prugniel (ESO, Garching), p. 309

Mateo, M., Mirabal, N., Udalski, A., Szymański, M., Kałuzny, J.,Kubiak, M., Krzemiński, W., & Stanek, K. 1996, ApJ, in press

Mateo, M., Olszewski, E., Welch, D. L., Fischer, P., & Kunkel, W. 1991, AJ, 102, 914

Mathieu, R. D. 1983, ApJ, 267, L97

Milgrom, M. 1995, ApJ, 455, 439

Oh, K. S., Lin, D. N. C., & Aarseth, S. J. 1995, ApJ, 442, 142

Olszewski, E.W., Pryor, C., & Armandroff, T.E. 1995, AJ, 111, in press

Piatek, S. & Pryor, C. 1995, AJ, 109, 1071

Pryor, C., Armandroff, T.E., & Olszewski, E.W. 1996, in preparation

Pryor, C., & Kormendy, J. 1990, AJ, 100, 127

Pryor, C., & Meylan, G. 1993, in Structure and Dynamics of Globular Clusters, edited by S. G. Djorgovski & G. Meylan (ASP, San Francisco), p. 357

Puche, D., & Westphal, D. 1994, in Dwarf Galaxies, edited by G. Meylan & P. Prugniel (ESO, Garching), p. 273

Sarazin, C. L. 1986, Rev. Mod. Phys., 58, 1

Silk, J., Wyse, R. F. G., & Shields, G. A. 1987, ApJ, 322, L59

Suntzeff, N. B., Mateo, M., Terndrup, D. M., Olszewski, E. W., Geisler, D., & Weller, W. 1993, ApJ, 418, 208

Trager, S. C., Djorgovski, S., & King, I. R. 1993, in Structure and Dynamics of Globular Clusters, edited by S. G. Djorgovski & G. Meylan (ASP, San Francisco), p. 347

Velásquez, H & White, S. D. M. 1995, MNRAS, 275, L23

Vogt, S. S., Mateo, M., Olszewski, E. W., & Keane, M. J. 1995, AJ, 109, 151

Wayte, S. R. 1991, in The Magellanic Clouds, IAU Symp. 148, edited by R. Haynes & D. Milne (Kluwer, Dordrecht), p. 447

Weinberg, M. D. 1994, ApJ, 421, 481

Weiner, B. J., & Williams, T. B. 1996, AJ, 111, in press