DARK MATTER IN DWARF GALAXIES

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ABSTRACT We begin by reviewing the history of Aaronson's entry into the study of dark matter and velocity dispersions. A short review of mass estimations and dark matter in spirals, small groups of galaxies, dwarf irregulars, and dwarf spirals follows. We then discuss velocity dispersions in the five dwarf spheroidals Fornax, Carina, Sculptor, Draco, and Ursa Minor. A new velocity histogram for Draco and Ursa Minor is shown. We then end with some questions and theoretical and observational needs.

1. PREAMBLE

I would like to begin this paper by giving you the history of the beginning of a new era in studying the outer halo of our galaxy, and of studying the properties of dwarf spheroidal galaxies. This history has been reconstructed by reading Marc Aaronson's papers, studying the MMT observing logs, and from a conversation I had with him at the MMT, while making more observations for the velocity-dispersion project. We should all remember that a decade ago many outer halo velocities were good to only 50-100 km s^{-1}, and even as recently as two years ago, the tabulated velocities of several outlying clusters and the Sculptor spheroidal were in serious error.

It all begins rather innocently in September, 1980. Marc Aaronson obtained a transmission grating prism plate of the Draco dwarf, in order to search for carbon stars. None were found. However, one star, now known as Draco C1, showed Hα in emission. Subsequent spectroscopy by John Stocke and Jim Liebert, with the Steward 90" in April 1981, revealed it to be a carbon star with emission lines. This carbon star is more like the warmer CH stars than the cooler carbon stars found in some of the southern spheroidals or the Magellanic Cloud clusters. A new search of the Draco plate showed three new C-star candidates, two which were reported as C2 and C3, and a third which was rejected

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because Stetson (1980) had derived a very low membership probability for it. (In 1985 and 1986 we confirmed that C4 did have a velocity consistent with Draco membership, and was itself a very unusual carbon star; it is the intrinsically faintest C star known in a dwarf spheroidal.)

On May 10, 1981, Jim Liebert got a reasonably-high-resolution spectrum of C1, with the MMT spectrograph, which allowed a radial velocity accurate to 6 km s^{-1} to be measured from the observed wavelengths of Hβ and HeII 4686. This velocity was the first modern-quality one determined for a dwarf spheroidal star; however, since C1 can be most easily understood if it is a binary, Aaronson, Liebert, and Stocke (1982) said, in classic Aaronsonese, "our result might in principle be the best existing determination of Draco's radial velocity. However, if the object is a binary... the emission line velocities could of course vary in wavelength."

The second, more deliberate stage in obtaining high quality velocities occurred on April 19, 1982, when Aaronson observed Draco C1 with the MMT Echelle. Until this date, he had never observed with the MMT. This 1^h 45^m exposure, proved that the C_2 bandheads could provide extremely accurate velocities, even with incredibly low S/N data, when correlated against a template carbon star of known velocity. During Spring 1982, good velocities were secured for all three C stars in Draco, and for the one in Ursa Minor. Marc (Aaronson 1983) then wrote his paper, "Accurate Radial Velocities for Carbon Stars in Draco and Ursa Minor: The First Hint of a Dwarf Spheroidal Mass-to-Light Ratio." A velocity dispersion based on only three stars was met with disbelief, prompting others to try to prove him wrong by measuring dispersions in the southern spheroidals. Aaronson said, "It is clearly of far-reaching significance to obtain radial velocities for additional stars in Draco in order to confirm the velocity dispersion suggested above, since the present case for a large dispersion rests mainly with the observation for one star (Draco C3). This will require measurement of accurate velocities for noncarbon stars."

The third stage began during the October 8-10, 1982, MMT observing run. First, Marc tried to measure C-star velocities in Sculptor and Fornax, and failed. (We tried again and succeeded with Sculptor in Sept, 1986.) Then, since monitoring Draco C1 at Hα took so little time, Marc switched to the magnesium triplet setting at 5187A, and tried the K-star Draco 536, which failed, and two Fornax globulars, both of which failed (we later succeeded in 1984 and 1985). Finally, on October 10, 1982, he measured Draco 473, whose velocity correlated against twilight sky was -285.6 km s^{-1}, confirming that Draco did have a large measured velocity dispersion. Again quoting Marc, "Several interesting implications follow if Draco's mass-to-light ratio is really similar to that estimated above. First, in some fundamental sense, the dwarf spheroidals, puny as they are, would be confirmed as true galaxies and not just extended versions of globular clusters. Second, considerable support would be given to the notion that the Galaxy possesses a massive halo. A final conclusion can be made relating to the nature of the hidden matter itself..."

Since the carbon stars and first K giants were observed, through May, 1987, we have amassed a total of 76 separate observations of 36 stars, 18 each in Draco and Ursa Minor. I hope you can see the excitement that was in Marc's mind as he realized how straightforward it now was to get excellent velocities, and as he tried to measure velocities of everything he could think of in every spheroidal the MMT Echelle could reach.

2. THE SUBJECT OF DARK HALOS

In 1987 there is very little hostility to the notion that there is dark matter; what form it is in, and whether it's the same stuff on all size scales are of course less certain. I think that we would all agree that there is an increase in M/L with radius in galaxies - If You Look Far Enough From Their Centers.

Before turning to the observational results in dwarf spheroidals, I want to mention the results for normal big galaxies, and for dwarf spirals and dwarf irregulars. These notes are not meant to be comprehensive, so please forgive me if I left out your work or your favorite results.

2.1. Our galaxy

Ostriker, Peebles, and Yahil (1974) showed that a number of techniques implied that the mass of spiral galaxies increased with the separation of the probe being used to estimate the mass, and claimed that we had to change our notion of the mass of galaxies by about a factor of 10. They derived a mass of the Milky Way to be 4×10^{12} $M_{\odot}$ from the tidal radii of the outer dwarf spheroidals, and that of the Milky Way-Andromeda system to be 5×10^{12} $M_{\odot}$ from timing arguments.

Later, Hartwick and Sargent (1978) measured new velocities for a variety of halo objects, and derived a mass of 7.6×10^{11} $M_{\odot}$, assuming isotropic orbits. Lynden-Bell, Cannon, and Godwin (1983) decreased this estimate a factor of 3, getting 2.6×10^{11} $M_{\odot}$, from velocities of the Magellanic Clouds and dwarf spheroidals. Olszewski, Peterson, and Aaronson (1986), using a number of new observations, and a sample of halo objects beyond the LMC distance, derived 5×10^{11} $M_{\odot}$, for the isotropic case. (See also Little and Tremaine (1987).) There are still several clusters, Eridanus, Pal 14, and Pal 15, whose published velocities are uncertain; it would also be good to know the velocities of distant halo stars.

2.2. Rotation curves of spirals

It is important to acknowledge the work that Rubin and her collaborators have done on this subject. Rubin (1987) gives a review from the point of view of constraining dark matter. Rubin _et al_. (1978a,b) and Rubin

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(1979) discuss optical rotation curves. Rubin also gives credit to Roberts (1976) as the first person to discuss flat rotation curves.

Two recent results point out examples of measuring spiral galaxy rotation curves to a radius well beyond that practical a few years ago. First, van Albada et al. (1985), reminded us that in general, optical rotation curves do not exist for radii of more than about 3-4 disk scale lengths, a radius inside of which we do not even expect to see the decrease in rotation velocity for Keplerian orbits. They also remind us that neutral hydrogen rotation curves do go out far enough in some galaxies that a dark halo is an inescapable conclusion. Van Albada et al.'s rotation curve for NGC 3198 extends to approximately 11 disk scale lengths. At 30 kpc, the modelled amount of mass in dark matter is substantially greater than in visible matter.

Kent (1986) has shown with new surface photometry of a large number of galaxies with rotation curves, that indeed optical rotation curves do not teach us much about dark matter. He also pointed out that models of some specific galaxies need no dark matter; presumably a number of people are making HI rotation curves of these galaxies.

2.3. Other mass estimators

2.3.1. Satellites

Dressler, Schechter, and Rose (1986) argued that a number of faint galaxies seen in the field of the 'isolated' elliptical NGC 720 were indeed gravitationally bound to it. Just as in the case of the Milky Way, the velocity dispersion and radius of the system of companions can be used as a gauge of the mass of the entire system. The companion galaxies are substantially less luminous and less massive than NGC 720, yet the mass of the group is calculated to be approximately 40 times that of NGC 720, again indicating a large dark halo mass.

2.3.2. Binary pairs

Lake and Schommer (1984) have created a sample of nine nearby isolated binary pairs of dwarf irregular galaxies. Recognizing that this procedure is difficult, and after trying to account for 'optical' as opposed to 'physical' pairs, remaining contamination, and velocity measurement errors, they conclude that dwarf irregulars have large mass-to-light ratios.

Sharp (1987) raises a number of objections to the use of binary pairs. Since good rotation curves are becoming more common, today we enjoy the luxury of being able to wait to see how this method will be viewed when many more pairs are analyzed.

2.3.3. Rotation curves of dwarf irregulars and dwarf spirals

As the image tube revolutionized measuring rotation curves 10 to 15 years ago, the sorts of measurements discussed below were made possible by technology changes: CCD detectors to measure the optical profiles, and very sensitive radio arrays to measure the HI rotation curves.

Sargent and Lo (1987) have presented HI data for about a dozen dwarf irregulars fainter than $M_V = -14$. The velocity dispersion expected for hot gas is of the same order as the line width of these galaxies; for some, no rotation could be deduced. For the seven faintest galaxies, M/L was of order 10-30, a fact which could not be blamed on enormous reservoirs of neutral hydrogen. LGS 3, which has an absolute magnitude of -9.4, M/L about 30, and very little HI, may be a transition object between irregulars and spheroidals. Certainly if it were allowed to fade for several more Gyr, it would have an M/L similar to that which Aaronson and Olszewski (1987a) deduce for the spheroidals Ursa Minor and Draco.

Comte, Lequeux, and Viallefond (1985) have made similar VLA measurements of the rotation curves of DDO 47 and Sextans B. They find large mass-to-light ratios, 62 and $\geq$90, respectively, in concordence with the above-quoted results by Sargent and Lo for other dwarfs.

At the Dark Matter Conference, Kormendy (1987) discussed work he has done with Bosma and Souviron on the faint, $M_B = -14.5$, dwarf spiral DDO 127. The rotation curve is still rising at 7.5 disk scale lengths. This scale length is so small that no 'maximum disk' model will fit the data.

A similar exceptional case can be seen in the dwarf irregular DDO 170. (Lake, Schommer, and van Gorkom have graciously allowed me to show two of their figures at this conference, and to mention their work in this paper. The figures can be seen in their paper (Lake, Schommer, and van Gorkom 1987).) This dwarf has $M_B \sim -16$, and is hydrogen rich. The rotation curve, obtained at the VLA, is also slowly rising at about 7 disk scale lengths. Again, the disk cannot alone account for the 'rising' part of the rotation curve, and a maximum disk model simply doesn't work. Most of the rotation curve is therefore determined by the dark matter, and assuming an isothermal halo, the halo parameters are relatively well determined. DDO 170 yields a core radius of 3 kpc for the dark matter, which is similar to the 2 kpc found by Kormendy, Bosma, and Souviron for DDO 127. The mass-to-light ratio at the last point in DDO 170's rotation curve is $\geq$30; as it fades with time, the halo may resemble the proposed halo of a dwarf spheroidal.

DDO 170 has the added attraction of having a smaller dwarf companion, also detected at HI, at about 50 kpc projected radius, with a velocity separation of 80 km s^{-1}. As I discussed above, isolated binary pairs of dwarf galaxies are useful for allowing us to measure the total mass within the system. The systemic velocity of the companion to DDO 170 falls on the best fit halo model of the rotation curve of DDO 170. If this is not a chance optical pair, then the orbit of the companion implies a total mass of about 10^{11} $M_\odot$. This of course simply comes from the rotation speed at 50 kpc. Since the luminosity of the system is only a few $\times 10^8$ $L_\odot$, the total mass-to-light ratio is about 100, on a scale of about 50 kpc.

3. DWARF SPHEROIDAL GALAXIES

Since Aaronson announced that the velocities of 3 carbon stars in Draco differ by 30 km s^{-1}, there have been a number of different attempts to measure velocity dispersions in the spheroidals. The changing detector technology has helped tremendously; as I will outline below, both red-sensitive CCDs and multi-object spectroscopy are being used. The intensified Reticon is still providing important spectra, and photon counting is extremely important when the resultant signal-to-noise will be low, as in Echelle work. I will first outline the observational situation in the five spheroidals studied to date, then end by making some comments about what new data and analysis may be needed.

3.1. Fornax

The first three studies of the Fornax velocity dispersion, by Cohen (1983), and Seitzer and Frogel (1985), and Aaronson and Olszewski (1986), involved either measuring the dispersion of the globulars or of only a very few of the approximately 50 known C stars (Westerlund, Edvardsson, and Lundgren 1987). The best guess for the velocity dispersion is about 6 km s^{-1}, which implies a mass-to-light ratio not terribly different from that of the Galactic globulars. The Fornax C stars have ages, deduced from their bolometric magnitudes, of as young as 2 Gyr. Clearly, when comparing various results, it should be remembered that we are sampling different stellar populations and generations.

Paltoglou and Freeman (1987) have provided exciting new observations. They obtained velocities of approximately 40 K giants in Fornax, 20 each in two patches along the major axis of the galaxy, using the AAT multiple-object spectrometer. They tested for the rotation of Fornax, which at 1 core radius, is smaller than about 3 km s^{-1}, and consistent with zero. The resultant velocity dispersion is 5 km s^{-1}, similar to the earlier results.

This sort of work is an obvious approach when the integration times are very long. It would be fun to get data even farther from the center of Fornax, since dwarf irregulars seem to have rotation velocities of about 10 km s^{-1} for a galaxy about 1 kpc in size.

3.2. Carina

There have been three studies of Carina's velocity dispersion, all based on only a few carbon stars. Cook, Schechter, and Aaronson (1983) have unpublished data on five C stars. Godwin and Lynden-Bell (1987) have measured six, and Seitzer and Frogel (1985) have also measured six.

Godwin and Lynden-Bell (1987) argue that all three groups have underestimated their measuring errors, and that for each group, the **measured** dispersions of 6 to 12 km s^{-1}, when corrected for errors, really imply a **true** Carina dispersion of about 1 km s^{-1}. I think that this is slightly unfair, since the Godwin and Lynden-Bell data have the largest errors. However, the important point is that single-epoch studies of a small number of stars, which may have atmospheric jitter or may be binaries, probably have larger errors than are estimated. Also, working at the observational limit of a telescope may make errors difficult to estimate correctly.

If the Cook, Schechter, and Aaronson, and the Seitzer and Frogel relative velocities are averaged together, the dispersion of Carina drops to about 3.5 km s^{-1}. The individual stars in the two data sets are not ordered by velocity in the same way, so it does seem that there is something to worry about in the data collected to date. Clearly, what is needed is a good multi-epoch study of the K giants, which may be difficult, since the Carina direction does have some foreground contamination, and since no color-magnitude diagram has been published for the entire body of Carina. When enough years have passed, a proper-motion study to weed out foreground contamination would be useful.

3.3. Sculptor

Sculptor is a galaxy from which we will learn much. Only slightly farther away than Draco and Ursa Minor, it is, however, substantially brighter and more massive. Again, there are three studies of the dispersion. Seitzer and Frogel (1985) measured three C stars. Armandroff and Da Costa (1986) have published velocities for 16 K giants, have unpublished new data for a similar number, and have more observing time coming up in late 1987. Aaronson and Olszewski (1987b) recently measured velocities for seven carbon stars. All three groups get similar velocity dispersions of about 6 km s^{-1}; Aaronson and Olszewski formally get about 11 km s^{-1} but claim that one extreme-velocity star is probably a binary, since two observations separated by two months give velocities differing by 4.6 km s^{-1}, or 4σ, for that star.

The approach Armandroff and Da Costa are taking is different from that in all of the Aaronson and Olszewski work. Armandroff and Da Costa are trying to measure velocities accurate to 5 km s^{-1} per observation, studying many stars to beat down the error in the dispersion. There is a very good reason for this; at Cerro Tololo, the 4m telescope, RC spectrograph, air-Schmidt camera, and GEC CCD system offers good throughput at the calcium triplet at 8500A. (This, by the way, is the setup used by Seitzer and Frogel.) Observations take only 20 min per star; with the MMT Echelle we spend 1.5 hours per star. Also, it makes sense to observe red stars in the red; typically, Shectograph-type systems must observe bluer where image tubes have good quantum efficiency. Armandroff and Da Costa's multi-epoch data will be very exciting to see.

To date, Armandroff and Da Costa claim a velocity dispersion of 6.2 km s^{-1}, which yields a mass-to-light ratio of 6. This M/L is greater than that found for Galactic globulars; they quote a mean globular cluster global M/L of 2.8 based on the most recent studies available. While it is difficult to address how different 6 is from 2.8 given the number of uncertainties in turning a velocity dispersion into a mass-to-light ratio, the Sculptor result is intriguing and interesting.

Aaronson and Olszewski show that warm carbon stars do give a good velocity dispersion, especially if binaries can be weeded out. They argue that Jura's (1986) reasoning, that Mira optical velocities may not be center-of-mass velocities, therefore all C stars are bad to use, not to mention M stars and even K stars, has no theoretical or observational justification. The nice thing about K giants is that so much velocity work has been done on them by the DAO group, SAO group, Gunn and Griffen, and the CORAVEL group. (See the many papers in IAU Colloq. 88, Stellar Radial Velocities.) There are also very many more K stars than C stars in a dwarf spheroidal; if the stars are bright enough, one should observe the K giants.

3.4. Ursa Minor and Draco

This is the fifth year in which we have devoted several nights of MMT time to deriving the velocity dispersions in Draco and Ursa Minor; in fact, I was at the MMT as Jeremy read this talk, successfully observing more stars in these galaxies. Since Aaronson last showed the histogram of velocities, at the Dark Matter Conference, we have concentrated on two specific areas: getting more epochs for the stars which define the extremes of the distribution, and adding new stars. We have not tried to derive orbits for those stars which seem to be binaries.

Figure 1 shows the histogram of velocities. Each box represents a star; the number inside the box is the number of different observing runs on which the star has been observed. Stars which we believe to be velocity variables, probably binaries, have their velocity extrema connected by a solid line. These stars are not used in the dispersion calculation. The velocities of all of the measurements of the nonvariable stars agree to within their errors, whose approximate size is noted in the figure. The dispersion in each system turns out to be ~10 km s^{-1}, with a resultant M/L $\geq$50 for each galaxy.

The MMT Echelle and intensified Reticon system gets better every year; in 1986, the image tube dark count, which defines our integration time and faint limit, was decreased to about 1 count per second on the array. This is about the count rate for a V= 17.5 star. We have slowly started to observe fainter stars, but mostly have been adding to this plot with newly discovered giants. The fainter giants are also bluer, with weaker lines; the giants are already weak-lined, since the mean metal abundance of each galaxy is about 1/100th solar.

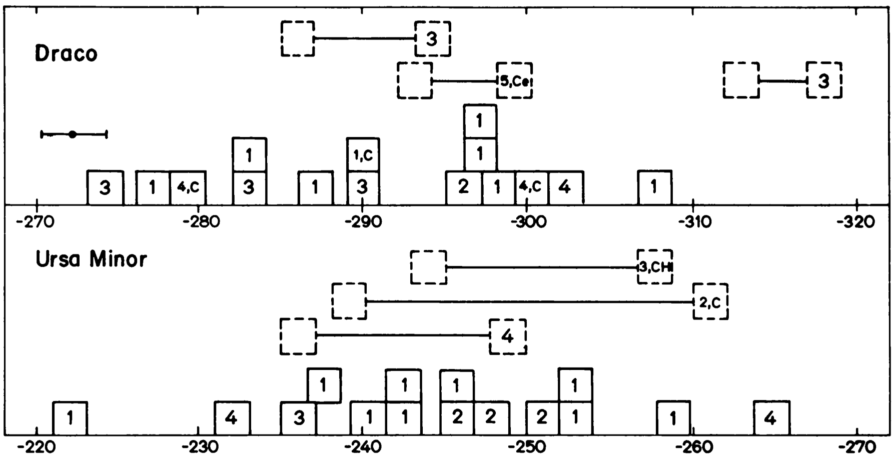

Figure 1. Histogram of velocities of stars observed in Draco and Ursa Minor through May, 1987. Inside each box is the number of epochs a star has been observed. Single boxes represent those stars whose measured variations are smaller than the estimated velocity errors; the measured extrema of the variables are noted. The C stars are also noted.

These stars lie outside the limits of the proper motion surveys done by Stetson (1980) for Draco, and by Cudworth, Olszewski, and Schommer (1986) for Ursa Minor. In each case, the field of the survey was defined by the first-epoch Hale Observatory 200" telescope plates; the field is not very different from the core radius of each galaxy. We have been picking new stars by finding stars whose colors would place them on the respective giant branches, then obtaining low resolution spectra of about 20 stars at a time with John Hill's MX (multiple object) Spectrometer, on the Steward Observatory 90". It is easy to tell late G and K dwarfs from giants; we then observe the giants on the MMT. We have observed two dwarf field stars, and in each case should have known better. We have also found two distant halo giants which have velocities quite different from those in the two spheroidals. One important success of the MX work, is that one new member star is the visually brightest member of Draco; it lies outside the region which has been studied in the past. It will be important to get IR photometry of this star.

We hope to observe 30 stars per galaxy eventually. To date the distributions of velocities are consistent with gaussians; however, they are still marginally consistent with flat distributions of velocities. With more epochs, we are able to limit the types of binaries which might be artificially inflating the true dispersions to the observed ones. As we pointed out before (Aaronson and Olszewski 1987a), a sample of 50% binaries with random inclinations and the field star spectrum of secondary masses and orbital ellipticities cannot create a dispersion of 10 km s^{-1} from a true 1 km s^{-1} dispersion. Tremaine (1987) has independently come to the same conclusion. One can still create ad hoc types of binaries, for instance a 5 $M_{\odot}$ black hole with a giant in an incredibly elliptical orbit, which would damage our distribution. Gunn and Griffin have pointed out that all of their standard stars have shown evidence of being binary after being observed for enough years; all we can do is continue to observe, and hope interest stays high enough to persuade suspicious time allocation committees.

We have argued before that atmospheric motions and binaries are not causing the large dispersions. It is very unlikely that we are catching both galaxies being destroyed by the Milky Way tide, since at 10 km s^{-1} the crossing time is less than 10^8 years. We hope to find enough stars far from the center to test for rotation. However, rotation does not save the day for small M/L; if these galaxies were to be hypothesized to have M/L ~1, they cannot be rotating fast enough to produce the observed distributions without substantial hidden mass. Thus they must have large M/L, even in this case.

We also note that small velocity dispersions, of $\leq$1 km s^{-1}, have been found in open clusters by Bob Mathieu (1983; the data are now presented in Mathieu et al. 1986), with identical Echelles and detectors, and identical software. The stars are brighter and have been observed more often, but our results don't seem to be a fundamental limitation of the equipment.

4. FINAL DISCUSSION WITH QUESTIONS

If we assume, for lack of a plausible alternative, that some kind of dark matter is causing the distribution of velocities in Draco and Ursa Minor, what sort of understanding do we come to? What sort of questions do we need the theoreticians to concentrate on? What new observations do we need?

Imagine Ursa Minor to have a large velocity dispersion. Without dark matter, Ursa Minor would have a dispersion of 1 km s^{-1}, so to first order all the dispersion is being caused by the dark matter. If we now place this dark matter about Fornax, which is about two orders of magnitude more massive than Ursa Minor, Fornax should also have a large dispersion. We can change the ratio of core radius of the dark matter to the core radius of the stars, but it would be nice to appeal to other observations. More work on the dwarf spirals and dwarf irregulars can help, but how do we bridge the gap between well studied objects like DDO 170, which is considered puny but is incredibly brighter and more massive than Ursa Minor? LGS 3 does have about the right magnitude, but the velocity field has been described as 'chaotic.' The parameters of its halo cannot be deduced from these data. We also need to make self-consistent models, because use of a King model carries the implicit assumption that the core radius of the dark matter is the same as that of the bright matter.

The dark matter might also be in remnants. This idea has gained in plausibility lately, especially because McClure et al. (1986) have noted systematic luminosity function differences in globular clusters of differing metallicity. No matter what form the dark matter is eventually shown to be in, Ursa Minor and Draco are exceptional objects.

Is it possible that Ursa Minor simply possesses a velocity anisotropy so that the observed dispersion gives the wrong M/L? Models made to date are for big ellipticals and seem to imply that even modest anisotropies are unstable to bar formation.

For Ursa Minor, especially, we need to make star counts which better constrain the core and tidal radius. We need to determine whether the spheroidals are relaxed systems, and/or how they have been affected by the Milky Way. We need to get absolute proper motions of these systems, so we can see what the orbits are like. We need more efficient, multiple-object Echelle spectrographs. We need more telescope time and bigger telescopes. And most of all, we need more scientists like Marc Aaronson, with lots of ideas, and the energy to see them to fruition.

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