# The Search for Dark Matter in Draco and Ursa Minor: A Three Year Progress Report

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ABSTRACT. We report the cumulative results of an on-going effort to measure the stellar velocity dispersion in two nearby dwarf spheroidal galaxies. Radial velocities having an accuracy $\lesssim$ 2 km $s^{-1}$ have now been secured for ten stars in Ursa Minor and eleven stars in Draco (including 16 K giants and 5 C types). Most objects have been observed at two or more epochs. Stars having non-variable velocities yield in both dwarfs a large (~ 10 km $s^{-1}$) dispersion. These results cannot be explained by atmospheric motions, and circumstantial evidence suggests that the effects of undetected binaries are also not likely to be important. Instead, it seems that both spheroidals contain a substantial dark matter component, which therefore must be "cold" in form.

## 1. INTRODUCTION AND OBSERVATIONS

The question of whether or not small galaxies contain dark matter has far reaching implications, both from the standpoint of the origin and evolution of these systems, and for the nature of the nonluminous material itself (e.g. Lin and Faber 1983, Aaronson 1983, Kormendy 1986). For dwarf irregulars, the issue is best attacked via H I observations. However, the lowest luminosity systems we know of are the halo dwarf spheroidals, and in particular Draco and Ursa Minor. These galaxies contain no gas or other signs of recent star formation, and the test for dark matter in them can only be done by measuring the velocity dispersion of stars at the tip of an old giant branch on a one-by-one basis. This necessitates velocities of ~ 1 km $s^{-1}$ accuracy for objects having V > 17 mag, measurements which until recently would have been thought to be totally unfeasible.

Prompted by the developing technology (both hardware and software), several groups have within the last few years initiated attacks on the halo spheroidals. A summary of the current situation, which has been rather controversial, was given by Kormendy (1985) at this conference. Here we report the latest results of our continuing efforts on Draco and Ursa Minor, where the observations have now become considerably more extensive than those for any other spheroidal.

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The measurements we present were taken over a period from April 1982 to the most recent observing run in May 1985, and were all obtained using the Multiple Mirror Telescope and echelle spectrograph with a photon counting Reticon detector, and reduced using cross-correlation techniques. This work initially began by concentrating on the carbon stars, because of the ease with which velocities could be obtained from the λ5636 $C_2$ Swan bandhead. Perhaps fortuitously, however, the presence of only two C stars in Ursa Minor and three in Draco quickly necessitated moving on to the K giants. For this purpose we have chosen to work in the area of the Mg triplet at λ5180, a region also densely populated by sharp features mostly due to Fe and Cr.

As a point of interest, the net photon counting rate with the MMT echelle is 2 per second at V ~ 17 mag, which is sufficient, though, to achieve ~ 1 km $s^{-1}$ accuracy (10 km $s^{-1}$ resolution) in 80 min when the dark count is comparably low. However, by V = 17.5 mag, the situation rapidly worsens, not so much from the smaller amount of flux, but because the giant branch stars become hotter, and the absorption features, already weak due to the low abundance, become barely discernable. It then takes some two hours of integration to obtain ~ 2 km $s^{-1}$ precision.

In both Draco and Ursa Minor, roughly ten proper motion members are known between V = 17 and 17.5, and velocities for all of these have now been obtained. The results are summarized in Figure 1. We note that the majority of stars have been observed at two or more epochs, separated by periods ranging from three months to two years, but most typically by a year. The nine stars in Draco which do not show any

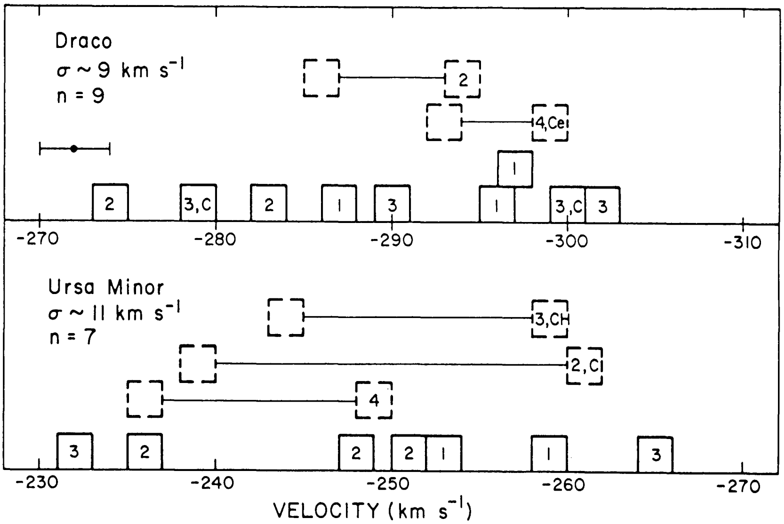

**Figure 1.** Velocity distributions in two dwarf spheroidals. Quantities inside boxes are the number of epochs a star has been measured. Single boxes represent mean speeds of stars showing no variation larger than the estimated errors, while variables are shown at the extreme range of their measured velocities. C stars are marked.

radial velocity variations give a dispersion (corrected for measuring error) of 9 ± 2 km $s^{-1}$, a value which remains unchanged if the two C stars are dropped; while the seven non-variable Ursa Minor stars yield a dispersion of 11 ± 3 km $s^{-1}$. A Kolmogorov-Smirnov test indicates that in both instances the velocity distribution does not differ from a gaussian at any level of statistical significance, but this is more a statement about small number statistics than anything else.

It is interesting that four of the five stars which show velocity changes might have been predicted to do so a priori. First, McClure (1984) has demonstrated that a high fraction of galactic CH stars are in binaries, as is apparently the CH star in Ursa Minor. Furthermore, the other Ursa Minor C star, which also appears to be binary, sits in a peculiar position in the HR diagram well below the tip of the giant branch. The third Ursa Minor binary candidate is star M, which is a somewhat anomalously bright K giant that may be a long period photometric variable, although no such stars have ever been conclusively detected in either Draco or Ursa Minor (see Aaronson and Mould 1985).

In Draco, the C star velocity variable has a peculiar emission line spectrum which almost certainly implies the presence of a degenerate companion (Aaronson, Liebert, and Stocke 1982). We note further that unlike the more luminous carbon stars found in the other halo spheroidals, the ones in Draco and Ursa Minor are of too small a bolometric magnitude to be accounted for by Iben's (1975) third dredge-up mechanism. On the other hand, the two remaining Draco C stars have yet to show any indication of duplicity; it was in fact the wide velocity difference between these two stars which led to the original suggestion of dark matter in this system (Aaronson 1983).

Finally, we point out that the velocity variations in the only two stars with observations at 4 epochs would have been apparent after the first 3 epochs, if the data had been reduced; i.e., these stars were not identified as velocity variables simply because we "tried harder" with them.

## 2. DISCUSSION

There are four possible contributors to the observed dispersion in Figure 1: atmospheric motion, tidal disruption, binarity, and self-gravitation. Now the multiple epoch observations appear to completely rule out atmospheric instability effects, as these stars simply do not show the jitter seen, for instance, by Mayor et al. (1984) in 47 Tuc. However, there is nothing inconsistent here, as 47 Tuc stars of the same color and magnitude as in our sample are stable, while the 47 Tuc stars that vary are considerably redder and more luminous.

Concerning tidal effects, there are two possibilities. First, if the systems are virialized and contain no dark matter, the expected dispersion is no greater than the escape velocity of ~ 1 km $s^{-1}$. The other alternative is that both systems are unbound. The present phase must then be short lived, since the crossing time is ~ $10^8$ years. On the other hand, the stars are ~ $10^{10}$ years old, which suggests only a

1% probability of viewing such an event once, let alone twice.

The binary question is the most problematic, but we can make the following points: First, Carney and Latham (1985) in an on-going survey of halo K giants are finding a binary fraction of merely ~ 15%. Second, during our most recent run in May 1985, ten stars were remeasured, and all but one were found to remain constant, which at face value does not suggest a high binary frequency. Third, there do exist systems for which very low dispersions have been obtained over a limited time base. For instance, Mathieu (1983) required just two years of observation to weed out large amplitude binaries and obtain an observed dispersion $< 1$ km $s^{-1}$ in M67 (for a sample that included the ten brightest M67 K giants, with only one being eliminated as a binary). Fourth, Monte Carlo simulations indicate that if the dwarfs contain binaries with the characteristics of a "normal" galactic distribution, dispersions measured from the present set of multiple epoch observations are very unlikely to be much affected by undetected binaries, a point illustrated in Figure 2. Of course, all of this evidence is circumstantial. The possibility remains that binary

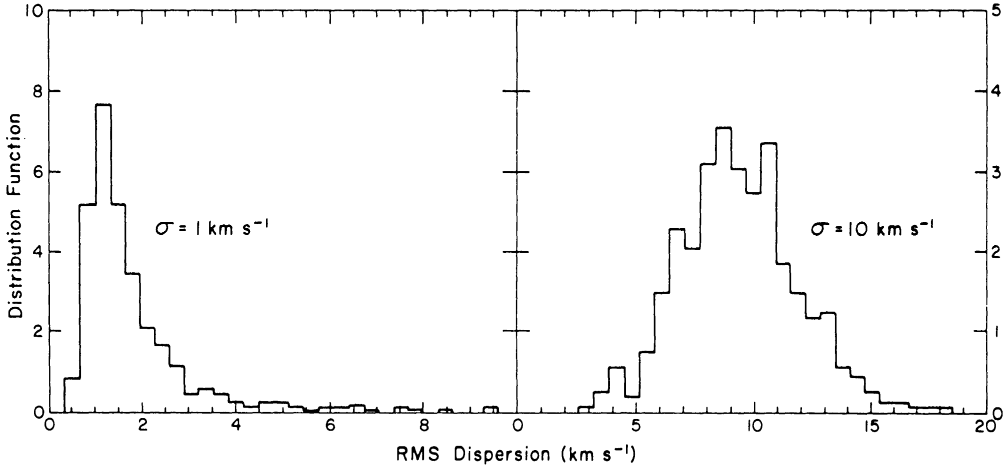

**Figure 2.** Monte Carlo simulations (500 trials each) of binary effects on observed dispersion in systems having a true dispersion of 1 and 10 km $s^{-1}$. Two observations of 10 stars taken one year apart are assumed, and cases with a velocity variation $> 4$ km $s^{-1}$ are removed from the sample. The primary has a mass of 0.8 $M_\odot$, the phase, inclination angle, and eccentricity are chosen at random, and the period and secondary mass distributions are based on galactic field studies (see Mathieu 1983 for details). The binary fraction is set at 0.5. The distribution functions are arbitrarily normalized.

formation processes in the low density environment of the dwarfs differ radically from that in the galactic disk, and furthermore, that by very bad luck a high fraction of our observed stars are in "worst case" orbits. Continued monitoring of the stars is essential, along with increasing the sample, work which is clearly going to take some time.

We come then to the final possibility that the observed dispersions are gravitationally supported. Kormendy (1985) has discussed some of the uncertainties involved in deriving masses. Plowing ahead, we give in Table 1 the total mass-to-light ratios obtained by assuming a King model [and employing eq. (3) from Illingworth 1976]. The results yield rather large values of $M/L_V \sim 40$ for Draco and ~ 100 for Ursa Minor. The uncertainties in Table 1 involve the formal errors in the dispersions only, and it could be argued that with additional leverage in the luminosities and tidal radii, the results are not significant at much more than the one sigma level. On the other hand, because the $\chi^2$ is assymetric, the dispersion errors quoted may be too conservative; e.g., the minimum Draco dispersion at the 10% confidence level given by a $\chi^2$ test is 7.5 km $s^{-1}$, while the maximum dispersion is 15 km $s^{-1}$.

**Table 1**
**Estimates of Dwarf Mass-to-Light Ratios**

| Name | $M_V$ | $M_\odot$ | $M/L_V$ | $\langle V^2\rangle^{1/2}$ | $M/L_V$ |
|---|---|---|---|---|---|
| Draco | -8.5 | $9.8\times10^4\langle V^2\rangle$ | $0.46\langle V^2\rangle$ | $9 \pm 2$ | $37 \pm 11$ |
| UMin | -8.7 | $2.2\times10^5\langle V^2\rangle$ | $0.86\langle V^2\rangle$ | $11 \pm 3$ | $104 \pm 40$ |

Are such great M/L ratios tenable? To begin with, Tinsley (1981) pointed out that the observed M/L values for larger galaxies suggested an increase in the percentage amount of dark matter in later-type systems. Lin and Faber (1983) demonstrated that the fading of a dwarf irregular, with an initial $M/L_V = 6$, would yield a final spheroidal having $M/L_V = 28$, and in this regard the evidence that the spheroidals share a heredity closer to dwarf irregulars than to ellipticals continues to accumulate (see Aaronson 1985). Perhaps most significantly, Sargent (1985) has recently reported H I observations by himself, Lo, and Young, of very low luminosity dI systems which yield indicative masses that do result in a rough increase in M/L with decreasing magnitude, such that the faintest systems (with $M_V \sim -12$ to -10) have M/L values in the range 20 - 30. Additional fading by factors of 2-3 in such objects would give results in the range observed here. Indeed, recent theoretical models of biased galaxy formation with cold dark matter proposed by Dekel and Silk (1985) nicely predict the change in M/L with luminosity that may now be established, with the smallest systems having M/L values of 10 - 100 and velocity dispersions of 5 - 10 km $s^{-1}$.

A possible monkey wrench in all this is the fact that efforts made in three other spheroidals (Carina, Sculptor, and Fornax -- see Kormendy 1985 for a summary) have not yielded a clear indication of substantial dark matter. Three points can be made in this regard. First, unlike the present data set, all of these observations (mostly of small numbers of C stars) are resolution and not signal-to-noise limited, and higher quality measurements of large K giant samples are desperately needed. Second, Kormendy (1986) has argued that the observed central surface densities are so large in the other systems that the effect of a dark halo may not be apparent in the central velocity dispersion. Finally, the M/L values for dI's reported by Sargent (1985) do exhibit considerable variation, and it may be simply that the ratio of dark to luminous material varies from one system to the next.

In summary, while not yet totally compelling, we believe the evidence for dark matter in the Draco and Ursa Minor dwarfs spheroidals has grown considerably stronger. The possibility that the nonluminous material consists of neutrinos can then be ruled out by phase-space density arguments (Tremaine and Gunn 1979). Rather, free streaming effects must be quite small, and the dark matter is therefore thermally cold in nature.

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## DISCUSSION

GUNN: What is the mean time interval between different measurements of the same star?

AARONSON: The observations are separated by intervals of three months to two years. The typical spread is about a year. In fact, for many of the stars there is a problem with aliassing of one-year periods, which are typical for K giants that have measured periods.

GUNN: I think there is a very strong observational selection in favor of finding only the short-period systems. Griffin and I have had a lot of trouble finding radial velocity standards because all of the velocities change when we watch them long enough. We have been at this for ten years now. So I think that it is very difficult to find all the binaries with a short baseline. Of course, it is true that as you go to long periods, you necessarily get small velocity excursions. But they are not small compared to your dispersion values. We should be very cautious.

LYNDEN-BELL: If you believe that there is cold dark matter in UMi and Draco, why is there none in Fornax?

KORMENDY: The total density in visible matter of assumed M/L = 2 is high enough in Fornax so that a dark halo like those in dwarf spirals will not affect the central velocity dispersion. This statement is true for Fornax, and marginally for Sculptor and Carina. Ursa Minor and Draco are the easiest objects in which to look for dark matter.

DEKEL: You might expect the value of M/L to change as you go to fainter objects. Draco may have the highest value of M/L because it is the smallest dwarf spheroidal. We have a theory about the formation of dwarfs, which Silk will talk about tomorrow, in which we predict a trend like this. Unfortunately, Seitzer and Frogel's observations of carbon stars give very low values of the velocity dispersion, lower even than we expect. So my question is: What is the hope of repeating the observations of Sculptor and Fornax in the near future?

AARONSON: I have no such plans. I am waiting until we get an 8 m telescope in the southern hemisphere. I think you need to measure K giants; carbon stars are too uncertain. As you saw for my observations of carbon stars, two of the five look as though they are binaries and a third has a lot of atmospheric jitter.

DEKEL: What is the problem with measuring K giants?

AARONSON: No proper motion studies have been made, so these fields have a lot of contamination. This is particularly a problem for Fornax and Sculptor, because their velocities are not large. At the moment it takes 2 hours to measure one star, and one doesn't want to waste that sort of time on foreground objects. This project is going to become feasible when you can observe a star in five minutes.

FREEMAN: How do you get luminosities to derive M/L ratios?

AARONSON: I use Zinn's values. He has made star counts and assumed that the luminosity function is the same as in M3.

OSTRIKER: Would Milgrom tell us what he would predict for the velocity dispersions in these systems? It would seem as though they are ideal test cases.

MILGROM: These objects have low surface densities and therefore low accelerations, so the prediction is that they should show large mass discrepancies. There are complications due to the fact that their internal dynamics are affected by the external field of the parent galaxy, so that there is a prediction of some galactocentric distance dependence. Typically, mass discrepancies (not M/L) should be 10 - 15 at distances of ~ 100 kpc.