Tidal Streams from the Carina and Draco Dwarf Galaxies

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Abstract.
A dwarf spheroidal system which is being tidally disrupted by the Milky Way is expected to produce tidal debris streams which lead and trail the system's motion. Our analyses of CCD photometry along the major and minor axes of the Carina and Draco dwarf galaxies indicate that in both cases such low surface density stellar debris streams exist. The surface densities of the debris streams are on the order of one percent of the central surface brightnesses of the Carina and Draco systems and may contain a substantial fraction of the mass originally within Carina and Draco.

1. Introduction

Theoretical calculations indicate that the tidal disruption of dwarf spheroidal galaxies in the gravitational potential of the Milky Way should lead to the production of stellar debris streams which lead and trail the motion of the dwarf galaxy. Kuhn (1993) specifically predicted that the Ursa Minor, Draco, Carina, and Sextans dwarf spheroidal systems should have a significant surface density of stars beyond their tidal radii. Hamlin's (1996) paper at this workshop includes a partial listing of references to models of extratidal stars in dwarf spheroidal and related systems. There is the expectation as well, confirmed in the case of Ursa Minor (Schweitzer 1996), that the direction of motion of the dwarf spheroidal system is coincident with the orientation of the major axis of the dwarf spheroidal system. Leakage of stars from dwarf spheroidal systems caused by tidal forces is thus expected to be preferentially seen, if it occurs at all, along the extension of the major axes of the dwarf spheroidal companions to the Milky Way.

The existence of a few stars seemingly associated with dwarf spheroidal systems, but apparently beyond the tidal radius, had been suggested by Innanen & Papp (1979). More recently, the star count data of Irwin & Hatzidimitriou (1995 - hereafter IH) suggested that extratidal stars associated with dwarf spheroidal systems could have a significant surface density. IH found that in all eight dwarf spheroidals there was an excess of stars beyond the tidal radius of a one-component King model, noting that in many cases the excess extended to more

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than twice the tidal radius, accounting for as much as 30% of the integrated light of the system.

Here we report on photometric searches for "extratidal" stars in two dwarf spheroidal systems, Carina and Draco. A major difference between these searches and the star counts of IH is the use of color information to help distinguish stars associated with the Carina and Draco systems from foreground field stars. This permits a search for extratidal stars to levels of surface density lower than could be detected in equivalent searches based upon star counts in a single color.

2. Search Method

The technique used to identify the component of extratidal stars associated with the dwarf spheroidal systems has been described in Kuhn et al. (1996). Photometry from CCD observations is used to obtain V, V-I color-magnitude diagrams for fields along the major and minor axes of the dwarf spheroidal galaxy. Fields on the minor axis, removed one or two degrees from the system center, are used to define a background, \( B(c,m) \), which is treated as a smooth function of V-I color, \( c \), and V magnitude, \( m \). A reference function for the dwarf spheroidal color-magnitude diagram, \( C(c,m) \), is then constructed by subtracting \( B(c,m) \) from the color-magnitude function observed for a central field in the dwarf spheroidal system. An estimate of the density of dwarf spheroidal and background stars in an arbitrary field with an observed color-magnitude function \( D(c,m) \) is then found by minimizing the expression \( \Sigma_{c,m}[D(c,m) - aC(c,m) - bB(c,m)]^2 \) with respect to the least squares parameters \( a \) and \( b \), where the sum extends over the V and V-I domain. In practice, the color-magnitude functions B, C, and D were determined by binning the color-magnitude data in 0.5 magnitude V bins and 0.1 magnitude bins in V-I. Statistical uncertainties were estimated for the derived parameters \( a \) and \( b \).

3. Results

3.1. Carina

The analysis of the Carina data has been described in Kuhn et al. (1996), and only a summary is given here. The Carina observations were obtained at Cerro Tololo Inter-American Observatory, using a 2K x 2K pixel CCD at the f/7.5 focus of the 1.5m telescope. Eleven fields were observed, nine along the major axis, including one field near the center of Carina, and two along the minor axis. The major axis fields extended approximately two degrees east and west of the Carina center, while the minor axis "background" fields were approximately one degree north and south of the center.

Results are shown in figure 1. As expected, the minor axis fields define a minimum Carina component, consistent with the idea that any tidal debris stream lies preferentially along the major axis. The analyses of the major-axis fields indicate the presence of a low surface density Carina component, extending out some two degrees from the center of Carina. In the region of overlap, out to about 80 arcmin, the surface density of this component is consistent with the
star count data of IH. IH determined the tidal radius of Carina to be about 28.8 arcmin.

3.2. Draco

The analysis of the Draco data is in an early stage, but we are able to give preliminary results on the existence of extratidal stars along the major axis to the east of the Draco center. CCD observations to $V = 22$ of fields near the Draco dwarf spheroidal were obtained with the 0.9 m telescope at Kitt Peak National Observatory. A 2K x 2K pixel CCD was used to obtained slightly overlapping CCD images extending three degrees to each side along the major axis of the Draco system and to plus and minus two degrees along the minor axis. Here we report the results for the major axis fields lying east of the center of Draco. Two fields along the northern extension of the minor axis, 1 and 1.3 degrees from the center, were used to set the background.

Results for Draco are shown in figure 2. There is evidence for a significant Draco component with low surface density extending to three degrees from the center of Draco. In the region of overlap, out to about a degree from the center, the color-magnitude diagram results are in good agreement with the star counts of IH. The tidal radius of Draco is about 28.3 arcmin according to IH.
Figure 2. Extratidal Draco component
4. Implications

The analyses of the CCD photometry of the Carina and Draco fields both corroborate and dramatically extend the results of IH. In the regions of overlap, the density of extratidal stars found from the CCD photometry is in good agreement with the star count data of IH. The CCD data indicate, however, that the excess of extratidal stars extends to some 4-6 tidal radii from the centers of the Carina and Draco systems, farther than could be measured with the star count data. IH noted that the extratidal stars in dwarf spheroidals may account for more than 30% of the luminous mass. Our new results confirm this, and suggest that the percentage of the luminous material which is extratidal is probably even higher.

The surface densities of the extratidal streams are several times $10^{-3}$ to a few times $10^{-2}$ of the central density. This is higher than expected in some models. For example, Oh et al. (1995) did not generate surface density enhancements greater than about $10^{-4}$ of the central density at radii greater than the tidal radius without catastrophic tidal disruption of the system. Time-dependent dynamical calculations (Kuhn & Miller 1989; Kuhn 1993) indicate that dwarf spheroidal systems which have been tidally "heated" by interaction with the Milky Way develop debris tails which extend several tidal radii, which are long lived, and which may, depending upon the form of the Milky Way potential at large galactocentric distances, persist for several orbits. These models appear to be capable of producing debris tails of the required surface density. The tidal "heating" predicted by the Kuhn & Miller models can in some circumstances be sufficient to inflate the stellar velocity dispersion of the dwarf spheroidal above its equilibrium value.

Spectroscopic observations would be a valuable complement to photometric evidence for extratidal stars in Carina and Draco. Radial velocity observations would not only confirm membership for extratidal stars, but could, if sufficiently accurate, provide a means of estimating the mass of the Milky Way galaxy at large radii (see Kuhn 1993).

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References

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