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A TIDAL EXTENSION IN THE URSA MINOR DWARF SPHEROIDAL GALAXY

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ABSTRACT

We report the detection of main-sequence and blue horizontal-branch stars of the Ursa Minor dwarf spheroidal galaxy beyond its tidal radius, indicating the existence of a possible tidal extension in this satellite of the Milky Way. This tidal extension could spread out well beyond the area covered in our survey ($R > 80'$), as suggested by the presence of a "break" to a shallower slope observed in its density profile. The *V*-band surface brightness for this possible tidal extension ranges from 29.8 to 31.5 mag arcsec^{-2}. The area covered in our survey (~1.65 deg^2) is not enough to discriminate if this extratidal population is part of a tidal tail or an extended halo around the galaxy. The existence of this tidal extension in Ursa Minor indicates that this satellite is currently undergoing a tidal disruption process by the Milky Way. We discuss the possibility of a tidal origin for the high mass-to-light ratio observed in this galaxy on the basis of our result and recent theoretical simulations of the tidal disruption of dwarf satellites in the Galactic halo.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: halos — galaxies: individual (Ursa Minor) — galaxies: structure

On-line material: color figure

1. INTRODUCTION

In hierarchical clustering scenarios for galaxy formation, such as cold dark matter–dominated cosmologies (White & Rees 1978; Blumenthal et al. 1984; Dekel & Silk 1986), dwarf galaxies should have formed prior to the epoch of giant galaxy formation and would be the building blocks of larger galaxies. The picture of building the Galactic halo from merging "fragments," which Searle & Zinn (1978, hereafter SZ) proposed on the basis of the properties of the Milky Way globular clusters, is regarded as the local manifestation of this galaxy formation scenario.

Recent evidence shows that the inner and intermediate region of the Galactic halo has mostly been formed in a fast process (Rosenberg et al. 1999). However, several results indicate that at least a part of the halo originated in a process similar to the SZ scenario and compatible with the hierarchical galaxy formation theory. The discovery of the Sagittarius dwarf galaxy (Ibata, Gilmore, & Irwin 1994), in the process of dissolving into the Galactic halo, favored the hypothesis that merging events can take place in the Milky Way, whose full formation history (through satellites merging into it) might not have finished yet. Isolated stellar tidal streams have also been identified in the Galactic halo by many authors (Majewski 1999; Côté et al. 1993; Arnold & Gilmore 1992; Helmi et al. 1999). Lynden-Bell & Lynden-Bell (1995) found that several dwarf spheroidal (dSph) galaxies and outer globular clusters appear to lie along two distinct streams that may be the remnants of larger parent satellite galaxies or SZ fragments. Some observational evidence also exists of the presence of tidal tails in dSph galaxy companions of the Milky Way (Kuhn, Smith, & Hawley 1996; Irwin & Hatzidimitriou 1995, hereafter IH; Majewski et al. 2000; Piatek et al. 2001). The possibility that accretion events may leave observable fossil records in the halo is also supported by theoretical models of tidally disrupted dSph galaxy satellites (Johnston, Spergel, & Hernquist 1995; Oh, Lin, & Aarseth 1995; Piatek & Pryor 1995; Gómez-Flechoso, Fux, & Martinet 1999).

Despite the evidence mentioned above, the question of whether other Milky Way satellites could have been tidally disrupted by the Milky Way is still open to debate. On the basis of this discussion, it is very important to investigate whether Galactic dSph galaxy satellites display tidal tails to understand if merging events played an important (Mateo 1996) or minor (Unavane, Wise, & Gilmore 1996) role in the formation of the Galactic halo. Moreover, determining if and how dSph galaxies dissolve is fundamental to several open questions concerning the dark matter content and the age spread of the halo, because the majority of them exhibit complex star formation histories (Mateo 1998) and apparently significant amounts of dark matter (Aaronson 1983; Olszewski, Pryor, & Armandroff 1996). These issues are intimately related to the difficulties in the interpretation of microlensing toward the LMC (Zhao 1998; Alcock et al. 1997; Zaritsky & Lin 1997) and to the existence of intermediate-age stars (Preston, Beers, & Schectman 1994) and main-sequence (MS) A stars (Rodgers, Harding, & Sadler 1981; Yanni et al. 2000) above the Galactic plane. The availability of a new generation of wide-field CCD cameras offers for the first time a good opportunity for successfully addressing these issues.

Ursa Minor (UMi) is one of the closest satellites of the Milky Way ($d = 69$ kpc) and is a strong candidate for being in the terminal phase of its complete tidal disruption (Hodge & Michie 1969). It also has the largest ellipticity (0.55; IH) if we exclude Sagittarius and displays, together with Draco, the highest observed velocity dispersion (Armandroff, Olszewski, & Pryor 1995). It also belongs to one of the intriguing alignments of dSph galaxies on the sky found by Lynden-Bell & Lynden-

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Bell (1995), suggesting that it could have been stripped from a larger "building block" a long time ago. This makes its study quite interesting in the aforementioned context. In this Letter, we report the detection of a tidal extension in UMi dSph galaxy from a systematic wide-field survey using broadband deep photometry.

2. OBSERVATIONS AND DATA REDUCTION

UMi dSph galaxy was observed in *B* and *R* Johnson-Cousins filters with the Wide Field Camera (WFC) at the prime focus of the 2.5 m Isaac Newton Telescope at the Roque de los Muchachos Observatory on the island of La Palma (Canary Islands, Spain). The WFC holds four 4096 × 2048 pixel EEV CCDs with pixel size 0″.33, which provides a total field of about 35 × 35 arcmin^2. Three fields were observed covering a total area of about 1 deg^2, as shown in Figure 1 (see Martínez-Delgado & Aparicio 1999 for more information). Total integration times were 1800 s in both filters.

Bias and flat-field corrections were done with IRAF. DAOPHOT and ALLSTAR (Stetson 1994) were then used to obtain the instrumental photometry of the stars. About 45,000 stars were measured in both bands. An overlap region between the adjacent fields of UMi was used to obtain a common internal photometric system for the galaxy. Atmospheric extinction and transformations to the standard Johnson-Cousins photometric system were obtained from observation of several standard stars of the Landolt (1992) list. Details about the photometric transformation are given in D. Martínez-Delgado, M. A. Gómez-Flechoso, A. Aparicio, & J. Alonso-García (2001, in preparation). Suffice it to say here that measurements of 17 standards were used and that the extinction was determined with an accuracy better than 0.02 mag, while the photometric transformation zero-point errors are 0.008 mag in *B* and 0.013 in *R*. The photometric transformations between the different WFC chips were obtained from observations of several standard fields in each different chip. These photometric zero points between different chips were estimated with an accuracy better than 0.01 mag. The total zero-point errors of the photometry are therefore about 0.025 in both filters.

3. METHODOLOGY

The detection of tidal tails in Local Group dSph galaxies is very challenging because of their large angular sizes and low surface brightnesses (LSBs) and requires using wide-field observations and a careful analysis of the foreground and background contamination (since extended objects are rejected by DAOPHOT and ALLFRAME, the background contamination will presumably include only stellar-shaped objects). An efficient technique is based on the analysis of wide-field, deep color-magnitude diagrams (CMDs; e.g., Mateo, Olszewski, & Morrison 1998). The LSB tail can be detected through star counts at the old population MS turnoff region. This feature is the most densely populated in the CMD and thus provides the best contrast against the foreground and background population. In the case of UMi, its extratidal structure can be traced also by the presence of blue horizontal branch (BHB) or blue straggler (BS) stars, because a gap exists in the distribution of contaminating foreground and background objects in coincidence with the BHB and BS regions.

Determining whether an extended population in UMi is or is not a tidal stream is also challenged because of the uncertainties about its angular size. The early work by Hodge (1964) provides a tidal radius of $r_t = 75' \pm 25'$, but model fitting to the same data by Lake (1990) and by Pryor & Kormendy (1990) yield $r_t = 59'$ and $r_t = 31'.3$, respectively. IH made a new study of the structural parameters of UMi using a wide-field scanned photographic plate. They found a tidal radius of $r_t = 50'.2$, reporting also the presence of possible extratidal stars. However, Kleyna et al. (1998), from two-color, CCD photometry, derived $r_t = 34'$ and argued that the larger value reported by the former authors might be the result of a biased estimate of the background contamination, which would also result in the detection of fake extratidal stars. Indeed, the two-color photometry of Kleyna et al. (1998) allows the removal of many contaminating objects from the density distribution on the basis of their place in the CMD. In this Letter, we will adopt the Kleyna et al. tidal radius, although we will also check the presence of extratidal stars beyond the IH value.

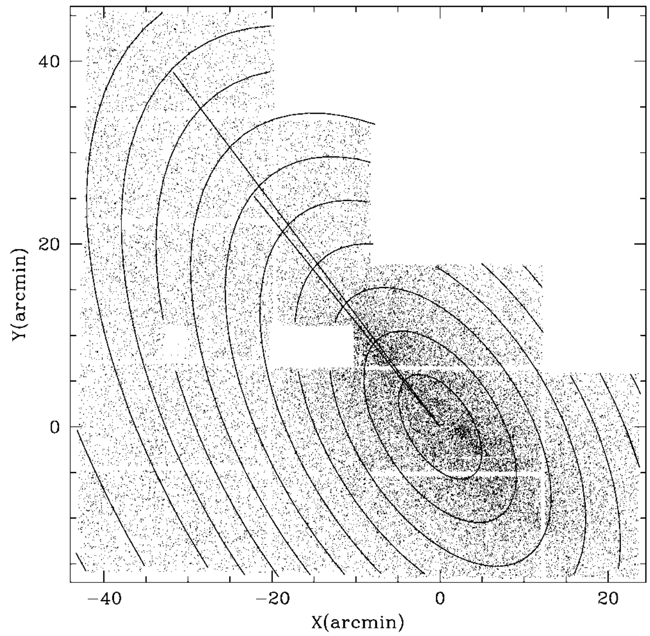

FIG. 1.—Spatial distribution of the stars measured in our survey together with the ellipses used to divide the galaxy for the density-profile study. The first ellipse has a semimajor axis of 6′.6. Further ellipses are obtained with a semimajor axis step of 5′.5. The 50′.6 and 34′ tidal radii obtained by IH and Kleyna et al. (1998), respectively, are indicated by the arrows. [*See the electronic edition of the Journal for a color version of this figure.*]

4. THE TIDAL EXTENSION OF THE UMi DWARF SPHEROIDAL

To study the extension of UMi, we have divided the galaxy into concentric elliptical annuli of the same eccentricity and position angle, for which we have adopted the IH values, and increasing semimajor axis (see Fig. 1).

Figure 2 shows the $[(B-R), V]$ CMDs of the stars in three selected elliptical annuli and of a control field situated 3° south of the center of UMi. The selected annuli are (1) the central region ($R < 6'.6$; with *R* the ellipse semimajor axis), (2) the region between the Kleyna et al. (1998) and IH r_t ($34'.0 < R < 50'.6$), and (3) the region between the IH r_t and the limit of our data ($50'.6 < R < 78'.1$).

Visual inspection of the CMDs indicates that the galaxy extends beyond the r_t of Kleyna et al. (1998; Fig. 2*b*), as shown by the presence of BHB and BS stars and other clear CMD features such as the MS turnoff and the subgiant sequence. A few BHB stars are also observed beyond the IH r_t (Fig. 2*c*), indicating the presence of the galaxy's stars even in this outer

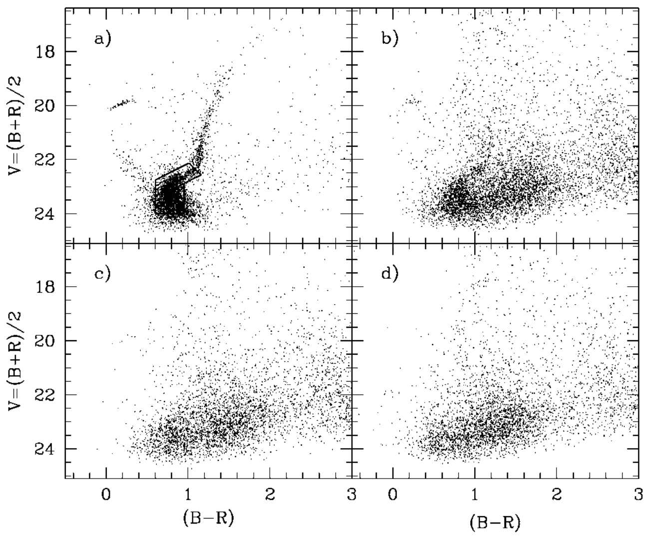

FIG. 2.—CMDs of the UMi fields. (*a*) CMD of the central region ($R <$ 6'.6) with the box used to count stars in the MS region. (*b*) and (*c*) show two extratidal fields of the galaxy ($34'.0 < R < 50'.6$ and $50'.6 < R < 78'.1$, respectively; see § 3). The detection of BHB and MS stars in these two fields reveals the existence of a tidal extension in UMi. (*d*) CMD of a control field, ~3° south from the center of the galaxy.

region. This is confirmed by the detection of a clump at the position of the MS turnoff [$(B-R) \sim 0.8$, $V = 23.5$], which is not observed in the control field.

We use the star counts method mentioned in § 3 (see also Mateo et al. 1998) to estimate quantitatively the extension and surface brightness of this possible tidal extension in UMi. We counted stars only within the MS box shown in Figure 2*a*, subtracting the counts from the control field for statistically removing the contribution of non-UMi stars in the box. We find that the differential reddening between the UMi and control fields is negligible from the extinction maps by Schlegel, Finkbeiner, & Davis (1998). Figure 3 (*upper panel*) shows the logarithm of the raw MS star counts per unit area (in units of square arcminutes) in each ellipse. The solid line shows the mean value for the control field with its Poisson error represented as dot-dashed lines. The logarithm of the net stars per unit area (once the contaminating objects are removed) are shown in the lower panel, where the error bars denote the Poisson uncertainties of each point.

Interestingly, the raw surface distribution shows a plateau for $55' < a < 78'.1$, which could be interpreted as the background density having been reached. This would mean that our density value obtained from the control field is too low. To check this possibility, we have estimated the number of galaxy members expected in the annuli $50'.6 < R < 78'.1$ (Fig. 2*c*), adopting the mean value of the background level from the radial profile at large radii ($R > 60'$) in Figure 3 (*upper panel*) (−0.04 in units as in Fig. 3, *upper panel*). The result is that only ~75 stars are expected in the MS box for the region of this annuli covered in our survey (see Fig. 1), and therefore no traces of the galaxy would be observed in the CMD plotted in Figure 2*c*. However, the presence of BHB and MS stars in this CMD shows that this is not the case. This suggests that this change to a shallower slope in the density profile could be a signature of the presence of a very faint tidal tail that extends to larger radii in this galaxy. Further observations are necessary to confirm this.

The surface brightness of this tidal extension can be estimated from our net star counts plotted in Figure 3. With this

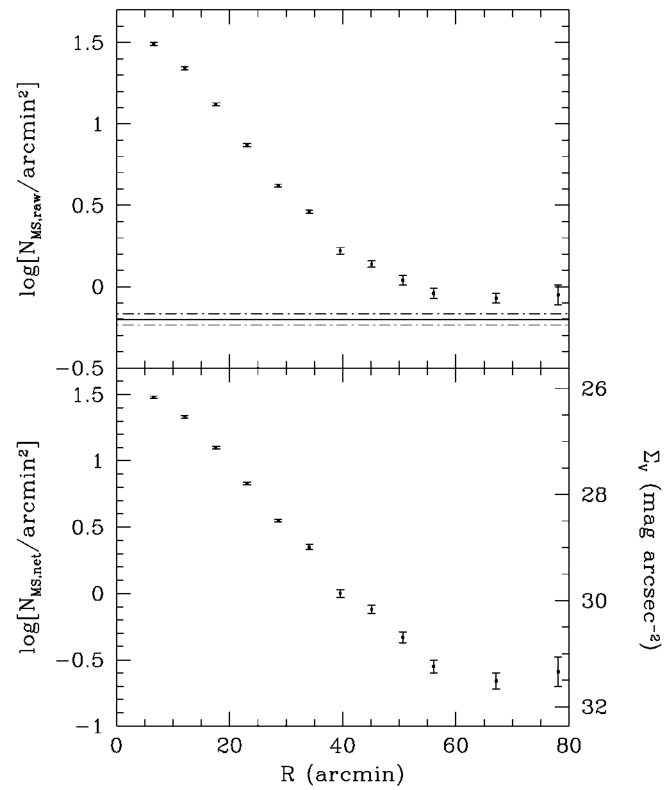

FIG. 3.—*Upper panel*: Raw data star counts per unit in the MS box (see Fig. 2*a*) in each UMi ellipse plotted in Fig. 1. The solid line shows the foreground level estimated from the control field. Dot-dashed lines show the Poisson uncertainties. *Lower panel*: Net star counts per unit area after subtraction of the foreground density.

purpose, we normalize to the *V*-band surface brightness estimated in the center region of UMi ($\Sigma = 25.5$ mag arcsec^{-2}) by Mateo (1998) to express the star counts in surface brightness units. This is also shown in the lower panel of Figure 3. The inferred *V*-band surface brightness profile for the possible tidal extension ranges from 29.8 to 31.5 mag arcsec^{-2}.

5. DISCUSSION

We report the detection of stellar members of the UMi dSph galaxy beyond the r_t given in previous studies, indicating the existence of a possible tidal extension in this galaxy. This tidal extension could spread out well beyond the area covered in our survey ($R > 80'$), as suggested by the presence of a "break" to a shallower slope observed in its density profile (see Johnston, Sigurdsson, & Hernquist 1999). Unfortunately, our data are insufficient to conclude whether this extratidal population is a part of a tidal tail or an extended halo around the galaxy.

The existence of this tidal extension in UMi indicates that this satellite is undergoing a tidal disruption process. In this context, it is important to discuss the possibility of a possible tidal origin for the UMi's observed high radial velocity dispersion, as has been suggested by several authors (Kuhn & Miller 1989; Gómez-Flechoso et al. 1999; Kroupa 1997). However, the interpretation of our results is difficult because of the open theoretical controversy about the origin of the high mass-to-light (*M*/*L*) ratios in dSph galaxies. In the case of a dSph galaxy satellite significantly perturbed by tides, one of the main alternative explanations for these large *M*/*L*-values is that the assumption of virial equilibrium may be not fulfilled. In these circumstances, a system having a low mass-to-luminosity ratio can present a large velocity dispersion (Kuhn & Miller 1989; Gómez-Flechoso et al. 1999) because of the tides increasing the energy of the stars in the dwarf galaxy and, accordingly, their internal velocity dispersion. However, Piatek & Pryor (1995) and Oh et al. (1995) found that, without dark matter, the velocity dispersion could not be as high as is observed, even considering its tidal disruption. Another alternative explanation has been proposed by Kroupa (1997) and Klessen & Kroupa (1998), who suggested that these dSph galaxies with large apparent M/L are actually long-lived tidal remnants whose main axis, together with the main axis of the velocity ellipsoid, could eventually be oriented close to the line of sight. In such a case, an observer would derive values for M/L that are much larger than the true M/L of the stars and would not need large quantities of dark matter to be accounted for. However, the observed width of the HB in Draco (Aparicio, Carrera, & Martínez-Delgado 2001) and UMi (D. Martínez-Delgado, M. A. Gómez-Flechoso, A. Aparicio, & J. Alonso-García 2001, in preparation) seems to indicate that this is not the case for these galaxies.

The presence of substructure in the main body of UMi also strengthens the idea that this satellite is being destroyed by Milky Way tides. Olszewski & Aaronson (1985) reported that the surface stellar density of UMi is patchy, finding two regions of high stellar density separated by a valley close to the center of the galaxy. This lumpy structure was also found in the recent studies by IH and Kleyna et al. (1998). We confirm the presence of lumpiness and asymmetry in the stellar distribution of UMi along its major axis (D. Martínez-Delgado, M. A. Gómez-Flechoso, A. Aparicio, & J. Alonso-García 2001, in preparation), although we are currently carrying out an analysis to test its statistical significance. If this substructure is real, more elaborate models, including details of the substructure and the presence of tides, will be needed to estimate the real dark matter content of UMi. A low dark matter content allows the formation of tidal tails besides the presence of substructures formed by tidal interaction. However, tidal tails and substructures are more difficult to understand in the context of a massive dark halo. A more extended systematic survey of the outer regions of Ursa Minor and accurate velocity measurements of these extratidal components are required to understand this important question concerning the dark matter content in UMi.

This work is based on observations made with the 2.5 m Isaac Newton Telescope operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de Los Muchachos of the Instituto de Astrofísica de Canarias.

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