A CANIS MAJOR OVERDENSITY IMAGING SURVEY. I. STELLAR CONTENT AND STAR-COUNT MAPS: A DISTINCTLY ELONGATED BODY OF MAIN-SEQUENCE STARS

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ABSTRACT

We present the first results from a large-area (∼80° × 20°), sparsely sampled, two-filter (B and R) imaging survey toward the Canis Major stellar overdensity, which is claimed to be a disrupting Milky Way satellite galaxy. Using stellar color–magnitude diagrams reaching to B ≈ 22 mag, we provide a first delineation of its surface density distribution using main-sequence stars. It is located below the Galactic midplane, and can be discerned to at least b = −15°. Its projected shape is highly elongated, nearly parallel to the Galactic plane, with an axis ratio of at least 5:1, substantially more so than what Martin and coworkers originally found. We also provide a first map of a prominent overdensity of blue, presumably younger main-sequence stars, which extends in latitude to b ≈ −10°. We estimate an upper limit on the line-of-sight depth σlos of the old population based on the main-sequence width, obtaining σlos < 1.8 ± 0.3 kpc at an adopted D0 = 7.5 ± 1 kpc. For the young stellar population, we find σlos < 1.5 kpc. The overall picture presented is one of a young stellar population that is less extended, both in terms of its line-of-sight depth and angular size, than the older population. While the data provide no firm arguments against an out-of-plane spiral arm interpretation, the data provide clear implications for others: (1) We infer from the strong elongation of the overdensity in longitude, and simulations in the literature, that the CMa overdensity is unlikely to be a gravitationally bound system at the present epoch, but may well be just a recently disrupted satellite remnant. The possible “flattening” of the young main-sequence population may, however, be a complexity for the satellite origin. (2) Based on modeling, the line-of-sight depth of the main-sequence overdensity in old stars is clearly inconsistent with published locally axisymmetric descriptions of the warped Galactic disk, such as those considered by Momany and coworkers. Without detailed modeling, the data set itself does not allow a distinction between interpretations as substructure in the warped outer Galactic disk or a disrupted satellite.

Key words: galaxies: dwarf — galaxies: individual (Canis Major) — galaxies: interactions — Galaxy: evolution — Galaxy: stellar content — Galaxy: structure

Online material: color figures, extended figure

1. INTRODUCTION

The current paradigm of how large disk galaxies like our Milky Way (MW) form (e.g., White & Rees 1978; White & Frenk 1991) is based on the successive coalescence and accretion of smaller systems of dark matter, stars, and diffuse interstellar gas into larger assemblies. Some of these smaller systems may be satellite dwarf galaxies that can be disrupted by tidal shocks and evaporation in a Galactic potential, and can spawn tidal tails. Numerical simulations exist that model distinct tidal stellar streams in and around large galaxies, indicating that at r ≈ 10 kpc such streams should remain detectable as coherent stellar overdensities for billions of years (Johnston et al. 1999; Ibata & Lewis 1998; Martínez-Delgado et al. 2004; Peñarrubia et al. 2006).

Recently, much work has focused on a possible low-latitude stellar stream, the so-called Monoceros Stream, encircling the MW at a galactocentric distance of around 20 kpc, which was found through color–magnitude diagrams (CMDs) from the Sloan Digital Sky Survey (Newberg et al. 2002; Yanny et al. 2003; also see Ibata et al. 2003; Conn et al. 2005; Martin et al. 2006). For stellar overdensities at low Galactic latitudes, it is not obvious a priori whether such a stream is of external origin, i.e., the tidal debris of a now (partially) disrupted satellite, or, alternatively, a distorted part of the preexisting outer stellar disk.

Arguments in favor of the dwarf satellite hypothesis have come from dynamical modeling (Peñarrubia et al. 2005), showing that it is possible to find a plausible model of the Monoceros Stream that explains all detected parts of this low-latitude stream as the wrapped tidal debris tails of a disrupting (model) dwarf galaxy. In this dynamical model the position of the Canis Major (CMa) overdensity is not an initial constraint, and yet the main body of the disrupting model satellite happens to be located in the direction of CMa at the present epoch. All kinematics, including the subsequently determined proper motion (Dinescu et al. 2005) of main-sequence (MS) stars in a small area (0.25 deg2) toward the CMa stellar overdensity are consistent with the dynamical model. Additional empirical support appears to come from the apparent bifurcation of suspected Monoceros Stream stars near a right ascension of 125° in Figure 1 of Belokurov et al. (2006), as could be expected in general based on the above-mentioned Peñarrubia et al. model.

The position and survival of the progenitor of this stellar stream is still under debate. The best candidate is a seemingly well-defined stellar overdensity of stars discovered in the direction of CMa using Two Micron All Sky Survey (2MASS) red giants (Martin et al. 2004a). This discovery has spawned a lively debate in the literature on whether this apparent overdensity of red giants could be part of the distorted outer stellar disk (Momany et al. 2004, 2006; see also Rocha-Pinto et al. 2006) or an accreted and possibly disrupting satellite (Martin et al. 2004b;
Martínez-Delgado et al. 2005a, hereafter MD05; Bellazzini et al. 2006, hereafter B06). However, a firm large-area kinematical, spatial, and chemical assessment between the three known stellar components of the overall debate (i.e., the young and old stellar overdensities and the Monoceros Stream) is lacking.

From deep, visible-band photometry there are signs of at least two different star formation episodes in the direction of CMa (Bellazzini et al. 2004, hereafter B04; MD05; Carraro et al. 2005). For the sake of clarity, we illustrate this in an annotated CMD. Figure 1, which corresponds to a field near the presumed center of the CMa overdensity, and for which the data are taken from this survey (see § 2). Whether the most recent burst of star formation activity occurred 1–2 Gyr ago, as suggested in B04, has been debated, with an opposing view in favor of a much younger stellar population of ≤100 Myr old stars (Carraro et al. 2005). The CMa overdensity itself, which is taken to lie near $D_0 = 7.5$ kpc (B04; MD05), comprises a predominantly older population of stars (4–10 Gyr; B04), and Moitinho et al. (2006) suggest that it may be a consequence of viewing a local armlike MW stellar substructure in projection. For a different and independent study of the stellar populations, we make use of the detailed CMD fitting in a forthcoming paper (de Jong et al. 2007).

To determine the full angular extent of the young and old MS stars toward CMa and to test whether they stem from a satellite galaxy, we conducted a large-area ($\sim 80^\circ \times 20^\circ$), sparsely sampled visible-band imaging survey of the CMa region, drawing on the wide-field image (WFI) at the ESO Max Planck Gesellschaft (MPG) 2.2 m telescope on La Silla. The survey subarea considered in this paper is $230^\circ \leq l \leq 260^\circ$, $-20^\circ \leq b \leq 15^\circ$.

1.1. Aim and Design of the WFI Survey

The principal goal of our imaging survey is to provide a database that can ultimately address whether the CMa stellar overdensity results from a dynamical distortion of the outer Galactic disk or whether it is the remains of a formerly large dwarf galaxy. As a step toward this goal, we aim to map its full angular extent through its star-count profile.

Recent reports (B06) based on 2MASS red clump stars suggest that the discernable part of the CMa overdensity may extend across several 100 deg$^2$ on the sky. Our survey goal is to cover this overdensity through sparse sampling, but with relatively deep visible-band imaging. Specifically, we want to obtain CMDs that reach well below the turnoff magnitude of an ancient stellar population; our target limiting magnitude is $B, R = 23$ mag (S/N = 10). We chose a wide color baseline ($B - R$) to have sensitivity to age-dependent and/or [Fe/H]-dependent CMD features (young MS, old MS turnoff [MSTO], and the red clump). The key difference (and merit) of the present CMa survey over previous large-area surveys, which have been based exclusively on 2MASS red giant stars and MW models, is that we base our analysis on CMDs that exhibit a well-defined stellar MS at a defined distance range. This provides an independent and high-contrast way of tracing the full angular extent of the CMa overdensity. The chief disadvantage of visible-band data is that Galactic extinction in many parts of this area is high, $A_V \geq 0.5$ mag.

1.2. Aim of this Paper

In this paper we present data from the first observing phase of our imaging survey, covering the region around $(l, b) =$ (240.5$^\circ$, −6.8$^\circ$) that had originally been identified as the overdensity in Martin et al. (2004a). As it turns out, these data provide only partial spatial coverage of the overdensity. Therefore, we refrain from a wide-spread quantitative comparison with Galaxy star-count models, except (1) to use a Besançon model CMD as a visual guide for the reader to help interpret the general morphology in our control CMDs, and (2) to aid the discussion in § 7.2.

We report our observations and present the data and their reduction in § 2. The issue of photometry completeness and uncertainties is assessed in § 2.1. The crucial issue of reddening by dust extinction and its correction is presented in § 2.2. In § 3 we explain the choice of control fields, which is followed by a description of the stellar content and morphology of the CMDs in § 4. In § 5 we provide a star-count analysis of young and old CMa MS stars. We estimate an upper limit on the line-of-sight (LOS) size of the CMa stellar overdensity in § 6. We briefly discuss our results in § 7 and summarize the key results in § 8.

2. OBSERVATIONS, DATA, AND DATA REDUCTION

All observations were carried out in service mode with the WFI on the 2.2 m ESO MPG telescope at the La Silla observatory (Chile) from 2004 December 9 to 20. The WFI’s field of view covers 0.25 deg$^2$, sampled at 0.238”/pixel$^{-1}$. Single-exposure images were taken in the $B$ and $R$ bands at 100 s per pointing and filter. The seeing was typically about 0.9”, with an overall range of 0.7”–1.1”. A total of 46 pointings (Table 1) provides a sparse map of the stellar overdensity region originally identified in Martin et al. (2004a). Pointings in the $B$ and $R$ bands typically differ by less than 2.5”, which leads to negligible field-to-field differences in the (effective) imaging area. Overscan, bias, flat-field corrections, and an astrometric correction were performed using a preduction pipeline (Schrimer et al. 2003). We obtained stellar photometry using DAOPHOT tools, available in IRAF. For each WFI pointing, we employed point-spread function (PSF) fitting using a spatially variable (order 2) Moffat function of exponent 2.5, derived from 100 stars. The DAOPHOT/ALLSTAR

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Footnote:

5 Table 1 includes a log of 13 additional observed fields, which are unused owing to extinction (see § 2.2).
TABLE 1

| ID          | \( l \) (deg) | \( b \) (deg) | \((B-V)_{	ext{med}} \pm \sigma\) (mag) | \((B-V)_{	ext{med}} \pm \sigma\) (mag) | \( N_{	ext{CMD}} \) (6) | \( N_{	ext{OMs}} \) \( \pm \sigma\) (7) | \( N_{	ext{Young MS}} \) \( \pm \sigma\) (8) |
|-------------|---------------|---------------|----------------------------------------|----------------------------------------|----------------|---------------------------------|---------------------------------|
| CMA 231.0–8.0 | 230.989       | –7.995        | 0.235 \( \pm 0.016 \)                  | –0.05                                  | 11964 | 941 \( \pm 69 \)               | 118 \( \pm 9 \)               |
| CMA 233.0–15.0 | 232.976       | –14.997       | 0.063 \( \pm 0.004 \)                  | ...                                   | 5684  | –101 \( \pm 70 \)             | 3 \( \pm 1 \)                |
| CMA 233.0–14.0 | 232.985       | –13.995       | 0.092 \( \pm 0.009 \)                  | 0.00                                   | 7256  | 123 \( \pm 46 \)              | 7 \( \pm 2 \)                |
| CMA 234.5–8.0 | 234.482       | –8.001        | 0.220 \( \pm 0.009 \)                  | –0.10                                  | 14641 | 926 \( \pm 64 \)              | 134 \( \pm 11 \)             |
| CMA 235.0–10.0 | 234.984       | –9.996        | 0.188 \( \pm 0.016 \)                  | –0.03                                  | 10412 | 573 \( \pm 67 \)              | 36 \( \pm 5 \)                |
| CMA 235.5–11.5 | 235.484       | –11.504       | 0.135 \( \pm 0.011 \)                  | –0.06                                  | 9221  | 503 \( \pm 46 \)              | 11 \( \pm 3 \)                |
| CMA 235.5–5.0 | 235.528       | –5.015        | 0.412 \( \pm 0.034 \)                  | ...                                   | 13195 | ...                            | ...                            |
| CMA 236.5–3.5 | 236.522       | –3.505        | 0.092 \( \pm 0.008 \)                  | ...                                   | 11923 | 3505                           | ...                            |
| CMA 237.0–12.5 | 237.983       | –12.494       | 0.118 \( \pm 0.004 \)                  | –0.10                                  | 8193  | 461 \( \pm 54 \)              | 13 \( \pm 3 \)                |
| CMA 237.5–9.0 | 237.478       | –9.993        | 0.219 \( \pm 0.032 \)                  | –0.07                                  | 12360 | 865 \( \pm 66 \)              | 84 \( \pm 8 \)                |
| CMA 237.5–8.0 | 237.480       | –7.995        | 0.219 \( \pm 0.018 \)                  | –0.02                                  | 15668 | 1224 \( \pm 84 \)             | 183 \( \pm 14 \)              |
| CMA 237.5–6.0 | 237.483       | –5.997        | 0.305 \( \pm 0.022 \)                  | ...                                   | 19815 | ...                            | ...                            |
| CMA 237.5–7.0 | 237.486       | –7.020        | 0.287 \( \pm 0.023 \)                  | –0.00                                  | 16331 | 1363 \( \pm 76 \)             | 193 \( \pm 13 \)              |
| CMA 238.5–5.0 | 238.476       | –4.993        | 0.489 \( \pm 0.050 \)                  | ...                                   | 15497 | ...                            | ...                            |
| CMA 238.5–11.0 | 238.478      | –10.976       | 0.141 \( \pm 0.007 \)                  | –0.09                                  | 10235 | 657 \( \pm 64 \)              | 12 \( \pm 3 \)                |
| CMA 238.5–6.5 | 238.481       | –6.500        | 0.277 \( \pm 0.030 \)                  | –0.08                                  | 13545 | 1163 \( \pm 68 \)             | 183 \( \pm 13 \)              |
| CMA 238.5–7.5 | 238.484       | –7.468        | 0.298 \( \pm 0.021 \)                  | –0.08                                  | 15544 | 1222 \( \pm 64 \)             | 111 \( \pm 12 \)              |
| CMA 239.7–9.2 | 239.680       | –9.244        | 0.143 \( \pm 0.004 \)                  | –0.00                                  | 12876 | 801 \( \pm 69 \)              | 66 \( \pm 8 \)                |
| CMA 239.7–10.0 | 239.681      | –10.001       | 0.127 \( \pm 0.007 \)                  | 0.00                                   | 12436 | 677 \( \pm 85 \)              | 26 \( \pm 4 \)                |
| CMA 239.7–6.0 | 239.687       | –6.994        | 0.304 \( \pm 0.021 \)                  | ...                                   | 15882 | ...                            | ...                            |
| CMA 239.7–6.8 | 239.691       | –6.754        | 0.338 \( \pm 0.024 \)                  | ...                                   | 15901 | ...                            | ...                            |
| CMA 240.0–5.0 | 239.981       | 4.991         | 0.152 \( \pm 0.004 \)                  | ...                                   | 14213 | 12 \( \pm 59 \)               | 7 \( \pm 2 \)                |
| CMA 240.0–15.0 | 239.981      | –15.000       | 0.100 \( \pm 0.004 \)                  | ...                                   | 15765 | –132 \( \pm 116 \)            | 2 \( \pm 1 \)                |
| CMA 240.0–20.0 | 239.985       | –19.997       | 0.047 \( \pm 0.002 \)                  | ...                                   | 3169  | 12 \( \pm 40 \)               | 1 \( \pm 0 \)                |
| CMA 240.0–15.0 | 239.986       | –14.996       | 0.052 \( \pm 0.003 \)                  | ...                                   | 3933  | –48 \( \pm 31 \)              | 1 \( \pm 1 \)                |
| CMA 240.0–8.0 | 239.988       | 8.000         | 0.109 \( \pm 0.004 \)                  | ...                                   | 9543  | –27 \( \pm 75 \)              | 8 \( \pm 3 \)                |
| CMA 240.0–2.7 | 239.999       | –2.693        | 0.531 \( \pm 0.004 \)                  | ...                                   | 1781  | ...                            | ...                            |
| ...          | ...           | ...           | ...                                    | ...                                    | ...   | ...                            | ...                            |

Notes.—Col. (1): Field ID. Cols. (2) and (3): Galactic longitude and latitude, respectively. Col. (4): Median differential extinction and standard deviation. For this, data were taken from the Schlegel et al. (1998) dust maps, modified using the correction from Bonifacio et al. (2000); their eq. (1). The standard deviation value is a measure of the total dispersion in \((B-V)_{	ext{med}}\) along the LOS in a given direction, based on the SFD98 dust extinction maps. Col. (5): Additional color dereddening, detailed in § 2.2. Col. (6): Number of stars in the CMD. Col. (7): Number of CMA MS stars determined using the method described in § 5.1. Col. (8): Number of young MS stars and the rms uncertainty, estimated inside the young MS extraction box outlined in Fig. 8. There is no \(N_{OMs}\) or \(N_{Young MS}\) estimate if \((B-V)_{\text{med}}\) > 0.3 mag. We note that fields with negative \(N_{OMs}\) estimates are set to zero for the surface density map in Fig. 10.
PSF-fitting task is run on each frame separately. As we have single exposures per pointing, cosmic rays are effectively filtered out during the PSF fitting and the matching of the \( B \) and \( R \) band photometry lists. Objects in each list are then assigned Galactic ''Magnitude system. Also, as we use dereddened CMDs in this paper, we applied an appropriate shift to the input magnitude scale of each completeness curve, denoted by "Magnitude\( _{\text{in}} \)." We refer to the magnitude-shifted \( B \)-and \( R \)-band completeness curves by \( B' \) and \( R' \) in the panels, respectively. See § 2 for further details. [See the electronic edition of the Journal for a color version of this figure.]

2.1. Completeness and Photometry Errors

To assess the point-source completeness, we performed artificial-star tests for a set of five fields, providing good coverage of the latitude range of the imaging survey. Specifically, we added a total of several thousand stars, in groups of 1300, in the (instrumental) magnitude range 15.5–25.5 mag, to each image. The fake stars that we added at random locations to these fields increase the number density by up to 10\%\(^\text{6}\), hence barely altering crowding effects. Stars injected in the \( B \)- and \( R \)-band images did not have the same locations. We then determined the completeness fractions, defined as the ratio of recovered artificial stars to the number of the injected ones, at 0.75 mag wide intervals. We brightened the \( B \) and \( R \) fake-star magnitudes by 0.52 and 0.12 mag, respectively, to shift them approximately from instrumental magnitudes to the flux-calibrated magnitude scale.\(^\text{6}\) Also, as we use dereddened CMDs in this paper, we shifted the magnitude scale of the completeness curves accordingly, and denote the shifted \( B \)- and \( R \)-band magnitudes by \( B' \) and \( R' \), respectively, in Figure 2. The completeness at (\( l, b \)) = (242.5\(^\circ\), −6.0\(^\circ\)) is above 90\% for \( B' \) or \( R' \) \(\leq 20.6 \) mag (see Fig. 2). In the matched \( B \)- and \( R \)-band photometry lists the completeness is less, and is typically above \(\sim 80\% \) at \( B' \sim 20.6 \) mag. This 80\% completeness limit varies by \(\pm 0.5 \) mag across the area surveyed at \(|b| \geq 6\(^\circ\).\)

Completeness at the faint-magnitude end varies from field to field for a number of reasons: differences in the seeing, stellar crowding, the cumulative effective of saturated stars (together with their stray light and ghost images, caused by internal reflections), cosmic rays, bright galaxies, and bright, nearby moving objects. This is different from the completeness in area) at each pointing, which is reduced by gaps between detector chips, bad columns, and pixels that are the same for each field. Based on the database of artificial-star photometry, we can assess the photometry errors (e.g., see Fig. 3). For example, 68\% of all artificial stars and, by inference, all detected stars with \( B' \sim 22.6 \) mag and
In the meanings of clarity, we restricted this diagnostic check to a subset of five fields from the survey area, with some at similar positions to check the local and global photometric quality. For the reddened color of the main sequence turn-off (MSTO) stars (although its distance may vary). With this assumption, the de-densit (e.g., see MD05) does not vary much from field to field and age of the stellar population that causes this CMa MS over-sulting CMDs and based on the assumption that the metallicity correction step, enabled by the prominent MS feature in the re-

be the full reddening correction. Therefore, we apply a second result CMD morphology in different fields shows that this cannot 

hereafter for the sake of clarity. However, the color of the red-

9 We refer to the blue, near-vertical, arclike overdense region at $B_0 \sim 18.5-20$ mag (e.g., see Fig. 1).
The (MSTO) color shifts resulting from the dereddening process, detailed above, are also given in Table 1; those values tend to grow with increasing Galactic longitude, and tend to diminish away from the Galactic midplane. The values suggest that the SFD98 data both overestimates and underestimates the foreground extinction across our survey area. In order to delimit the impact of dereddening errors further, we take an (ad hoc) extinction threshold \( E(B - V)_{SFD} = 0.30 \) mag. This means that fields whose median \( E(B - V) \) value is above 0.30 are ignored in this paper. The \( E(B - V)_{SFD} \) data and its standard deviation, which is a measure of its dispersion, is given in Table 1 for each field.

A final issue is the reddening dispersion in each field. The only attempt at compensating for it in this paper is through the first dereddening step, detailed above, which we apply on a star-by-star basis. As the actual reddening dispersion is unknown, we can only proceed on the assumption that the predominant variation from field to field is in the (median) foreground dust extinction, which we have attempted to correct for, and that there are no significant differences in the residual (foreground) dispersion from field to field.

3. CONTROL FIELDS

The overall density and the LOS distribution of the outer Galaxy’s stellar constituents (halo and thick/thin disk) vary with position on the sky. As we do not precisely model how the known (locally) axisymmetric contributions vary in the area of sky sampled in this paper, we try to minimize the dependence of our results on the current generation of synthetic MW models. We therefore adopt an empirical estimate of the MW components’ contribution to our CMDs. To illustrate how we select such “control fields,” we plot in Figure 5 a subset of CMDs for three fields of similar \( |b| \), from above and below the Galactic midplane. It is immediately apparent from this that the CMa overdensity is not present in each field, and those without obvious visible evidence of the CMa overdensity are termed control fields. As the thick- and thin-disk contribution to CMDs is expected vary with latitude, we consider several control fields. As we have control fields both above and below the Galactic midplane, we take the simple approach of using the field at \((l, b) = (240^\circ, +8^\circ)\) for the latitude range \(-14^\circ \leq b \leq 8^\circ\), and take the \((240^\circ, -20^\circ)\) field when \(b < -14^\circ\). At \(b > 8^\circ\), the field at \((240^\circ, +15^\circ)\) is the control field. We stress that the full imaging survey will provide a larger array of control fields for a better assessment and usage of them in future analyses.

4. COLOR-MAGNITUDE DIAGRAM MORPHOLOGY

AND THE STELLAR POPULATIONS TOWARD CMa

4.1. CMD Morphology and Stellar Content of a Control Field

Figure 4 shows the CMD of a field that we take as a control field from the current phase of the imaging survey, together with the Besancon MW model counterpart.\(^8\) It was chosen as a control-like field because it shows no obvious presence of the old CMa MS reported in B04 and MD05, based on a visual inspection. The Besancon model is meant to be a description of a MW galaxy without inhomogeneities (e.g., spiral arms). As such, it is very useful for exploring what types of stars at what distances and from which MW components (halo, disk, or spiral arms) contribute to different parts of the CMD.

The CMD in Figure 4 comprises a range of stellar populations at widely differing distances. The most prominent feature of the control field and its model counterpart is the so-called blue edge of MSTO stars. The color of this edge at \(B'_0 \leq 19 \) mag is influenced by metal-rich thick-disk stars and probable metal-poor halo MSTO stars. It is \(-0.1 \) mag bluer at fainter magnitudes, where it is dominated by metal-poor, outer-halo MSTO stars (spectral type F). We note (1) that apart from possible photometry scatter, some of the stars at \(B_0 < 14.5\) in the control field owing to detector saturation, and at \(B_0 > 22\) because of the magnitude limit. It can be seen in the Galactic model CMD that fainter MS stars at a given color are farther away. The marked density of model stars at \(B_0 > 22\), \(B - R_0 \sim 0.6-0.8\) mag in the synthetic CMD comprises ancient, metal-poor MSTO stars in the outer Galactic halo, but their number density may be inaccurate. [See the electronic edition of the Journal for a color version of this figure.]

\(^8\) The default Besancon model is available at http://bison.obs-besancon.fr/ modele/ (Robin et al. 2003).
Figure 5 illustrates that the structure of the CMDs for fields above (right) and below (left) the midplane over the full latitude range at $l = 240^\circ$. A comparison with Figure 4 (bottom) shows that the structure of the control-field CMDs can be reproduced using a standard Galactic model such as the Besançon model, but below the midplane an extra population is needed to create the CMa overdensity, which is attributed to the MS of a distinct stellar system near $D_\odot = 7.5$ kpc in B04 and MD05 (their Fig. 1); see § 7.2 also.

4.2. CMD Morphology and Stellar Content of CMa Fields

Figure 1 explains what one expects to see in a typical CMa CMD. Comparing the control fields (i.e., $b = +15^\circ$, $+8^\circ$, and $-20^\circ$ in Fig. 6) and this CMa field, we can now discern more robustly the same CMa features picked out by MD05 for a pointing near the presumed center of the CMa overdensity. A prominent feature is the old MS (B04; MD05), which has a blue, arclike (possible MSTO) region near $B_0 = 19$ mag. At brighter magnitudes there is a blue plume of young MS stars at $[B_0, (B - R)_0] \sim (15, -0.2)$ to $(18, 0.5)$ mag. Furthermore, there is the hint of a red giant branch in many CMDs, which is visible from $[B_0, (B - R)_0] \sim (15.5, 1.5)$ to $(17.5, 1.2)$ and may contain some CMa stars.

Figures 6 and 7 show a set of 15 tiles\footnote{A CMD for each of the other fields analyzed in this paper is available in the online version of the Astronomical Journal.} from our sparse map and provide a view of the stellar content in the CMa stellar region.
overdensity. These figures cover a good range in Galactic longitude and latitude, and provide a first qualitative picture of the stellar content of the CMa stellar overdensity over a large angular area. Unlike the model CMD for $b = C_0^20$ in Figure 4 (bottom), fields closer to the Galactic midplane have a stronger contribution from the thin and thick disk. This results in the prominent sloped ridge of MS stars, visible at $B_0 \approx 18$ mag, $(B - R)_0 \approx 0.5$ mag [e.g., at $(l, b) = (240^\circ, +8^\circ)$ in Fig. 6 or $(l, b) = (237.5^\circ, -8^\circ)$ in Fig. 7]. We see that the old MS is a very high contrast feature in several of those tiles, e.g., Figure 6 (center panel) or Figure 7 (top right). The density of old MS stars exhibits a prominent variation with latitude, seen to decrease away from the Galactic disk at $b \approx -7^\circ$ (Fig. 6). Comparing with CMDs along the longitude direction (Fig. 7), a distinct elongation in the old MS stellar population is immediately apparent. In contrast, we see that the young MS population is less evident and less populous at greater longitudes. From Figures 6 and 7, it is apparent that the old MS is still present at $b = -15^\circ$, while the younger population is still present at $b = -10^\circ$.

The number density and shape of the young MS star population varies among the CMDs. Figure 6 shows that there are dense plumes with a broad $B$-band spread, e.g., $(l, b) = (240.5^\circ, -6.8^\circ)$, but there are also narrow, dense plumes, e.g., $(l, b) = (237.5^\circ, -8.0^\circ)$ (see Fig. 7). The diversity in the shape ($B$-band width and density) of the young MS is reminiscent of the Small Magellanic Cloud (e.g., see CMDs in Noël et al. 2006), where there has been ongoing and bursty star formation over the past few billion years (Harris & Zaritsky 2004). The blue MS in the CMa CMDs may contain some blue straggler stars. It is likely to be dominated by young MS stars, which is how we refer to this population for the remainder of this paper. Carraro et al. (2005) report that this young MS is also observed in all of their fields, closer to the Galactic midplane, and that this suggests it is associated with the MW spiral galaxy. However, this interpretation may be complicated by the observed differences in its morphology (density and magnitude width) at different Galactic longitudes (Fig. 7).

This young (CMa) MS star plume should not be confused with the other similarly blue swath of foreground ($\approx 2$ kpc) white dwarfs at fainter magnitudes in most of our CMDs. Exceptions occur close to the Galactic midplane, owing to the possibly inaccurate dereddening of such nearby stars. The young (CMa)

![Figure 6: Sequence of CMDs across the Galactic plane along a fixed longitude ($l \sim 240^\circ$), running from $b = +15^\circ$ to $-20^\circ$. The text in each panel refers to the $(l, b)$ position. The axes are labeled $B_0$ and $(B - R)_0$ because the photometry was dereddened in two different steps (see § 2.2). Exceptions are the fields at $b = +15^\circ$, $+8^\circ$, $+5^\circ$, and $-20^\circ$, whose correct axis labeling is $B_0$ and $(B - R)_0$, but which are excluded for the sake of clarity. Magnitude and color error bars are given for the $(240, +5)$ field at $(B - R)_0 = 0$ (based on Fig. 3), which is expected to be typical for the bulk of these CMDs. The 80% completeness limit (dashed line) is shown in one panel, illustrating the faint limiting magnitude of the photometry. [See the electronic edition of the Journal for a color version of this figure.]
MS stars are also different from young (<2–3 Gyr) foreground (≤4 kpc) thick- or thin-disk MS stars that can occur at similar and brighter magnitudes than the young MS stars [e.g., at \(B_0 < 19\), \((B - R)_0 < 0.4\) mag] marked in Figure 1. Such MW disk stars can be seen at \(b = +5.0^\circ\) \((l = 240^\circ)\) in Figure 6, for example. Based on the model CMD (see Fig. 4, top), those stars are foreground thin- or thick-disk MS stars at \(D_o ≤ 2\) kpc. That such MS stars are not detected in every field may be a consequence of field-to-field differences in the saturation magnitude, which in turn depends on foreground dust extinction\(^{10}\) and observing (atmospheric) conditions.

5. MAPPING CMa ON THE SKY

5.1. Method: Old and Young MS

To estimate the old MS star counts that are attributable to the CMa overdensity at each pointing, we apply a simple analysis of the dereddened photometry using CMD extraction boxes. We estimate the number of old CMa MS stars, \(N_{\text{CMaMS}}\), in the relevant extraction box (see Fig. 8) at a given pointing \((l, b)\) as follows:

\[
N_{\text{CMaMS}} = \gamma \left( \frac{N_{\text{MSbox}}}{N_{\text{control field:MSbox}}} - \frac{N_{\text{control field:ref box}}}{N_{\text{ref box}}} \right),
\]

where \(N_{\text{MSbox}}\) is the star count in the MS extraction box in the relevant control field. Here \(N_{\text{MSbox}}\) and \(N_{\text{ref box}}\) are the star counts at a given \((l, b)\) in the CMa old MS box and a reference box, respectively. These boxes are outlined in Figure 8. Also, \(\gamma\) is the scale factor needed to compensate for the fraction of area (actually star counts) at \(16 < B_0 < 20\) above the adopted extinction threshold, \(E(B - V)_{\text{SFD}} = 0.30\) mag, in each field. For the majority (>90%) of these fields \(\gamma = 1\), and 1–2 otherwise. Based on the artificial-star tests (§ 2.1), incompleteness is expected to be well below 15% at 16 mag \(< B_0 < 20\) mag in over 90% of fields used, based on visual inspection of the CMDs; this value is adopted as a conservative upper limit for all CMa fields used, and is not included in the density estimates. A density estimate and its (random) uncertainty for each pointing is then obtained through data resampling; i.e., 100% of the stars are selected at random, allowing repeated selection, and a MS width estimate is recorded. After repeating this 100 times, we fit a Gaussian function to a histogram of the density estimates. The mean value from the fit is taken as the density estimate and the width parameter from the fit is taken as an estimate of the associated (random) error. Both of them are recorded in Table 1.

\(^{10}\) Sufficient foreground extinction can cause otherwise undetected (saturated) stars to be detected by dimming them.
We also map the surface density of young MS stars. We do this by counting stars in the extraction box overlaid on the young MS in Figure 8. While there are many fewer young MS stars than old MS stars, any contamination of the former by field stars appears to be negligible, based on either a visual inspection of our CMDs or the Besançon model CMD in the same direction. For this reason we do not subtract a background estimate. Each density estimate and its error (Table 1) is determined through data resampling.

5.2. Results: Comparison of Young and Old MS Star-count Profiles

Figure 9 shows the estimated number of young and old MS stars per WFI field against Galactic latitude and longitude. These are the key results:

The old MS stellar overdensity is highly elongated in Galactic longitude in the area of sky Although complicated by low-latitude extinction (and missing sky coverage), surveyed (also see Fig. 10, bottom), its profile in longitude appears flat at $l \gtrsim 240^\circ$, with a possible drop-off at smaller longitudes. A visual inspection of the density profiles suggests that CMa lies predominantly (e.g., $>60\%$) below the Galactic midplane, as found in the 2MASS red giant star analysis in Martin et al. (2004a). The survey data constrain the projected aspect ratio of the old stellar overdensity. There is little surface density gradient in longitude across the survey area, and it is therefore quite reasonable to infer that its FWHM exceeds the survey width, i.e., $>27^\circ$. In the latitude direction, the angular width estimate of the CMa density profile is complicated by the fact that the density maximum can only be constrained to be at $b \gtrsim -7^\circ$ in Figure 9. Taking the turnover to be at $b \sim -7^\circ$, the FWHM$_B$ is $\sim 6^\circ$, based on a visual inspection, and CMa’s projected aspect ratio is therefore $\gtrsim 5:1$. For the young...
MS, taking FWHM$_B > 20\degree$, conservatively, and FWHM$_g \sim 2\degree$ would give a projected aspect ratio of $>10:1$.

The young and old MS star populations overlap on the sky, but the young stars are markedly more localized in latitude. The detection of a compact distribution of young stars in the longitude direction is especially significant because of the essentially uncontaminated sample.

The overdensity of young MS stars is not as extended in projection as that of the older stellar population (see Fig. 9), but is possibly more flattened. The young MS stars exhibit a possible maximum density at $l \sim 240^\circ$, $b \sim 7^\circ$, with a drop-off in their counts at $l < 240^\circ$ and $l > 240^\circ$, as can be verified qualitatively from a visual inspection of the CMDs in Figure 7. While it is unclear whether reddening has affected the estimated density of young MS stars at $(258^\circ, -8^\circ)$, the presence of probable young MS stars with $(B - R)_0 \sim 0.0$ mag suggests that reddening is probably not the predominant cause of the drop-off in their density at $l \gtrsim 240^\circ$. The overall conclusions regarding the young and old stars can also be drawn from Figure 10, which shows a sky map of their number density. Finally, there are wiggles in the young and old MS profiles, but there is the possibility that they result from having a small set of control fields, a possible spatial variation in the stellar population, and/or unknown reddening dispersion.

6. LINE-OF-SIGHT DEPTH OF CMa

MD05 argued that the quite narrow distance range of the CMa stars points toward a disrupting satellite, rather than a flaring or warping of the outer Galactic disk. Here we explore the LOS extent of CMa by estimating the MS width in the magnitude direction for $(l, b) = (242.5^\circ, -9^\circ)$, a low-extinction field near the presumed center of CMa. As this estimate is expected to be the same over the CMa overdensity, we compare with the MS width estimated in MD05 for $(l, b) = (240^\circ, -8^\circ)$.

6.1. Estimating the MS Width

We model the $B$-band star-count distribution $f_{\text{sd}}(B'_0)$ in a given CMD color slice as the linear sum of two components, namely, a smooth (underlying) distribution of stars from the Galactic stellar halo and thick and thin disks $f_{\text{bgd}}(B'_0)$, and the CMa MS $f_{\text{MS}}(B'_0)$:

$$f_{\text{sd}}(B'_0) = a f_{\text{bgd}}(B'_0) + A f_{\text{MS}}(B'_0),$$

where

$$f_{\text{MS}}(B'_0) = \left[1/(\sqrt{2\pi\sigma_{B'_0}})\right] \exp\left[-(B'_0 - \bar{B}_0)^2/(2\sigma_{B'_0}^2)\right],$$

and the coefficients $(a, A)$ are scale factors. We describe the background distribution of stars $f_{\text{bgd}}(B'_0)$ as a second-order polynomial, as detailed below, and allow only its amplitude to vary.

In order to have a compact $B$-band distribution of CMa stars, while having a wide color slice, $1.0 < (B - R)_0 < 1.1$, for signal-to-noise ratio $(S/N)$ reasons we consider the distribution $B'_0 = B'_0 - 3.5((B - R)_0 - 1.05)$, instead of $B'_0$ alone. The slope is chosen to closely match the slope of the old MS in our CMDs. The method is illustrated in Figure 11 for $(l, b) = (242.5^\circ, -9^\circ)$, a field near the presumed center of CMa, and the reference field $(l, b) = (240^\circ, +8^\circ)$. The analysis differs from MD05, who had no control field and a fainter magnitude limit, which allowed them to consider a narrower color slice further down along the MS. The functional form of $f_{\text{bgd}}$ is given in Figure 11 (top left), with its amplitude scaled to match $f_{\text{bgd}}$ at $B'_0 = 18 - 19$ mag, binned at 0.25 mag intervals. After subtracting $f_{\text{bgd}}$, $f_{\text{MS}}$ is fitted. The error introduced by the binning and shot noise is assessed through data resampling. For the observed MS width, we obtain $(\sigma_{B'_0}) = 0.49 \pm 0.05$ mag.

In the above construction we have assumed a symmetrical distribution of star counts $N(B'_0)$, which appears to be a reasonable first approximation based on a visual inspection of Figure 11 (bottom left). To convert the estimated width of the observed MS, $(\sigma'_{B'_0})$, into a physical LOS depth, we firstly subtract in quadrature the contribution from the photometric uncertainty and the intrinsic width, based on an (assumed) stellar population with a zero distance range, thereby obtaining $\sigma_m$. In principle, a reddening dispersion should also be subtracted, but our only available way of attempting this is already implemented through the star-by-star dereddening detailed in §2.2. We then transfer $\sigma_m$ to a physical depth estimate by making use of $m - M = 5 + 5 \log D_\odot$, where $D_\odot$ (in parsecs) is the heliocentric distance of a star of magnitude $m$. The determination of $\sigma_{B'_0}$ is complicated by the fact that the adopted $f_{\text{MS}}$ may not be completely accurate, as remarked in López-Corredoira (2006). A good first approximation for the physical depth, in terms of the LOS 1 σ “radius” or depth, is this:

$$\sigma_{B'_0} \approx D_\odot (10^{\alpha_D/5} - 1),$$

where $D_\odot$ is the distance to the barycenter of the CMa overdensity along the LOS. It is taken to be $7.5 \pm 1$ kpc, a midway estimate between values in the literature ($7.2 \pm 1$ kpc, B06; 5–8 kpc, MD05).

6.2. An Upper Limit on the Line-of-Sight Depth of CMa

To estimate the depth of the old and young CMa overdensities, we compare the width of its MS to that of a reference population. We now consider the old MS population and return to the young MS later below. For the old overdensity, the reference is a simple stellar population with essentially no depth (i.e., $\sigma_{\text{old,ref}}/D_{\odot,\text{ref}} << 1$). Thus, by construction we do not account for a likely spread in the chemical composition of the (old) CMa stellar population and can therefore provide only an upper limit estimate of its LOS extent.

For the old reference stellar population, we use photometry of the low-concentration, high-latitude ($b = -47.7^\circ$) Galactic globular cluster Pal 12 from Martínez-Delgado et al. (2002; see Fig. 12, left). Note that we chose the Pal 12 comparison for its matching filter and S/N; it does have a slightly different metallicity ([Fe/H]$_{\text{Pal 12}} = -0.94$ dex; Harris 1996) than the old CMa MS ([Fe/H] $\sim -0.7$ dex; B04). Taking $E(B - V)_{\text{SFD98}} = 0.037$ mag and a standard Galactic reddening law (see §2.2), we apply a single dereddening value to the Pal 12 photometry. As it is a very sparse cluster, we use the inner region ($r < 1.5'$), which reduces the field-star contamination. We then apply essentially the same procedure to the Pal 12 photometry (Fig. 12, right) as in the CMa analysis, except that we use a slightly wider color range to have a well-defined MS. We obtain $\sigma_{\text{MS, Pal 12}} = 0.16 \pm 0.02$ mag through data resampling.

For the young overdensity, we adopt two single-metallicity reference stellar populations spanning a wide age range, as found for the young MS (Carraro et al. 2005; B04; MD05). Specifically,

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11 The color interval (mean color and width) is a compromise taken between incompleteness at faint magnitudes (and red colors) and the rising steepness of the MS in the CMD at blue colors.
Fig. 11.—Estimating the LOS depth of CMa. We show the star-count distribution (left panels) and the associated CMD (right panels) for a reference star field (top) and a field [(l, b) = (242.5°, −9°); bottom] near the presumed center of the CMa overdensity. The “thickness” of the old MS, reflecting the LOS extent, is estimated in the color interval bounded by vertical lines (vertical dashed lines) in the bottom right panel. As a guide to the photometric quality, the 80% completeness limit is also marked (horizontal dashed line). In the bottom left panel, the functional form from the top left panel (dotted line), together with a Gaussian function, is fitted (dashed line) to the histogram. The data in this panel are representative, and correspond to only one iteration of data resampling. See § 5.1 for further explanations of the depth estimation. We note that the axis labels on the top panels have no prime, as they had only one dereddening step (see § 2.2). [See the electronic edition of the Journal for a color version of this figure.]

Fig. 12.—Estimating the MS width of a reference stellar population, the globular cluster Pal 12. We have applied a similar procedure to that shown in Fig. 11. We extracted photometry from a narrow color interval in the CMD (left). We then fitted a Gaussian distribution (right, dashed line). The 1σ width data given in the right panel are from one iteration of data resampling. For more information, see § 6.2. [See the electronic edition of the Journal for a color version of this figure.]
we consider two metal-rich \((Z = 0.006)\) synthetic populations\(^{12}\), namely, 1–13 and 0.1–13 Gyr, at the adopted \(D_\odot = 7.5\ \pm\ 1\ \text{kpc}\), without binaries, with an adopted constant star formation rate and a zero distance range.

6.2.1. Result: Depth of the Old MS

We compute the depth \(\sigma_m\) in magnitudes as follows: \((0.49^2 - 0.16^2)^0.5 = 0.46\ \text{mag} \ (\pm 0.05)\), where the (squared) values in parentheses are for observed MS width (see § 6.1) and an estimate of the intrinsic width of a simple stellar population (see § 6.2). The photometry error is negligible, based on Figure 3. As this is an upper limit, we have \(\sigma_m < 0.46\ \text{mag}\). Finally, using equation (5) we obtain \(\sigma_{\text{los}} < 1.8 \pm 0.2 \pm 0.2\ \text{kpc}\), where the errors stem from the uncertainty estimate for \(\sigma_m\) and the adopted distance uncertainty, respectively. Alternatively, FWHM\(_{\text{los}} < 4\ \text{kpc}\).

As a check, we use data given in MD05 (their Table 1). Subtracting their tabulated (random) errors in quadrature from the total (observed) MS width, we obtain \(\sigma_m = 0.45\ \text{mag}\). Applying equation (5), we have \(\sigma_{\text{los}} = 1.8\ \text{kpc}\), which is in excellent agreement with the estimate in the present paper. Note that we do not generate an estimate for the field at \((240.1^\circ, -7.9^\circ)\) from our survey for a direct comparison with the MD05 result, owing to strong reddening and shorter exposures.

6.2.2. Result: Depth of the Young MS

We now attempt a first estimate of the LOS depth of the young MS, in a way similar to that used in the old CMa MS analysis. As illustrated in Figure 13, we determine the \(B\)-band width of the young MS in the color range \(0.2\ \text{mag} < (B - R)_0 < 0.5\ \text{mag}\).
Photometric errors for young MS stars, as inferred from Figure 3, are negligible. For the 0.1–13 and 1–13 Gyr synthetic populations, the estimated $B$-band width is $0.37 \pm 0.17$ and $0.51 \pm 0.05$ mag, respectively. This suggests that there is a dependence on the age of the youngest synthetic stars, and a different metallicity may alter this further. The $B$-band width of the observed young MS is $0.38 \pm 0.17$ mag. To estimate a preliminary upper limit on the LOS depth, we consider the observed MS width plus its uncertainty (i.e., $0.38 \pm 0.17$ mag), and subtract the width of the synthetic MS in quadrature. This gives $\sigma_{\text{los}} = 0.39$ and $0.17$ mag for the $0.1$–$13$ and $1$–$13$ Gyr populations, respectively. Using equation (5) we obtain $\sigma_{\text{los}} \lesssim 1.5$ and 0.6 kpc, respectively. Considering that a binary fraction and a metallicity spread have been omitted, which would decrease the estimated physical depth further, a strong implication is that the LOS depth of the young overdensity is $\sigma_{\text{los}} \lesssim 1.5$ kpc.

7. DISCUSSION

7.1. Comparison with Previous Work

We have obtained, presented, and analyzed a set of 46 CMDs toward the CMa overdensity. Toward CMa, those CMDs reveal a prominent overdensity of old and young MS stars at a defined distance range. In Figure 11 (bottom right), one can see that the number density of old MS stars over the expected MW background in the color-magnitude plane is substantial, more than a factor of 2 for most (>70%) of the old MS width. The density profile of old MS stars shown in Figure 9 provides unambiguous evidence for a stellar overdensity toward Canis Major. This validates the 2MASS red giant–based detection of an overdensity in this direction by Martin et al. (2004a). We find CMa to be substantially more elongated in longitude than what Martin et al. found, in general agreement with B06 (see also Rocha-Pinto et al. 2006), whose work was also based on red giants from the 2MASS catalog.

We also presented a first extended map that traces the surface density map of the young MS stars toward the CMa stellar overdensity (Fig. 9). While a kinematical link between the old and young MS populations is lacking, the map shows they are roughly coplanar on the sky and that the younger of the two stellar populations is less spatially extended in latitude, and possibly also in longitude.

Figure 9 (right) shows a comparison of the young and old MS profiles, together with the red clump surface density profile at $b \sim -8^\circ$ from B06 (estimated from their Fig. 9). From Table 2 in B06 the density of red clump stars reaches a maximum near $l = 244^\circ$, which appears to be compatible with the possible peak in the young MS density profile. No such peak is obvious in the old MS data, which are consistent with a near-flat profile in longitude across the entire survey width. Qualitatively, the old MS profile appears to be compatible with the result of Rocha-Pinto et al. (2006): a large, low-latitude stellar body whose surface density extends beyond $l > 270^\circ$. In this scheme, the “original” CMa overdensity (Martin et al. 2004a; B04; MD05) would be an outlying part of a larger overdensity. Overall, it is noteworthy that we detect an overdensity of both young and old MS stars in the same direction as the red clump star-count profile given in B06 (their Fig. 9). Yet, it is unclear what actual relationship, if any, exists between them. Further study is required to place these issues on a firm statistical footing.

We placed an upper limit of $\sigma_{\text{los}} < 1.8 \pm 0.3$ kpc (FWHM$_{\text{los}} \leq 4$ kpc) on the LOS depth of the (old) CMa stellar overdensity and found that it is highly elongated in projection ($\Delta l / \Delta b \gtrsim 5 : 1$). A comparison with the nearest known dwarf galaxy (Sgr), whose RR Lyrae star–based LOS FWHM estimate is 5.3 kpc, corresponding to $\sigma_{\text{los}} \sim 2.3$ kpc [deduced from $(m-M)_V$ data in Cseresnjes et al. 2000], only suggests that the CMa depth of a few kiloparsecs estimated in this paper is not necessarily incompatible with an origin as a dwarf galaxy. We also found that the depth of the young MS population, $\sigma_{\text{los}} < 1.5$ kpc, is apparently smaller than that of the older stellar population. The overall picture portrayed by the data in this paper is one of a young stellar population that is less extended, in terms of both its LOS depth and angular size (at least in latitude), than the older population.

In § 7.2 we scrutinize this briefly with regard to different interpretations of the CMa overdensity.

7.2. On the Different Interpretations of the CMa Overdensity

As outlined in § 1, there are three broad classes for the different interpretations of the CMa overdensity, namely, (1) it is a predominantly old (several gigayears old) dwarf galaxy that may be partially disrupted (Bellazzini et al. 2004, 2006; MD05); (2) it can be explained by a LOS crossing a warped but locally axisymmetric (i.e., substructure-free) outer Galactic disk (Momany et al. 2004, 2006; López-Corredoira 2006); and (3) the overdensities in the young and old MS stars arise from out-of-plane MW spiral arms and the Local Arm, respectively (Carraro et al. 2005, Moitinho et al. 2006). We discuss these in turn.

1. If the strongly elongated old overdensity that we have mapped is the central part of a dwarf galaxy, could it still be partially bound? In a disrupting satellite, stars are lost from the gravitationally bound main body and carried into tidal tails, one leading the satellite and one trailing it. If a satellite is on a near-circular, low-latitude coplanar orbit, as the CMa dwarf would have to be (e.g., Peña-Rubia et al. 2005), the predominant tidal forces are always in the direction toward the Galactic center. This leads to perturbations over the entire orbital period, allowing stars to continually escape, unlike eccentric orbits, as evidenced by the modeled disruption of the globular cluster Pal 5 in Dehnen et al. (2004). But in such tidal disruption events (e.g., Piatek & Pryor 1995; Dehnen et al. 2004; Peña-Rubia et al. 2005), the still-bound portion of the stars does not become highly flattened. The tidal debris, however, would be wrapped around the Galactic center, as modeled by Peña-Rubia et al. (2005) and Martin et al. (2005). Based on these generic simulation results, we infer from the strong elongation of $\gtrsim 5 : 1$ in longitude that CMa has been undergoing recent tidal disruption and is still localized, but no longer gravitationally bound.

Support for the dwarf galaxy hypothesis has come from the proper-motion analysis in Dinescu et al. (2005), which is based on young MS stars in a small area ($0.25$ deg$^2$) near the suspected center of the CMa overdensity. It reveals a large ($7$ σ) deviation from the expectation for stars belonging to the warped part of the Galactic disk, a motion that fits the preexisting dynamical model (Peña-Rubia et al. 2005), which is itself tied only to known parts of the Monoceros Stream. This argument, of course, hinges on the assumption that the young tracer stars are in fact associated with the predominantly older, larger, and more complex CMa stellar overdensity, an issue that is debated in Carraro et al. (2005).

Footnote:

13 Thirty-one of the 46 CMDs used in the analysis are given in the online version of the Astronomical Journal.

14 We note that modeling of the progenitor of the Monoceros Stream is discussed in Martínez-Delgado et al. (2005b), and shows a comparison of the $N$-body Monoceros model with the integrated orbit of CMa.
Simulations of dwarf galaxies in dynamical equilibrium suggest that young stars may well be kinematically colder than older populations (McConnachie et al. 2006). However, to firmly establish a link between the young and old CMa stellar populations or the absence of it, a kinematical (and chemical) study of both is essential.

There is one aspect of the projected old and young MS overdensity distributions that is not easily reconciled with the idea of both arising from a recently disrupted satellite: the large extent of the young population in longitude, given its more compact distribution in latitude. If the young stars were at the center of the putative precursor dwarf galaxy (as seen in, e.g., Phoenix [Martínez-Delgado et al. 1999] and Fornax [Stetson et al. 1998]), then they should have been disrupted last, and hence be the least “stretched out” subpopulation. Only yet more extensive imaging (in area coverage) can resolve this issue.

2. Could the old CMa stellar overdensity simply be a consequence of viewing the warped outer stellar disk (Momany et al. 2004, 2006) nearly edge-on? The 2MASS red giant star surface density map of Figure 9 (bottom) in Momany et al. (2006) appears to be broadly compatible with the flat or possibly gradual density variation across our survey width from $l = 231^\circ$ to $258^\circ$. The angular density distribution of CMa that we have mapped appears, taken by itself, to be qualitatively consistent with a warped Galactic disk (Momany et al. 2006). From their analysis (their § 4.2), one would infer however that at $D_o = 7.3$ kpc star counts at $b = +8^\circ$ should match those at $b \sim -15^\circ$. This is not reflected in our data, as is evident from a comparison of the CMDs for $b = +8^\circ$ and $-15^\circ$ in our Figure 5. Rather, an additional stellar population is present at $l = 230^\circ - 260^\circ$, extending up to 2 kpc below the Galactic midplane.

More importantly, our LOS depth estimate can shed new light on this matter. In Figure 14 we compare the LOS distribution predicted by the model in López-Corredoira et al. (2002, hereafter LC02) and Yusifov (2004) to the one observed here. This figure shows (1) that the maximum reached by the old stellar overdensity is significantly farther [$\Delta(m - M) \sim 4.8$ mag or $\sim 10.5 \sigma_{\text{old MS}}$] from the maximum expected for a locally axisymmetric, warped, and flared MW disk, based on LC02 (without spiral arms or other substructure). The distinctiveness of the old stellar overdensity is still evident if we compare with the pulsar-based Yusifov (2004) model, which yields [$\Delta(m - M) \sim 2.8$ mag or $\sim 6 \sigma_{\text{old MS}}$]. In the Yusifov (2004) model, the density profile has a more gradual drop-off with galactocentric distance, and therefore reaches a maximum at larger heliocentric distances than the LC02 model. Figure 14 also shows (2) that the observed CMa depth is much smaller than expected for a LOS intercepting a warped disk. We conclude that the existing smooth (i.e., locally axisymmetric) descriptions of the warped outer Galactic disk are unlikely explanations of the CMa overdensity. As the $\sigma_{\text{los}}$ discrepancy (distance and width) seems generic, variations on the existing warp models are also unlikely to match all data.

Figure 15 reiterates this point by showing a color-magnitude comparison of an observed CMa field, a control field, and a synthetic field for a warped and flared MW stellar disk. The synthetic population is 4–10 Gyr old with $-0.4 < [Z/Z_\odot] < -0.5$ dex, and has been convolved with the LC02 MW density profile plotted in Figure 14. It is in fair qualitative agreement with Figure 7 in B06, who used a simple stellar population (47 Tuc) as the template population. Our model CMD is not meant to be an exact simulation of the MW’s contribution to CMa CMDs, but rather serves to illustrate that smooth (locally axisymmetric) components of the warped outer Galactic disk alone do not account for the CMa overdensity.

In the model MW CMD (Fig. 15, right), there is a relative increase in star counts at $(B - R) \sim 0.8$ mag, $19 < B < 17$ that is not observed in the control field. It might be a signature of viewing the warped outer Galactic disk in projection, and differs substantially from the CMD feature known as the CMa stellar overdensity, which is evident in Figure 15 (left).

Finally, we note a possibly strong low-latitude $(b = -3.4^\circ)$ detection in Bragaglia et al. (2006) of the CMa overdensity toward the Galactic anticenter where the Galactic warp is largely absent. This could be related to a tidal tail of the (candidate) dwarf galaxy, and appears to disfavor a projection effect of the warped outer MW disk.

3. There are interpretations of the young MS population that do not invoke a satellite origin, but instead infer that known types of MW substructure may have been detected (Carraro et al. 2005; Moitinho et al. 2006). In this scenario the young stellar overdensity is a $\lesssim 100$ Myr old spiral arm population, and the old overdensity is merely a projection effect of looking along a nearby interstellar arm structure (the Local Arm). While we cannot provide firm evidence against the interstellar arm scenario, it is unclear whether it can be reconciled with the old stellar population, which is still detected at $b \sim -15^\circ$ in our survey, and is distributed over a larger area than the young stellar population. A comparison of the bluest stars in the empirical and synthetic CMDs in Figure 13 suggests that the most recent star formation activity could indeed have occurred less than $\sim 100$ Myr ago, but this depends on reddening and the choice of metallicity and distance. Young ($\lesssim 100$ Myr old) stars are not necessarily incompatible with the MD05 study, in which the age used for the youngest MS stars is very uncertain, because of the same degeneracy between the distance, the stellar population (age $Z$), and foreground reddening; the youngest stars could be 100 Myr old if the overdensity is farther away (e.g., $\sim 10$ kpc), as needed for the Peñarrubia et al. (2005) model, which places the progenitor
of the Monoceros Stream at larger distances too. A reliable distance estimate, based on RR Lyrae stars, for example, as well as spectroscopic estimates and extinction information, are necessary to solve this controversy unequivocally. We note that young (e.g., 100 Myr) stars themselves are not strong evidence against a tidally disturbed dwarf galaxy: for example, the star formation activity was probably ongoing 100 Myr ago in the M31 satellite dE/NGC 205 (Butler & Martínez-Delgado 2005) and possibly <1 Gyr ago in the MW dSph/Sgr dwarf galaxy (Bonifacio et al. 2004).

There is also the issue of why the young stellar overdensity can be spotted 10° (up to 1.3 kpc) below the Galactic midplane (b = 0°). If we are observing 100 Myr old members of a MW spiral arm or an interspiral arm structure, such stars at \( D_\odot = 7.5 \) kpc would have drifted away from their parent stellar associations by a negligible amount (a few times 100 pc), leaving them absent at \( b \sim -10° \). This suggests that the young stars may have unusual kinematics, as was found for previous detections of young (<100 Myr) stars several kiloparsecs from the midplane (e.g., Rodgers et al. 1981; Lance 1988); such young out-of-plane stars have been attributed by several authors to possible accretion events, based on stellar kinematics.

8. SUMMARY AND CONCLUSIONS

We have presented initial results from our imaging survey of the Canis Major stellar overdensity, provided color-magnitude diagrams of fields used\(^{15}\) from our survey area, a depth estimation for the young and old MS populations, and a first analysis of their surface density distribution. In particular, our key findings are these:

1. Using “old” MS stars, we can delineate an overdensity of MS stars elongated along Galactic longitude at a distance of \( D_\odot \approx 7.5 \) kpc. It coincides with the overdensity of 2MASS red giants discovered in Martin et al. (2004a), but our surface density mapping reveals it to be markedly more elongated than initially thought. Its projected aspect ratio is probably \( \approx 5:1 \), which is consistent with the more recent 2MASS analyses (B06; Rocha-Pinto et al. 2006). We also map the angular distribution of the much bluer MS stars (the “young” MS).

2. The distributions of young and old stars are approximately cospatial in projection, but the young MS density profile is markedly more localized, with a possible shallow maximum near \( l \sim 240°, b \approx -7° \).

3. We report the clear detection of young and old MS stars up to 1.3 and 2 kpc, respectively, below the Galactic midplane at \( l \sim 240° \).

4. We derive an upper limit on the LOS depth of the (old) stellar overdensity by assuming that its stellar population is simple (as, e.g., the globular cluster Pal 12), and that its MS width soley reflects a distance spread. We obtain \( \sigma_{\text{los}} < 1.8 \pm 0.3 \) kpc (or \( -4 \) kpc, FWHM\(_{\text{los}} \)) at the adopted \( D_\odot = 7.5 \pm 1 \) kpc. The young MS stars are consistent with \( \sigma_{\text{los}} \lesssim 1.5 \) kpc.

We discussed these results in the context of three broad explanations put forth in the literature for the CMa overdensity.

(1) We infer from the strong elongation of the overdensity in longitude and simulations in the literature that, if it is a satellite galaxy on a near-circular, low-latitude orbit, it is unlikely to be still gravitationally bound at the present epoch; it would have to be a recently disrupted satellite.

(2) The distance and LOS depth of the overdensity is in disagreement with all published smooth (or locally axisymmetric) models of the Galactic warp. Those produce a density profile that is markedly more extended along the LOS and reaches a maximum significantly closer.

Finally, regarding an out-of-plane spiral arm hypothesis for the young MS stars, we note that the presence of young out-of-plane stars is not uncommon in the MW, and such stars in the literature have been attributed to possible accretion events, based on stellar kinematics.

\(^{15}\) CMDs of all fields used are available in the online version of the Astronomical Journal.
Without detailed modeling the data themselves are not yet sufficient to discriminate between an interpretation as substructure in the preexisting warped outer Galactic disk or a disrupted satellite.

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