Why the Canis Major overdensity is not due to the Warp: analysis of its radial profile and velocities

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ABSTRACT
In response to criticism by Momany et al. (2004), that the recently-identified Canis Major (CMa) overdensity could be simply explained by the Galactic warp, we present proof of the existence of a stellar population in the direction of CMa that cannot be explained by known Galactic components. By analyzing the radial distribution of counts of M-giant stars in this direction, we show that the Momany et al. (2004) warp model overestimates the number of stars in the Northern hemisphere, hence hiding the CMa feature in the South. The use of a better model of the warp has little influence on the morphology of the overdensity and clearly displays an excess of stars grouped at a distance of $D = 7.2 \pm 0.3$ kpc. To lend further support to the existence of a population that does not belong to the Galactic disc, we present radial velocities of M-giant stars in the centre of the CMa structure that were obtained with the 2dF spectrograph at the AAT. The extra population shows a radial velocity of $v_r = 109 \pm 4$ km s$^{-1}$, which is significantly higher than the typical velocity of the disc at the distance of CMa. This population also has a low dispersion (13 $\pm$ 4 km s$^{-1}$). The Canis Major overdensity is therefore highly unlikely to be due to the Galactic warp, adding weight to the hypothesis that we are observing a disrupting dwarf galaxy or its remnants. This leads to questions on what part of CMa was previously identified as the Warp and how to possibly disentangle the two structures.

Key words: Galaxy: structure – Galaxy: formation – galaxies: interactions

1 INTRODUCTION
The recently-discovered Canis Major overdensity (hereafter CMa) appears to be an ongoing accretion event that will contribute to the build-up of the Galactic thick disk (Martin et al. 2004, hereafter Paper I). Found close to the plane of the Milky Way disc, we argued this putative dwarf galaxy may be the progenitor of the ‘Ring’ of stars that encircles the Galaxy (Ibata et al. 2003; Crane et al. 2003), which is seen most clearly in the Galactic anticentre direction (Newberg, Yanny et al. 2002; Yanny, Newberg et al. 2003). This ‘Ring’ of stars may have been built progressively as stars were removed from that dwarf galaxy by the disruptive tidal forces of the Milky Way.

In Paper I, we extracted candidate M-giant stars from the 2 Micron All Sky Survey (2MASS), following selection criteria used to study the tidal stream of the Sagittarius dwarf galaxy (Majewski et al. 2003). By comparing the M-giant distribution above and below the Galactic plane, we brought to light several large-scale Galactic asymmetries that we interpreted as the CMa dwarf galaxy and the CMa tidal stream. Bellazzini et al. (2004, hereafter Paper II) presented deep photometry of a field at 4.2$^\circ$ from the center of CMa and of Galactic open clusters that lie fortuitously in front of the CMa overdensity. These data give a good constraint on the distance to this population, $(m - M) = 14.6 \pm 0.3$, and also constrain the dominant stellar population to be of intermediate age ($\sim 4$–10 Gyr) and to be metal-rich ($-0.7 \leq [M/H] \leq 0.0$).

However, Momany et al. (2004, hereafter M04) questioned the existence of the CMa overdensity. They claimed that it could be entirely explained by a simple shift of the Galactic plane of 2 degrees to the South to model the Galactic warp that is known to exist in this part of the sky. Using the UCAC2 proper motion catalogue, they also showed that the M-giants composing the overdensity are rotating around
the Milky Way in a prograde manner and at a tangential velocity that is compatible with the disc. Here, we use the radial starcount distribution and the radial velocity of M-giants in the direction of CMa to show the CMa overdensity cannot be explained by the Warps and that its morphology and kinematics are clearly different from what would be expected from the Warp. We refer the reader to Paper II for a comparison of observations in the CMa region with the Besançon model of the Galaxy [Robin et al.

Throughout this work, we assume that the Solar radius is $R_\odot = 8\,\text{kpc}$, that the LSR circular velocity is $220\,\text{km}\,\text{s}^{-1}$, and that the peculiar motion of the Sun is $(U_0 = 10.00\,\text{km}\,\text{s}^{-1}, V_0 = 5.25\,\text{km}\,\text{s}^{-1}, W_0 = 7.17\,\text{km}\,\text{s}^{-1}$; Dehnen & Binney 1998).

\section{2 RADIAL DISTRIBUTION OF CANIS MAJOR M-GIANTS}

To account for M04’s criticism on the use of Schlegel, Finkbeiner & Davis (1998, hereafter S98) values for dust extinction (which have been claimed to overestimate the extinction in regions of high reddening), we now use the Bonifacio, Monai & Beers (2000, hereafter B00) asymptotic correction of these and redefine our sample of M-giants (sample A of Paper I) accordingly. The magnitudes we consider in this letter have all been de-reddened in this way.

\subsection{2.1 Distances}

In Paper I, we used the Red Giant Branch of the Sagittarius dwarf galaxy as a reference to calculate the distances to the M-giant stars in our sample A. As we already noted, the uncertainty on the metallicity and age of the different stellar populations leads to a possible $\sim 30\%$ uncertainty on the distances, with the values obtained being a lower limit.

Since the present argument on the existence of an overdensity in Canis Major is mainly based on distance distributions, it is desirable to have an independent and more robust method to validate our distance estimates. Therefore, we first apply the Tip of the Red Giant Branch (TRGB) algorithm of McConnachie et al. (2004), which they used to determine the distances to the M31 group of dwarf galaxies. As has been explained there, the I-magnitude has the advantage of being only slightly dependent on metallicity. It is therefore particularly adapted for the study of the CMa population for which the metallicity has not yet been precisely determined. However, to account for this lack of precise metallicity, we double the uncertainties adopted by McConnachie et al. (2004) for the I absolute magnitude of the tip, leading to $I = -4.04 \pm 0.10$ (Bellazzini, Ferraro & Pancino 2001).

Since the 2MASS catalogue we are using only provides J, H and $K_s$ magnitudes, we cross identified our sample A with the DENIS catalogue that contains 190 million objects down to $I=18.5$. With the TRGB algorithm being sensitive to contamination from foreground stars, we study a large area to obtain sufficient statistics. In the region $230^\circ < l < 250^\circ$ and $-20^\circ < b < -5^\circ$, 3628 stars among the 6480 2MASS M-giant stars have their counterpart in DENIS and can be used to determine the TRGB of the CMa population.

Applying the TRGB algorithm leads to $i = 10.25 \pm 0.03$ for the magnitude of the tip, which corresponds to a heliocentric distance of the Canis Major population of $D = 7.2 \pm 0.3\,\text{kpc}$. This is statistically equivalent to the previous values of $7.1 \pm 1.3\,\text{kpc}$ of Paper I and of $8 \pm 1.0\,\text{kpc}$ of Paper II but with a smaller uncertainty.

With this distance modulus, we are now able to obtain a photometric parallax to the CMa stars in the same way Majewski et al. (2003) did for the Sgr stars. Using the 2MASS colour-magnitude diagram of the same region, we compute a linear fit to the Red Giant Branch (RGB) of the CMa population. As in Majewski et al. (2003), we restrict the fit to those stars having $0.9 < J - K_s < 1.1$ and apply a 2.5$\sigma$ iterative rejection algorithm to discard the contaminating disc stars. This leads to the following fit:

$$K_s = -8.9(J - K_s) + 18.0$$

with uncertainties slightly lower than 0.1 on the values. This result is close to the one deduced for the Sagittarius dwarf, which explains the compatibility between the TRGB estimated distance to CMa and the estimate of Paper I based on the Sgr fiducial.

Using a TRGB algorithm and a CMD fit of the slope of the Red Giant Branch of the Canis Major population, we have derived a relation to estimate the distance to CMa stars. Contrary to our previous estimates, this relation does not require the use of the Sgr RGB as a reference and should reduce the uncertainties discussed in Paper I. Throughout this letter, we will now use relation (1) to estimate the distance to stars in the CMa region.

\subsection{2.2 The Canis Major overdensity is not the Warp}

Momany et al. (2004) discarded the possibility of an unknown population in Canis Major, arguing that the overdensity presented in Paper I could be accounted for by correcting S98 extinction values with the asymptotic correction introduced by B00 and using $b = -2^\circ$ as the symmetric plane of the Galaxy to model the Warp in the $235^\circ < l < 245^\circ$ region.

Since the CMa overdensity appears strong and peaked in the radial distribution of M-giants in Paper I, we checked the assumption of M04 by studying the radial distribution of M-giants in the same region that they used: $|b| < 20^\circ$ and $235^\circ < l < 245^\circ$, where $b'$ is the Galactic latitude calculated from the warped Galactic plane. This is shown on Figure 1 with the Galactic plane taken as $b = -2^\circ$. Even when using this simple warp model of M04, the radial distribution of M-giants in the direction of CMa shows a clear overdensity of stars at the position we previously identified in Paper I (centred on $D = 7.2\,\text{kpc}$). Moreover, the star counts of the Northern hemisphere display an asymmetric behaviour with an overabundance of stars, with respect to the South, for $D \lesssim 5\,\text{kpc}$ and $D \gtrsim 11\,\text{kpc}$. The star counts should be symmetric in the lower distance interval since the Warp only begins at $D \sim 6\,\text{kpc}$ in the direction of CMa (Yusifov 2004, hereafter Y04). Furthermore, underestimating the displacement of the Warp at large distances should produce an overestimate of the counts in the Southern hemisphere for $D \gtrsim 11\,\text{kpc}$. The low distance overestimate is to be expected from contamination by local dwarfs; this is an artefact of the simple M04 warp model at short distances.
where the warp should not have any influence. In the same way, fainter dwarfs that are contaminating the sample are wrongly taken as M-giants at large distances.

Due to the fact that in M04, the star counts are summed up along the line of sight, these overestimates of the Northern counts hide the presence of the (Southern) CMa overdensity visible at around 7–7.5 kpc. However, since the angular maximum of the Southern warp is thought to be only 30° away (at l ∼ 270°, see e.g. Djorgovski & Sosin 1988, López-Corredoira et al. 2002, Y04), the Galactic warp should indeed be taken into account when dealing with the CMa overdensity. Therefore, we re-analyze the radial distribution, but this time using the Y04 model of the warp.

To avoid as much as possible contamination of the M-giants by local dwarfs, we impose a low latitude cut at b′ = 5° and we restrict the color range of our stars to 0.9 < J − Ks < 1.3. These limits are particularly important since extinction reaches high values near the plane and even with the B00 correction, a small underestimate of the extinction shifts red disc stars a little redder and they can enter the M-giant selection box. Shifting the lower colour limit to the red also minimises this contamination.

The results are shown on Figure 2 and, as could be expected from the improvement over the previous simple warp model, the CMa overdensity becomes more clearly visible. Reducing our sample to higher latitudes (e.g. 7° < |b′| < 20°) does not affect the distributions, meaning that systematic selection effects produced be extinction are not responsible for the overdensity in the Southern hemisphere. It can also be noticed that our more conservative M-giant selection and this better modeling of the Warp corrects the asymmetry of Figure 1 at D ≤ 5 kpc and D ≥ 11 kpc, which was caused by overestimating the warping of the Galactic plane at low distances and from asymmetric contamination of local dwarfs in the high distance M-giant sample. Even considering that the Y04 warp model does not have as large a displacement as the 2MASS-based model (see e.g. Figure 2 of Y04), it is only at higher distances than the bulk of the CMa overdensity that the two models actually deviate from each other. It could also be argued that we are in fact observing the south Warp curling back up to the Galactic plane at the edge of the disc as it is seen for the gaseous warp (Burton 1988). In this case, we would indeed expect the stars to pile up along the line of sight when the Warp returns to the mean plane. However, this happens for the gas at much higher distances (DG C ∼ 18 kpc) and at the estimated CMa distance, the gaseous warp gently dives in the Southern hemisphere (as modeled here). Therefore, a model that is highly different from what is currently known of the stellar/gaseous warp should be summoned to explain the CMa overdensity in a Warp scenario.

Thus, we have to conclude that the CMa overdensity presented in Paper I really is an unknown feature that appears in addition to the Galactic warp.

Using the warp model changes only slightly the counts and morphology of CMa compared to Paper I. Indeed, the number of M-giants that belong to the overdensity only drops by ~10%, the distance to the structure is still in the same range and in good agreement with the TRGB result presented above, and its FWHM remains the same. This means that at this location, the Warp is only contributing a minor number of M-giant stars compared to the CMa overdensity.

### 3 Radial Velocities of Canis Major M-Giants

To study this population and other low latitude structures at higher longitude in greater depth we undertook a series of observations on the nights of April 7–12, 2004.
with the 2-degree field (2dF) spectrograph at the Anglo-
Australian Telescope (AAT). We employed two different
spectrograph settings, with the 1200V grating on spectro-
graph 1 (covering 4600–5600 Å at 1 Å/pixel) and with the
1200R grating on spectrograph 2 (covering 8000–9000 Å,
also at 1 Å/pixel). While a detailed analysis of this dataset
will be presented in forthcoming papers, we focus here
on the radial velocities of stars selected to be M-giant
candidates obtained with spectrograph 1 in a field cen-
tered on the CMD overdensity. These were chosen from
the colour-magnitude region of sample A: 0.85 < J − Ks < 1.30,
0.561(J − Ks) + 0.22 < J < 0.561(J − Ks) + 0.36, and
with estimated distances (using the above calibration) in
the range 4 kpc < D < 20 kpc.

The spectra were extracted using the ‘2dfdr’ reduction
software (Taylor et al., 1996), but then calibrated in wave-
length and corrected for contamination from sky emission
using algorithms developed by our group. Using Fourier
cross-correlation methods, the velocities of the stars were
calculated by comparison to a range of radial velocity stan-
dard stars of type F–M (both dwarfs and giants). The veloc-
ity value corresponding to the template that best-matched
the spectrum of the survey star was selected. The typical re-
sulting radial velocity uncertainty of well-measured M-giant
stars was 10 km s\(^{-1}\) in spectrograph 1.

The top panel of Figure 3 shows the distribution of the
radial velocities of the 75 M-giant stars present in two 2dF
fields centred on the bulk of the CMa overdensity — within a
degree of (l, b) = (240.0\(^\circ\), −8.8\(^\circ\)) and (l, b) = (240.0\(^\circ\), −6.8\(^\circ\)) — and within 2 kpc of its mean distance — 5.2 kpc < D <
9.2 kpc. The most striking feature is the bimodality of the
distribution. A Kolmogorov-Smirnov test shows that there
is less than 0.1% probability that this distribution is drawn
from the best single-Gaussian fit of the data. Therefore, a
maximum-likelihood fit of the sum of two normal distri-
butions was performed and shows a first peak centered at
maximum-likelihood fit of the sum of two normal distri-
butions was performed and shows a first peak centered at
109 ± 9 km s\(^{-1}\) with a dispersion of 9 ± 1 km s\(^{-1}\) and a more
peaked peak centered on 109 ± 2 km s\(^{-1}\), with a disper-
sion of 13 ± 4 km s\(^{-1}\) (see Figure 4). Taking the radial ve-
cocity uncertainties into account in the maximum-likeli-
hood fit, as estimated from the cross-correlation peak width, the
velocity dispersions of the two peaks are 0 ± 9 km s\(^{-1}\) and
10 ± 4 km s\(^{-1}\), respectively.

Since the second peak contains almost twice as many stars
as the first and since its stars are centered around the
distance of CMa (see bottom panel of Figure 3), we
entirely identify it with the large CMa overdensity that
appears on Figure 2. Moreover, if these stars are orbiting
the Galaxy, they have a mean rotational velocity (v\(_{\text{rot}}\) ∼
160 km s\(^{-1}\)) that is too low for a thin disc, and is even
low for a slower thick disc population (v\(_{\text{rot}}\) ∼ 170 km s\(^{-1}\))
where we assume a circular velocity of 220 km s\(^{-1}\) and take
the thick asymmetric drift of −51 ± 5 km s\(^{-1}\) found by
Soubiran, Bienaymè & Siebert (2003). Though the precise
kinematic properties of the outer rim of the Galactic disc
are poorly known (and extrapolations from local measure-
ments are likely to be misleading), the low observed ve-
cocity dispersion is surely incompatible with a thick disc
population, which has Solar Neighbourhood velocity dis-
persions of (σ\(_{\mu}\), σ\(_{V}\), σ\(_{W}\)) = (63 ± 6, 39 ± 4, 39 ± 4) km s\(^{-1}\)
(Soubiran, Bienaymè & Siebert, 2003).

Figure 3. The top panel shows the distribution of radial ve-
clocities of the M-giant targetted in our two 2dF fields (see text
for details). A clear bimodality is present that we fit by a dou-
ble Gaussian model (thin line) using a maximum-likelihood algo-
rithm. We identify the second, more numerous population centred
on v\(_{\text{r}}\) = 109 km s\(^{-1}\), as the CMa overdensity. The bottom panel
presents the expected phase space behaviour of a population of
stars orbiting around the Galaxy with a mean rotational velocity
of v\(_{\text{rot}}\) = 240 km s\(^{-1}\) (full line), v\(_{\text{rot}}\) = 200 km s\(^{-1}\) (dashed line)
or v\(_{\text{rot}}\) = 160 km s\(^{-1}\) (dotted-dashed line). The positions of the
M-giants have been overplotted as filled circles and the mean dis-
tance of the CMa overdensity is represented by the heavy dotted
line at D = 7.2 kpc. The light dotted lines represent our distance
selection criteria for the histogram of the top panel.

Figure 4. Likelihood contours of the mean and dispersion of the
double Gaussian model fit to the radial velocity data displayed
on Figure 3. The contours are spaced at 1σ intervals. The radial
velocity distribution of the CMa population is well constrained,
with a mean value of 109 ± 4 km s\(^{-1}\) and a dispersion of 13 ±
4 km s\(^{-1}\).
The position and dispersion of the first peak are difficult to explain. Indeed, its stars appear too far away to coincide with a thin disc population contaminating our sample which we would expect to be located at a distance of $D \sim 3.5$ kpc at this radial velocity (assuming a circular velocity of $220 \, \text{km s}^{-1}$). It is possible that we are significantly overestimating the distances to these stars; the fit to the RGB we determined in section 2 is adequate for CMa but populations of different metallicity and/or age could follow a different relation. However, the very low dispersion of the peak is unexpected for a disc population. Another explanation would be that the CMa overdensity is composed of two populations with different mean velocity. The low dispersion of the two peaks, similar to what is observed in tidal streams (see e.g. Ibata et al. 1997 for the Sgr dwarf or Ibata et al. 2004 for the M31 stream), argues in favour of an accretion scenario.

To summarize, the observed kinematics of M-giants stars in the centre of the CMa structure do not show a distribution that would be expected for a single disc population or a Warp orbiting the Milky Way.

4 DISCUSSION AND CONCLUSIONS

The clear asymmetry in addition to the Warp in the direction of Canis Major and the peculiar radial velocity of these stars show that there is an extra population in this direction, rotating around the Milky Way in a prograde direction at a lower mean rotational velocity than what would be expected for disc stars. This structure at the edge of the disc may indicate that the Galaxy shows the same kind of substructure that were recently discovered at the edge of the disc of M31 (Ferguson et al. 2002).

As we have already mentioned in Paper I, this CMa population could be the remnant of the accretion of a dwarf galaxy onto the Galactic plane. With a mean value of $v_r = 109 \pm 4$ km s$^{-1}$, the radial velocities of CMa falls in the range of the radial velocities of the grouping of globular clusters identified in Paper I (see their Figure 12), while it also correlates well with the Crane et al. (2003) radial velocities of M-giants belonging to the ring-like Galactic Anticentre Stellar Structure. Moreover, the low dispersion of the distribution of radial velocities of CMa M-giants is compatible with an accretion scenario. While this could be a sign that the ‘Ring’ and the CMa overdensity are related, it should also be noted that the distances to these two features are different. Therefore, it may not prove possible to link the two in a direct way and would require an alternate accretion scenario, in which the CMa dwarf has been in the process of being accreted for a longer time than previously thought.

In this case, it would not have created the ‘Ring’ and the CMa overdensity in the same passage around the Milky Way but in successive orbits, with its tidal arms wrapped a few times around the Galactic disc. If simulations reveal this is a plausible scenario, it could also be interesting to see whether the low latitude structure presented by Rocha-Pinto et al. (2004) in the Triangulum-Andromeda direction can be explained in this way or whether it is too far away from the Galaxy to be created by the same accretion process.

Finally and with the recent discovery of a putative distant spiral arm in (mainly) the fourth quadrant of the Milky Way (McClure-Griffiths et al. 2004), it is worth considering the possibility that the CMa overdensity is in fact the prolongation of this spiral arm to lower longitudes. Even if their observations do not overlap with CMa, the radial velocity we present here could be compatible with their velocities that reach $v_r \sim 110$ km s$^{-1}$ at $l \sim 255^\circ$. The age of the CMa stars (Paper II) and the structure of the overdensity (Paper I) would however be hard to explain in this scenario.

The confusion between the CMa overdensity and the Warp that caught Momany et al. (2004) brings up questions on the real nature and dimensions of the Warp. How much of the Canis Major overdensity has until now been taken as the Warp? Disentangling the role and extent of each may prove to be a difficult task.

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