# THE GALACTIC BULGE AS SEEN BY GAIA

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## ABSTRACT

Gaia will give tremendous results on galactic structure and evolution. One expects to get unprecedented information even in dense regions like the Galactic bulge. However, due to extinction and crowding, part of the inner Galaxy may be unreachable. Using the Besançon model of the Milky Way and assuming different extinction maps, we estimate the stellar density of stars as a function of galactic latitude and longitude, and magnitude. We explore the possibility of reaching bulge stars in regions where the extinction is not too high to allow for a significant number of bulge stars to be detected by the different Gaia instruments. We also address the problem of crowding in these regions. We show that there are a significant number of regions where bulge stars will be detected and accurately measured.

Key words: Galaxy: bulge; Gaia.

## 1. INTRODUCTION

Large-scale observation of the bulge is important for understanding the Galaxy structure and history. However, two major obstacles are the high interstellar extinction in the central regions of the Galaxy, in particular in the optical, and crowding in low spatial resolution instruments. Crowding is very sensitive to extinction, and may vary strongly from field to field on a quite small spatial scale, as the extinction is generally very patchy.

If the extinction is too high, the number of stars will be low (no crowding) but conversely the bulge stars would be out of reach, being too faint. If the extinction is low (like in Baade's windows), bulge giants on the red clump are bright enough to be reached, but the crowding will limit the number and/or the quality of their measurements.

Given an extinction in a direction of the Galactic bulge, we address here the following questions: are there bulge stars still visible in this given direction, what kind of stars are they, and how crowded is the field? In order to answer them, we have computed stellar densities with the Besançon model of the Galaxy (Robin et al. 2003) which allows us to simulate star counts as a function of magnitude, directions and extinction. These, of course, depend on the assumptions about galactic structure, and particularly the bulge model, but even more strongly on the assumed extinction.

## 2. INTERSTELLAR EXTINCTION

Several extinction maps have been published in the past years (Schlegel et al. 1998; Schultheis et al. 1999; Dutra et al. 2003; Drimmel et al 2003)). Schultheis et al. (1999) (hereafter SGS) have produced a detailed map in the Galactic central region ($-9^\circ < l < 9^\circ$ and $-1.5^\circ < b < 1.5^\circ$). By varying extinction, they fitted isochrones to colour magnitude diagrams from near-infrared DENIS data. The typical uncertainty is smaller than 2 magnitudes in windows with $A_V$ <25. In regions where $A_V$ >25, the measurement is no longer reliable due to the lack of detection in the J band. In this case, the given value is an underestimate of the true value. Dutra et al. (2003) have shown that their map, based on 2MASS data, agrees well with the DENIS extinction map up to $A_V \approx 15$. Above this limit, the comparison is affected by increased internal errors in both extinction determinations. The resulting map gives the total extinction to a distance of 8 kpc from the Sun.

Schlegel et al. (1998) (hereafter SFD) have produced a whole sky extinction map using far-infrared dust emission from IRAS and COBE/DIRBE. They noted that for $b < 5^\circ$ their determination is less reliable. The resulting map gives the total extinction along the line of sight.

Comparing SGS and SFD maps in the galactic plane leads to systematic differences. In the bulge, we expect SFD values to be a significant overestimate of the extinction. In the plane, the total extinction would be about twice the value at the distance of the bulge, the difference being due to extinction in the background. At higher galactic latitudes, this overestimate should become smaller and smaller. We have chosen to rely on the SGS map in regions where it exists ($|b| < 1.5^\circ$) and on the SFD map at higher latitudes.

## 3. THE BESANÇON MODEL OF THE GALAXY

In order to estimate the stellar densities, we have used predictions from the Besançon model of the Galaxy (Robin et al. 2003)[1]. The model is based on a population synthesis scheme. Four distinct populations are considered (thin disc, thick disc, bulge, and halo), each deserving a specific treatment. In the central regions, only the bulge and thin disc are important; the thick disc and halo being negligible at the magnitudes considered here.

The thin disc is a prominent population in the bulge region, especially at optical wavelengths. The scale length is quite short (2350 pc) giving a high density, although it undergoes a progressive central hole of scale length 1320 pc (Robin et al. 2003). It is described by an evolutionary scheme with a constant star formation rate over the past 10 Gyr. A detailed analysis of the bulge stellar density and luminosity function has been made by fitting model parameters to DENIS data in a set of 94 windows situated in the bulge (Picaud & Robin 2004).

Thereafter, we use this model to compute the number of bulge stars as a function of position, apparent magnitude, and interstellar extinction. We also compute the total number of stars in order to address the problem of crowding. The absorbing clouds are assumed to be located at 1 kpc from the Sun in the first spiral arm. The apparent magnitude is the broad-band unfiltered Spectro telescope magnitude $GS$, computed from the colour-colour expression:

$$GS-V = -0.06724+0.00946(V-I)-0.30490(V-I)^2 +0.04185(V-I)^3 - 0.00239(V-I)^4.$$

## 4. CROWDING IN THE GAIA INSTRUMENTS

The Gaia photometers will make measurements up to magnitude 20, and the Radial Velocity Spectrograph up to magnitude 17. The crowding in the Gaia instruments depends on the sensitivity and on the spatial resolution of each instrument. The Broad-Band Photometer (BBP) (and AF astrometer) qualifications have been chosen in order that over crowding is rarely reached and are able to measure up to about 3 million stars deg$^{-2}$ (Jordi et al 2002).

In the Medium-Band Photometer (MBP), the first conservative crowding limit has been estimated to be between 50 000 and 100 000 stars per deg$^2$ (Høg 2002). Recent estimates for the new Spectro instrument show that regions with up to 120 000 stars deg$^{-2}$ for $GS < 20$ can be measured (Høg 2004). Høg & Jordi (2004) show that 30% of the transits still will be observed when the density is 250 000 stars deg$^{-2}$. Furthermore, Evans (2004) shows that photometric data reduction is possible to a limit of 200 000 to 400 000 stars deg$^{-2}$ using accurate PSF fitting and astrometry known from the Astro telescope.

Zwitter (2003) has estimated how the accuracy on radial velocities may depend on the crowding. He argues that the overlaps degrade the radial velocity accuracy only at faint magnitudes (V = 17.5) and in highly crowded fields. This is mainly because the estimates of the overlapping spectra can be done during the Gaia survey: photometric medium band photometry and accurate astrometry will allow to correct at the first order at each transit the overlapped spectrum knowing the accurate position and magnitude, and an estimate of the spectral type of the overlapping star. However the recovering of other astrophysical parameters (temperature, gravity, metallicity) will be limited to bright targets in not-too-dense environments. In estimating the possibility of observing bulge stars with the Radial Velocity Spectrograph (RVS), we have assumed a crowding limit of 20 000 stars deg$^{-2}$, following recommendation from the RVS Working Group (Katz, private communication).

[1]The model is available on http://www.obs-besancon.fr/model/

## 5. REACHING BULGE STARS WITH THE GAIA PHOTOMETERS

Using the Besançon model of the Galaxy, we are able to estimate the density of bulge stars reachable with the limiting magnitude $GS$=20. As it strongly depends on the assumed extinction, we have alternatively used the two maps described above, knowing that the SGS map is more reliable at low galactic latitudes and that the SFD map is suitable at higher latitudes.

Figure 1 shows the predicted bulge stellar density up to $GS$ = 20 assuming SFD extinction values. In the Southern Galactic hemisphere, the bulge density can reach up to 2 million stars deg$^{-2}$ in Baade's window ($l = 1.0°, b = -3.9°$). The density of bulge stars is smaller in the Northern Galactic hemisphere, due to higher interstellar extinction. Therefore, this region is less affected by the crowding problems in the MBP. Iso-contours of total stellar densities are shown for the values 120 000 (white line) and 400 000 (black line) stars deg$^{-2}$.

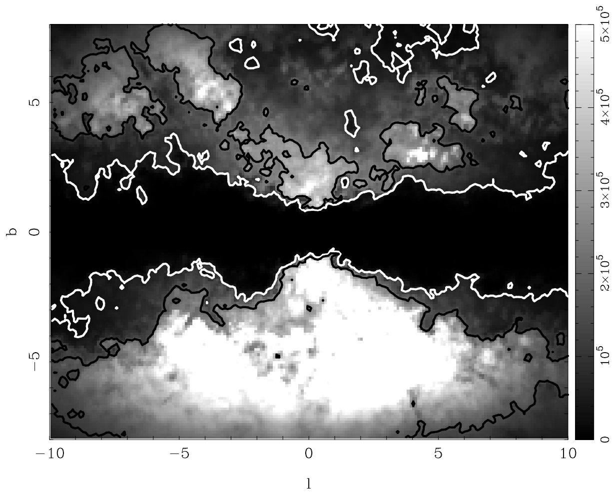


*Figure 1. Density of bulge stars per square degree at magnitude $GS$=20 according to SFD extinction values. The contours show the total stellar densities of 120 000 (black) and 400 000 (white) stars deg$^{-2}$.*

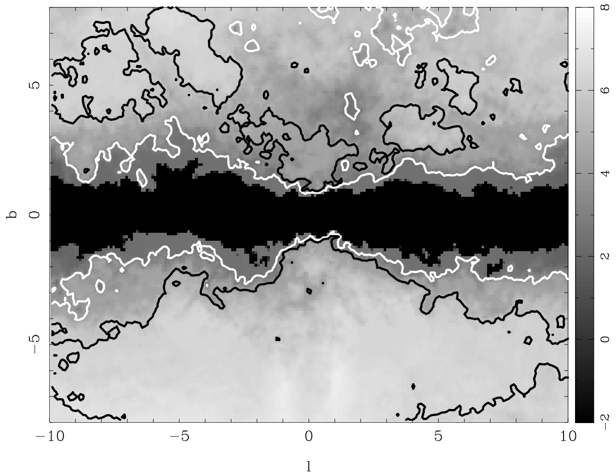


*Figure 2. Absolute magnitude $M_V$ of bulge stars just reached at magnitude $GS = 20$, according to SFD extinction values. The contours show the total stellar densities of 120 000 (white) and 400 000 (black) stars deg$^{-2}$. Black regions contain less than 100 bulge stars deg$^{-2}$.*

If the crowding limit is 120 000 stars deg$^{-2}$, the MBP will get accurate measurements within a small lane on each side of the very obscured dust lane in the Galactic plane (see also Figure 2), and also in some regions in the Northern hemisphere around $l = 5.0°, b = 7°$. If the crowding limit is higher, more bulge stars can be measured around the dust lane, and in most parts of the Northern hemisphere, excepted in the regions of lower extinctions.

The number of bulge stars that the MBP should measure properly is given in Table 1, depending on how far the crowding limit can be increased. The crowding limit of the BBP ($3 \times 10^6$ stars deg$^{-2}$) is never met. The total number of bulge stars in the region shown in the graph (-10° $< l <$ 10° and -8° $< b <$ 8°) is $61 \times 10^6$ stars. This corresponds to the predicted number of bulge stars observed with BBP.

*Table 1. Predicted number of bulge stars in the central region ($-10°$ $<l<10°$ and $-8°$ $<$ $b$ $<8°$) accurately measured depending on the crowding limit. The corresponding area is also given (the very obscured dust lane where the number of bulge stars is not significant, less than 100 bulge stars deg$^{-2}$, being excluded.*

| Total number of stars (stars deg$^{-2}$) | Number of bulge stars (stars) | Area (deg$^2$) |
|---|---|---|
| < 120 000 | 720 000 | 36 |
| < 200 000 | $3 \times 10^6$ | 73 |
| < 400 000 | $13 \times 10^6$ | 156 |
| $<3 \times 10^6$ | $61 \times 10^6$ | 277 |

The Besançon model of the Galaxy can also be useful to learn what kind of stars will be observed with the Gaia photometers. Figure 2 shows the absolute magnitude $M_V$ of the intrinsically faintest bulge stars reached at $GS = 20$, as predicted by the model assuming SFD extinction values. An absolute magnitude $M_V = -2$ means that the number of bulge stars is not significant (smaller than 100 bulge stars deg$^{-2}$), due to high extinction. In between the dust lane and the iso-contour of 120 000 stars deg$^{-2}$, the absolute magnitude of the bulge stars is $M_V \sim$ 1 to 2, and these stars are mainly clump giants. At higher latitudes, turn-off stars ($M_V \sim 4$) will also be measured if the crowding limit is higher, and at least in the BBP where crowding is not an issue.

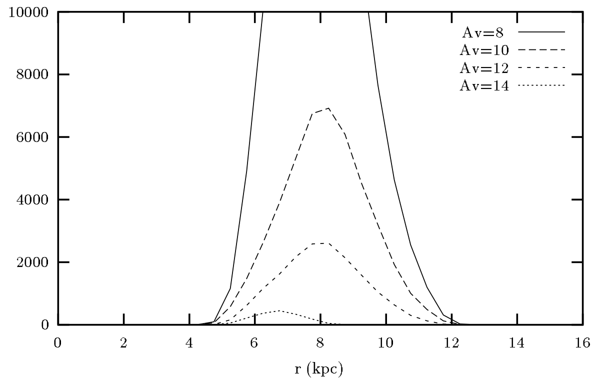


*Figure 3. Number of bulge stars ($GS$ <20) in a field of 1 square degree at $l = 2°, b = -0.5°$ with different values of visual extinction.*

Due to the 3D modelling, bulge stars are considered in depth, their distances ranging between 5 and 12 kpc in the line of sight. Therefore, in some cases only the close side of the bulge is visible while in more favorable cases the bulge will be deeply observable. Figure 3 shows the distribution in distance along the line of sight of bulge stars at extinction of $A_V$ = 8, 10, 12 and 14 mag, located at latitude $b = -0.5°$ and longitude $l = 2°$. The density varies slowly with longitude such that these numbers should be valid for most of the bulge on each side of the dark dust lane within an order of magnitude. Most of the fields at these latitudes have visual extinction in the range 8–14 mag, with most probable values in the range 12–13 mag. The bulge stars in these fields have a distance distribution, allowing the measurement of radial gradients in depth in the bulge.

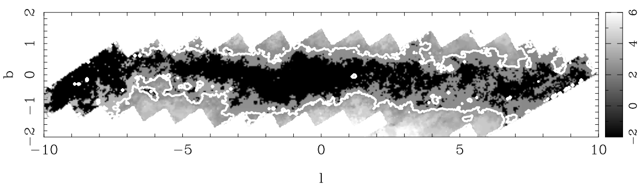


*Figure 4. Absolute magnitude $M_V$ of bulge stars just reached at magnitude $GS = 20$, according to SGS extinction values. The contour shows the total stellar density of 120 000 stars deg$^{-2}$. Black regions contain less than 100 bulge stars deg$^{-2}$.*

In the dark dust lane, and around the Galactic centre, extinction is too high and most of the bulge stars are not accessible even at $GS =$ 20. However, as shown in Figure 4, clump giants could be observed in some parts of the bulge very close to the plane or even in the plane (in particular around $l = -6°$ and $l = 5°$ ).

## 6. REACHING BULGE STARS WITH THE RADIAL VELOCITY SPECTROGRAPH

Figure 5 shows the density of bulge stars at magnitude $GS =$ 17 assuming SFD extinction values. The contour shows the crowding limit of 20 000 stars deg$^{-2}$ for the RVS. Radial velocities should be measured accurately in regions where crowding is not an issue, and where bulge stars are still visible. These regions are the region of higher extinction in the Northern hemisphere, as well as around the obscured dust lane (see also the upper panel in Figure 6). The corresponding total number of bulge stars is 52 000 stars over an area of 44 deg$^2$.

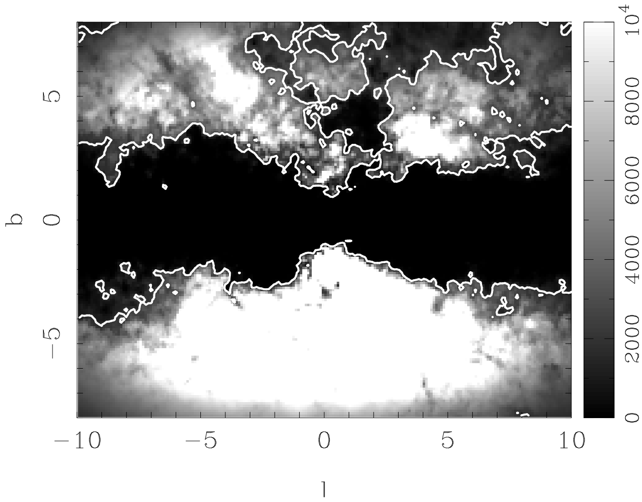


*Figure 5. Density of bulge stars per square degree at magnitude $GS$ = 17 according to SFD extinction values. The contours show the total stellar densities of 20 000 stars deg$^{-2}$.*

As shown in Figure 6 (upper panel), bulge stars in these regions have an abolute magnitude $M_V \sim 1$ to 2, and they are mainly clump giants. Assuming SGS extinction values closer to the Galactic plane (Figure 6, lower panel), we see that very few radial velocities of bulge stars will be obtained in the plane.

In the crowded regions, the RVS may still obtain useful spectra but limited to brighter stars. A map of the apparent magnitude $GS$ at which the total stellar density of 20 000 stars deg$^{-2}$ is reached shows that most regions will not suffer from crowding at $GS = 15$.

## 7. DISCUSSION AND CONCLUSIONS

The result on the bulge visibility strongly depends on the assumed extinction. The bulge model used may also be inaccurate is some cases, particularly very near the galactic centre, but it has been adjusted to a wide set of data in the near-infrared. Hence, the reliability of the results is limited by the accuracy of the extinction map rather than the Galaxy model.

We have shown that there will be opportunities for Gaia to access reliable measurements in the Galactic bulge. The BBP–AF will provide accurate photometry and astrometry, parallaxes, and proper motions, in nearly all the bulge regions. Bulge stars in the MBP will be measured on each side of the dust lane, in a range of latitudes that depends on the crowding limit. This range of latitudes also strongly depends on the assumed extinction. However, if the extinction maps do not suffer from systematics, there should be accessible windows well spread in longitude quite close to the dust lane. Observable bulge stars will also be spread in depth well inside the bulge.

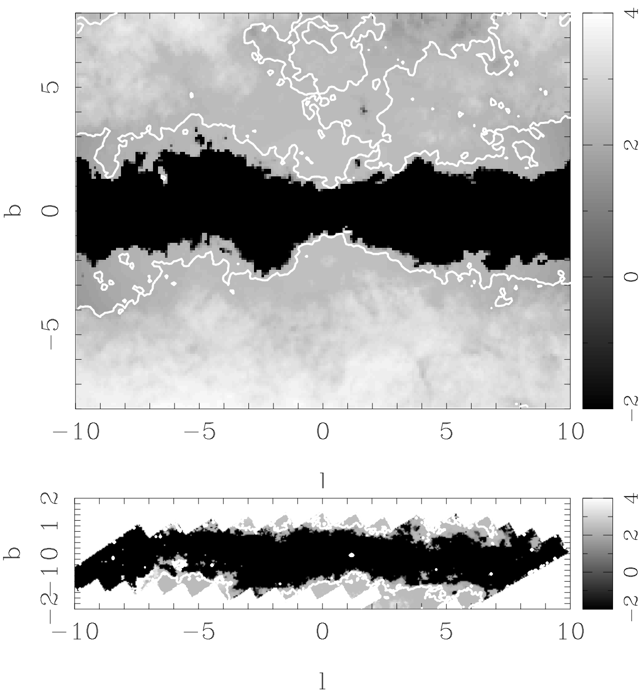


*Figure 6. Absolute magnitude $M_V$ of bulge stars just reached at magnitude $GS$ =17, according to SFD (upper graph) or SGS (lower graph) extinction values. The contour shows the total stellar density of 20 000 stars deg$^{-2}$. Black regions contain less than 100 bulge stars deg$^{-2}$.*

At low latitudes in the dense dust lane, most of the bulge stars will be too faint (due to extinction) to be reached even at $GS = 20$. However, in a few fields close to the Galactic plane in windows of lower extinction, stars in the giant clump should be observed by both photometers. In any event, the position of these fields given here should be taken with caution because of the extreme sensitivity of the computation to the extinction which is not known to better than about 2 magnitudes in these very obscured regions.

Putting together observations of the different instruments including RVS, Gaia should produce a detailed survey of bulge giants in terms of photometry as well as kinematics. Detailed analysis of these data sets should allow us to put strong constraints on the bulge structure and history.

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