COLOUR-MAGNITUDE DIAGRAMS FROM MICROLENSING PROJECTS AND GALACTIC STRUCTURE

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Abstract

The Colour-Magnitude Diagrams (CMDs) from the microlensing projects provide valuable information, to improve our understanding of galactic structure. A description is given of the extinction along the line of sight. The MACHO and OGLE microlensing candidates ([1],[19]) are used to tune up the population model and to determine the contribution from various stellar populations in the CMD. About 5%, 25%, 40% and 30% of the stars are found to be located in respectively the halo, bulge, bar and disc of our Galaxy. The contribution from the disc is probably lower, if the disc density drops considerably between 3–4 kpc from the galactic centre.

1 Introduction

The HRD-GST (Hertzsprung-Russell Diagram Galactic Software Telescope) is a new galactic structure model. It is developed to study the properties of the stellar populations, which contain a wealth of information about the formation and evolution of our Galaxy. The analysis tool is based on the stellar population synthesis technique. Its basis is formed by the latest stellar evolutionary tracks calculated by the Padova group [3]. A smooth metallicity coverage is obtained through interpolation between the sets of tracks from low ($Z=0.0004$) to high ($Z=0.10$) metallicity. Figure 1 shows a schematic diagram of the HRD-GST, see [8] and [12] for additional details. The difference between the HRD-GST and other (semi-) empirical models is that the stars in a particular age-metallicity population all have the same scale-height and scale-length. For a detailed description of the results obtained thus far, see [4, 5] and [9] – [17].

2 Extinction

Any study undertaken with the HRD-GST starts with a careful determination of the extinction. Figure 2a shows the extinction along the line of sight, determined from the disc sequence for OGLE’s Baade’s Window (BW) subfield #3 [18, 14, 11]. The blue edge of this sequence is mainly populated by the stars near the main sequence turn-off, while the red edge shows the core-H exhausted stars.
Figure 1. Schematic diagram of the HRD-GST. Input for the stellar population synthesis engine is the Padova library of stellar evolutionary tracks (see [12, 3] and references cited in those papers for details). The luminosities and effective temperature for each synthetic star of arbitrary metallicity is then transformed to an absolute magnitude in a photometric passband with the method outlined by [6, 7]. A synthetic HR-diagram is generated, after specification of the stellar luminosity function through the initial mass function, the star formation rate and the age & metallicity range. Synthetic stars from those diagrams are then ‘observed’ and ‘detected’ with the galactic model, through a Monte-Carlo technique. In this model the density distribution of each galactic component along the line of sight is specified. This results in a synthetic CMD of the field of interest. The synthetic CMD ought to be comparable with the observed CMD, when a realistic set of input parameters is used. If there is a marginal agreement then check the input for each step of the HRD-GST.

Figure 2b shows the extinction along the line of sight for the metal-rich globular cluster NGC 6528 [17]. The study of the extinction along the line of sight [11] complements the extinction map obtained by Stanek [21]. In general, a linearly increasing extinction up to 2 kpc is assumed ([2, 18]). Figure 2a shows, that a distance up to 4 kpc would be more appropriate. An even better two step, linear approximation is

$$A_V(d) = \begin{cases} 
0.5 \, d & \text{for } d \leq 2 \, \text{kpc} \\
1 + \left( A_V[21] - 1 \right) \left( \frac{d}{3} - 2 \right) & \text{for } 2 < d \ (\text{kpc}) \leq 5 
\end{cases}$$

where $A_V[21]$ refers to the value from the extinction map. This relation is only valid for $A_V < 2^{m.5}$.

3 The Bar population

The first indication with the HRD-GST of the bar was found in the study of a field in the galactic plane towards NGC 6603 [8, 4]. This study suggested an inclination angle $\phi = 18^\circ \pm 3^\circ$. From the red HB (horizontal branch) stars evidence was found in the OGLE CMDs for the galactic bar [20]. Its population was identified with the HRD-GST in OGLE’s CMD of BW [15, 14]. The age is 8–9 Gyr with an estimated uncertainty of 2 Gyr. This uncertainty is mainly due to the large metallicity spread, ranging from $Z = 0.005$–0.030 among the bar stars. The origin of this large metallicity spread is unknown. Studies of globular clusters [16, 17] made thus far do not indicate that this result is an artifact of the HRD-GST.

In (V, V–I) CMDs the direction of the metallicity gradient is almost parallel to the extinction vector. This makes it difficult to separate one from the other. It is demonstrated, that a large amount of differential extinction cannot account for the red horizontal branch (RHB) morphology [11]. The RHB morphology is most likely a combination of differential extinction combined with a range in metallicities of the RHB stars. Actually, near-infrared observations can be useful to settle this question. Figure 3 shows a simulation for a (J, J–K) CMD with suitable photometric errors. It shows, that in this plane the RHB with a metallicity gradient is decoupled from the extinction vector.

4 Do we have a hole in the disc?

Indications that the disc density towards the galactic centre decreases significantly, while the density of the bar/bulge/halo continues to increase, have been found in various studies with the HRD-GST [12, 4, 14]. Figure 4 shows the magnitude distributions of the stars for various the colour slices through the CMD. Frame f shows that the simulated distribution for an exponential disc near $V = 19^{m}$ is about two times larger than expected from the observations. The results do not confirm a start of the decrease at $\sim 2.5$ kpc distance from the Sun. Instead, the decrease sets in at about 3–4 kpc distance from the galactic centre.
Figure 2a. The extinction along the line of sight in BW3 (thick line,[14]). Linearly increasing (long-dashed line) and step-like (dashed line) extinction curves for various distances are also shown. Details about the corresponding simulations can be found in [11].

Figure 2b. The extinction along the line of sight to-wards the metal-rich globular cluster NGC 6528 (dots,[17]); the thick solid line shows the extinction for BW3 [14].

Following [4], this decrease can be described by multiplying the disc density law with $A \exp(-\alpha (R_{\text{hole}} - r) / R_{\text{hole}})$ for $r \leq R_{\text{hole}}$, where $R_{\text{hole}}$ is the radius at which the hole starts, $A$ is a constant calculated from the normalization at $r = R_{\text{hole}}$, and $\alpha$ describes the power of this decrease. This description or a power-law will be adopted in a more detailed study of the decrease of the disc density.

5 Star counts

The microlensing candidates from the MACHO and OGLE collaborations are used to improve the galactic population model and to determine the relative contributions from the various stellar populations in the CMDs, see [14] for details about the procedure. This relative contribution give at the same time the relative probability that a source is from the bar, bulge, halo or disc. About 5%, 25%, 40% and 30% of the stars are found to be located in respectively the halo, bulge, bar and disc of our Galaxy. The probability that the lensed star will drop with a factor two if the decrease of the disc density is taken into consideration. Figure 5 shows the probability calculated for the bulge population, which was lower for the first events found. This behaviour was not noticed for the other populations. It appears that the OGLE was in the beginning less sensitive for bulge events than MACHO. This result basically reflects the difference between the use of a dedicated (MACHO) and a non-dedicated (OGLE) telescope for the project.

In [14] the star counts are shown for a galactic model with and without the bar population, respectively Figs. 11.9 and 6. From these figures one might be tempted to conclude that the model without a bar population is in better agreement with the data than the model with a bar and that
Figure 4. Simulated magnitude distribution (solid line) together with the observations for all the 9 subfields in Baade’s Window (open dots) and BW3 (filled dots). The dotted line shows the combined contribution from the halo/bulge and bar, while the long dashed line gives the contribution of the disc. See [14] for details.

we therefore do not have a bar. This example is mainly used to emphasize, that star counts alone do not mean anything. They are only meaningful, when shown in combination with the colour and magnitude distributions. In principle, one would rely first on the direct comparison of the observed with the synthetic CMD. The colour and magnitude distributions and the star counts are only of secondary and tertiary importance.

6 Age-metallicity relation for the galactic stellar populations

The stellar populations found with the HRD-GST and used in the simulations are shown in figure 6. The ages and metallicities of these populations contain information about the formation and the metal enrichment history of the Galaxy [10, 14]. Apparently the star formation stopped earlier in the bulge (inner part) than in the halo. This is probably an indication for replenishment with (new) barely enriched material from the outer parts. It implies that assumption about a closed box model might be invalid. Secondly, the bar formed during a second, major star formation epoch. If the bar is formed through a merger, then the age of the bar indicates that this event occurred about 9 Gyrs ago. Such an event would puff up the disc. A study of the older disc populations could be used to investigate if they contain records of this event. A detailed study of the CMDs towards the LMC is interesting, because they might contain this information.

Note, that the bulge is old. The bar population might have been mistakenly identified with the bulge. An age as young as 5 Gyr does not appear to be possible. Does this exclude an age as young as 5 Gyrs for stars in the ‘bulge’? It might be an artifact, induced by the assumption of solar metallicity for the bulge stars. To match the lower value of the metallicity range, one has to assume a younger age. On the other hand, the carbon stars in the direction of the ‘bulge’ suggest, that stars are present with an upper limit for the age of 5 Gyr. To solve this dilemma, it is important to determine the nature of the carbon stars and verify if some of them are distributed inside a (flattened) spheroid.
Figure 5. The stellar population probability derived from BW3, that the four MACHO [1] and the twelve OGLE [19] events could be bulge stars.

Figure 6. The interpolated age-metallicity relation obtained thus far with the HRD-GST from the galactic stellar populations.

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