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Spectrophotometric study of the inner Galaxy

Carlos González-Fernández[1], Francisco Garzón[2,3], and Andrés Asensio-Ramos[2,3]

[1] DFISTS, Universidad de Alicante, Apdo. 99, 03080 Alicante, Spain
[2] Instituto de Astrofísica de Canarias, 38205, La Laguna, Tenerife, Spain
[3] Departamento de Astrofísica, ULL, 38205, La Laguna, Tenerife, Spain

Abstract

The study if the large scale structure and properties of the Milky Way has always walked hand in hand with the availability of photometric and spectroscopic large scale surveys. Using the data from programs as 2MASS or UKIDSS, we show how we can derive large scale properties of our Galaxy, such as the behavior of the interstellar extinction or the spatial distribution of the stellar content of the inner Milky Way.

1 Introduction

The place that a population of stars of a given absolute magnitude (M_K) and intrinsic color ($(J-K)_0$) occupy over an, in this case infrared, color magnitude diagram (CMD) is dictated by their distance to the observer and the interstellar reddening along the line of sight according to:

$$m_K = M_K + 5\log(d) - 5 + A_K \quad (1)$$

$$(J-K) = (J-K)_0 + (A_J - A_K), \quad (2)$$

where A_J and A_K represent the interstellar extinction in each passband. These magnitudes are tied together by the extinction law, an useful analytical formula that expresses the amount of light of a given source, in magnitude units, absorbed by the interstellar medium along the line of sight at each wavelength. In the infrared, this value A_λ is usually modeled as a simple power law of the form $A_\lambda \propto \lambda^{-\beta}$ (see for example [8, 3]), although other more complex relations are also proposed [4].

Once this law is known, we can derive A_J/A_K from the extinction law. From Eq. 1 it follows:

$$A_K = \frac{(J-K)-(J-K)_0}{A_J/A_K - 1} \quad (3)$$

And so we can derive the distance to a given source from its observed magnitudes, provided we know M_K and $(J-K)_0$.

In this paper, instead of relying in the canonical A_J/A_K value (from [8]), we propose a method for the calculation of these coefficients, assuming a (A_λ, λ) relation, through the use of the red clump stars, and we apply it to the 2MASS [10] and UKIDSS [7] data available for the inner Galaxy ($5° < l < 30°, b = 0°$), where extinction is more severe.

2 The photometric data

For our study, we will use 0.25 square degree fields centered on the nominal galactic coordinates both for 2MASS All-Sky Point Source Catalog and the GPS DR4 release data. As we will be comparing both surveys, before proceeding any further we need to ensure that both are calibrated in a coherent fashion. Even though it has a slightly different filter set, UKIDSS is calibrated against 2MASS, following the expressions [7]:

$$\begin{aligned} J_{\rm UK} &= J_{\rm 2M} - 0.065(J_{\rm 2M} - H_{\rm 2M}) + 0.015E(B-V) \\ H_{\rm UK} &= H_{\rm 2M} + 0.07(J_{\rm 2M} - H_{\rm 2M}) + 0.005E(B-V) - 0.03 \\ K_{\rm UK} &= K_{\rm 2M} + 0.01(J_{\rm 2M} - K_{\rm 2M}) + 0.005E(B-V), \end{aligned} \quad (4)$$

where $E(B-V)$ comes from the maps of [9]. These expressions try to account for the effect of the extinction on the different sets of filters of UKIDSS and 2MASS, but as it is discussed in [7], in the regions where this extinction is more severe differences between 2MASS and UKIDSS magnitudes appear. We find that for our fields:

$$\begin{aligned} \Delta(J) = J_{\rm UK} - J_{\rm 2M} &= -0.079 \pm 0.016 \text{ mag} \\ \Delta(H) &= 0.067 \pm 0.009 \text{ mag} \\ \Delta(K) &= 0.006 \pm 0.014 \text{ mag}. \end{aligned} \quad (5)$$

Another effect of this calibration will affect our calculations. As equations 4 try to account for the differences that the interstellar extinction introduces in the different photometric systems, if we want to derive the subjacent extinction law we need to correct (in a sense, decalibrate) these extinction corrected magnitudes, and so we have to subtract the color terms present in these equations.

3 Calculation of $A_\lambda/A_{\rm V}$

3.1 Isolating the red clump giants

Red clump giants (RCG) are the dominant population among the giants of our Galaxy, and they have a narrow luminosity function (see [1] for a detailed description of the properties of these stars) that makes them and ideal subject to study the properties of the Milky Way.

They occupy a prominent area in a color-magnitude diagram (see Fig. 1), and so they can be easily isolated using the method developed by [1]. The base of this method is the

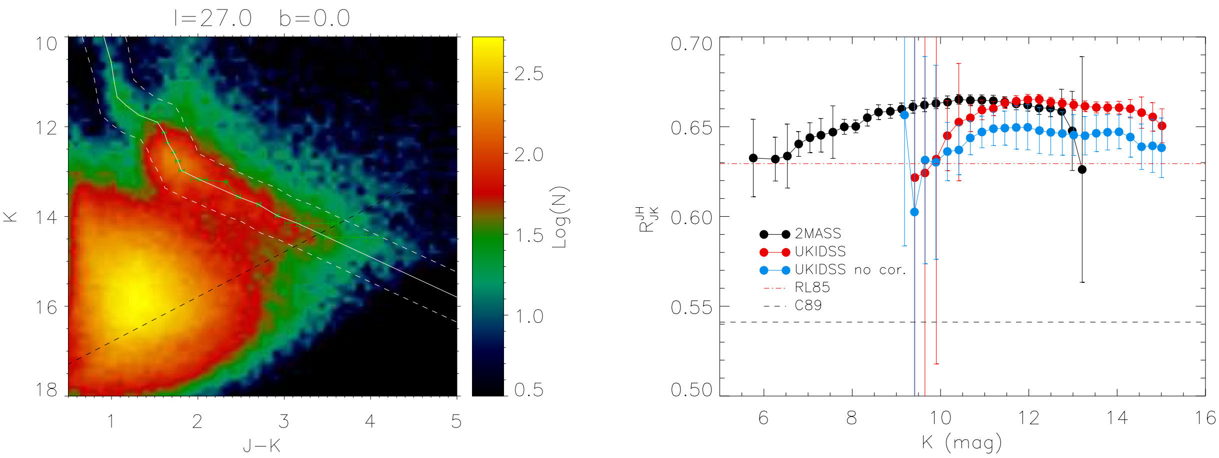

Figure 1: *Left*: DCM corresponding to the fields $l = 27°$, $b = 0°$. The black line denotes the completitud limit, while the white ones the area occupied by the red clump giants. *Right*: variation of the mean excess color ratio with magnitude.

derivation of the $(J - K)$ for the maximum of the distribution of RCG's at several successive values of m_K.

Once the position $(J - K, m_K)_{\rm RC}$ of the red clump is measured over the entire DCM (the green line in Fig. 1), we are ready to filter the red clump stars. For this, we determine an optimal width above and below the fiducial trace; all the stars within these limits will considered to be RCG's (see [6] for details).

3.2 Colour excess ratios and evidences for a variable extinction law

Once we have a sample of RCG's, since they have a well calibrated luminosity function (i. e. absolute magnitude and intrinsic color), we can estimate the color excess ratios. As can be shown, under the assumptions of [8, 3, 4], these ratios are only a function of the exponent of the extinction law:

$$R^{12}_{23} = \frac{A_1 - A_2}{A_2 - A_3} = \frac{m_1 - m_2 - (M_1 - M_2)}{m_2 - m_3 - (M_2 - M_3)} = f(\alpha). \tag{6}$$

Being so, if there is a variation in this exponent, it should reflect in R^{12}_{23}. The ideal ratio to check for this behavior is R^{JH}_{JK} as it is less sensitive to observational errors. We check for variability both against distance along the line of sight and latitude:

- As we do not have yet an estimation of A_J/A_K, we use the magnitude in the K band as a proxy for distance, and we average out all the lines of sight into a single plot (Fig. 1, right panel). We can show statistically that *there is* evidence for a variable law. For sources below $m_K \sim 8$ (roughly $d \sim 2$), the excess ratios approximate the canonical value of [8]. Beyond that limit, the ratio deviates significantly.

- For each line of sight we can construct a diagram such as that of Fig. 1, right panel, and see how R^{JH}_{JK} varies with galactic latitude. In this case, the ratio remains constant –within errors–, and so there is no evidence of a variation with azimuth.

As the vast majority (approx. 95%) of our sample has magnitude well below $m_K = 8$ it is possible to define mean values for the color excess ratios for all the lines of sight in our study. We obtain:

Table 1: Mean color excess ratios derived from our sample.

Ratio	2MASS	UKIDSS
$(J-H)/(J-K)$	0.661 ± 0.003	0.644 ± 0.013
$(H-K)/(J-H)$	0.517 ± 0.006	0.56 ± 0.03
$(H-K)/(J-K)$	0.343 ± 0.003	0.360 ± 0.013

3.3 Infering the extinction law

If we use the expression of [4], we see that:

$$\frac{A_1 - A_2}{A_2 - A_3} = \frac{\frac{1+(\lambda_2/\lambda_0)^\alpha}{1+(\lambda_1/\lambda_0)^\alpha} - 1}{1 - \frac{1+(\lambda_2/\lambda_0)^\alpha}{1+(\lambda_3/\lambda_0)^\alpha}}. \tag{7}$$

And so from the values in Table 1 we can derive the exponent for this law (α) and the equivalent from [8] (β):

Table 2: Exponent of the extinction law for the two photometric systems and the selected laws.

System	α	β
2MASS	2.74 ± 0.04	2.52 ± 0.06
UKIDSS	2.8 ± 0.3	2.5 ± 0.3

As can be seen in Table 2, the exponents are consistent within the errors. The higher uncertainty in the UKIDSS determinations is associated with the fact that these data need to be "decalibrated" in order to recover the true effect of the extinction over the filter system. With these values, we can calculate directly the $A_\lambda/A_{\rm V}$ ratios:

The values from Table 3 differ significantly from those of [8]. This is, in part, due to the fact that these ratios are normalized to A_V, that is measured in a wavelength regime well

Table 3: Extinction ratios derived using the law from [4] (α) and a power law (β). The systematic error accounts for the uncertainty in the luminosity function of the RCG's.

	α		
Ratio	UKIDSS	2MASS	Sys. error
A_J/A_V	0.196 ± 0.011	0.197 ± 0.009	0.02
A_H/A_V	0.099 ± 0.006	0.097 ± 0.006	0.016
A_K/A_V	0.046 ± 0.003	0.048 ± 0.003	0.011
	β		
A_J/A_V	0.174 ± 0.024	0.167 ± 0.025	0.012
A_H/A_V	0.087 ± 0.013	0.084 ± 0.013	0.009
A_K/A_V	0.044 ± 0.007	0.040 ± 0.007	0.006

beyond the near infrared. Even taking this into account it is clear that, from this data, the extinction in the inner Galaxy appears to be much less severe (A_K/A_V is only a third of the canonical value).

4 Inner Milky Way structure

Once A_J/A_K is measured, it follows from Eqs.1 and 2 that we can invert the distance from the position in the CMD of a star and vice versa. If we do so for each of the RCG's isolated in Section 3.1, we obtain a sample of the distribution of stars along the line of sight. This distribution shows clearly an overdensity that appears at lower magnitudes (i. e. larger distances) with decreasing Galactic longitude. This can be fitted with the combination of a gaussian and a 2nd degree polynomial (see [1] for details). The μ of this fit gives us the position of this overdensity. As can be seen in Fig. 2 (left panel), these maxima trace a larger structure contained in the galactic plane, forming an angle of $\sim 43°$ (a more detailed analysis of these results can be found in [2]).

As we now know the (d, A_K) relation, we can select giants pertaining to this structure and, using low resolution spectroscopy, derive [Fe/H] values. For a small but significative sample of $\sim$ 250 objects, we find that they can be classified into three groups, one with low metallicity ([Fe/H] < -0.6), other with medium values ($-0.6 <$ [Fe/H] < -0.3) and a third one with the most metallic stars ([Fe/H] > -0.3). While the first group is distributed homogeneously with Galactic longitude, for the later two groups a clear gradient appears (see Fig. 2). This points to some mechanism that can act as a conveyor belt between the innermost part of the Galaxy and the inner disk regions. It has been shown that bars are very effective performing this sort of labor [5].

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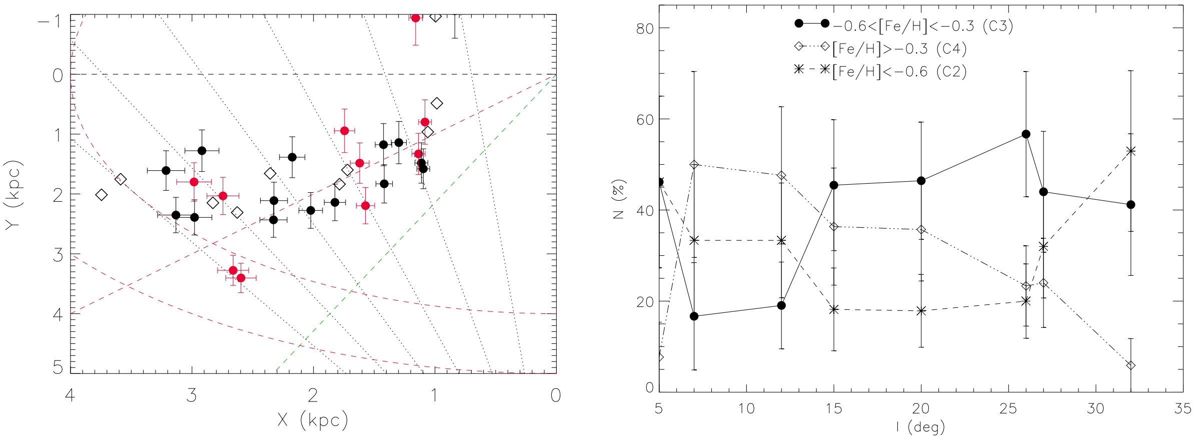

Figure 2: *Left*: Position of the stellar density maxima along several lines of sight in the inner Milky Way. The red line marks 45° with Sun-Galactic center line, and the green trace does so for an angle of 23° (i. e. the position angle of the bulge). *Right*: Relative distribution of low, medium and high metallicity stars with Galactic longitude.

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