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Faint limiting magnitudes as a test for Galactic Models

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Abstract. We present the results of a Galactic model able to reproduce star counts and synthetic color-magnitude diagrams of field stars, including the white dwarf (WD) population in an evolutionary consistent way. The results on the expected distribution of the Galactic WD population appear in rather good agreement with recent estimates of the local WD luminosity function. Uncertainties still present in Galactic model calculations will be critically discussed and the effects on the theoretical predictions of different WD evolutionary models, ages, initial mass functions and relations between progenitor mass and WD mass will be analyzed.

Key words. Galaxy: stellar content – Galaxy: structure – White Dwarfs

1. Introduction

Star counts have been widely used to constrain the Galactic structure since the pioneering works by Bahcall and Soneira (B&S model (1980); see also Gilmore & Reid 1983). This field experienced recently a great development thanks to the availability of precise low luminosity observational data. The most updated galactic models are synthetic models which rely on evolutionary tracks and suitable assumptions on the initial mass function (IMF) and the star formation rate (SFR) (see e.g. Haywood, Robin, Creze 1997, HR&C model; Castellani et al. 2002, Paper II). Recent star count galactic models assume three components: a spheroid, a thin disc and a thick disc (Gilmore & Reid 1983, Ojha et al. 1996, Norris & Ryan 1991). However, up to now, sensitively different values for the thick disc structural parameters (density law, local density etc..) have been proposed (see e.g. Reid & Majewski 1993, Yamagata & Yoshii 1992, Ojha et al. 1996). As suggested by different authors, the thick disc's local density range from 2 to 8 % of that of the thin disc, and its scale height h_z results in the range 700 $\div$ 1300 pc, while the thin disc h_z ranges from 200 to 400 pc. The scale lengths of the discs are suggested to vary from 2000 to 3500 pc. The quoted large spread is due to both the uncertainties on the observational data and to the degeneracy of three components, i.e. different combinations of disc/thick disc/spheroid parameters can give the same star counts (see e.g. the discussion in Castellani et al. 2001, Paper I).

An additional relevant source of uncertainty for low luminosity star counts regards the poorly known disc and spheroid luminosity functions.

Figure 1 (left panel) shows recent observational data for the faint end of the disc luminosity function together with the distribution originally assumed in the B&S model.

A decrease of the luminosity function beyond $M_V= 13$ has been firstly suggested by Wielen, Jahreiss, Kruger (1983) on the basis of parallax-star studies, and then confirmed by Jahreiss & Wielen (1997). An even more drastic decrease, starting at $M_V= 12$, was more recently suggested by Gould, Bahcall and Flynn (1996, 1997) from an analysis of HST data and confirmed by Zheng et al. (2001). The results from a large-area multicolor survey by Martini and Osmer (1998) and those from photometric parallax surveys by Reid & Gizis (1997) appear intermediate between the Wielen, Jahreiss, Kruger (1983) and the Zheng et al. (2001) results. All these luminosity functions coincide at a visual magnitude lower than ~ 9.

A similar situation occurs for the spheroid component (see Fig. 6 of Paper I), once again there is not agreement among results of different authors at low luminosities. Dahn et al. (1995) from parallaxes studies of nearby subdwarf stars found a peak of the luminosity function at $M_V \approx 11.5$. However, Gould, Flynn and Bahcall (1998) investigated HST data and suggested a flat LF below $M_V= 7$, while very recently Gizis & Reid (1999), by using a sample of stars from the Palomar Sky Surveys, support the luminosity function results by Dahn et al. (1995).

Figure 1 (right panel) shows the effects of the adoption of different combination of disc/thick disc/spheroid LFs. Theoretical models are computed adopting the consistent set of disc/thick disc/spheroid parameters of the HR&C model. We compare the predicted star distributions with deep observational data taking advantage of WFPC2 Hubble data of Galactic field stars in the direction of the globular cluster NGC 6397. The sample is composed of about thousand stars and it is fairly complete (more than 95% detection level) down to $V \sim 25$, with a reliable evaluation of the completeness reaching $V \sim 27$ (King et al. 1998). One finds that at faint magnitudes the fit depends on the choice of the combination of disc/thick disc/spheroid faint LFs. As a whole, a satisfactory agreement of magnitude star counts can be achieved in the field of NGC 6397 if extreme combinations of disc and spheroid LFs are not assumed (see paper I for more information).

2. The model

We develop a three components synthetic Galactic model which closely follows the "classical" Galactic models by Bahcall & Soneira (1984) (see also Gilmore & Reid 1983) concerning the spatial density distribution of stars. However, it relies on suitable assumptions on the evolutionary status and on the initial mass function (IMF) of the various Galactic populations to reproduce the luminosity functions used as an input in the previous quoted papers. In this way, we are able to predict star counts and synthetic color-magnitude diagrams of field stars from the main sequence to the white dwarf (WD) evolutionary phase for various photometric bands and Galactic coordinates.

We recall here the main characteristics of the model referring for a detailed discussion to Castellani et al. (2001, Paper II). Predicted results are obtained by randomly generating star masses according to the adopted IMF (Kroupa 2001) and by using stellar models to derive luminosities in the selected bands for each given value of the stellar mass and age. Spheroid stars are assumed to be almost coeval and thus they are reproduced by populating a suitable theoretical isochrone (age= 12 Gyr, Z= 0.0002, Y= 0.23), while for both the thick disc and the disc one has to take into

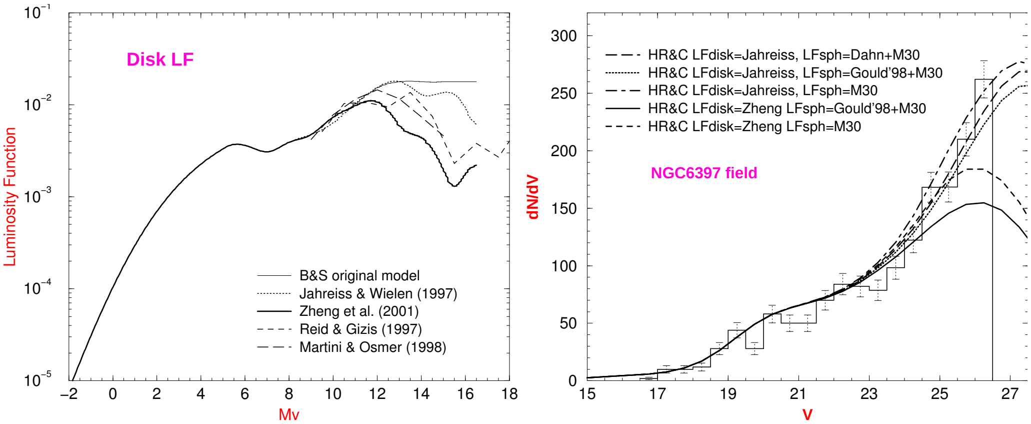


Fig. 1. Left panel: Disc luminosity functions as determined by several authors as labeled. The original B&S choice for the disc LF is also shown. Right panel: The histogram of the observed magnitudes as compared with theoretical predictions with parameters as in Haywood et al. (1997) (HR&C) for the labelled combinations of disc/thick disc/spheroid LFs at faint magnitudes. The thick disc parameters are: scale height = 710 pc and thick disc/disc local density ratio of 4.6%. Observations are corrected for incompleteness. Error bars give the expected 1σ statistical fluctuations of the observed counts in the completeness region.

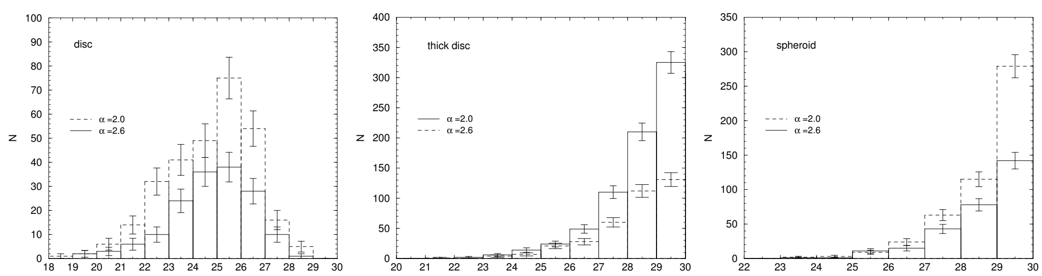


Fig. 2. Comparison between the predicted V-magnitude distribution (in a field at $l = 0°$, $b = 50°$ of extension 0.5 square degrees) obtained by adopting, for $M > 0.6M_{\odot}$, as IMF exponent either $\alpha = 2.0$ (solid line) or $\alpha = 2.6$ (dashed line) for the disc (upper panel), the thick disc (middle panel) and the spheroid (lower panel).The error bars indicate the poissonian statistical uncertainty on the counts. The adopted theoretical WD tracks are from Salaris et al. (2000). The assumed age for the spheroid is 13.5 Gyr.

account prolonged episodes of star formation. Thus for these two components star masses and ages are both randomly generated, the mass distribution reproducing the selected IMF, while a flat age distribution is adopted within the range assumed for each component. For the disc we assume a constant star formation rate (SFR) from 50 Myr to 9 Gyr to populate evolutionary tracks (Z=0.02 Y=0.27) until the asymptotic giant branch and the WD cooling sequences. For the thick disc, following Gilmore, Wyse, Jones (1995), a metallicity of $\sim$Z=0.006 and a SFR centered at $\sim$ 10 Gyr with a spread of few Gyr is adopted. Thanks to this theoretical approach the model spontaneously predicts the occurrence of stars in the various evolutionary phases. The main goal of our work is the introduction of disc, thick disc, and spheroid WD population in an evolutionary consistent way. We assume that stars with $M > 8M_{\odot}$ evolved up to supernova explosion, while stars more massive than the evolving AGB ones are WDs, whose mass is obtained from suitable initial-final mass relations for the different WD populations.

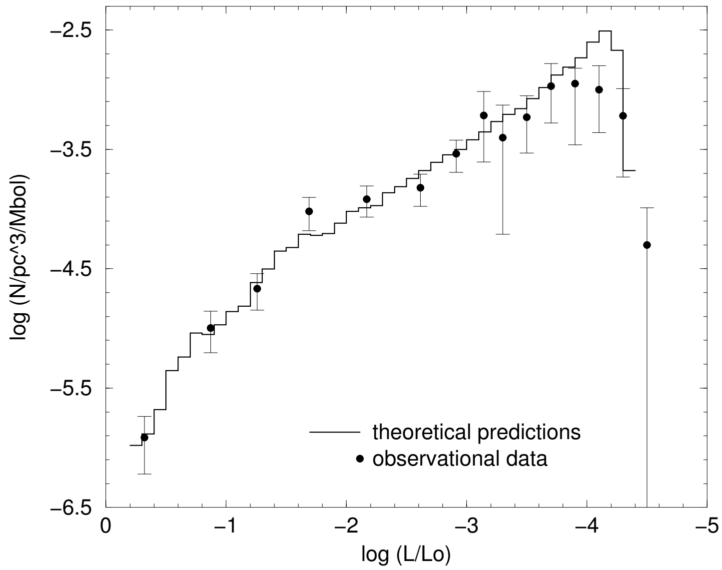
3. The white dwarf population

The present Galactic model can easily predict the expected abundance of WDs, since each star evolved beyond the AGB phase and less massive than the lower mass limit for supernovae (M_{up}) is assumed to be a WD. However, to predict the CM location of white dwarfs one needs further theoretical ingredients, as given by: i) a WD mass - progenitor mass relation ii) theoretical WD models giving luminosity and temperature of a WD as a function of mass and age and iii) suitable color transformations. The dependence of the predicted star count on these assumptions has been deeply investigated in Paper II. In the present work we adopt for $T_{eff} <$ 4000K the color relations by Saumon & Jacobson (1999), which include a detailed treatment of collision induced absorption of H_2, whereas for higher temperature, the results of Bergeron, Wesemael, Beauchamp (1995) were used. Regarding the WD cooling tracks, we chose the models by Salaris et al. (2000). As is well known, there is a quite large uncertainty in the relation between the WD mass and the progenitor mass owing to the poor knowledge of the final evolution of AGB stars, particularly during the thermal pulses and at the onset of the super-winds, and to the still present debate about the predicted extension of the convective core during central burning phases (see e.g. Dominguez et al. 1999). For the spheroid we adopt the theoretical relation by Dominguez et al. (1999), where the final WD mass is given by the helium core mass at the first thermal pulse, as obtained by assuming a standard extension of the convective core. For disc and thick disc we adopted the semi-empirical relation by Weidemann (2000), as inferred from the comparison among observations of young open cluster and theoretical models. In the present discussion we mainly focus on the influence of the input parameters concerning the stellar population. As a first point the predicted halo WD population obviously depends on the assumed halo age, the larger is the age the fainter is the bulk of the WD population (see fig. 5 in Paper II). This is a well understood feature: the increase of the time spent in the cooling sequence implies a progressive decrease of the WD luminosity.

Furthermore, the distribution of WD populations significantly depends on the adopted IMF. The number of WDs is obviously affected only by IMF variations for masses which could evolve into WDs in a time shorter than the estimated age of the Universe. Fig. 2 shows the effect on the distribution of a variation of the IMF for masses greater than 0.6 $M_{\odot}$. As range of variation we assume the uncertainty on the Salpeter exponential, as evaluated by Kroupa (2001). A steeper IMF (α=2.6) depopulates the WD stars. This behavior can be easily understood as a consequence of the decrease in the number of stars in the mass range able to produce WDs.

4. Results

As a first test of the model, Fig. 3 compares the predicted local WD luminosity function with recent observations by Liebert, Dahn, Monet (1988) and Leggett, Ruiz, Bergeron (1998). We remind that the only normalization adopted in our model is the one of the hydrogen-burning stars in solar neighborhood. Thus, the density distribution of WDs naturally arises from the model and the plotted WD luminosity function is just the output of our code without any additional normalization.



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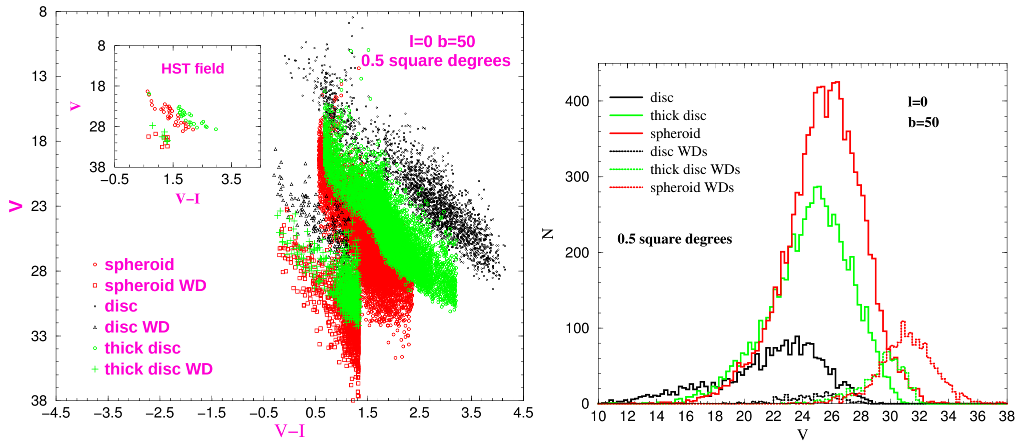

Fig. 4. Left panel:. Theoretical $(V, V-I)$ CMDs for field stars in the Galactic direction: $l = 0°$, $b = 50°$; the area is 0.5 square degrees. Different symbols refer to stars of the various Galactic populations, as labeled; white dwarfs are separately shown. Note that in our model we do not introduce artificial color dispersion simulating observational spread in colors.

Figure 4 (left panel) shows the $(V, V-I)$ color-magnitude diagram for the field stars in an area of extension 0.5 square degrees, at the Galactic coordinates $l = 0°$, $b = 50°$ The diagram is extended down to magnitude $V = 38$ to display the strong presence of spheroid WDs at extremely low luminosities. The inset panel shows the CMDs obtained for a field of about 6.6 arcmin^2, that is the area generally covered by *Hubble Space Telescope* (*HST*) observations (see e.g. King et al. 1998); note that in this small field the disc population is still absent at intermediate latitude. We note that the bulk WD population takes place at colors bluer then $V - I \sim 1.5$. Inspection of this figure reveals that there are regions of the CMDs in which the contribution of WDs to star counts seems to be distinguishable from other Galaxy stars. At sufficiently blue colors, i.e. $V - I \lesssim 0.5$, and not too high luminosity ($V \gtrsim 16$), the sample should be constituted exclusively by WDs.

The right panel of the same figure shows the predicted contribution of each Galaxy component to the V-magnitude distribution. An important finding of our prediction is that observations down to $V = 28$ include almost the whole disc population and disc WDs. However, only a few percent of thick disc and spheroid WDs are observable to this luminosities; in fact Fig. 4 shows that the thick disc WD distribution appears centered at $V \sim 30$, while the spheroid distribution is centered at $V \sim 31$, with a tail reaching faint luminosities down to $V \sim 36$.

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