**Hipparcos and the age of the Galactic disc**

Raul Jimenez, ¹ Chris Flynn² and Eira Kotoneva²

¹Institute for Astronomy, University of Edinburgh, Royal Observatory Edinburgh, Blackford Hill, Edinburgh EH9 3HJ
²Tuorla Observatory, Pūkki, FIN-21500, Finland

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**ABSTRACT**

We use the Hipparcos colour–magnitude diagram of field stars with Tycho colours to make a new minimum age estimate for the Galactic disc. The method is based on fits to the red envelope of subgiants in the Hipparcos colour–magnitude diagram with synthetic isochrones covering the range of disc metal abundance. The colours and luminosities of the isochrones as a function of abundance are checked using new techniques involving ‘red-clump’ stars in the giant branch region and on the main sequence using G and K dwarfs. We derive a minimum disc age of 8 Gyr, in good agreement with other methods.

**Key words:** stars: abundances – stars: evolution – stars: late-type – Galaxy: evolution.

1 INTRODUCTION

The age of the Galactic disc has been measured in the past using a variety of independent methods. A classical technique is to utilize the cooling rates of white dwarfs in combination with the lack of old, cool field white dwarfs in the local disc to place a lower limit on the age of the Galactic disc of 6 to 10 Gyr, limited chiefly by uncertainties in the cooling rates of white dwarfs (Winget et al. 1987; Liebert, Dahn & Monet 1989; Bergeron, Ruiz & Leggett 1997). Recently, a new technique of searching for white dwarfs as proper motion companions to brighter stars (Oswalt et al. 1996) has led to a rather precise minimum age for the local disc of 9.5 ± 1 Gyr. The ages of evolved F and G stars can be determined from distances, photometry and isochrones, and studies of this type indicate that the disc is between 10 and 12 Gyr old (Edvardsson et al. 1993). Radioactive dating (e.g., isotope ratios) establishes a method for measuring the age of the disc which is technically quite difficult but places a lower limit of approximately 9 Gyr (Butcher 1987; Morell, Källander & Butcher 1992). A fourth method uses the lower locus of the red giant branch in the colour–magnitude diagram (CMD): this method places a firm lower limit of 8 ± 1 Gyr on the age of the disc through a comparison of the CMD of field G and K giants with the giant branch of the old open cluster NGC 188 (Janes 1975; Wilson 1976; Twarog & Anthony-Twarog 1989).

In this paper we measure a lower limit on the age of the Galactic disc from nearby field stars by comparing the CMD of the local disc as measured by Hipparcos with sequences of stellar isochrones. Constraints on the isochrones are obtained through the use of metallicities of the G and K clump giants from Høg & Flynn (1998) and of G and K dwarfs from Flynn & Morell (1997) in conjunction with the Hipparcos CMD. Our lower limit on the disc age comes essentially from the fit of the isochrones in the subgiant region to the Hipparcos data.

This paper is organized as follows. In Section 2 we describe the data from the Hipparcos satellite. In Section 3 we describe our theoretical isochrones and develop observational checks on them using red-clump stars and main-sequence G and K dwarfs for which metallicities are known. In Section 4 we use the Hipparcos data to derive a minimum disc age, and we conclude in Section 5.

2 HIPPARCOS COLOUR–MAGNITUDE DIAGRAM

Our study is based on the CMD of local stars observed by the European Space Agency’s Hipparcos Satellite. Data from Hipparcos were released in 1997 July and were obtained from the Centre de Données Astronomiques de Strasbourg (ESA 1997). We show in Fig. 1 the CMD of Hipparcos stars with Tycho colours for which the parallax has been measured to better than 15 per cent, and for which the B−V colours have accuracies to better than 0.02 mag. The red giant branch (RGB) rises rapidly and is populated by first-ascent giants as well as the remarkably clear clump (or He core burning) giants at an absolute magnitude $M_V = 0.8$ and a colour $B - V = 1.1$. There is a locus of giants and subgiants, below or to the red of which very few stars are found, and this is the primary feature used here to constrain the age of the disc.

To illustrate the effects of age and metallicity on the giant and subgiant branches and the main sequence, we plot in Fig. 2 synthetic CMDs for different scenarios of star formation and metallicities of a population representative of the local disc. We have computed these diagrams using the latest version of our synthetic stellar population code described in Jimenez et al. (1998), to which we refer the reader for full details. Fig. 2(a) shows synthetic stellar populations in which star formation took place in an initial burst of $1 \times 10^6$ yr and then decayed exponentially with $\tau = 3$ Gyr, calculated for the metallicities [Fe/H] = 0.3, 0.0 and −0.7 (from right to left). Fig. 2(b) shows a model where metallicity was kept fixed to [Fe/H] = 0.0 and we used a constant star formation rate to model the disc population. In both scenarios the disc age was chosen to be 10 Gyr and the helium enrichment parameter is $dY/dZ = 2.5$. 

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3 ISOCHRONES

We have computed stellar tracks using the latest version of our stellar evolution code JMSTAR15 (see Jimenez & MacDonald 1996 for details). We have used a version of the MARCS atmospheric code, developed by Uffe G. Jørgensen (see Gustafsson & Jørgensen 1994 for details), to compute stellar photospheric models in the range $T_{\text{eff}} = 8000$ to 2000 K and $\log g = -0.5$ to 6.0. We have used these photospheric models to compute boundary conditions for JMSTAR15 interior models, producing self-consistent stellar tracks, so that at each point on the stellar track the corresponding photospheric model is known. We compute directly the $B$ and $V$ magnitudes for the track using the appropriate transmission filter functions (Kurucz 1992) on the corresponding photospheric model. We have calibrated the value of the mixing length using the observed luminosity, $T_{\text{eff}}$ and age for the Sun (we use $M_V = 4.83$) using a stellar track with $1 \, M_\odot$, $Y = 0.273$ and $Z = 0.019$; see Jimenez & MacDonald for details of the physics input used in JMSTAR15. Using this set of stellar tracks we compute isochrones in the range 8–15 Gyr.

Fig. 2 shows that the colour and absolute magnitude of the turn-off stars are sensitive to stellar age, as is well known, being redder and less luminous for older, more metal-rich stars. This is manifested in the Hipparcos CMD as the red edge of the giant and subgiant branches, below and to the red of which very few stars are found. In the next section we use isochrones to fit this feature and establish a minimum age for the Galactic disc. Ideally, we would measure metallicities of stars along this lower locus, particularly in the turn-off region, in order to fit the appropriate isochrones. Unfortunately, the determination of metallicity in cool subgiant stars is not yet practical. However, metallicities can be determined in late-type G and K giants and in cool main-sequence dwarfs. In this paper we attempt to circumvent the problem of the unknown metallicities in the subgiant region by using the metallicities of clump giants above the turn-off, and K dwarfs below it, to check our isochrones.

3.1 Isochrone checking above the turn-off: the clump stars

A remarkable feature of the Hipparcos CMD is the horizontal branch clump (Fig. 1). Contrary to the situation in globular clusters where the HB is a sharply defined horizontal and thin line, the equivalent in the field is much thicker in absolute magnitude. The clump has a width of about 0.7 mag (FWHM) in Fig. 1, much more than the scatter in the absolute magnitudes due to measurement error, which is only 0.15 mag (Høg & Flynn 1998).

![Figure 1](https://example.com/figure1.png)

**Figure 1.** CMDs for the Hipparcos catalogue with stars whose parallaxes have relative errors < 0.15, and with Tycho colours with errors less than 0.02 mag.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Synthetic CMD for different star formation histories and metallicities. The left-hand panel shows the synthetic CMD for a population with three metallicities (from right to left, [Fe/H] = 0.3, -0.0 and -0.7); for each of these the star formation history has an initial burst that decayed exponentially with $\tau = 3$ Gyr, and the total age of the population is 10 Gyr. The right-hand panel shows a population with a constant star formation rate over 10 Gyr.
As is well known, metallicity has a strong effect on the colour of clump stars formed. We show in Fig. 3 a calculation using JMSTAR15 (Jimenez & MacDonald 1996) of the zero-age horizontal branch (ZAHB) for different masses at several metallicities. We note two features.

(i) For masses larger than 0.8 M\(_{\odot}\) (i.e., ages less than 16 Gyr) the HB is not horizontal but vertical. This means the clump has a well-defined red edge for masses between 0.8 and 1.3 M\(_{\odot}\) (i.e., ages between 16 and 2 Gyr).

(ii) The red edge of the clump becomes redder with increasing metallicity. The metallicity distribution of a stellar population can be estimated from the colour distribution of the clump stars. These two features allow us to establish fiducial points in the clump with which to check our isochrones.

In Fig. 4 we show our calculated red edge of the clump for the four metallicities analysed in Fig. 3 (left to right: [Fe/H] = -2.0, -0.7, 0.0 and 0.3) plotted over the Hipparcos data, where we have transformed \(T_{\text{eff}}\) into \(B-V\) using the prescription described at the beginning of Section 3. Metallicities for most of the giants in this diagram have been measured by Høg & Flynn (1998), who have analysed the metal-rich K giants in the Hipparcos catalogue in the range \(0.95 < B-V < 1.4\) in order to calibrate a photometric indicator of K giant absolute magnitude. Metallicities for the giants were calculated using the Janes (1975, 1979) technique based on the DDO intermediate-band photometry method. We now use these metallicities to check our predicted colours of the red edge of the clump.

We isolate the clump stars using the dashed box in Fig. 4, and in Fig. 5 we show \(B-V\) colours of the stars in this box as a function of their metallicity. Most of the objects chosen will be true clump stars, although there will also be some first-ascent giants within this region. Clump stars dominate, as they can be clearly seen in Fig. 5 despite the background signal from normal giants. Fig. 5 shows our calculated theoretical trend (solid line) of an increasingly red limit to the clump as a function of metallicity, which matches the observed red edge of the clump quite well. These fits indicate that the colour of the red clump could be used as a metallicity indicator in old (2 to 16 Gyr) metal-rich populations. Importantly for the present paper, this establishes that the colours of the giant branch in our theoretical isochrones are quite well matched (within 0.05 mag in \(B-V\)) to the available data.

### 3.2 Isochrone checking below the turn-off: G and K dwarfs

Accurate, spectroscopically determined metallicities for K dwarfs have only very recently become feasible, as a result of improvements in stellar atmosphere models for these cool stars (Morell 1994). Morell obtained very high-dispersion spectra of 26 G and K dwarfs with the ESO/CAT, and measured detailed abundance ratios for 17 elements. A photometric abundance indicator for G and K dwarfs has been developed from these data by Flynn & Morell (1997), who use \(R-I\) to estimate effective temperature, and the Geneva intermediate-bandwidth \(b_1\) filter in the blue to estimate abundance. The parallaxes of the Flynn & Morell stars have now been measured by Hipparcos, so that we can use them to check our isochrones along the main sequence.
In Fig. 6 we plot isochrones of different ages (8, 11, 13 and 15 Gyr) and metallicities ([Fe/H] = −0.5, 0.0 and 0.3) over the Hipparcos CMD. To check the isochrones we isolate Flynn & Morell dwarfs in three abundance windows: metal-poor (−0.6 < [Fe/H] < −0.4), solar (−0.05 < [Fe/H] < 0.05) and metal-rich (0.25 < [Fe/H] < 0.35). We cannot compare the colours and absolute magnitudes of the stars in these windows directly with the isochrones, because the scatter in the photometrically determined abundances of the stars of 0.2 dex (Flynn & Morell 1997) is large relative to the range of abundances in the disc. Consequently, the true abundances of the stars in our three metallicity windows depends on the overall abundance distribution in the disc. (For example, there will be many more metal-rich than metal-poor stars scattering into the range −0.6 < [Fe/H] < −0.4.) We have estimated the size of this bias as follows. We adopt the observed metallicity distribution for disc G and K dwarfs measured by Flynn & Morell, and deconvolve this distribution with a 0.2-dex Gaussian to obtain the true metallicity distribution. We can then compute the mean metallicity of stars that would appear in each of our metallicity windows using the true distribution and our known observational scatter of 0.2 dex. The true mean abundance of the stars in the windows is found to be [Fe/H] = −0.26 for the metal-poor window, [Fe/H] = −0.04 for the solar window, and [Fe/H] = 0.10 for the metal-rich window. The difference between the true and observed mean metallicity in each window is then converted to a colour difference, and the stars in the windows are shifted appropriately in B − V. The colour offsets are ∆(B − V) = −0.05 (i.e., to the blue) for the metal-poor window and ∆(B − V) = 0.07 (i.e., to the red) for the metal-rich window, while for the solar metallicity window the shift is smaller than 0.01 mag.

Flynn & Morell G and K dwarfs of solar abundance (−0.05 < [Fe/H] < 0.05) are plotted as squares and match well the solar-abundance isochrones, (We note that the tight fit of the stars to the theoretical isochrone is consistent with the assumption that star-to-star variations in the mixing length parameter of the convective envelope do not occur during the evolution of a star in the disc main sequence, as seen directly in the narrow giant branches observed in globular clusters; see Jimenez et al. 1996, and references therein.) Flynn & Morell dwarfs in the range −0.6 < [Fe/H] < −0.4 are plotted as triangles (using the colour shift noted above), and these match the [Fe/H] = −0.5 isochrones well. A small number of stars with abundances in the range 0.35 < [Fe/H] < 0.25 and shifted in colour as noted above are shown as circles for comparison with the [Fe/H] = 0.3 isochrones. We have verified that the stars fit isochrones of the appropriate metallicity ([Fe/H] = −0.26, −0.04 and 0.10), for which no colour corrections are needed. We conclude from this analysis of G and K dwarfs that the main-sequence part of our isochrones matches the available data well.

4 DISC AGE FROM THE SUBGIANT BRANCH

Having established that our isochrones are good fits to the available data above and below the turn-off, we now use the red envelope of Hipparcos subgiants to determine a minimum age for the Galactic disc. The CMD is shown in Fig. 7, where we plot contours by stellar number density in this plane in order to show the red envelope of the subgiants clearly (we have counted stars in bins of 0.01 in colour and 0.1 in magnitude, and applied a light smoothing using a 2D Gaussian with σ = 0.5 bins). Our isochrones as in Fig. 6 are also shown.

We now use qualitative arguments to set a minimum limit on the age of the disc. Ideally, we would like to have measurements of the metallicities of the turn-off stars along the red edge of the subgiant envelope, but this is not yet possible. We therefore start by assuming that these subgiants have the practical maximum metallicity in the disc, since this will produce the lowest minimum age estimate. Assuming [Fe/H] = 0.3, we note that the 8-Gyr isochrone in Fig. 7 forms a reasonable red envelope to the Hipparcos subgiants. If the
most metal-rich subgiants have this abundance, this would set the minimum disc age to be 8 Gyr. If the most metal-rich subgiants are actually more metal-rich, than the minimum disc age estimate decreases by approximately 1 Gyr per 0.1 dex (for example, at [Fe/H] = 0.4 a minimum age of 7 Gyr would be obtained).

It is unlikely that the oldest disc stars are actually as metal-rich as [Fe/H] = 0.3. This can be seen in the age–metallicity relation (e.g. fig. 14, Edvardsson et al. 1993) in which the elderly metal-rich disc stars are close to solar metallicity. Comparison of the solar-metallicity and [Fe/H] = 0.3 isochrones in Fig. 7 indicates that the red edge of the turn-off region is likely to be composed of a mixture of younger more metal-rich stars in addition to the oldest metal-poor stars. Therefore, in order to measure the disc age quantitatively from this feature, one would require direct measurements of the stellar abundances of the subgiants, which should be possible in the near future as the stellar atmospheric models for these stars are maturing rapidly (B. Edvardsson, private communication) and their luminosities are well established by Hipparcos. Alternatively, one could use detailed modelling of the disc’s metallicity distribution, plausible age–metallicity relations, star formation rates, and the rate of evolution off the main sequence as functions of age and metallicity, in order to model this feature. We are currently obtaining a volume-limited sample of K dwarfs in order to determine the disc metallicity distribution and chemical evolution of the disc, which will be a first step in this direction.

Under the conservative assumption that the most metal-rich subgiants are not more metal-rich than [Fe/H] = 0.3, our minimum disc age is 8 Gyr. This is age estimate is broadly consistent with all previous measures of the disc age. Edvardsson et al. (1993) obtained the disc age–metallicity relation for the field F and G dwarfs from distances and isochrone-fitting. The disc ([Fe/H] > −0.5) stars in their sample have ages of up to 12 Gyr. Recently, the ages of their stars have been reetermined using the Hipparcos parallaxes (Ng & Bertelli 1998), and these authors confirm this age for the oldest disc stars. All stars which they find to be older than 12 Gyr have [Fe/H] < −0.5 and are kinematically members of the thick disc (Edvardsson et al. 1993, fig. 16).

A method closely related to ours uses the lower locus of giants in the CMD of the old metal-rich open cluster NGC 188, in comparison with the field stars, to set a strict lower age limit on the disc of 8 Gyr (Janes 1975; Twarog & Anthony-Twarog 1989). Comparison of Twarog & Anthony-Twarog’s figs 3 and 4 with the Hipparcos CMD shows that this is still a strong lower limit. However, both our method and the comparison to open cluster CMDs suffer from the problem of the unknown metallicities along the subgiant branch. NGC 188 (or NGC 6791) were long been considered ideal for a comparison of this type since they were thought to be the oldest open clusters, but there is now mounting evidence that there are open clusters which are as old as or even older than some globular clusters (see the review by Friel 1995). In particular, Janes & Phelps (1994) have developed a method for ranking open cluster ages, and from their age distribution they find that the disc is at least 10 Gyr old; recently, a strong case for 12 Gyr has been argued based on Berkley 17 (Phelps 1997). With metallicities becoming increasingly available for cool stars above, below and in the subgiant region, we expect that the constraints on the isochrones and the disc age from the Hipparcos CMD will become very interesting in the near future.

5 CONCLUSIONS

We have used the Hipparcos CMD (with Tycho colours) to determine a minimum age for the Galactic disc by comparison with theoretical isochrones. Accurate metallicity measures for G and K giants and dwarfs are used to check the metallicity dependence of the isochrones. We introduce a new technique involving horizontal branch (clump) stars to check the isochrones, which shows that the colour of the clump can be used to estimate stellar population metallicity. Using the morphology of the lower locus of the subgiant branch in the Hipparcos CMD, it is possible to set a minimum age of 8 Gyr for the local Galactic disc.

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