Hipparcos and the Age of the Galactic Disc

Raul Jimenez¹, Chris Flynn² and Eira Kotoneva²

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

ABSTRACT

We have used the Hipparcos satellite colour magnitude diagram to determine the age of the Galactic disc. We first measure the metallicities of the clump stars using DDO photometry (Høg & Flynn 1997). We then use isochrones covering the range of disc metal abundance and the morphology of the turn off and sub-giant region to place constraints on the minimum age of the Galactic disc. We derive a minimum age of 11 ± 2 Gyr. In conjunction with the new ages derived for globular clusters using the same method (Jimenez et al 1996) our results indicate that the delay between the formation of the halo and the disc was up to 2-3 Gyr. We show that a Reimers mass-loss law is sufficient to explain the morphology of the red clump.

1 INTRODUCTION

The age of the Galactic disc has been measured in the past using a variety of independent methods. The cooling rate of white dwarfs and the lack of old, cool white dwarfs in the local disc places an upper limit on the age of the Galactic disc of 6 to 10 Gyr, limited chiefly by uncertainties in the cooling rates of white dwarfs (Liebert et al 1989, Winget et al 1987, Bergeron et al 1997). The ages of evolved F-stars can be determined from photometry and isochrones, indicating 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 although technically quite difficult but with a lower limit of approximately 9 Gyr for the age of the Galactic disc (Butcher 1987, Morell et al 1992). A fourth method use the lower locus of the red giant branch in the colour magnitude diagram: this method places a firm lower limit of 8 ± 1 Gyr on the age of the disc through a comparison of the colour magnitude diagram of field G and K giants with the giant branch of the old open cluster NGC 188 (Janes 1975, Wilson 1976, Twarog and Anthony-Twarog 1989).

In this paper we measure the age of the Galactic disc from the field stars, by comparing the colour magnitude diagram of the local disc as measured by the Hipparcos mission with a range of stellar isochrones. Constraints on the isochrones are obtained through the use of accurate metallicities of the G and K giants from Høg & Flynn (1997) and for G and K dwarfs from Flynn and Morell (1997). Our lower limit to the disc age comes essentially to the fit of the isochrones in the sub-giant region to the Hipparcos data. Having constrained the age in this way, we then study how mass-loss determines the red clump morphology and its relation with the red giant branch morphology. Our method is based on the one developed by Jimenez et al (1996) to study the ages of globular clusters.

This paper is organised as follows: In section 2 we describe the data from the Hipparcos satellite. In section 3 we describe the models we use to estimate the age of the disc and the morphology of red clump. We discuss our derived age in section 4 and conclude in section 5.

2 COLOUR MAGNITUDE DIAGRAM AND METALLICITIES

Our study is based on the colour magnitude diagram (CMD) of local stars observed by the European Space Agency’s Hipparcos Satellite.

Data from Hipparcos were released in July 1997. We prepared a CMD for all stars for which the parallax, \( \pi \), had been measured to better than 15\%. The resulting subsample in the entire Hipparcos catalogue is plotted in Fig. 1(a). The rapidly rising red giant branch (RGB) is populated by first ascent giants as well as the remarkably clear clump (or He core burning) giants at an absolute magnitude of \( M_V \approx 0.8 \).

Stellar evolutionary state of the giant branch is quite sensitive to metal abundance, and we require estimates of \([\text{Fe/H}]\) for the giants to determine the disc age. Høg & Flynn (1997) have analysed the metal rich K giants in Hipparcos with \((0.95 < B - V < 1.4)\) in order to calibrate a photometric indicator of K giant absolute magnitude. The photometric indicator uses intermediate band DDO photometry (Janes 1975), with which metal abundances for the individual giants in our sample have been derived using the Janes (1975, 1979) method. The CMD of these stars is shown in Fig. 1(b).

We note that the typical error on the parallaxes for these giants is only 8% (as discussed in Høg and Flynn 1997) or an absolute magnitude error of 0.15 mag. This is so accurate that no Lutz-Kelker type corrections to the parallaxes were necessary (see Høg and Flynn 1997).
Fig 1(b). We note that the Høg & Flynn sample was limited to metal rich giants \([\text{[Fe/H]} > -0.5\) and \(0.95 < B - V < 1.35\), meaning that the bluer, metal poor clump stars are not included. Stars with \([\text{[Fe/H]} < -0.5\) are either from the thick disc or halo, with different kinematics and possibly formation history to the disc, which is why we exclude them from the sample. Finally, there are few intrinsically luminous red giants in the sample, because we have limited ourselves to stars with parallax measurements of better than 15%. This tends to exclude intrinsically bright \((M_V < -1)\) giants. This causes us no concern either because the clump stars are well below this limit.

### 3 AGE MEASUREMENT

Nearby K giants provide a snapshot of the chemical history of the local Galactic disc. Over the lifetime of the disc, successive generations of main sequence stars have formed, and we see a particular selection of them today by age, mass and metal abundance passing through the giant phase. The measurement of age from the Hipparcos CMD is therefore somewhat more involved than in open or globular clusters, where one has a homogeneous population of stars.

One of the most remarkable features of the Hipparcos CMD is the Horizontal Branch clump (see 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. From Figure 1 one can see that the clump is about 0.7 magnitude broad (FWHM), much more than the scatter in the absolute magnitudes due to measurement error which is only 0.15 mag.

The vertical and horizontal extent of the clump and the width of the giant branch seen in the Hipparcos CMD are caused by the range of stellar age and metallicity currently passing through this evolutionary phase. We illustrate this in Figure 2, where we plot 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 most recent version of our synthetic stellar population code (Jimenez et al. 1997). A detailed description of the code has been given in Jimenez et al. 1997 to which we refer the reader for full details. Fig. 2(a) shows synthetic stellar populations in which star formation took place in a initial burst of \(1 \times 10^6\) years and then decayed exponentially with \(\tau = 3\) Gyr. It was calculated for three different metallicities: \([\text{[Fe/H]}] = 0.3\), \([\text{[Fe/H]}] = 0.0\) and \([\text{[Fe/H]}] = -0.7\) (from right to left). In all cases \(dY/dZ = 2.5\). Fig. 2(b) shows a model where metallicity was kept fixed to \([\text{[Fe/H]}] = 0.0\) and we used continuous star formation to model the disc population. In both cases the age of the population was chosen to be 10 Gyr. Although both of these model types have plausible star formation laws, no model at a single metallicity would provide a good match to the Hipparcos data. Not unexpectedly, the metallicity spread is an important factor in the CMD, causing scatter along the main sequence and giant branch.

\[^\dagger\] It is possible that star-to-star variations in the mixing length parameter \(\alpha\) are causing some of the scatter. However, this would be in contradiction to a recent analyses of variations of \(\alpha\) in globular clusters (c.f. Jimenez et al. 1996), and we do not consider this a likely scenario amongst disc stars.
Figure 2. Synthetic CMD for a different star formation histories and metallicities. The left panel shows the synthetic CMD for a population with 3 metallicities ([Fe/H]= 0.0, [Fe/H]= −0.7 and [Fe/H]= −2.0), for each of these the star formation history with an initial burst that decayed exponentially with \( \tau = 2 \) Gyr, the total age of the population is 10 Gyr. The right panel shows a population with a constant star formation rate over 10 Gyr. It transpires from both panels that a spread in the RGB and the main sequence can only be due to the spread in metallicity in the disc.

As is well known, metallicity has a strong effect on the colour of clump stars formed. We show in Fig. 3 a calculation using the Jimenez et al code of the zero age horizontal branch for different masses at several metallicities. It is worth noticing three features:

(i) For masses larger than 0.8 \( M_\odot \) (i.e. ages less than about 16 Gyr) the HB is not horizontal but vertical. This means that a well defined red limit exists to the clump for masses between 0.8 and 1.3 \( M_\odot \) (i.e. ages between 16 and 2 Gyr).

(ii) The higher the metallicity the redder the red limit. Therefore the metallicity distribution of a stellar population can be estimated from the colour distribution of the clump stars.

(iii) The lower locus of the sub-giant branch is occupied by the oldest stars in the population and also the most metal rich. A minimum age estimate for the Galactic disc can be obtained from these stars if accurate metallicities and distances are known.

In Fig. 4 (left panel) we have superimposed our calculated red limits of the clump for the four metallicities analyzed in Fig. 3 (left to right: [Fe/H]= −2.0, −0.7, 0.0, 0.3) on the Hipparcos data. The metallicities of the stars are seen to be in the range −0.6 <[Fe/H]< 0.2, in good accord with the known abundance distribution of the disc (see e.g. Freeman 1987). Note that the lines show the red limit of the clump rather than the mean colour at a particular metallicity.

In the case of these bright disc giants, detailed individual abundances are available from Hog and Flynn (1997), and we make use of this information in what follows. In order to determine the metallicity content of the clump, we isolate it using the two dashed lines shown in figure 4 and plot the metallicities of the stars as a function of colour (Fig. 5). Most of the stars in this cut are true clump stars, although some normal first ascent giants are also moving through this region. Clump stars dominate however, as they can be still clearly seen in Fig. 5 despite the background signal from normal first ascent giants. There is a trend along the clump of increasing metallicity with increasing colour as expected from the results shown in Figure 3.

3.1 Disc age from the reddest clump stars and the morphology of the sub-giant branch

We now estimate the disc age as follows. Consider giants of solar metallicity [Fe/H] = 0.0, in Fig 5. At this metallicity, the red limit of the clump appears at \( B − V \approx 1.17 \pm 0.02 \). The mean absolute magnitude of such giants (from Hipparcos) is \( M_V = 0.7 \). This defines a fiducial point for solar metallicity isochrones. We can construct two further fiducial points, for giants with [Fe/H]=−0.5 and [Fe/H]=0.3, i.e. the lowest and highest disc metallicities (see also Fig.5). The fiducial points are shown as crosses in Figure 6.

We now construct isochrones of different ages (8,11,13 and 15 Gyr) for the above metallicities, and overlay them on the Hipparcos CM, shown in Figure 6 and 7. The isochrones all pass very close to the fiducial points, giving us some con-
Figure 3. The position of the ZAHB for four different metallicities and different masses. There is a well defined red limit that depends on the metallicity of the stars. For a range of masses between 0.8 and 1.3 $M_\odot$ (i.e ages between 16 and 2 Gyr), the HB is vertical.

Figure 4. The CMD for the Hipparcos catalogue and the Hog & Flynn sample. Superimposed are the red limits defined by the theoretical ZAHB models for different metallicities (from right to left: $Z = 2Z_\odot$, $Z = Z_\odot$, $Z = Z_\odot/5$ and $Z = Z_\odot/100$). It is clear that the metallicity of the HB clump is well constrained between solar and 1/5 solar metallicity. Dashed lines are used to isolate clump stars plotted in figure 5 (as discussed in section 3).

We now set limits on the age of the disc. First, one sees from Fig. 6 that ages younger than 8 Gyr can be ruled out. If we examine the [Fe/H] = 0.3 isochrones in Fig 6(a), then the 8 Gyr isochrone forms a reasonable lower locus to the faintest Hipparcos sub-giants. This sets the minimum disc age to be 8 Gyr, since a younger age could only be obtained for isochrones more metal rich than [Fe/H] = 0.3, but this is the practical maximum disc metallicity (see Figs. 4 and 5). We can show that the disc must in fact be older than 8 Gyr by examining the isochrone set for solar abundance (Fig 6b). A maximum disc age of 8 Gyr seems a poor fit for solar metallicity stars. If the oldest disc stars were only 8 Gyr old, then all the stars below the 8 Gyr solar metallicity isochrone would have to be explained as stars with [Fe/H] > 0.0. This is in contradiction with two facts: from Fig. 5 (and also from Fig. 4) it is clear that only about 10% of the stars in the red clump have metallicities larger than solar, and only a fraction of these will be as old as the disc. Even at a metallicity of [Fe/H]=0.3 (Fig. 6 panel (a)) there are sub-giants stars below the 8 Gyr isochrone that are only fitted at an age of 10-11 Gyr. A consistent picture is obtained by adopting 11 Gyr as the minimum age of the disc. In this case, the solar abundance isochrones fit the sub-giant region of the Hipparcos data well and there is no discrepency with the super-solar isochrones. Of course, disc stars can be comfortably older than 11 Gyr as long as they are of less than solar metallicity, as seen in Figure 6(c). We conclude that the minimum disc age is 11 Gyr.

3.2 Error estimate of the disc age

We now discuss in turn the main sources of error in the age estimate, which are the metallicity scale and the colour transformations of the isochrones.
Relative to the solar abundance dwarfs, our solar metallicity isochrone is a little too red, but by not more than 0.1 mag. Our \([\text{Fe/H}] = -0.5\) isochrone matches the data better, although it is a little too blue for the brighter dwarfs. A small number of dwarfs in the range \(0.2 < [\text{Fe/H}] < 0.4\) were also examined but are not shown for clarity. From these our \([\text{Fe/H}] = 0.3\) isochrone appears to be too red by 0.1 mag. We conclude that a systematic colour error is possible in the isochrones in the sub-giant and dwarf region of up to 0.1 mag. Examining the isochrones in Fig 6, one can see that in the sub-giant region, shifting the isochrones by 0.1 mag to the red is equivalent to increasing the disc age estimate by 2 Gyr.

An obvious concern in our method is that we have assumed that the helium enrichment follows \(dY/dZ = 2.5\). If we adopt other values for \(dY/dZ\) the absolute values of the age of the Galactic disc will change accordingly, but so will the age of the Sun. For example changing \(dY/dZ\) at solar metallicity to 1.1 would imply a change in the disc age from 10 Gyr to 14 Gyr, but this would change the Sun’s age to 6 Gyr. Our age scale for the disc is thus firmly tied to a solar age of 4.5 Gyr, and the ages of the disc and globular clusters (Jimenez et al 1996) are all relative to this.

We conclude from the discussion of metallicity and colour effects in this section that our age error is of order 2 Gyr.

### 3.3 The morphology of the Red Clump

The age estimate of 11 ± 2 Gyr above is partially based on the reddest stars in the clump as a function of metallicity. The thickness of the clump in absolute magnitude could itself be used to measure the age, if it were not for the uncertain amount of mass-loss taking place. Specifically, if we neglected mass-loss, the luminosity of the least luminous stars of the red clump of Fig 3 would lead to a minimum age estimate of the disc of circa 30 Gyr, much older than our age estimates for the globular clusters of about 13 Gyr using the same method (Jimenez et al 1996). We conclude that mass loss plays an important role in field red clump’s morphology, as it does in the HB in globular clusters (Jimenez et al 1996). The only alternative explanation would be cumbersome variations of the helium content in the Galactic disc that require fine tuning.

We can fix the age of the disc as derived in the previous section at 11 ± 2 Gyr, and determine the amount of mass loss in the clump instead. We have isolated, using the Høg & Flynn (1997) abundances, the red end of the clump for two particular metallicities \([\text{Fe/H}]= 0.0\) and \(-0.45\) (see Fig. 8). A comparison with Fig. 3 shows that the red clump covers a mass range between 0.8 and 1.5 \(M_\odot\) in both cases. Fixing the age at 11 Gyr, the mass of the stars on the RGB should be about 1 \(M_\odot\). Since the lowest luminosity stars in the red clump have masses of about 0.8, they must have lost 20% of their mass. This is in excellent agreement with what is expected from the (empirical) Reimers mass-loss law (Reimers 1975). In Table 1 we show the predictions for a Reimers mass law with the \(\eta\) parameter (see Reimers 1975) in the range 0.0 to 0.8.

Using the number of stars in the clump for each metallicity it is possible to predict the distribution in the \(\eta\) parameter. From the bottom panel of Fig. 6 we conclude that
Figure 6. Colour magnitude diagrams of the Hipparcos data, as in Figure 1, overlayed by isochrone fits. The crosses show the colours of the reddest stars in the clump as a function of metallicity (see Figure 5), for three metallicities [Fe/H] = 0.3, 0.0, and −0.5, chosen to bracket the disc abundance distribution. A minimum disc age of 11 ± 2 Gyr is derived from these plots and is discussed in detail in section 3.

Table 1. Derived disc ages for different clump masses, mass-loss rates, metallicities and He abundance Y. Manque means that the stars evolve directly from the RGB into a white dwarf.

| Mass/M$_\odot$ | Mass/M$_\odot$ | Mass/M$_\odot$ | Mass/M$_\odot$ | Mass/M$_\odot$ | Mass/M$_\odot$ | Mass/M$_\odot$ |
|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| RGB (η = 0.0) | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.5 |
| Age/Gyr       | 42.7 | 26.1 | 16.9 | 11.5 | 8.0 | 5.8 | 2.6 |
| Clump Mass/M$_\odot$ | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.5 |
| RGB (η = 0.4) | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.5 |
| Clump Mass/M$_\odot$ | Manque | 0.61 | 0.75 | 0.88 | 1.0 | 1.12 | 1.43 |
| RGB (η = 0.8) | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.5 |
| Clump Mass/M$_\odot$ | Manque | Manque | 0.52 | 0.72 | 0.87 | 1.0 | 1.3 |
| RGB (η = 0.0) | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.5 |
| Age/Gyr       | 33.9 | 20.7 | 13.4 | 9.1 | 6.4 | 4.6 | 2.0 |
| Clump Mass/M$_\odot$ | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.5 |
| RGB (η = 0.4) | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.5 |
| Clump Mass/M$_\odot$ | 0.51 | 0.65 | 0.78 | 0.90 | 1.01 | 1.10 | 1.41 |
| RGB (η = 0.8) | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.5 |
| Clump Mass/M$_\odot$ | Manque | Manque | 0.62 | 0.77 | 0.91 | 1.04 | 1.3 |

η is peaked at about 0.4, which is in excellent agreement with measurements in the field and the morphology of the HB in globular clusters (Jimenez et al. 1996). We remark that the underlying population of first ascent giants in the red clump is not of concern for this analysis since it only adds an offset to the bottom diagrams of Fig. 6 but does not change significantly the shape of the distribution.

We note that the morphology of the red clump cannot be due to star-to-star variations in the mixing length parameter. This is because the red clump mass distribution is vertical for giants of the typical age and mass found in the disc and is therefore unaffected by variations of this type.

© 0000 RAS, MNRAS 000, 000–000
Figure 8. The upper panels show colour versus absolute magnitude for stars in the clump for two metallicity ranges. For each star a mass can be estimated using the models plotted in Figure 3. The mass distributions are in the lower panels (note the use of non-equal bin sizes for practical reasons). These distributions of mass in the red clump can be well modelled by the conventional Reimers mass-loss law.

4 DISCUSSION

Our result is that the disc has a lower age limit of $11 \pm 2$ Gyr. We can compare this estimate to that obtained for the field F and G dwarfs for which age estimates can be made via distances and isochrone fitting (Edvardsson et al. 1993). The oldest disc stars ($[\text{Fe/H}] > -0.5$) in their sample are as old as 12 Gyr. Recently, the ages of their stars have been re-done using the Hipparcos parallaxes (Ng and Bertelli 1997) and these authors confirm this age for the oldest disc stars. All stars which they find are older than 12 Gyr have $[\text{Fe/H}] < -0.5$ and are kinematically members of the thick disc (Edvardsson et al. 1995, Figure 16). Hence this age is consistent with our determination of $11 \pm 2$ for the disc ($[\text{Fe/H}] > -0.5$) stars.

We now compare this to the ages derived for the globular clusters in the Jimenez et al. (1996) sample. There are six halo globular clusters (we define this as $[\text{Fe/H}] \leq -1.2$: M3, M5, M22, M68, M72 and M92) and two disc globular clusters (M107, 47 Tuc) in the sample. The mean age of the six halo clusters is 13.0 Gyr, with a remarkably small dispersion of 0.3 Gyr; if these clusters are at all representative then the halo formed rapidly at this time, 13 Gyr ago. This is a relatively young age for the halo, but recently substantial support for this age scale has come from the analysis of Hipparcos parallaxes for nearby sub-dwarfs (Reid 1997), which shows that the distance moduli to globular clusters have been traditionally underestimated and the ages overestimated. Reid estimates that the average age of the globular clusters is less than 14 Gyr, and may be as low as 12 Gyr.

Our results do not favour a substantial age spread in the globular clusters (Bolte 1989), which has long been a proposal for explaining the large range of horizontal branch colour seen in globular clusters, the so-called second parameter problem. Rather, the remarkably co-eval formation times of these clusters is in good agreement with the idea that the globular cluster mass-scale is an important one and may represent the dominant mode by which stars formed at that epoch (Padoan, Jimenez and Jones 1997).

The two disc clusters have ages of 12.0 and 11.5 Gyr, while the disc age as measured in this paper is $11 \pm 2$ Gyr. We should be careful to draw the distinction between the disc age measured in this paper near the sun (at a Galactocentric distance of 8 kpc) and the ages of disc globular clusters, which are mostly closer to the center of the Galaxy than 4 kpc, where the disc may be older than at the solar circle. In any case, the sequence of ages in this small sample indicates that there was a delay of 2-3 Gyr between the formation of what now traces the halo and the time when most of the gaseous phase of the proto-galaxy had settled into place in the disc. This is very much in accord with a relatively gentle bottom-up picture of the formation of the Galaxy (cf Padoan, Jimenez and Jones 1997, Reid 1997), as well as the results of deep imaging with the Space Telescope (Pascarelle et al. 1996).

Discs are relatively easy to disrupt via accretion (Toth and Ostriker 1992). At an age of 11 Gyr, it is unlikely that the disc has suffered a major accretion event during this time. The formation redshifts of the Galactic disc in two representative cosmologies are $z = 1.8$ in a closed Universe.
8 R. Jimenez, Chris Flynn & Eira Kotoneva

(i) Using the accurate absolute magnitudes of clump giants in the Hipparcos CMD for which metallicities are available from Høg & Flynn (1997), we have obtained an accurate age for the Galactic disc. We find the Galactic disc to be $11 \pm 2$ Gyr.

(ii) An age of 11 Gyr for the Galactic disc implies that it formed rapidly after the most metal rich globular clusters. In conjunction with the new ages derived for globular clusters by Jimenez et al (1996), the delay between the formation of the halo and disc was 2-3 Gyr.

(iii) The reddest stars in the red clump can be used to determine the metallicity of stellar populations between 2 and 12 Gyr. We have shown that the metallicity for the Galactic disc inferred using this method is in good agreement with the one measured by Høg & Flynn (1997).

(iv) The morphology of the red clump is well modelled by a Reimers mass loss law, with $\eta$ changing from 0.0 to 0.8.

REFERENCES

Alcock C. et al, 1997, astro-ph/9707311
Bergeron J., Ruiz M.T., Leggett S.K., 1997, ApJS, 108, 339
Bolte M., 1989, AJ, 97, 1688
Butcher H.R., 1987, Nature, 328, 127
Edvardsson B., Andersen J., Gustafsson B., Lambert, D.L., Nissen P., Tomkin J. 1993, A&A, 275, 101
Freeman K., 1987, ARA&A, 25, 603
Flynn C. and Morell O. 1997, MNRAS, 286, 617
Fuchs B., 1997, astro-ph/9708209
Høg E., Flynn C. 1997, astro-ph/9708061
Janes K., 1975, ApJS, 29, 161
Janes K., 1979, ApJS, 39, 135
Jimenez R., Dunlop J., Peacock J., MacDonald J., Jørgensen U.G., 1996, submitted to MNRAS.
Jimenez R., Thejll P., Jørgensen U.G., MacDonald J., Pagel B., 1996, MNRAS, 282, 926
Lee Y., 1992, AJ, 104, 1780
Lieber J., Dahm, C., Monet, D. 1989, in White dwarfs; Proceedings of IAU Colloquium 114, Springer-Verlag, p. 15-23.
Lu L., Sargent W., and Barlow T.A., 1997, astro-ph/9711116
Morell O., Källander D., Butcher H.R., 1992, A&A, 259, 543
Ng Y., and Bertelli, G. 1997, astro-ph/9707043
Paczyński B., and Stanek K.Z., 1997, astro-ph/9708080
Padoan P., Jimenez R., Jones B. 1997, MNRAS, 285, 711
Pascarelle S.M., Windhorst R., Keel W.C., Odewahn S., 1996, Nature, 383, 45
Reid N., 1997, AJ, 114, 161
Reimers D., 1975, Mem. Soc. Roy. Sci. Liege, 8, 369
Toth G, Ostriker J.P., 1992, ApJ, 389, 5
Twarog B.A., Anthony-Twarog B., 1989, AJ, 97, 759
Wilson O.C., 1976, ApJ, 205, 823
Winget D.E, Hansen C.J., Liebert J, van Horn H.M., Fontaine G., Nather R.E., Kepler S.O., Lamb D.Q., 1987, ApJ, 315, 77
Vogt N.P. et al, 1996, ApJ, 465, L15

5 CONCLUSIONS

The main conclusions of our work are:

Figure 7. Colour magnitude diagram of the Hipparcos data, showing the lower main sequence, overlaid by isochrone fits. G and K stars on the main sequence for which abundances are available from Flynn and Morell (1997) have been plotted in two metallicity ranges $-0.6 < [\text{Fe}/\text{H}] < -0.4$ (squares) and $-0.05 < [\text{Fe}/\text{H}] < 0.05$ (crosses). The lower set of isochrones have $[\text{Fe}/\text{H}] = -0.5$ and match the data quite well. The middle set of isochrones has $[\text{Fe}/\text{H}] = 0.0$ and appears too red by about 0.07 mag. The upper set of isochrones has $[\text{Fe}/\text{H}] = 0.3$, and it too is too red by about 0.1 mag (the comparison stars have not been shown for clarity). The uncertainty in the position of the isochrones of 0.1 mag sets a limit of about 2 Gyr to the accuracy with which we can measure the disc age.

(with $H_0 = 48$ km s$^{-1}$ Mpc$^{-1}$) and $z = 3.2$ in an open Universe ($\Omega = 0.3$, $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$). Rotation curves and morphologies of disc galaxies can now be studied at redshifts as high as $z = 1$ (Vogt et al, 1996), while absorption line studies of QSOs offer indirect evidence that some disc galaxies were in place at redshifts as high as $z = 3.15$ (Lu, Sargent and Barlow, 1997). More likely the Galaxy was formed at a redshift of between 1 and 2 (Lacey et al 1997).

Our results weakly indicate that the inner disc is older than the disc at the solar circle, which naturally turns our attention to the center of the Galaxy. There is some evidence that the bulge is older than the halo (Lee, 1992) from its RR Lyrae stars, although the results of the MACHO survey indicate that RR Lyrae stars preferentially tracing the inner halo, rather than bulge (Alcock et al 1997). It may be possible to place age limits on the bulge from the stars in the OGLE micro-lensing data (Paczynski and Stanek, 1997).