

Possible Systematic Decreases in the Age of Globular Clusters

X. Shi^a, D. N. Schramm^{a,b}, D. S. P. Dearborn^c and J. W. Truran^a

^aThe University of Chicago, Chicago, IL 60637-1433

^bNASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Box 500,
Batavia, IL 60510-500

^cLawrence Livermore National Laboratory, Livermore, CA 94550

Abstract

The ages of globular clusters inferred from observations depends sensitively on assumptions like the initial helium abundance and the mass loss rate. A high helium abundance (e.g., $Y \approx 0.28$) or a mass loss rate of $\sim 10^{-11} M_{\odot} \text{ yr}^{-1}$ near the main sequence turn-off region lowers the current age estimate from 14 Gyr to about 10–12 Gyr, significantly relaxing the constraints on the Hubble constant, allowing values as high as 60 km/sec/Mpc for a universe with the critical density and 90 km/sec/Mpc for a baryon-only universe. Possible mechanisms for the helium enhancement in globular clusters are discussed, as are arguments for an instability strip induced mass loss near the turn-off. Ages lower than 10 Gyr are not possible even with the operation of both of these mechanisms unless the initial helium abundance in globular clusters is > 0.30 , which would conflict with indirect measurements of helium abundances in globular clusters.

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I. INTRODUCTION

The latest estimate of the age of globular clusters (GCs) is about 14 Gyr with an spread of different clusters of about ± 2 Gyr [1]. This severely constrains H_0 , the Hubble constant, for a Λ (the vacuum energy density) = 0 Friedman-Robertson-Walker cosmology. For Ω (the ratio of the density of the universe to the critical density) = 1, the Hubble constant H_0 must be less than 45 km/sec/Mpc [1]; while for a baryonic universe where $0.01/h^2 < \Omega < 0.015/h^2$ (with $h = H_0/100$ km/sec/Mpc) as constrained by Big Bang Nucleosynthesis [2], $H_0 \lesssim 70$ km/sec/Mpc. Currently dynamic measurements of the density of the universe favor $\Omega > 0.3$ [3], which yields $H_0 \lesssim 58$ km/sec/Mpc. Direct measurements of the Hubble constant, however, yield values that range widely from 40 km/sec/Mpc to 100 km/sec/Mpc [4].

A reconciliation of the direct measurement of the Hubble constant and that inferred from the age of the globular clusters may well require not only improvements of the distance scale systematics but also continued investigation of the assumptions implicit in the inferred age of globular clusters.

It is noted that the estimate of the age depends sensitively on many uncertainties of globular clusters, such as the actual turn-off luminosity (distance) determination, the metallicity, the oxygen to iron ratio, the helium diffusion in stars, and the initial helium abundance. To this we add the uncertainty due to an unobservable low mass loss rate inferred from lithium observations of stars. The uncertainties of the turn-off luminosity, the metallicity and the oxygen to iron ratio have been widely discussed in the literature [5–7], and has been included in the current age estimate of 14 ± 2 Gyr [1]. The helium diffusion in stars is also estimated to lower the age of GCs by 5%–15% [8–10]. Uncertainties in the initial helium abundance and the mass loss rate of stars near the turn-off point, however, have not been thoroughly discussed, and a full consideration of them may significantly influence the age estimate.

II. AGE DATING OF GLOBULAR CLUSTERS

Two methods are commonly used to estimate the age of a globular cluster (see review of ref. [11]). One is to fit theoretical isochrones (temperature-luminosity curves for stars at certain ages) to the shape of a globular cluster on the observed color-magnitude diagram, using a distance modulus determined from fitting either a zero age main sequence (ZAMS) or a zero age horizontal branch (ZAHB). It is also necessary to transform a luminosity-temperature diagram of a theoretical calculation to a color-magnitude diagram with an interstellar reddening correction [7]. Besides of the uncertainties mentioned in the introduction, this method is very sensitive to the transformation between the luminosity-temperature diagram and the color-magnitude diagram, the fiducial sequence of globular clusters extracted from their scattered color-magnitude diagram, the subjectivity in fitting isochrones to the fiducial sequence, and the effectiveness of a constant mixing length in describing the convection. It also depends sensitively on the adopted interstellar reddening if using ZAMS fitting to obtain distances.

The difficulty in improving the fitting method lies mainly in the fact that the color of both observed GCs and theoretical isochrones on the color-magnitude diagram is hard to determine precisely. The color of observed GCs depends on the interstellar reddening which can be very uncertain; while the color of isochrones is sensitive to the treatment of convection in stellar models. Figure 1 shows isochrones with similar parameters but different mixing lengths (parametrized by α , the ratio of the mixing length to the scale height of pressure) in the convection zone. The color shift due to a different choice of α is especially prominent on the upper subgiant and the red giant branch of isochrones. Although the uncertainty in choosing different mixing lengths may be partially resolved by calibrations of ZAMS stars [12], it still persists since mixing lengths may change in different evolution phases, such as the subgiant branch and the red giant branch.

A more reliable method is to relate the age with the turn-off luminosity of a GC, regardless of its detailed morphology. The turn-off luminosity is obtained from the calibrated

visual magnitude of RR Lyrae stars on the horizontal branch (HB) and the observed visual magnitude differences between RR Lyrae stars and main-sequence turn-off points, with bolometric corrections [1,13] (i.e., using a distance from ZAHB fitting). This method is independent of the interstellar reddening, the subjectivity of fitting isochrones to the observed GC sequence and the mixing length adopted in stellar modeling. It also suffers from the uncertainties mentioned in the introduction.

III. THE HELIUM UNCERTAINTY

The age turn-off luminosity relation of GCs has been shown by Iben and Renzini [13] to be

$$\log\left(\frac{\text{Age}}{\text{yr}}\right) = 8.497 - 1.88(Y - 0.24) - 1.44(Y_{\text{HB}} - Y) - 0.088 \log Z + 0.41 \Delta M_{\text{TO}}^{\text{RR}}(\text{bol}), \quad (1)$$

where Y is the helium abundance of GCs, Z is their metallicity, Y_{HB} is the helium abundance at the envelope of the HB stars, and $\Delta M_{\text{TO}}^{\text{RR}}(\text{bol})$ is the bolometric magnitude difference between the RR Lyrae stars and the turn-off point. The coefficients in the equation have been refined over the years, but no significant changes have been made.

$Y_{\text{HB}} - Y$ is estimated to be 0.01–0.02 [13]. Therefore a strong dependence of the age on the helium abundance Y is manifest in eq. (1). The Y in GCs cannot be directly measured because the helium line strength is weak at the temperature involved. Instead Y is indirectly inferred from comparisons between stellar models and observations. One way is to compare the observed color and period of stars at the blue edge of the instability strip with the helium dependent temperature and pulsation period relation found in stellar models. This method yields $0.20 < Y < 0.30$ [13,14]. However, as mentioned above, the temperature of stars cannot be confidently inferred from their observed colors due to the uncertainty in the interstellar reddening and stellar modelling.

The latest efforts compare the measured ratio of the number of stars on the horizontal branch to the number of stars with higher luminosities on the red giant branch with that

predicted by stellar models [15–17]. These efforts yield Y values for individual clusters that scatter between 0.20 and 0.30, with an average of 0.24 and a spread of ± 0.02 . However, this method may suffer from uncertainties in treating the semi-convection and mass loss, both of which affect the life-time of the HB phase [18]. A recent comparison between the morphology of the horizontal branch in 47 Tuc and stellar models also suggested $0.2 < Y < 0.3$ [19]. So far, all calculations constrain the helium abundances in GCs to be less than 0.30.

A maximal helium abundance of 0.30 in GCs seems also to be consistent with that inferred from luminosities of the HB stars. It is well known that the bolometric magnitude of RR Lyrae stars, $M_{\text{RR}}(\text{bol})$, is sensitive to Y_{HB} at their envelopes [13]:

$$M_{\text{RR}}(\text{bol}) = 0.943 - 3.5(Y_{\text{HB}} - 0.30) + 0.183 \log Z. \quad (2)$$

Current calibrations of the visual magnitude of RR Lyrae stars yield a 0.2–0.3 magnitude spread for different methods, and an uncertainty of 0.2 magnitude within each method [20,21]. Therefore, an uncertainty of 0.06 in Y_{HB} (or equivalently Y since $Y_{\text{HB}} - Y \approx 0.01$) is marginally tolerable by determinations of luminosities of the horizontal branch. In other words, Y can be as high as 0.30 for individual clusters, given a primordial value of 0.24. It should be noted that the observation of RR Lyrae stars in the disk of the galaxy may not serve a valid constraint on Y_{HB} in globular clusters.

It is conventionally assumed that $Y = 0.24$ (as in ref. [1]) or 0.235 (as in ref. [7]) in GCs, in agreement with the observed primordial helium abundance $Y = 0.235 \pm 0.01$ [22] and the prediction of Big Bang Nucleosynthesis [2]. However, as discussed above, a higher Y is allowed, that can significantly reduce the age estimate of GCs. For example, a Y of 0.3 will reduce the age by as much as 30% with respect to a Y of 0.24, according to eq. (1).

Determining the age of GCs with the isochrone fitting method has a similar Y sensitivity as in eq. (1) if a distance modulus from ZAHB fitting is used. If a distance from ZAMS fitting is used in the isochrone fitting, the effect of a higher Y in GCs on their age is not easy to quantify. Figure 2 shows 10 Gyr and 11 Gyr isochrones with $Y = 0.30$ and $Z = 0.0002$, compared with isochrones of 12 Gyr, 14 Gyr and 16 Gyr with $Y = 0.24$ and the same Z . The

figure also shows the 11 Gyr $Y = 0.30$ isochrone shifted by $\Delta(B - V)=0.05$ and $\Delta M(\text{bol})=0.18$ magnitude. Therefore, if we use the magnitude of ZAMS as a distance indicator, a 11 Gyr $Y = 0.30$ isochrone may resemble a 14 Gyr $Y = 0.24$ isochrone at the main sequence and the subgiant branch, if a reddening of 0.05 is added. The mismatch at the red giant branch may be easily remedied by a modest adjustment of the mixing length as seen from Fig. 1.

A helium abundance higher than the primordial value in GCs is possible to achieve under certain scenarios. The simplest scenario is the enrichment by the first generation supernovae (SNe) of GCs [23]. Measurements of low metallicity HII regions in irregular galaxies and extragalactic HII regions showed that their helium abundance Y correlates with their oxygen abundance O by $Y = 0.24 + 130O$ (i.e., $dY/dZ = 5$) [22,24]. For GCs with $[\text{Fe}/\text{H}]=-1$, their oxygen abundances are about 1/3 of the solar value [5], i.e., $O \approx 2 \times 10^{-4}$. If GCs follow the same helium-oxygen correlation as those low metallicity HII regions, then $Y \approx 0.27$, which is significantly above the primordial value. Of course, it is debatable whether GCs follow the same Y - O relation as low metallicity HII regions, although both of them have low metallicities compared with the solar value. The sun, on the other hand, has $Y = 0.28$ and $O = 6 \times 10^{-4}$, which would require a different relation $Y = 0.24 + 70O$ (i.e., $dY/dZ = 3$). Therefore, solar-type disk stars must have had quite a different chemical history from low metallicity gases, like those of GCs and HII regions. It is worth noting that VandenBerg, Bolte and Stetson [25] found a 2–3 Gyr age spread among GCs with $[\text{Fe}/\text{H}] > -1.6$ and no significant age spread among GCs with $[\text{Fe}/\text{H}] < -1.6$. If an enhancement in the helium abundance correlates with an increase of metallicity in GCs, as suggested above, the age spread among metal-rich GCs may be easily at least in part explained by different enhancements of the helium abundance in different clusters.

Exotic models, like Pop III stars [26,27], may enrich helium but not heavier elements. It is calculated that if the oxygen cores of these Pop III stars are larger than $\sim 100M_{\odot}$, the cores will collapse completely into blackholes without ejecting heavy elements. However, processed helium in Pop III stars can be deposited into the interstellar medium through mass

loss and mixing of Pop III stars. The maximal amount of helium enrichment is $\Delta Y = 0.17$ for an initial helium abundance of 0.24, if all gases are processed once in Pop III stars. Therefore, in order to enhance the helium abundance in a $10^6 M_\odot$ cloud from 0.24 to about 0.30, at least $3 \times 10^5 M_\odot$ gas has to be turned into Pop III stars. This requires quite a different mass function from the M^α power law with $\alpha = -2.35$ observed today [28]. For the metallicity of the cloud is low, the required mass function must have $\alpha > -0.5$, so that there are no more than ~ 100 SNe in a $10^6 M_\odot$ cloud.

An enhancement of the helium abundance may also arise during the formation of globular clusters. For example, the difference in the first ionization energy between the hydrogen and the helium (13.6eV vs. 24.6eV) enables the helium to recombine earlier than the hydrogen, and hence prone to earlier collapses.

One class of model for forming globular clusters, based on Peebles & Dicke [29], argues that GCs form from primordial baryon density fluctuations after recombination, which have a Jeans mass similar to the mass of typical GCs, $10^6 M_\odot$. According to the standard recombination picture of the universe, hydrogen recombined at $T \sim 3000\text{K}$ (redshift $z \sim 1000$) [30] while helium recombined at $T \sim 10^4\text{K}$ or $z \sim 3000$ (inferred from Fig. 5 of ref. [31]). In the period after helium recombination and before hydrogen recombination, the helium falls quickly into the potential well of dark matter, following the density fluctuation of dark matter [32]. As hydrogen recombines, the density fluctuations in the hydrogen and the helium begin to grow jointly. The overdensed region, however, already has an enhanced helium abundance from the in-fall of helium early on. Assuming the density fluctuation in dark matter at $z \sim 1000$ to be $\delta\rho/\rho$ and the primordial helium abundance $Y_p = 0.24$, the enhanced helium abundance in the overdense region at $z \lesssim 1000$ is

$$Y = \frac{Y_p(1 + \delta\rho/\rho)}{Y_p(1 + \delta\rho/\rho) + 1 - Y_p} \approx 0.24(1 + 0.76\delta\rho/\rho). \quad (3)$$

To enhance the helium abundance to $Y = 0.30$ on the $10^6 M_\odot$ scale requires a $\delta\rho/\rho \sim 1/3$ on this scale, which means $\delta\rho/\rho$ on the $10^6 M_\odot$ scale will become nonlinear at a z of several hundred. This cannot be realized in the standard cold dark matter (CDM) model, where

structures at this scale become non-linear at $z \lesssim \mathcal{O}(10)$ [32], but may be possible in models where primordial seeds such as topological defects provide nonlinear fluctuations on small scales [33–35]. A $\delta\rho/\rho$ of 1/3 at $z \sim 1000$ with $\sim 10^6 M_\odot$ scales will certainly distort the cosmic microwave background radiation (CMBR) and produce non-gaussian fluctuations at the arcsecond angular scale in CMBR. Potentially conflicting CMBR anisotropies reported on the 0.5 to 3° angular scales are interpreted by some as possibly being indicative of non-gaussian fluctuations [36–38].

Another class of models, based on that of Fall and Rees [39], argues that GCs form out of cold clouds with $\sim 10^6 M_\odot$ in proto-galaxies [40]. A higher helium content may then arise if Pop II stars form in the shock waves from the first generation supernovae in the cloud [41]. The temperature of these clouds is typically 10^4K due to sharp drop in the cooling function of the gas cloud at 10^4K [31]. At this temperature hydrogen is partially ionized and interacts with the radiation fields in the cloud, but helium remains neutral. The sound speed in helium, c_{He} , is then ~ 10 km/sec, while the sound speed in hydrogen, c_{H} , is much larger. (The reason for different sound speeds is that perturbations in hydrogen can propagate much faster by interactions between hydrogen and photons, while perturbations in helium have to propagate at least initially through interactions between helium atoms and ambient atoms or charged particles.) When the velocity of a shock wave drops below c_{H} , the shock no longer compresses hydrogen in the cloud medium into the shock front but continues to do so with helium. Therefore stars formed from the compressed gas at the shock front will have a higher helium abundance than the primordial value.

To have all the gas in the $10^6 M_\odot$ cloud swept by a $\sim 10\text{km/sec}$ shock, the energy output of SNe has to be $0.5(10^6 M_\odot)c_{\text{He}}^2 \approx 10^{51}$ ergs without considering energy losses of the shock, which is the kinetic energy output of one SN. If we consider the radiation and ionization losses of the shock, the energy output of SNe has to be at least 10 times larger, or $\gtrsim 10^{52}$ ergs [23]. By requiring the shock to sweep through the cloud within 10^7 yrs, the formation timescale of $\sim 1 M_\odot$ stars, we need a SN rate of $\gtrsim 10^{-6} \text{ yr}^{-1}$ per $10^6 M_\odot$, which is roughly in line with the SN rate required to generate a metallicity of 10^{-1} – $10^{-2} Z_\odot$ in GCs [23], and is also

consistent with the order of magnitude estimate of SN rates ($\sim 10^{-2}$ per year per galaxy) inferred from the quasar absorption line systems [42].

The propagation of the shock front is illustrated in Figure 3. After the speed of the shock drops below c_H , the helium abundance in the compressed shell of the shock front is

$$Y \approx \frac{Y_p M_{\text{sh}}}{(1 - Y_p) M_{\text{tot}} \delta / l + Y_p M_{\text{sh}}} \quad (4)$$

where M_{sh} is the mass swept by the shock, M_{tot} is the total mass of the cloud, and $Y_p (= 0.24)$ is the helium abundance before the shock. δ is the thickness of the shock front and l is the thickness of cloud after being caved by the shock wave. If the SNe rate $\gtrsim 10^{-6} \text{ yr}^{-1}$ per cloud, the shock wave can propagate through the entire cloud at a speed larger than c_{He} . Then $M_{\text{sh}} \sim M_{\text{tot}}$. If $l \gg \delta$, i.e., the density inside the shell is much larger than the density outside, Y can be significantly larger than Y_p .

We have briefly discussed several scenarios to enhance the helium abundance in GCs. There may be other possible scenarios, such as a magnetic field, that may also segregate charged gas from neutral gas. If those scenarios operate only in GCs, they will not have a direct effect on HII regions where the primordial helium abundance is measured. The small amount of helium-enriched gas from disrupted GCs can only contaminate interstellar medium modestly. Helium-enriched stars from disrupted GCs may also constitute only a small population of halo stars. Once again, a spread in Y after these helium enhancement processes may be a candidate to account at least in part for the spread in age estimates for different GCs which assume a universal Y .

IV. THE UNCERTAINTY IN MASS LOSS

Mass loss has been proposed to explain the lithium depletion in F type Pop I stars with surface temperatures of $6600 \pm 200 \text{ K}$ and were motivated by the coincidence of their locations with an extrapolation of the instability strip down to the main sequence [43]. The same mechanism may also operate in some Pop II stars which are observed to have lithium

depletion. The position of the instability strip on Pop II main sequence is quite uncertain. By a simple extrapolation from Pop I stars, the temperature range of the instability strip is in the vicinity of the turn-off temperature of GCs [44]. The narrowness of the observed lithium dip constrains any proposed mass loss to a restricted temperature range between 6500K and 6700K.

The temperatures of GC stars increase until they eventually turn off and evolve to the giant branch. Without mass loss, stars spend about 90% of their lifetime getting to the turn-off, and about 10% following the turn-off. When mass loss occurs at the temperature of the turn-off, the small reduction in mass causes the model to redden earlier. The turn-off is then seen to be at a lower luminosity, and stars appear to spend an increased fraction of their life beyond the turn-off. This results in bump on the luminosity function. This bump, in fact, further constrains the magnitude of mass loss that is possible. The GCs will then appear older due to their lower turn-off luminosities according to eq. (1) [44,45]. A narrow instability strip does not affect the lower main sequence and so avoids the arguments against large-scale mass loss through out the entire lower main sequence [43].

The mass loss rate needed to explain the lithium depletion in Pop II stars is about $10^{-11} M_{\odot} \text{ yr}^{-1}$, which is far too small to be detected directly. It may, however, have detectable impacts on the luminosity function of GCs [46] due to above mentioned bump in the luminosity function. Therefore, globular cluster observations utilizing high-sensitivity CCD photometry may provide a definitive test of the mass loss hypothesis. Observations of low metallicity blue stragglers, on the other hand, seems to indicate the instability stripe is bluer than the turn-off point of GCs with similar metallicities [47]. However, blue stragglers may be too pathological to draw conclusions on the main sequence of GCs.

Dearborn and Schramm [44] have calculated the effect of a mass loss rate $\sim 10^{-11} M_{\odot} \text{ yr}^{-1}$ in the temperature range of $6500 \pm 200\text{K}$ and $6600 \pm 200 \text{ K}$ on the evolution of GCs. Such assumptions result in GCs of 11 Gyr to 13 Gyr old looking $2\sim 3$ Gyr older.

To combine the mass loss with a higher helium abundance, we construct isochrones based on Dearborn's stellar code with a gaussian mass loss rate

$$\text{Mass Loss Rate} = 10^{-11} M_{\odot} \text{yr}^{-1} \exp\left[-\left(\frac{T - 6500\text{K}}{240\text{K}}\right)^2\right], \quad (5)$$

and $Y = 0.28$. Z is taken to be 0.0002 ($[\text{Fe}/\text{H}] = -2.0$) for the isochrones. Figure 4 shows such isochrones at 10 and 11 Gyr old as well as standard isochrones without mass loss and with $Y = 0.24$ at 14 Gyr, 16 Gyr and 18 Gyr old. Again, the 11 Gyr isochrone with mass loss and a higher helium shifted by $\Delta(B - V) = 0.04$ and $\Delta M(\text{bol}) = 0.14$ may resemble standard isochrones at ~ 16 Gyr. Quantitatively, the age- $\Delta M_{\text{TO}}^{\text{RR}}(\text{bol})$ relation for these non-standard isochrones is well approximated by

$$\log\left(\frac{\text{Age}}{\text{yr}}\right) = 15.41 - 3.45\Delta M_{\text{TO}}^{\text{RR}}(\text{bol}) + 0.546[\Delta M_{\text{TO}}^{\text{RR}}(\text{bol})]^2. \quad (6)$$

For $[\text{Fe}/\text{H}] \approx -2$ clusters such as M30, M68, M92 and NGC6397, age estimates from eq. (6) will be 2–3 Gyr lower than the estimates of Sandage using standard assumptions [1], as shown in Table 1.

V. SUMMARY

As seen above, either a higher helium abundance of $Y \approx 0.28$ and/or a mass loss rate of $\sim 10^{-11} M_{\odot} \text{yr}^{-1}$ at temperatures around 6500–6600 K will significantly lower the age of GCs by 2–3 Gyr. Therefore the currently quoted age estimate of 14 ± 2 Gyr is potentially subject to systematic shifts and its uncertainties are model dependent and not well represented by the quoted error. A GC age of 10 Gyr is not out of reach considering the aforementioned uncertainties, and is entirely consistent with the age of the beginning of nucleosynthesis of heavy elements (i.e., SNe events) measured by radioactive dating that gives a lower limit of 10 Gyr [48,49]. It is also consistent with the age of the disk, 10 ± 2 Gyr, measured from the cooling of white dwarfs [50], provided that the disk collapsed from the halo within 1 or 2 Gyr.

A GC age lower than 10 Gyr, however, is still untenable even with a combination of a reasonably high Y and a reasonable mass loss rate, unless $Y > 0.30$ is allowed, which would conflict with indirect measurements of Y in GCs.

Better determinations of the helium abundance in GCs and the mass loss hypothesis need improved observations of GCs and understanding of stellar physics. In particular, the determination of the luminosity functions of GCs through observation and the improved modelling of the horizontal branch and red giant branch stars are essential.

If GCs are indeed 10 Gyrs old, the current constraints on cosmological parameters will be significantly relaxed. For a baryonic universe where $0 \leq \Omega \ll 1$, the Hubble constant can be as high as 90 km/sec/Mpc; for $\Omega > 0.3$, $H \lesssim 72$ km/sec/Mpc; if $\Omega = 1$, $H < 60$ km/sec/Mpc. Obviously, if the measurements of the Hubble constant eventually converge, it will put constraints on Ω in a $\Lambda = 0$ Friedman-Robertson-Walker universe and improve our understanding of the age of globular clusters.

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TABLE I. The age estimates from eq. (6) with a higher helium abundance and mass loss vs. the age estimates of Sandage [1] for four globular clusters with $[\text{Fe}/\text{H}] \approx -2$.

Globular Clusters	$[\text{Fe}/\text{H}]$	Ages from Eq. (6)	Ages from Sandage [1]
M30	-2.13	11.5 Gyr	13.7 Gyr
M68	-2.09	10 Gyr	12.1 Gyr
M92	-2.24	13 Gyr	15.2 Gyr
NGC 6397	-1.91	13 Gyr	15.4 Gyr

Figure Captions

Figure 1. Two isochrones with similar parameters but different mixing lengths. The dashed line: $\alpha = 1.50$; the solid line: $\alpha = 1.69$.

Figure 2. Isochrones with and without an enhancement of the helium abundance in GCs. The solid lines: 12 Gyr, 14 Gyr and 16 Gyr isochrones with $Y = 0.24$ and $Z = 0.0002$; the long-dashed lines: 10 Gyr and 11 Gyr isochrones with $Y = 0.30$ and the same Z ; the short-dashed line: the 11 Gyr $Y = 0.30$ isochrone shifted by $\Delta(B - V) = 0.05$ and $\Delta M(\text{bol}) = 0.18$ magnitude.

Figure 3. The propagation of a SN shock front inside a $10^6 M_{\odot}$ cloud.

Figure 4. Isochrones with and without a higher helium abundance and mass loss. The solid lines: 14 Gyr, 16 Gyr and 18 Gyr isochrones with $Y = 0.24$ and no mass loss; the long-dashed lines: 10 and 11 Gyr isochrones with $Y = 0.28$ and a mass loss rate that satisfies eq. (5); the short-dashed line: the 11 Gyr isochrone with $Y = 0.28$ and mass loss shifted by $\Delta(B - V) = 0.04$ and $\Delta M(\text{bol}) = 0.14$.

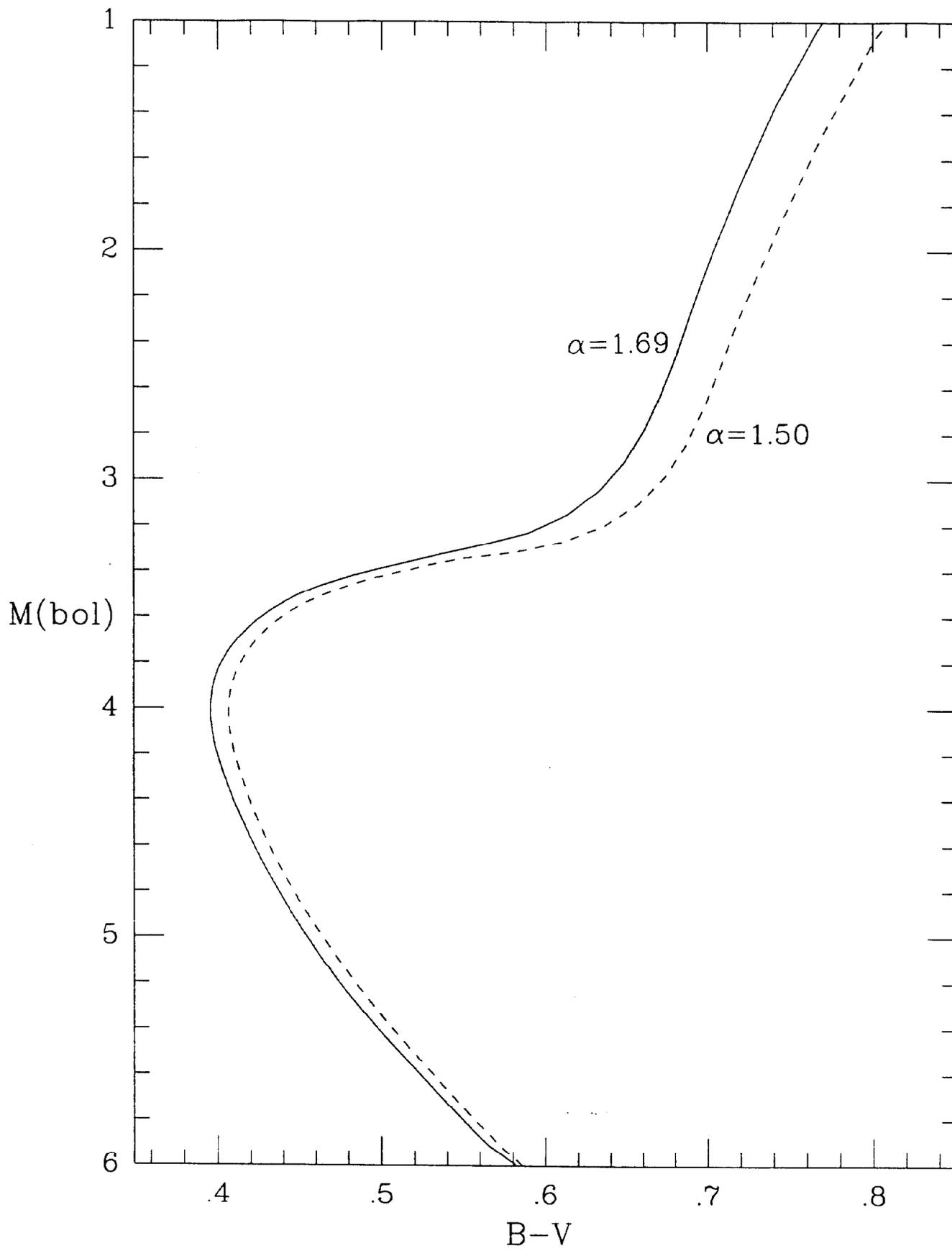


Figure 1

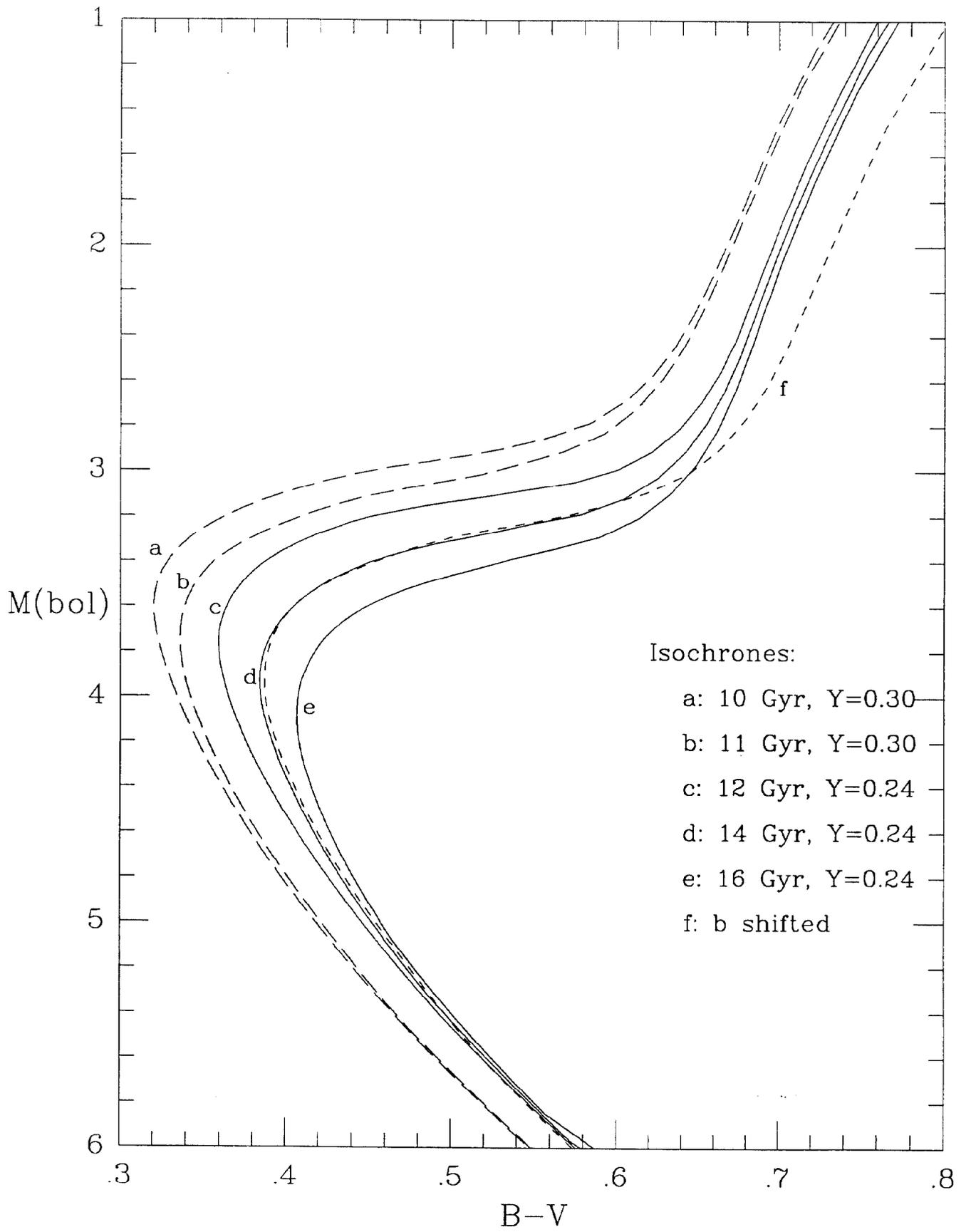


Figure 2

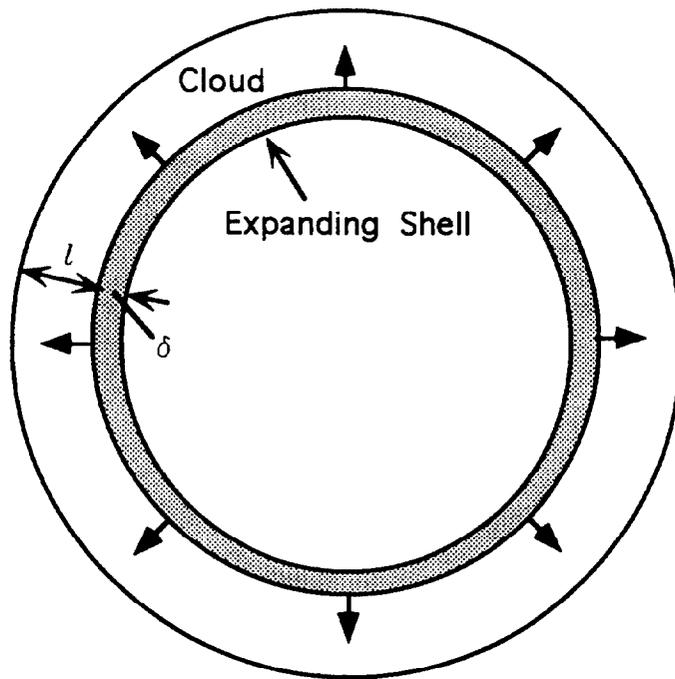


Figure 3

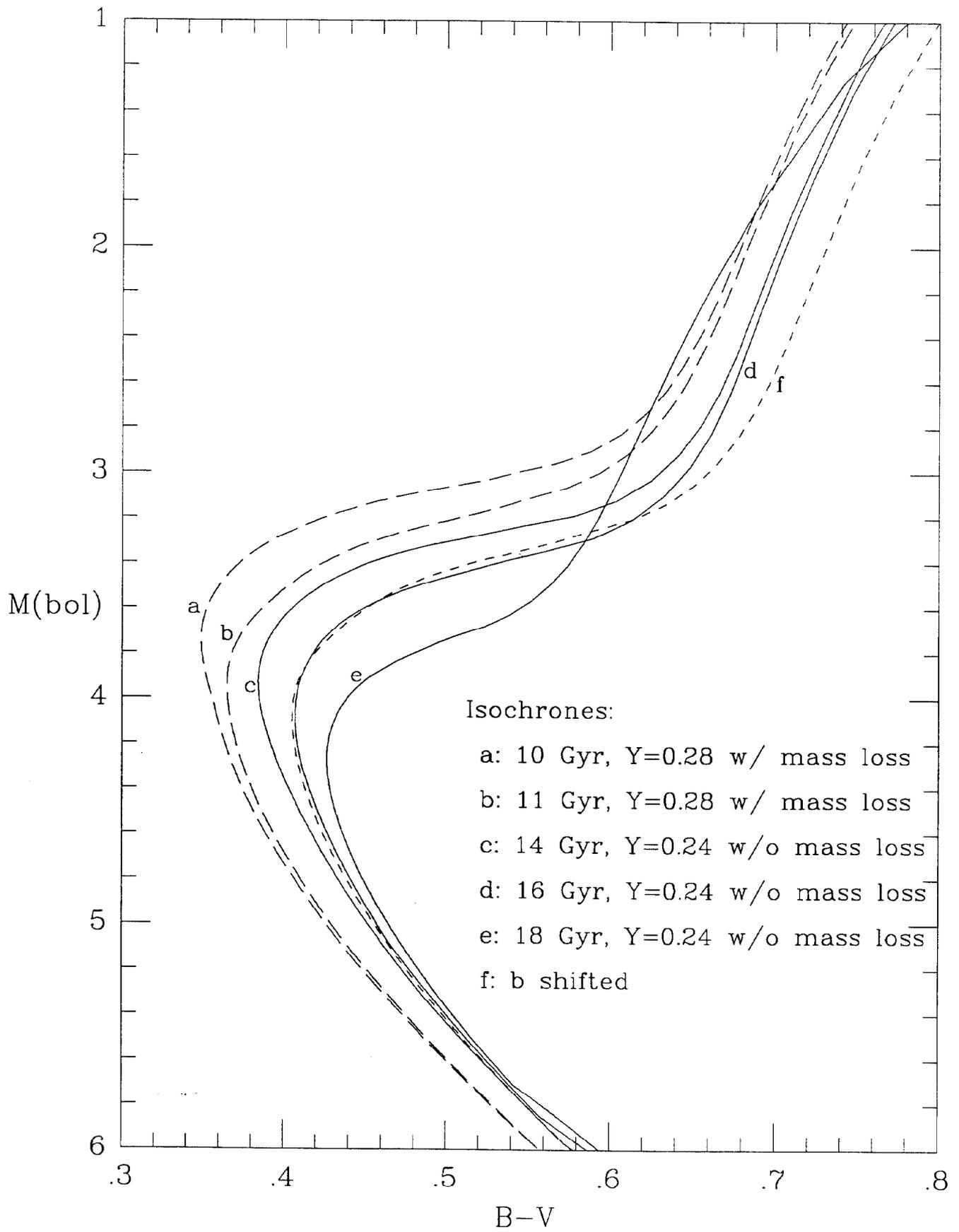


Figure 4