

Cosmic Star Formation from the Milky Way and its Satellites

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Abstract. We use observations and evolutionary models of local objects to interpret a recent determination of the star-formation history of the universe. By fitting the global star-formation rate, the model predicts the ratio of spheroid to disk mass of ~ 1 , an intergalactic medium (IGM) whose mass is ~ 2.3 times the mass in stars, and whose metallicity is $\sim 0.1 Z_{\odot}$.

1. Introduction

It is conventional to interpret observations of high-redshift galaxies using sophisticated galaxy evolution models. However, unless the observed spectra are of sufficiently high S/N, the resulting interpretations may not be unique (c.f. O'Connell 1996). On the other hand, deep color-magnitude diagrams of objects like globular clusters, dwarf spheroidals, and gas-rich systems such as the Galactic disk and the Magellanic Clouds in principle show us their complete star formation history (c.f. contributions in Leitherer et al. 1996 and this volume). To the extent that these systems can be considered representative of the universe as a whole (the mean density of the local group is close to that of the universe), we should be able to use them to deduce a global star-formation history.

2. The Cosmic Star-Formation History

The starting point for this work is the diagram of Madau et al. (1996) and an updated version of this diagram from Madau et al. (1998) which shows the cosmic star-formation rate (SFR) in units of $M_{\odot} \text{ yr}^{-1} \text{ vol}^{-1}$ as a function of redshift z . Very similar results had been derived previously by Pei & Fall (1995) by modeling the observed column densities of H I and their metallicities in damped Ly α systems. Because we will use the results of stellar evolution calculations as input, it is convenient to transform the abscissa from z to lookback time by assuming a specific cosmological model. (The ordinate must also be modified slightly to take into account the model change.) The model assumed has $H_0=70 \text{ km sec}^{-1} \text{ Mpc}^{-1}$, $\Omega_0=0.2$, $\Omega_{\Lambda}=0.8$, and $t_0=14.91 \text{ Gyr}$. This transformed cosmic SFR with a rescaled ordinate is shown in Fig. 1.

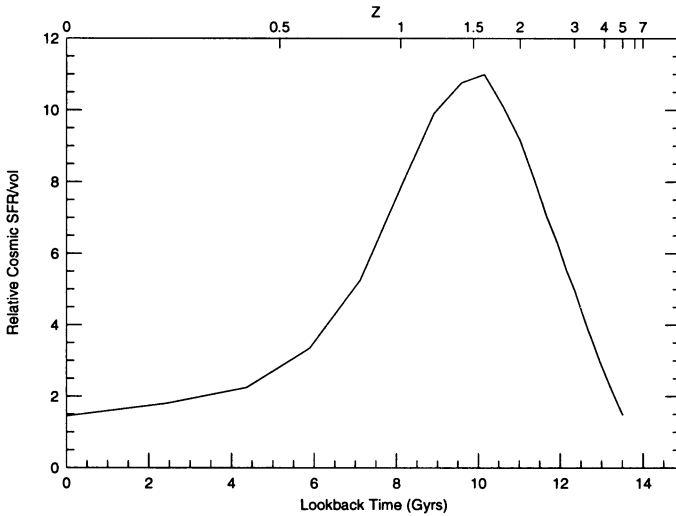


Figure 1. The relative star-formation rate density by Madau et al. (1998) plotted as a function of look-back time.

3. Modeling the Cosmic Star-Formation Rate

Results from the CFRS (Lilly et al. 1998) tell us that while large disks show increases in SFR by factors of ~ 3 by $z=0.7$, the red (spheroid) components show no evolution. We shall interpret the above observations as ‘spheroids form early and disks form late’ (i.e. we consider the hump at ~ 10 Gyrs in Fig. 1 as predominately due to evolution of the spheroid component while the plateau at shorter lookback times to be due predominately to disk evolution).

In order to model the spheroid component we shall use the one-zone mass-loss chemical evolution model of Hartwick (1976) which has been shown to reproduce the metal abundance distribution of Galactic halo components quite well (e.g. Fig. 1 of Hartwick 1983). The model predicts a metal abundance (Z) distribution given by

$$dS/d\log Z = \ln 10 \times S_{tot} \times (Z/P_{eff}) \times e^{-Z/P_{eff}} \quad (1)$$

where P_{eff} is the effective yield and varies inversely as the star formation (mass loss) rate, S is the cumulative number of stars formed and $S_{tot} = S_{Z=\infty}$.

For a given age-metallicity relation (AMR), we can calculate the star-formation rate by taking the product of eqn 1 with the derivative of the AMR, $d\log Z/dt$. An AMR was constructed by assuming an age of 13 Gyrs for M92 ($[Fe/H] = -2.3$), 11 Gyrs for M5 ($[Fe/H] = -1.4$), and passing through $[Fe/H]=0$ at $t = 0$. The resulting expression (shown dashed in Fig. 5) is

$$\log Z/Z_{\odot} = 0.117531 \times (1 - e^{t_0/4.3}) \quad (2)$$

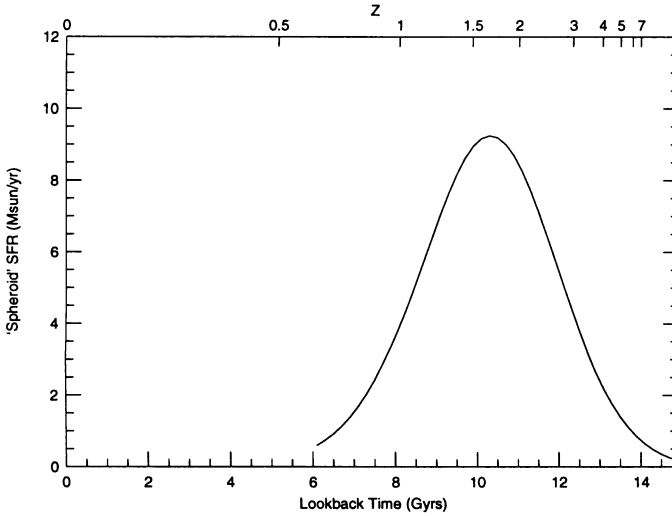


Figure 2. The star-formation rate for the spheroid component of the model.

where t_9 is the lookback time in Gyrs.

For an assumed value of $P_{eff} = -1.0$ and $S_{tot} = 3.9 \times 10^{10} M_{\odot}$, the resulting SFR is shown in Fig. 2. Note that the maximum SFR of $\sim 10 M_{\odot} \text{ yr}^{-1}$ (which depends only on the value of S_{tot} and the AMR slope) is in the range of values deduced by Steidel et al. (1996) for the $z > 3$ ‘UV-dropout’ galaxies.

For the disk component we are guided by the SFR derived recently for the Galactic disk by Rocha-Pinto & Maciel (1997) which is shown in Fig. 3. For ease of computation we have adopted the relation shown by the two straight line segments. (Note the increase in SFR by a factor of ~ 3.4 between $t = 0$ and $t = 9$ Gyrs.)

The disk SFR of Fig. 3 can now be added to the spheroid SFR component of Fig. 2 and compared with the cosmic SFR of Fig. 1. This is shown in Fig. 4. Given the simplicity of the model, the agreement seems quite remarkable! We should emphasize that the composite galaxy modeled above is not expected to exist as a single object in nature. Rather, if the universe contained only one galaxy that is what it might look like!

4. Discussion and Predictions

As indicated above, the star-formation rate of each component was chosen to fit the relative SFR of Fig. 1. In doing so the model makes several predictions. The value of S_{tot} required to match the observed SFR implies a total baryon mass of $18.5 \times 10^{10} M_{\odot}$ and a total mass of long-lived stars and remnants of $3.1 \times 10^{10} M_{\odot}$. Integrating the assumed disk SFR of Fig. 3 yields a stellar mass of $2.5 \times 10^{10} M_{\odot}$. Allowing an additional 10% of the disk mass in gas we calculate the ratio of spheroid to disk mass of 1.1. Schechter & Dressler (1987) have determined this ratio observationally and find it to be ~ 1 . Further, the ratio of total

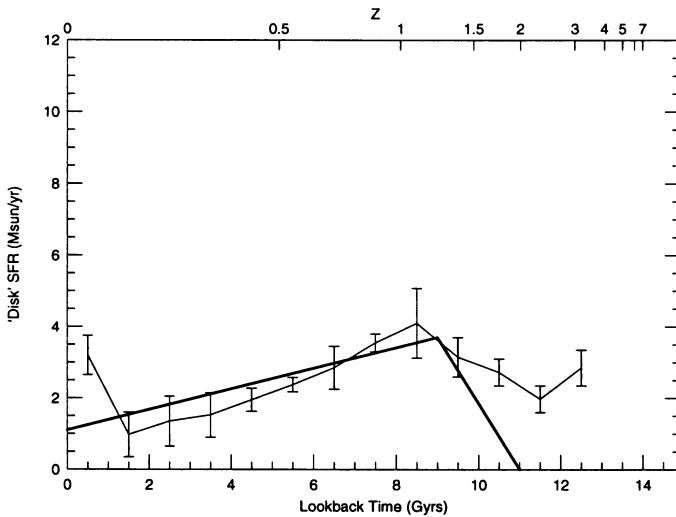


Figure 3. The adopted star-formation rate for the disk component of the model (heavy lines) plotted on top of the derived rate for the Galactic disk from Rocha-Pinto & Maciel (1997).

baryon mass to mass in stars is 3.3. Equating this ratio to $\Omega_{baryon}/\Omega_{stars}$ and assuming $\Omega_{stars}=0.003$ (Persic & Salucci 1992) we find $\Omega_{baryon}=0.01$ compared to $\Omega_{BBN}=0.03$. Thus, the model predicts an alleviation of the ‘dark baryon problem’ by putting 2.3 times the mass in stars into the IGM as metal-enriched gas. Fig. 5 shows how the enrichment of the IGM is expected to vary as a function of lookback time. Note that the present metallicity of the IGM is predicted to be $0.1 Z_{\odot}$ (assuming that it is well mixed).

How robust are these results? The cosmological model dependence is expected to be small, amounting basically to an expansion or contraction of the abscissae in Figs. 1-5. However drastic changes to the original Madau et al. (1998) cosmic star-formation rate will have an appreciable effect. For example, if recent suggestions (Hughes et al. 1998) of a factor of 5 increase in SFR at redshift $z \sim 3$ are confirmed, then the spheroid contribution would have to rise substantially and increase the derived spheroid to disk ratio upsetting the already good agreement with available observations. However, if the dust-enshrouded star-formation component is more nearly evenly distributed in redshift, then our results should remain valid, requiring only a change in normalization.

5. How Do the Milky Way’s Satellites Fit into This Picture?

The above model does not differentiate between star formation taking place in one large object or in many smaller ones. Indeed, star formation followed by mass loss may also be effective if it takes place during collisions between large numbers of smaller objects. It is easily shown that if the collisions which suddenly heat and/or sweep out the gas are Poisson distributed about mean

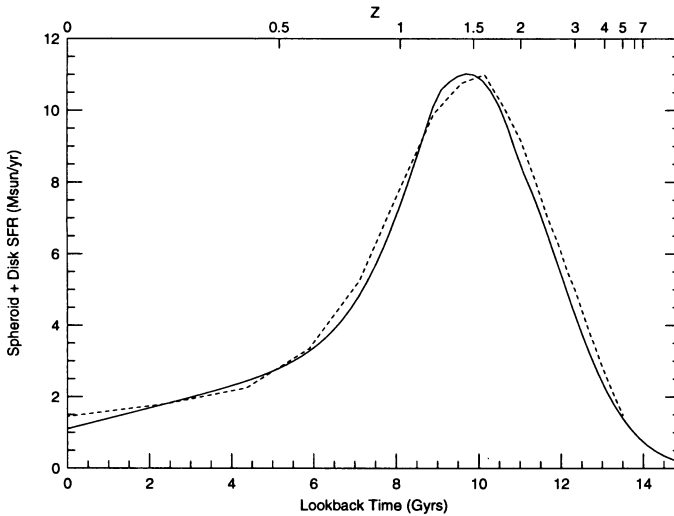


Figure 4. The model spheroid component of Fig. 2 and the model disk component of Fig. 3 combined (solid line) compared to the observed relation (dashed) from Madau et al. (1998) in Fig. 1.

$Z=P_{eff}$, then the expected metallicity distribution is virtually identical to eqn (1). Furthermore, collisions are likely to initiate bursts of star formation as well as eventually to quench them. This picture appears to favor a hierarchical galaxy formation process (e.g., Searle & Zinn 1978) whereby numerous small sub-units collapsed, began forming stars, then collided during assembly over an extended period of time. The gas removed by collisions between the building blocks would then either be lost to the IGM and/or settled down later to form the disk. The removal of gas might then be expected to leave an object resembling a dwarf spheroidal galaxy, if it could survive the sudden mass loss and potential tidal disruption. The large age spread observed from deep color-magnitude diagrams of individual dwarf spheroidal galaxies (e.g., Da Costa 1997) could be taken as evidence for the prolonged spheroid assembly seen in Fig. 2.

The Large Magellanic Cloud would appear to be a candidate for a massive leftover building block given that its most metal-poor clusters appear to be identical to those of the Galaxy (Olsen et al. 1999; Johnson et al. 1999). Such a picture would also allow a rationalization of the disk-like motions of the LMC clusters (Schommer et al. 1992) with the pressure-supported kinematics of the most metal-poor Galactic globular clusters.

Apparently the Magellanic Clouds have so far managed to avoid major mass loss by collision/star formation so that in the above scenario they would be considered relics, having remained relatively self-contained from the time of formation of the first stars. The other gas-rich dwarf irregular galaxies in the Local Group may be similar examples.

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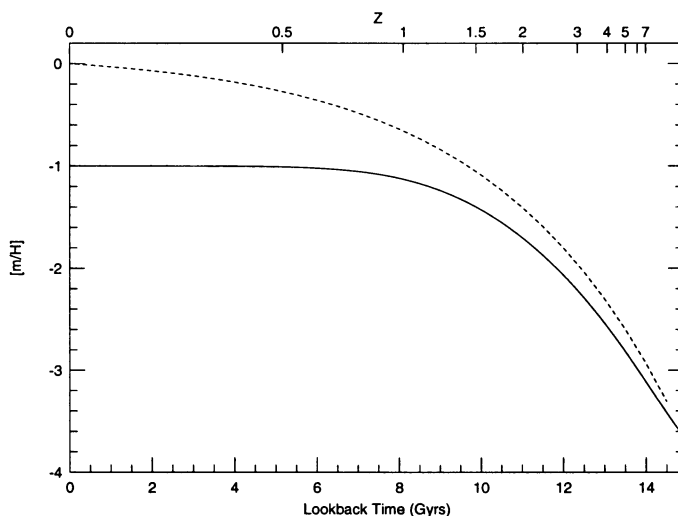


Figure 5. The predicted metallicity of the gas lost during spheroidal star formation (solid line). A fixed fraction of this gas forms the disk while the rest becomes the IGM. Dashed line: the assumed age-metallicity relation of eqn 2.

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Discussion

Rebecca Elson: A couple of comments. We have a similar project underway in Cambridge to consider the Local Group in a cosmological context. We find that the dwarf galaxies contribute less than 10% of the total star formation at any redshift, and that none of the dwarf galaxies would be visible in the Hubble Deep Field at redshifts greater than approximately 0.5.

Hans Zinnecker: In its starkest form, can we claim that all galactic globular clusters were made in Magellanic Cloud type systems which later collided and merged to build up the Milky Way Galaxy?

Hartwick: Possibly, but I also could imagine that when gas lost from spheroidal formation eventually collapsed to build up the disk, another generation of more metal-rich clusters might have formed with more disk-like kinematics and spatial distributions.

William Harris: In response to Zinnecker's question, the Galaxy's globular clusters can't all have pre-formed in LMC-like things because a lot of them are very metal-rich by comparison with any clusters in the LMC or other dwarf galaxies. The bigger the galaxy, the more the globular cluster metallicity distribution is weighted to the high end, so the more you have that problem. I agree that you need to form clusters inside dwarf-sized systems, but the bottom line seems to me that you can't do it all in Magellanic-sized things beforehand and then just combine them later - you would get the wrong metallicity distribution.

Simon Morris: The CNOC2 survey is finding that the SFR at $z = 0.2$ to $z = 0.5$ has a substantial contribution from Magellanic (LMC) luminosity objects. This seems to differ from the situation in the Local Group.

David Graff: Since the Madau plot is based on observations of an ensemble of galaxies, it seems natural that its peak should be wider than that of any single galaxy. I don't think your model should be pushed to provide a detailed fit with the Madau plot.

Hartwick: The model I have described is a composite one. I would not expect any individual galaxy to resemble it.

Dominik Bomans: Recent results from JCMT indicate a large population of dusty star-forming galaxies at high redshift, flattening the downturn of the Madau diagram beyond $z = 2$. What effect would this have on predictions of your model?

Hartwick: As long as the dust-enshrouded component contributes a similar amount at all redshifts, then all that is required is an increase in model normalization and all predictions remain the same.