GLOBAL EVOLUTION OF THE STARS, GAS, METALS, AND DUST IN GALAXIES

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Abstract. We outline a method to infer the global history of star formation in galaxies from absorption-line observations of quasars. The application to existing data leads to the conclusion that most stars formed at relatively low redshifts ($z \lesssim 2$). The results obtained by this absorption-based method are consistent with those obtained subsequently by emission-based methods.

1. Introduction

In this article, we consider the evolution of, and relations between, various large-scale average properties of the population of galaxies as a whole. It is often convenient to express these "global" properties as mean comoving densities and to normalize them to the present closure density. We are particularly interested in the comoving densities of stars, gas, metals, and dust within galaxies, which we denote respectively by Ω_s, Ω_g, Ω_m, and Ω_d. The last three of these are meant to refer to the interstellar media (ISM) of galaxies, exclusive of the intergalactic medium (IGM), although in practice such a distinction may only be approximate. As defined here, Ω_m includes metals in both the gas and solid (i.e., dust) phases of the ISM. It is usually more informative to reexpress Ω_m and Ω_d in terms of the mean metallicity, $Z \equiv \Omega_m/\Omega_g$, and the mean dust-to-gas ratio, $D/G \equiv \Omega_d/\Omega_g$. It is clear that all of these properties are related in the sense that, as new stars form, Ω_s will increase, while in most cases, Ω_g will decrease and Z and D/G will increase. The goal here is to quantify such notions through the equations of "cosmic chemical evolution."

Until recently, there were no emission-based estimates of the global rate of star formation $\dot{\Omega}_s$ at $z \gtrsim 0.3$. The reason for this is that samples of galaxies selected by emission become progressively incomplete and include

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only brighter objects at higher redshifts. In contrast, samples of galaxies selected by absorption against background quasars do not suffer from this bias. Such observations are exquisitely sensitive to small column densities of absorbing or scattering particles. In principle at least, they enable us to estimate Ω_g, Ω_m, and even Ω_d as functions of redshift. From these and the equations of cosmic chemical evolution, we can then infer the global rate of star formation $\dot{\Omega}_s$. It is amusing to note that this idealistic program does not require the detection of a single stellar photon! We can also combine our estimates of $\dot{\Omega}_s$ with stellar population synthesis models to compute the mean comoving emissivity $\mathcal{E}_\nu$ and the mean intensity of background radiation J_ν. One might then claim to have predicted the "emission history" of the universe from its "absorption history." This article describes a first attempt by Yichuan Pei, Stéphane Charlot, and the author to carry out such a program; a complete account of our work is given elsewhere (Pei & Fall 1995; Fall et al. 1996).

2. Damped Lyman-Alpha Galaxies

Before proceeding, it is worth recalling some facts about the statistics of absorption-line systems. Let $f(N_x, z)$ be the column density distribution of particles of any type x that absorb or scatter light. These might, for example, be hydrogen atoms ($x =$ HI), metal ions ($x = m$), or dust grains ($x = d$). By definition, $H_0(1+z)^3|dt/dz|f(N_x, z)dN_x dz$ is the mean number of absorption-line systems with column densities of x between N_x and $N_x + dN_x$ and redshifts between z and $z + dz$ along the lines of sight to randomly selected background quasars. These lines of sight are very narrow (less than a light year across) and pierce the absorption-line systems at random angles and impact parameters. One can show that the mean comoving density of x is given by

$$\Omega_x(z) = \frac{8\pi G m_x}{3cH_0} \int_0^\infty dN_x f(N_x, z) N_x, \tag{1}$$

where m_x is the mass of a single particle (atom, ion, or grain). Equation (1) plays a central role in this subject. It enables us to estimate the mean comoving densities of many quantities of interest without knowing anything about the structure of the absorption-line systems. In particular, we do not need to know their sizes or shapes, whether they are smooth or clumpy, and so forth. A corollary of equation (1) is that the global metallicity, $Z \equiv \Omega_m/\Omega_g$, is given simply by an average over the metallicities of individual absorption-line systems weighted by their gas column densities.

The absorption-line systems of most interest in the present context are the damped Lyα (DLA) systems. It is widely believed that they trace the ISM of galaxies and protogalaxies and are the principal sites of star formation in the universe. There are excellent reasons to adopt this as a working hypothesis. First, the DLA systems have, by definition, $N_{\rm HI} \gtrsim 10^{20}$ cm^{-2}, and this, at least at low redshifts, coincides roughly with a threshold for the onset of star formation (Kennicutt 1989). Second, the DLA systems contain at least 80% of the HI in the universe and appear to be mostly neutral (Lanzetta et al. 1995). The other absorption-line systems, those with $N_{\rm HI} \lesssim 10^{20}$ cm^{-2}, probably contain more gas in total than the DLA systems, but this must be diffuse and mostly ionized. In the following, we regard non-DLA systems as belonging to the IGM, even though some of them might actually be associated with the outer, tenuous parts of galaxies. This distinction—between the mostly-neutral ISM, where stars form, and the mostly-ionized IGM, where they do not—is clearly valid at the present epoch. Thus, it seems appropriate to refer to the DLA systems as DLA galaxies. The precise nature of these objects—whether they large or small, disk or spheroid—remains to be determined, probably by direct imaging. However, as we have already emphasized, the global properties derived from equation (1) are not affected by this uncertainty.

The sample of known DLA galaxies now includes about 80 objects (Wolfe et al. 1995). They are distributed over a wide range in redshift, $0 \lesssim z \lesssim 4$, although, as a consequence of selection effects, most of them are confined to the narrower range $2 \lesssim z \lesssim 3$. From observations of DLA galaxies in various subsets of this sample and comparisons with present-day galaxies, the following trends have emerged. The mean comoving density of HI decreases by almost an order of magnitude, from $\Omega_{\rm HI} \approx (1-2) \times 10^{-3} h^{-1}$ at $z \approx 3$ to $\Omega_{\rm HI} \approx 2 \times 10^{-4} h^{-1}$ at $z = 0$, with $h \equiv H_0/(100$ km s^{-1} Mpc$^{-1})$ (Lanzetta et al. 1995; Wolfe et al. 1995; Storrie-Lombardi et al. 1996). The mean metallicity increases by about an order of magnitude, from $Z \approx 0.1 Z_\odot$ or slightly less at $z \approx 2$ to $Z \approx Z_\odot$ at $z = 0$ (Pettini et al. 1994, 1997b; Lu et al. 1996). The mean dust-to-gas ratio increases by a similar factor, while the mean dust-to-metals ratio remains roughly constant at about the present value in the local ISM (Pei et al. 1991; Kulkarni et al. 1997; Pettini et al. 1997a; Welty et al. 1997; Vladilo 1998). The abundances of H_2 and CO generally appear to be lower at $z \gtrsim 2$ than at $z = 0$ (Levshakov et al. 1992; Ge & Bechtold 1997). Unfortunately, the estimates of $\Omega_{\rm HI}$, Z, and D/G are dominated by relatively few systems—those with the highest values of $N_{\rm HI}$, N_m, and N_d. As a result, they are less certain than is sometimes appreciated.

3. Cosmic Chemical Evolution

The global properties defined above are governed by a set of coupled equations, which are sometimes referred to as the equations of cosmic chemical evolution. In the approximation of instantaneous recycling (and $Z \ll 1$), they take the form

$$\frac{d}{dt}(\Omega_g + \Omega_s) = \dot{\Omega}_f, \tag{2}$$

$$\frac{d}{dt}(Z\Omega_g) + (Z - y)\frac{d}{dt}\Omega_s = Z_f\dot{\Omega}_f, \tag{3}$$

where y is the IMF-averaged yield. These are the cosmological analogs of the usual equations for the chemical evolution of individual galaxies (Pagel 1997). They are exact in the limit that all galaxies evolve in the same way but otherwise must be regarded as approximations. The "source" terms on the right-hand sides of the equations allow for the exchange of material between the ISM of galaxies and the IGM; they represent the inflow or outflow of gas with metallicity Z_f at a rate $\dot{\Omega}_f$. To illustrate a range of possibilities, we consider three types of evolution: a closed-box model ($\dot{\Omega}_f = 0$), a model with inflow of metal-free gas ($\dot{\Omega}_f = +\nu\dot{\Omega}_s$, $Z_f = 0$), and a model with outflow of metal-enriched gas ($\dot{\Omega}_f = -\nu\dot{\Omega}_s$, $Z_f = Z$). Our inflow and outflow models are the cosmological analogs of the standard models of chemical evolution in the disk and spheroid components of the Milky Way (Larson 1972; Hartwick 1976). We fix the yield y in each model by requiring $Z = Z_\odot$ at $z = 0$. Then the only adjustable parameters are the "initial" comoving density of gas in galaxies $\Omega_{g\infty}$ (in practice, the value of Ω_g at $z \gtrsim 4$) and the relative inflow or outflow rate ν.

To complete the specification of the models, we make two other approximations, both motivated by the observations summarized in the previous section: (1) We neglect any ionized or molecular gas in the ISM of galaxies and set $\Omega_g = 1.3\Omega_{\rm HI}$ (to account for He). (2) We assume that just over half of the metals in the ISM are depleted onto dust grains and set $D/G = 0.6Z$. Our models are designed to reproduce (as input) the observed decrease in the mean comoving density of HI between $z \approx 3$ and $z = 0$. The main complication here is that the observed values of $\Omega_{\rm HI}$ tend to underestimate the true values as a consequence of the obscuration of quasars by dust in foreground galaxies (Fall & Pei 1993). We make a self-consistent correction for this bias in the models by linking the obscuration of quasars to the chemical enrichment of galaxies. It is worth noting that, while this correction has a substantial effect on $\Omega_{\rm HI}$, especially at $z \sim 1$, it does not entail large numbers of "missing" quasars [only ~20% at $z = 2$ and ~40% at $z = 4$, consistent with observational constraints (Shaver et al. 1996)]. We neglect another potential bias—that caused by gravitational lensing—because it appears not to be important in the existing samples of DLA galaxies (Le Brun et al. 1997; Perna et al. 1997; Smette et al. 1997). Our models reproduce (as output) the observed increase in the mean metallicity between $z \approx 2$ and $z = 0$ without any fine tuning of the parameters $\Omega_{g\infty}$

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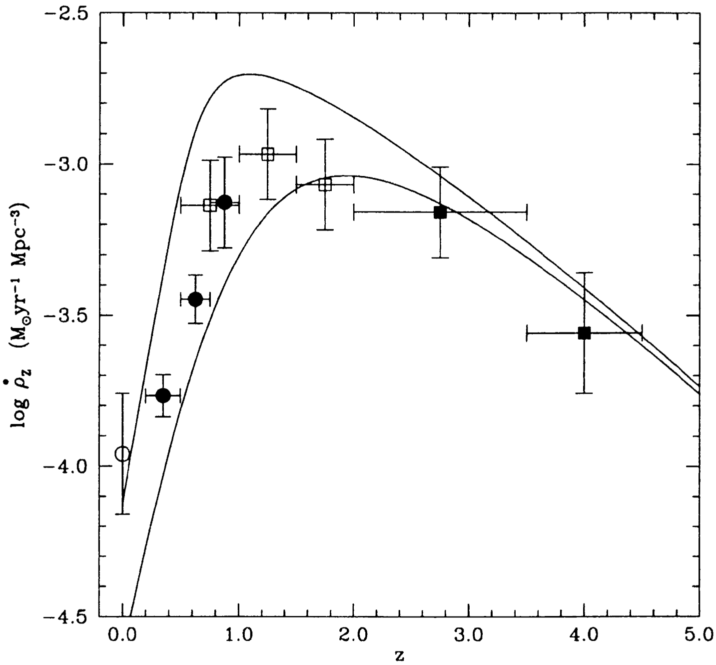

Figure 1. Comoving rate of metal production $\dot{\rho}_z$ as a function of redshift z (for $h = 0.5$, $q_0 = 0.5$, and $\Lambda = 0$). The upper curve represents the inflow model and the lower curve represents the closed-box and outflow models, with $\Omega_{g\infty} = 4 \times 10^{-3} h^{-1}$ and $\nu = 0.5$ [the standard parameters of Pei & Fall (1995)]. The data points represent global Hα and UV emissivities (Gallego et al. 1995; Lilly et al. 1996; Madau et al. 1996, 1998; Connolly et al. 1997).

and ν. The reason for this is that most of the star formation and hence most of the metal production occur at $z \lesssim 2$.

Figure 1 shows the evolution of the comoving rate of metal production in our models, given by $\dot{\rho}_z = y(3H_0^2/8\pi G)\dot{\Omega}_s$. The predicted rates have maxima at $1 \lesssim z \lesssim 2$ and decline rapidly at lower redshifts (Pei & Fall 1995). Figure 1 also shows emission-based estimates of $\dot{\rho}_z$ from several recent surveys, including the Canada-France Redshift Survey and the Hubble Deep Field (Gallego et al. 1995; Lilly et al. 1996; Madau et al. 1996, 1998; Connolly et al. 1997). These were derived from rest-frame Hα and UV emissivities and the approximate proportionality between UV emission and metal production in stellar populations. The main systematic uncertainties in $\dot{\rho}_z$ stem from corrections for incompleteness at low luminosities (which have been included) and corrections for absorption by dust (which have not been included); as a result, the true uncertainties are probably larger than indicated by the error bars in Figure 1. Evidently, the predicted and observed rates are in broad qualitative, and even some quantitative, agreement (within factors of about two). This is remarkable because our models were constructed only with absorption-line observations in mind, before the emission-based estimates of $\dot{\rho}_z$ were available. We have also combined our chemical evolution models with stellar population synthesis models to compute directly the mean comoving emissivity $\mathcal{E}_\nu$ and, by an integration over redshift, the corresponding mean intensity of background radiation J_ν (Fall et al. 1996). These calculations include a self-consistent treatment of the absorption and reradiation of starlight by dust. The predicted far-IR/sub-mm background is consistent with recent results from the DIRBE and FIRAS experiments on *COBE* (Hauser 1996; Puget et al. 1996).

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