WHAT FRACTION OF STARS FORMED IN INFRARED GALAXIES AT HIGH REDSHIFT?

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Abstract
Star formation happens in two types of environment: ultraviolet-bright starbursts (like 30 Doradus and HII galaxies at low redshift and Lyman-break galaxies at high redshift) and infrared-bright dust-enshrouded regions (which may be moderately star-forming like Orion in the Galaxy or extreme like the core of Arp 220). In this work I will estimate how many of the stars in the local Universe formed in each type of environment, using observations of star-forming galaxies at all redshifts at different wavelengths and of the evolution of the field galaxy population.

Keywords: Galaxies, Cosmology

1. Introduction

It is now possible to estimate the star-formation history of the Universe. This is performed most directly by summing the contributions from star-forming field galaxies in optical (corresponding to rest-frame ultraviolet at high redshift) surveys. The direct contribution from ultraviolet-bright star-forming galaxies to the comoving star-formation rate density is about $3 \times 10^{-3} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ at redshift $z = 0$, rising to $4 \times 10^{-2} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ at $z = 1$, before slowly declining to $1.5 \times 10^{-2} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ at $z = 6$ ($h = 0.7, \Omega_\Lambda = 0.7, \Omega_m = 0.3$; Salpeter IMF; ref. 1). This is normally presented in the uncorrected form of the “Madau” or “Madau-Lilly” plot.

But galaxies that are forming stars also experience significant dust extinction – we know this because we see that local star-forming regions like Orion are dusty and because local spiral galaxies have spectral energy distributions (SEDs) which peak in the far-infrared. Correcting for this, Giavalisco et al. [1] find that the total contribution from optically selected galaxies to the co-moving star-formation rate density is about $1.3 \times 10^{-2} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ at $z = 0$, rising to $0.13 M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ at $z = 1$, where it stays roughly constant out to at least $z = 6$. The corrections used come from the analysis of
Adelberger & Steidel (ref. 2), which is based on multi-wavelength studies of a large sample of star-forming galaxies.

An additional contribution may come from extremely dusty galaxies where the dust is optically thick – these may be missing altogether from optical surveys. Local ultraluminous infrared galaxies (ULIGs) are examples of this kind of galaxy; the $V$ extinction to the core of Arp 220 is $> 10$ mag [3]. Another example is the host of GRB 010222 [4], which is an optical sub-$L^*$ galaxy but has a submillimetre star-formation rate of $\sim 600 \, M_\odot \, yr^{-1}$. This kind of galaxy may be similar to the SCUBA galaxies [5] seen in submillimetre surveys which might have a redshift distribution quite different from galaxies in optically selected samples.

In this work I assess the contributions from all three of these modes of star formation in generating the current cosmological density in stars $\Omega_\ast$. I provide estimates given current observations and outline how future observations may provide stronger constraints.

2. Definitions

The total density in stars in critical units is $\Omega_\ast = \Omega_{\ast}^{\text{UV}} + \Omega_{\ast}^{\text{IR/Opt}} + \Omega_{\ast}^{\text{IR}}$.

The density of stars seen forming directly in optical galaxies $\Omega_{\ast}^{\text{UV}}$ equals the integral of the uncorrected ultraviolet star formation rate density over redshift. The density of stars that formed in dusty regions within those same galaxies $\Omega_{\ast}^{\text{IR/Opt}}$ equals the integral of the ultraviolet star formation rate density multiplied by an extinction correction (which may depend on $z$) over redshift. Finally, the density of stars $\Omega_{\ast}^{\text{IR}}$ that formed in highly obscured regions whose presence cannot be inferred from optical observations equals to the infrared star formation rate density (as measured by SCUBA or in the future ALMA) minus the contributions to the previous integral, integrated over redshift.

The partition between $\Omega_{\ast}^{\text{IR/Opt}}$ and $\Omega_{\ast}^{\text{IR}}$ is somewhat arbitrary. Here we put in $\Omega_{\ast}^{\text{IR}}$ all star formation in galaxies whose bolometric luminosity is greater than some threshold luminosity corresponding to that at which the optical luminosity no longer tracks the bolometric (mainly far-infrared) luminosity; locally this happens at a 60-µm luminosity of $6.3 \times 10^{10} \, L_\odot$ (ref. 6). The extinction in these luminous galaxies surely comes from optically thick dust. Optically thin extinction would tend to happen in galaxies contributing to $\Omega_{\ast}^{\text{IR/Opt}}$.

Star formation that happened in ULIGs would be included in $\Omega_{\ast}^{\text{IR}}$.

The fraction of star formation that is obscured in any particular galaxy varies from 0% to about 99% [2]. Obscured star formation at the low end of this range mostly contributes to $\Omega_{\ast}^{\text{IR/Opt}}$ and at the high end to $\Omega_{\ast}^{\text{IR}}$. The host of GRB 010222 would be at the very high end of this range.
3. The current cosmological stellar content: what needs to be produced

The time integral of the cosmic star formation rate must equal the luminosity integral of the galaxy luminosity function:

$$
\Sigma_i \int L \phi_i(L) \Gamma_i \, dL = \int_{t(z)} \rho_\star \, dt,
$$

where $\Gamma_i$ is the mass-to-light ratio of stellar population $i$ (this is derived from stellar population synthesis models). From the combination of the SDSS survey measurements at the bright end [7] and CCD mosaic surveys [e.g. ref. 8] at the faint end, the galaxy luminosity function appears to be well-described by a Schechter function with $M_R^\star = -22.0$ and $\alpha^\star = -1.28$ brightward of $M_R = -19$ and a power law with $\alpha = -1.24$ faintward of $M_R = -19$. Performing the sum of integrals on the LHS of this equation,

$$
\Omega_\star = 0.0036 \pm 0.0020
$$

in units of the critical density. About 3/4 of this is in spheroids and 1/4 in disks. If a Salpeter, not KTG [9] IMF is used, $\Omega_\star$ is a factor of two higher.

4. Observational Constraints

4.1 Field Galaxy Evolution

Multi-colour photometry of a near-infrared selected sample of galaxies has permitted Dickinson, Papovich and colleagues [10] to measure the evolution of $\Omega_\star$ with redshift. Between $z = 0$ and $z = 1$ they found that about 40% of the present-day stars in the Universe formed. Between $z = 1$ and $z = 2$, their best-fitting models suggest that a further fraction > 50% formed and only a few percent of the stars that we currently see had formed by $z = 2$. However, there is considerable uncertainty in the star-formation histories used in modelling the SEDs of the sample galaxies and the fraction of stars in place by $z = 2$ may be as high as 25%. An integral of the extinction-corrected Madau Plot [1] over redshift from $z = \infty$ up to $z = 2$ gives a fraction of about 25%.

Near-infrared surveys [11] have shown that about 30% of the massive early-type galaxies seen today were already in place by $z = 2$ – these are the distant red galaxies (DRGs). Therefore most of the stars that we believe formed at $z > 2$ are not only in massive galaxies today but were already in massive galaxies by $z = 2$. If these formed within the large galaxies, they would have had to form in very extreme bursts.
4.2 GRB host galaxies

Long-duration gamma-ray bursts (GRBs) are thought to be linked to the deaths of massive stars, as suggested by the coincident between SN 2003dh and GRB 030329 [12]. Since massive stars do not live long, this opens up the possibility of using GRB host galaxies as a SFR-selected sample of galaxies. There are, however, complications. In the context of a collapsar [13] model, GRBs originate preferentially from stars of high mass and low metallicity. This means that there will be more GRBs per unit SFR in galaxies which have a high-mass biased IMF or a low metallicity. Perhaps these two effects explain the preponderance of GRBs in ULIGs at \(z \sim 1\) [14] and Ly\(\alpha\)-emitters [ref. 15; see also ref. 16 about the very low metallicity and high gas column density of the host of GRB030323], neither of which significantly contribute to \(\Omega_\ast\).

4.3 Infrared and submillimetre backgrounds and counts

The extragalactic background light (EBL) is high at infrared wavelength: COBE/DIRBE measured it as \(32 \pm 13\) nW m\(^{-2}\) sr\(^{-1}\) at 140 \(\mu\)m and \(17 \pm 4\) nW m\(^{-2}\) sr\(^{-1}\) at 240 \(\mu\)m [17]. The submillimetre background is somewhat lower: \(0.55 \pm 0.15\) nW m\(^{-2}\) sr\(^{-1}\) at 850 \(\mu\)m [18]. The optical extragalactic background light also appears to be high: \(12/15/18\) nW m\(^{-2}\) sr\(^{-1}\) at 300/550/800 nm, with an uncertainty of 50% [19].

Madau & Pozzetti [20] estimated the total EBL as \(55 \pm 20\) nW m\(^{-2}\) sr\(^{-1}\). This is lower than the value of \(100 \pm 20\) nW m\(^{-2}\) sr\(^{-1}\) quoted by Bernstein et al. [21], the main difference being an additional component from the optical background that was previously undetected (however see ref. 22).

Most of this background is generated by stars, not AGN, else the local density of supermassive black holes would be overproduced [20]. Assuming a recycling fraction of 0.4 (much of the material in stars is returned to the ISM via winds and supernovae; ref. 23), the EBL implies a stellar density of \(\Omega_\ast = 0.003 - 0.006\), consistent with the number in Section 3.

One reason the range here is quite large is that the redshift distribution of infrared star-forming galaxies is unknown, and the contribution of each galaxy to the EBL \(\propto (1 + z)^{-1}\).

The submillimetre background has been resolved and redshifts determined for a number of bright sources [24]. However, there are indications [25] that the galaxies which dominate the infrared background are a different population to the galaxies which dominate the submillimetre background. The models described by Chary et al. [25] suggest that these infrared galaxies have lower bolometric luminosities and lower redshifts than the ULIGs observed by Chapman et al. [24].
What fraction of stars formed in infrared galaxies at high redshift?

4.4 Optical/Infrared observations of star-forming galaxies

The instantaneous cosmic SFR at any redshift equals the infrared and optical contributions. Making extinction corrections to star formation rates for high-redshift galaxies is a substitute for direct measurement at infrared wavelengths. Only at low redshift \( z < 1 \) can the two be measured directly. The CFRS+ISO survey [26] showed that about (i) 30% of star formation at \( z < 1 \), was visible at optical wavelengths, (ii) most of the remaining 70% that was in infrared galaxies was in disturbed systems with red \( I - K \) colours, and (iii) about 18% of the star formation happened in ULIGs with SFRs in excess of 100 M\(_\odot\) yr\(^{-1}\). An implication of these results is that most of the star formation at \( z < 1 \) happened in infrared galaxies that are neither optical galaxies with high internal extinction nor ULIGs of the kind seen by SCUBA.

The first Spitzer results [25] seem to point towards a similar situation at higher redshifts. The main difference between low and high redshift is that while the redshift distributions of optical and infrared galaxies are similar within the \( 0 < z < 1 \) range, they are very different at high redshift.

Another implication of these results is that in optically-selected star-forming galaxies, most of the star formation is being observed directly and these are at the low end of the obscuration range described by Adelberger and Steidel [2]. Many of these may be blue compact emission-line galaxies of the type described at this conference by Lowenthal and Bershady.

5. The IMF and density in infrared galaxies

The local star-forming region 30-Doradus has a stellar IMF that is Salpeter \((\propto m^{-2.35})\) above 3 M\(_\odot\) [27]. Lyman-break galaxies at high redshift also have Salpeter IMFs at high masses, an inference based on optical spectroscopy of cB58 at \( z = 2.7 \) [28]. This IMF is attractive in that it evolves into the KTG [9] IMF seen locally [29]. Unfortunately, no equivalent analysis can be made for infrared galaxies and it remains a possibility that they have a different IMF – if it is high-mass biased then they will generate more energy per unit mass of stars formed than will optical galaxies.

Stars that form in infrared galaxies probably form in dense star clusters which need to dissipate in order to produce local galaxies. Dissipation timescales are long for dense clusters but are shorter if the cluster is embedded in a gaseous medium. Simulations of this physical process [30], along with inferences about the star-formation history of the Universe from stellar populations of nearby galaxies [31] will provide additional constraints on the total amount of cosmic star formation that occurred in infrared galaxies and when it happened.
6. Concluding thoughts

My current thinking is that (i) roughly equal amounts of stars formed in each of the following four types of environments: optically visible regions, dust-enshrouded regions within optical galaxies, heavily obscured galaxies with $L_{\text{IR}} < 10^{12} \, L_\odot$ and ULIGs with $L_{\text{IR}} < 10^{12} \, L_\odot$, and (ii) most star formation in optically visible regions was in small galaxies at all redshifts [32, 33] while most star formation in ULIGs happened at high redshift, perhaps producing the DRGs. But these are not strongly held convictions and I share the optimism felt at this conference that the puzzle of star formation in galaxies will be solved over the next few years.

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