Where stars form and live at high redshift: clues from the infrared

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Received 7 December 2011 / Accepted 24 December 2011

ABSTRACT

The relation between dark matter halos and the loci of star formation at high redshift is a pressing question in contemporary cosmology. Matching the abundance of halos to the abundance of infrared (IR) galaxies, we explore the link between dark matter halo mass ($M_h$), stellar mass ($M_\star$) and star-formation rate (SFR) up to a redshift of 2. Our findings are five-fold. First, we find a strong evolution of the relation between $M_h$ and SFR as a function of redshift with an increase of SFR$/M_h$ by a factor $\sim 30$ between $z = 0$ and $z = 2.3$. Second, we observe a decrease of SFR$/M_\star$ with stellar mass. These results reproduce observed trends at redshift $z > 0.3$. Third, we find that the star formation is most efficient in dark matter halos with $M_h \approx 5 \times 10^{11} M_\odot$, with hints of an increase of this mass with redshift. Fourth, we find that SFR$/M_\star$ increases by a factor $\sim 15$ between $z = 0$ and $z = 2.3$. Finally, we find that the SFR density is dominated by halos masses close to $7 \times 10^{11} M_\odot$ at all redshift, with a rapid decrease at lower and higher halo masses. Despite its simplicity, our novel use of IR observations unveils some characteristic mass-scales governing star formation at high redshift.

Key words. galaxies: star formation – galaxies: statistics – galaxies: halos – dark matter – infrared: galaxies

1. Introduction

The loci of star formation at high redshift is one of the salient questions of galaxy formation theory. In particular, uncertainties in the relation between the host halo mass and the IR luminosity function (LFIR) currently limit models of the clustering of star-forming galaxies as revealed e.g. by the anisotropies of the cosmic infrared background (CIB). This comes from the fact that the clustering of galaxies is directly driven by the mass of their host halos. The so-called abundance matching technique is another valuable tool that provides insights on this relation (Vale & Ostriker 2004). While unexplored in the IR, a recent improvement of LFIR measurements makes this approach now both promising and timely. We will illustrate its power in this letter. In particular, working in the IR provides the unique possibility to constrain the star-formation rate (SFR) directly without any extra assumption regarding the physical processes that drive the star formation.

Considering the latest observational and theoretical developments in the IR, we introduce in Sect. 2 the abundance matching technique. We describe in detail the mass and luminosity functions used in Sect. 3. Matching abundances allows us to infer relations between halo and stellar mass (Sect. 4.1), SFR and stellar mass (Sect. 4.2) and SFR and halo mass (Sect. 4.3). In these sections, we will illustrate in particular how this simple but well-informed approach satisfyingly reproduces trends observed in the IR, but also at other wavelengths. Focusing on what is required for the modeling of the CIB, we exclude the so-called starbursting galaxies here because they are non-significant outliers. Critical in the context of abundance matching, this assumption is well motivated and discussed in Sect. 3.

Throughout this paper, we adopt a Chabrier (2003) initial mass function (IMF)\textsuperscript{1} and a ΛCDM WMAP-7 cosmology (Larson et al. 2011).

2. Simple abundance matching

Our goal is to find an observationally supported relation between the SFR of galaxies, their stellar and their host halo mass. While this relation is statistical in nature, the abundance matching technique (e.g. Conroy & Wechsler 2009) provides a way to relate the means of this relation. Observations suggest a small scatter around this relation and we will therefore neglect it: 0.16 dex for the relationship between stellar and halo mass (More et al. 2009), and 0.2 dex between the stellar mass and the SFR (Rodighiero et al. 2011; see also Behroozi et al. 2010 for a more general discussion of scatter).

The key assumption of this matching technique is the existence of a continuous and monotonic relation between the halo mass, the stellar mass, and the SFR: SFR = $f(M_h)$, SFR = $g(M_\star)$ and $M_\star = h(M_h)$, where SFR is the SFR, $M_\star$ the galaxy stellar mass (SM), and $M_h$ the dark-matter halo mass (HM).

We solve for the functions $f$, $g$ and $h$ that satisfy the following relations between the infrared luminosity function, the halo mass function, and the stellar mass function:

\begin{align}
 n_{\text{LIR}}(>M_\star) &= K^{-1} \times f(M_\star) = n_{M_\star}(>M_\star) \quad (1) \\
 n_{\text{LIR}}(>M_h) &= K^{-1} \times g(M_h) = n_{M_h}(>M_h) \quad (2) \\
 n_{M_\star}(>M_\star) &= h(M_h) = n_{M_h}(>M_h) \quad (3)
\end{align}

\textsuperscript{1} Stellar masses and SFR computed assuming a Salpeter (1955) IMF can be converted to Chabrier (2003) IMF applying a $-0.24$ dex correction.
where \( n_{LR} \) is the number of galaxies per unit comoving volume brighter than the bolometric infrared luminosity \( L_{IR} \), and \( n_M \) and \( n_{M_h} \) are the number of galaxies more massive than the stellar mass \( M_\star \) and the halo mass \( M_h \), respectively. \( K \) is the Kennicutt (1998) factor, which links the infrared bolometric luminosity integrated between 8 and 1000 um and the SFR: \( K = 10^{10} M_\odot \text{yr}^{-1} L_{IR}^{-2} \).

As we discuss below, a key assumption in this matching is that all (sub)halos contribute to the IR.

### 3. Mass and luminosity functions

The key inputs to our discussions are the bolometric infrared luminosity function (LFIR), the stellar mass function (SMF) and the halo mass function (HMF).

It is well known that the LFIR is inconsistent with the Schechter (1976) form and presents an excess at the bright end (e.g. Saunders et al. 1990). However, it has been shown that this excess is mainly caused by starbursting galaxies, which are well outside the SFR-SM main sequence. Yun et al. (2001) showed that the 60\( \mu \)m LF of the IRAS 2 Jy sample can be fitted by the sum of two Schechter functions. More recently, Sargent et al. (2011) showed that the LFIR can be decomposed as a sum of two approximate Schechter functions. The first one is responsible for \(-85\%\) of the IR energy output, and is caused by the so-called main-sequence objects that have very similar specific sSFR at a given \( M_\star \) and redshift. The second one dominates the bright-end of the LF, and is caused by starbursting galaxies with an sSFR about 0.5 dex higher than the main sequence. These starbursts contribute only \(-2\%\) to the mass-selected star-forming galaxies number density (Rodighiero et al. 2011), and \(-15\%\) to the SFR density (Sargent et al. 2011), and consequently to the CIB. The former guarantees that starbursts constitute a negligible fraction of IR objects, i.e. do not contribute significantly to the IR abundances. The latter suggests that they can be neglected for our purpose. Additionally, because a bimodal relation between LFIR and sSFR would violate our hypothesis of a monotonic relation between masses and SFRs, we henceforth ignore the starburst components. Focusing on the main-sequence population, we therefore write the LFIR as a Schechter (1976) function

\[
\frac{dN}{dL_{IR}} = \phi_\star(z) \frac{L_{IR}}{L_\star(z)}^{-\alpha(z)} \exp \left( \frac{L_{IR}}{L_\star(z)} \right) \frac{1}{L_\star(z)},
\]

where \( dN/dL_{IR} \) is the LFIR, and \( \phi_\star(z) \) and \( L_\star(z) \) are the characteristic density and luminosity at a given redshift, respectively. We use the evolution of \( \phi_\star(z) \) and \( L_\star(z) \) measured by Magnelli et al. (2011) up to \( z = 2.3 \).

In contrast to the LFIR, the SMF is much closer to a Schechter (1976) function. Pérez-González et al. (2008) have measured the SMF up to \( z = 4 \) and we used their parameters of the Schechter function fit. We performed our abundance matching at the same redshift as the center of the redshift bins of Pérez-González et al. (2008). We checked that there is no inconsistency between the SFR derived from our LFIR and that derived from the SMF following Wilkins et al. (2008).

For the HMF, we used the Tinker et al. (2008) \( z \)-dependent HMF and the associated sub-halo mass function proposed in Tinker & Wetzel (2010) with \( \Delta = 200 \). Our results are fairly insensitive to the inclusion of the sub-halo mass function.

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2 Note that \( n \) can be deduced from the luminosity/mass function: \( n_X(z_{\text{max}}) = \int_{X_{\text{min}}}^{X_{\text{max}}} n_X(z) \text{d}X \), where \( X \) is \( L_{IR} \), \( M_\star \) or \( M_h \).

3 The Kennicutt factor was re-scaled from the Salpeter to the Chabrier IMF.

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4. Results

#### 4.1. Relation between stellar mass and halo mass

The abundance matching between the HMF and SMF has been extensively studied for \( z < 1 \) (e.g. Comrey & Wechsler 2009) and has been discussed in detail up to \( z \sim 4 \) by Behroozi et al. (2010). Because \( M_\star/M_h \) as a function of \( M_h \) is one basic element of our analysis, we first investigated it using our mass functions. Figure 1 shows this relation relation up to \( z = 2.25 \). It agrees with the measurements at \( z = 0 \) and \( z = 1 \) (Mandelbaum et al. 2006; Comrey et al. 2007; Reyes et al. 2011). However, constraints are poor except at \( z = 0 \) for \( M_h > 10^{11} M_\odot \). We find that \( M_\star/M_h \) peaks near \( M_h = 10^{12} M_\odot \) and decreases at lower- and higher-mass. This suggests that the integrated star-formation efficiency \( (\langle M_\star/M_h \rangle) \) decreases for smaller as well as higher-mass halos. Figure 1 also indicates that the mass corresponding to the peak of integrated star-formation efficiency evolves with redshift, being a factor of 8 larger at \( z = 2.25 \) than at \( z = 0 \). We extended our analysis to higher redshifts using the latest SMF measurements (Caputi et al. 2011; Kajisawa et al. 2009) and confirm this trend. However, as discussed in Behroozi et al. (2010), these results have to be taken with care because the current uncertainties make these evolutions quite uncertain.

#### 4.2. Relation between star-formation rate and stellar mass

Matching the abundances derived from the LFIR and the SMF, we plot in Fig. 2 the sSFR as a function of \( M_\star \) and redshift. We observe a strong increase of the sSFR with redshift (about 1.5 order of magnitude between \( z = 0 \) and \( z = 2 )\), which qualitatively agrees with observations (Elbaz et al. 2011; Karim et al. 2011). We also see a slight decrease of the sSFR with \( M_\star \) (0.5 dex between \( M_\star = 10^9 M_\odot \) and \( M_\star = 10^{11.5} M_\odot \)), which again agrees with the observations (Rodighiero et al. 2011; Karim et al. 2011). To further illustrate this qualitative agreement, we also plot in Fig. 2 the most recent sSFR measurements. We reproduce their trends quite well. We note the large dispersion between the measurements, however. For example, Karim et al. (2011) and Rodighiero et al. (2011) differ significantly at high-mass
at \( z \approx 0.3 \) and at all masses for \( z \approx 1 \) (note however that the redshift bins are quite different). Also, at higher redshift the measurements seem to differ by factors \( \sim 2 \) around \( 10^{10} M_\odot \).

4.3. Relation between star-formation rate and halo mass

We have seen in Sects. 4.1 and 4.2 that matching abundances leads to elucidating connections between the stellar halo mass on the one hand, and the stellar mass and the sSFR on the other hand. It is therefore natural to investigate the connection between the halo mass and the SFR. We can make this connection in two ways. In Fig. 3 (upper panel), we plot the redshift evolution of the ratio between SFR and halo mass as a function of halo mass. The solid lines use a direct matching between the LFIR and the HMF. The dotted-dashed lines stem from a combination between the function linking the stellar mass and the halo mass, and the power-law fit of the sSFR-\( M_h \) relation by Karim et al. (2011) (their Fig. 10). The distribution is quite sharp with a rapid decrease at smaller and higher mass. We also see an increase of the halo mass where the instantaneous star formation is the most efficient, from \( M_h = 3 \times 10^{11} M_\odot \) at \( z = 0 \) to \( 1 \times 10^{12} M_\odot \) at \( z = 2.25 \). This evolution is even more pronounced with the second method. The relationship between \( M_h \) and SFR/\( M_h \) is close to a log-normal distribution with a typical width \( \sim 0.75 \) (\( \sim 0.65 \) if we use the second method), but presents an excess at high mass (\( M_h > 10^{12} M_\odot \)). This differs notably from the SFR-\( M_h \) relation found by Conroy & Wechsler (2009) at high mass (\( M_h > 2 \times 10^{12} M_\odot \)). However, at these high masses the conversion between their stellar mass growth and SFR is less reliable (see their Sect. 3.2). In contrast to Conroy & Wechsler (2009) we made no assumption regarding the relation between star formation and halo growth.

From the SFR-\( M_h \) relation, we can easily derive the differential contribution of each halo mass to the global SFR density \( \rho_{\text{SFR}} \):

\[
\frac{d\rho_{\text{SFR}}}{d\log(M_h)} = \frac{d^2 N}{dM_h dV} \times SFR(M_h),
\]

(5)

where \( d^2 N/(dM_h dV) \) is the HMF and SFR(\( M_h \)) is the SFR associated to a given halo mass provided by the abundance matching. Figure 3 shows the evolution of this observable with halo mass and redshift. We find that the SFR density is dominated by halo masses close to \( \sim 7 \times 10^{11} M_\odot \), in agreement with the analysis of Conroy & Wechsler (2009) (their Fig. 10). The distribution is quite sharp with a rapid decrease at smaller and higher mass. We see specifically from this figure that the bulk of star formation at \( z \leq 2.3 \) never occurs in small systems.

5. Discussion

We presented a first application of the abundance matching technique to current infrared data. Our exercise turned out to be surprisingly elucidating. Despite its simplicity, this technique provides a reasonable picture of the evolution of the SFR with the stellar mass, in qualitative agreement with the multi-wavelength measurements at \( z > 0.3 \) (Sect. 4.2). It confirms the strong link between these two quantities. The success of this analysis relies on the hypothesis that the contribution of main-sequence outsider objects to the IR energy output is negligible. Matching
the L FIR and the SMF including the starburst contribution into L FIR leads to a very strong increase of the sSFR-$M_*$ relation for $M_*>10^{11} M_\odot$, which is not observed. Similarly, it artificially increases the sSFR-$M_h$ relation for $M_h > 3 \times 10^{12} M_\odot$. The tightness of the sSFR-$M_*$ relation indicates that the SFR is not driven by merger-induced starbursts but instead by a continuous mass-dependent process that is gradually declining with time. Reproducing the evolution of this relation is a challenge for models of galaxy formation (e.g. Davé 2008; Damen et al. 2009).

Our analysis neglects the presence of quiescent massive galaxies at high mass. By comparing the matched abundances with or without quiescent galaxies in the SMF using the Ilbert et al. (2010) measurements, we found that their contribution is negligible ($\lesssim 0.2$ dex) for $z \geq 0.3$, but reach 0.25 dex at $z = 0.3$. A smaller effect ($\sim 0.15$ dex) at low $z$ is found using the measurements of van der Wel et al. (2010). Because the CIB is dominated by $z \geq 0.3$ galaxies, neglecting the contribution of quiescent galaxies has little impact on its modeling.

Figure 3 demonstrates that the halo mass with the most efficient star formation does not evolve strongly with redshift, with only a decrease of only a factor $\sim 3$ since $z \approx 2.3$. This may contradict with one meaning of the downsizing phenomenon, which implies which stars are being formed in preferentially smaller systems at later times. This lack of evidence has also been observed by Conroy & Wechsler (2009) up to $z \approx 1$. This effect could be produced by a poor estimate of the faint-end slope of the L FIR. To investigate this, we repeated our analysis using higher slopes (up to $\alpha = 1.8$) and found that our conclusion still holds.


The tSFR is the main quantity that defines the matter clustering on large scales, the link between SFR and halo mass is not only fundamental for understanding the evolution of the galaxies, but also the CIB anisotropies. The current CIB anisotropy models, based on halo occupation distribution prescriptions (Pénin et al. 2012; Planck Collaboration 2011; Amblard et al. 2011), do not take into account that the brighter infrared sources tend to be in more massive halos (although Shang et al. 2011 attempted to address this). Our analysis showed that the relation between SFR and the halo mass has a fairly constant shape from $z = 0$ to $z = 2$, but significantly shifts with the redshift, the characteristic halo mass varying by a factor $3$ with redshift (see Fig. 3). With improved models of CIB anisotropies, we can hope to accurately constrain this relation and its evolution with halo mass and redshift. This modeling may be able to decrease the tension between wavelengths discussed in the Planck Collaboration (2011).

Acknowledgements. We thank Andrew Wetzel, whose questions stimulated this work, Mark Sargent, Emanuele Daddi and Lingyu Wang for their insightful comments, Gil Holder for his special perspective. M.B. acknowledge financial support from ERC-StG grant UPgal 240039. Part of this research was carried out at JPL/Caltech under a contract from NASA.

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