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Gas exchanges between local spirals ancestor and the intergalactic medium in the past 6 Gyrs

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Abstract. Using a representative sample of 66 intermediate mass galaxies at $z \sim 0.6$, we have investigated the interplay between the main ingredients of the chemical evolution: metal abundance, gas mass, stellar mass and SFR. All quantities have been estimated using deep spectroscopy and photometry from UV to IR and assuming an inversion of the Schmitt-Kennicutt law for the gas fraction. Six billions years ago, galaxies had a mean gas fraction of 32% ± 3, i.e. twice that of their local counterparts. Using higher redshift samples from the literature, we explore the gas-phases and estimate the evolution of the mean gas fraction of distant galaxies over the last 11 Gy. The gas fraction increases linearly at the rate of 4% per Gyr from $z \sim 0$ to $z \sim 2.2$. We also demonstrate for a statistically representative sample that < 4% of the $z \sim 0.6$ galaxies are undergoing outflow events, in sharp contrast with $z \sim 2.2$ galaxies. The observed co-evolution of metals and gas over the past 6 Gyr favours a scenario in which the population of intermediate mass galaxies evolved as closed-systems, converting their own gas reservoirs into stars.

Key words. galaxies: evolution –galaxies: ISM – galaxies: high-redshift

1. Introduction

It is thought that half the stellar mass in the Universe formed within the last 8 Gyrs, mainly within intermediate mass galaxies ($9.8 < logM*/M < 11.5$) (Bell et al. 2005; Hammer et al. 2005). Present-day intermediate mass galaxies are mostly spiral galaxies similar to the Milky Way. How have these galaxies assembled half of their stars over the past 8 Gyrs? Our aim is to put observational constraints on the relative contributions of mergers, gas infall, feedback and star formation processes, as a function of time, to the stellar mass assembly of local disk progenitors.

We have investigated the interplay between the main ingredients of chemical evolution (metal abundance, gas mass, stellar mass and star formation rates) in a representative sample of 65 intermediate-mass galaxies at z 0.6 from the IMAGES survey (Hammer et al. 2005). All quantities have been estimated using deep spectroscopy (VLT/FORS2 - R=1000) and deep photometry from UV to infrared (HST, Galex, Spitzer). Our aim is to constrain the total transfer of matter between the popu-

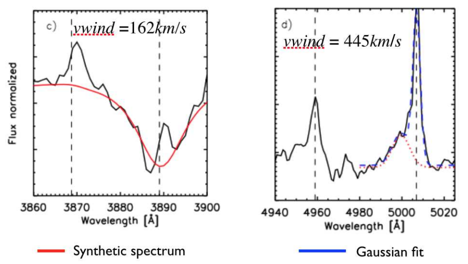

Fig. 1. Detection of possible presence of outflows two intermediate mass galaxies at $z \sim 0.6$ from FORS2 spectra (black solid line). **Left panel:** Outflow detected from the difference of the velocity between gas emission lines and absorption lines from the stars. Synthetic absorption spectra estimated from STARLIGHT (Cid Fernandes et al. 2005) are over-plotted with red lines. Dashed vertical lines indicate the position of the [NeIII], H8 lines in the rest position. **Right panel:** The spectrum of J033229.64-274242.6 showing the possible presence of outflows from the morphology of the collisional line $[OIII]\lambda5007$. Dashed vertical lines indicate the position of the $[OIII]$ doublet lines in the rest position. Its $[OIII]\lambda5007$Å line is formed by two components: a narrow component and a broad bleu-shifted component (red dot line). Adapted from Rodrigues et al. (2012)

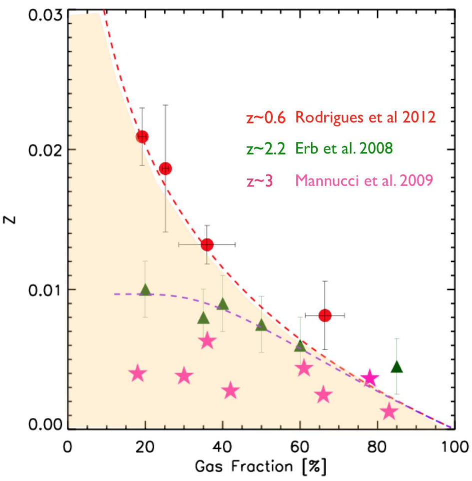

Fig. 2. The gas fraction - metallicity relation at $z \sim 0.6$ (red circles). The green triangles and the pink stars are respectively the $z \sim 2.2$ and $z \sim 3$ galaxies from (Erb 2008) and Mannucci et al. (2009). The red dashed line is the theoretical relation in the case of a closed-box model with a yield equal to solar. The green dashed line is the best fit of the Erb (2008) objects to models with infall and outflow: $f_{inf} = 1.3$, $f_{outflow} = 1.6$. Adapted from Rodrigues et al. (2012)

lation of disk progenitors and the intergalactic medium. This is done via an analysis of the chemical evolution of the galaxies. The contribution of external processes to galaxy evolution can be estimated by studying the departure of the observed evolution of the star-formation rate (SFR), gas, stellar mass (m*) and metallicity from the evolution predicted by analytical chemical evolution models using the simple case of isolated galaxies or a closed-box model.

2. Results

2.1. No evidence of large-scale outflows

We have evaluated the contribution of large-scale outflows powerful enough to expel gas and metals from their host galaxy and to enrich the intergalactic medium. The kinematics and morphology of emission and absorption lines have been analyzed in the individual and mass-combined spectra. Figure 1 illustrates a successfull detection of two strong wind flow in two of the individual spectra. In J033225.26-274524.0 (left panel) the outflow is detected from the difference of the velocity between gas emission lines and absorption lines produced by young stars. The gas lines are systematically shifted to the right relatively to the reference absorption lines by $\sim 162 km/s \pm 75 km/s$. In J033229.64274242.6, the asymmetric emission profile of the [OIII] 5007 Å collisional lines, with a tail in the blue wing, is due to a the presence of gas expelled in our direction at $v_{wind} = 445 km/s$.

From the 66 galaxies in our representative sample of intermediate mass galaxies, only two host a powerful outflow with $v_{wind} = 400 km/s$ and three may have moderate outflows with $v_{wind} < 300 km/s$. This suggests that large-scale outflows do not play an important role in intermediate mass galaxies at $z \sim 0.6$. The fraction of galaxies with outflows represents 8% of the

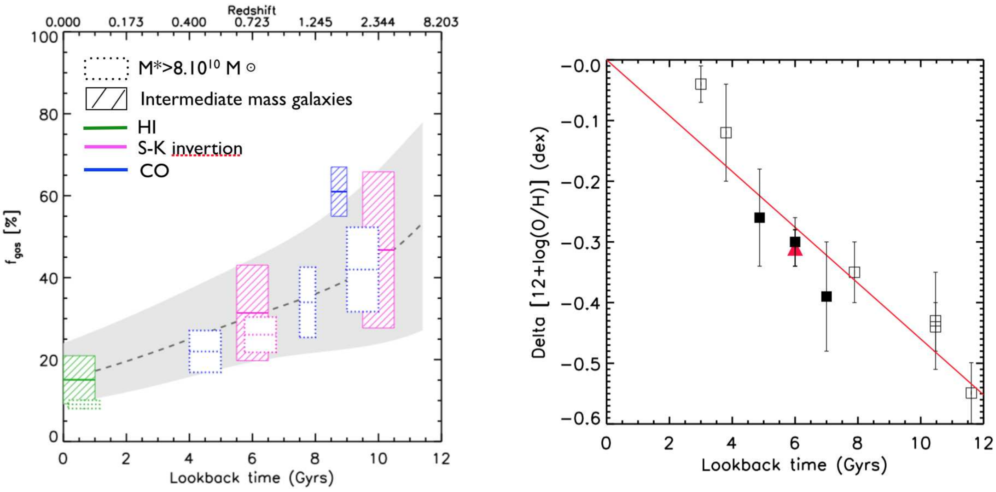

Fig. 3. Left panel: evolution of the mean f_{gas} as a function of lookback time from the observation of Schiminovich (2008); Catinella et al. (2010); Erb et al. (2006b); Mannucci et al. (2009); Geach et al. (2011); Daddi et al. (2010). The dashed box corresponds to intermediate mass samples, having stellar mass between $9.8 < \log M*/M\odot < 11.5$. The dotted line boxes are samples with stellar mass superior to $\log M*/M\odot = 10.8$. The colours code how gas fractions have been estimated: green for HI measurements, pink for inverse K-S law estimations and blue for CO estimations. **Right panel**: Evolution of the metallicity of the gas as a function of loopback time. The metallicity shift from the local relation of the 4 high-z sample as a function of the lookback time is plotted as black open squares. The metallicity shift for the 3 redshift bin of the IMAGES sample are in black squares and the median of the 3 bins as a red triangle. The red line is the linear fit of the 5 high-z data points verifying $\Delta[12 + log(O/H)] = 0$ at $z = 0$. Adapted from Rodrigues et al. (2008, 2012).

population of star-forming galaxies and 4% of the population of intermediate mass galaxies at $z \sim 0.6$.

2.2. Yield: Gas fraction vs metallicity

As a zero-order approximation of chemical evolution, the closed box model (Pagel et al. 1979) provides a first insight into the metal enrichment of galaxies. In a simple closed-box model galaxies have no interaction with their environment. They are homogeneous and well-mixed boxes. Galaxies evolve passively, transforming their initial mass of pristine gas M_{Gas} into stars M_* and enriching the ISM by newly formed metals M_Z. The chemical cycle of galaxies can be described analytically (Searle & Sargent 1972; Pagel et al. 1979) and the relation between the metallicity of the gas and the gas fraction is given by:

$$Z = y_{true} \times ln\frac{1}{f_{gas}} \quad (1)$$

where y_{true} is the true nucelosynthesis yield, defined as the rate at which metals are returned to the ISM relative to the current SFR. In Figure 2 we have plotted the metallicity versus the gas fraction for galaxies in our sample. They have been binned by gas fraction and compared with predictions from a closed-box mode assuming a nucleosynthetic yield equal to solar $y = y_{\odot} = 0.0126$ (Asplund et al. 2004). The data follow closely the prediction of the closed-box and suggests that the population behaves like a closed system. We note that the closed-box model track is *not* a best-fit to the data. It represents equation 1 assuming the usual nucelosynthetic yield from the literature. Exchanges of gas with the environment will move galaxies under the closed box model limit (dashed red line) and into the orange area. We have used chemical evolution models which include outflows and infalls (Erb 2008) to estimate the maximum limit of contribution of external exchanges to the population of intermediate-mass galaxies: $4 \pm 2M\odot/yr$ per galaxy and outflow $1 \pm 1M\odot/yr$.

2.3. Co-evolution of gas and metals during the past 6 Gyrs

We have tested if the observed metallicities and gas content of local galaxies are consistent with a scenario in which $z \sim 0.6$ galaxies have evolved in isolation until now. In the closed-box model, the variation of the metallicity as a function of the variation of gas fraction can be determined by deriving equation (1) (Liang et al. 2006). Figure 3 shows the evolution of the gas fraction (left panel) and metals (right panel) during the past 6 Gyrs. Six Gyr ago galaxies were two times more gas rich and two times more metal poor. This co-evolution over the past 6 Gyr favors a scenario in which the population of intermediate-mass galaxies evolved as closed systems, converting their own gas reservoirs into stars.

3. Impact on the evolution of spirals

Our observations suggest that the population of intermediate-mass galaxies have evolved as closed systems over the past 6 Gyr, in contrast to past episodes of intense outflow and infall at $z > 2$. This result implies that external gas contributions are not required to explain the mass assembly of local spirals during the past 6 Gyrs. However, contributions from infall and outflows on a case-by-case basis cannot be excluded. Accounting for the observational uncertainties, 10-30% of the gas fraction in local galaxies may come from the infall of gas during the last 6 Gyrs. We are now analyzing how the transfer of gas between systems of intermediate-mass spirals via mergers and galactic fountains could shape various scaling relations: e.g. the observed dispersion of the metallicity fundamental plane.

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