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# Quasar feedback in the early Universe: the case of SDSS J1148+5251

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## ABSTRACT

Galaxy-scale gas outflows triggered by active galactic nuclei have been proposed as a key physical process to regulate the co-evolution of nuclear black holes and their host galaxies. The recent detection of a massive gas outflow in one of the most distant quasars, SDSS J1148+5251 at $z = 6.4$, presented by Maiolino et al., strongly supports this idea and suggests that strong quasar feedback is already at work at very early times. In a previous work, Valiante et al., we have presented a hierarchical semi-analytical model, GAMETE/QSODUST, for the formation and evolution of high-redshift quasars, and we have applied it to the quasar SDSS J1148+5251, with the aim of investigating the star formation history, the nature of the dominant stellar populations and the origin and properties of the large dust mass observed in the host galaxy. A robust prediction of the model is that the evolution of the nuclear black hole and of the host galaxy are tightly coupled by quasar feedback in the form of strong galaxy-scale winds. In the present Letter, we show that the gas outflow rate predicted by GAMETE/QSODUST is in good agreement with the lower limit of $3500\,M_{\odot}\,yr^{-1}$ inferred by the observations. According to the model, the observed outflow at $z = 6.4$ is dominated by quasar feedback, as the outflow rate has already considerably depleted the gas content of the host galaxy, leading to a downturn in the star formation rate at $z < 7$–8. Hence, we predict that supernova explosions give a negligible contribution to the observed winds at $z = 6.4$.

**Key words:** galaxies: evolution – galaxies: high-redshift – quasars: general.

## 1 INTRODUCTION

The energy released by the black hole (BH) accretion process can be powerful enough to drive gaseous galactic-scale outflows. Such a negative feedback mechanism is expected to play an important role in the formation and evolution of quasars (QSOs), by self-regulating the BH growth and eventually quenching star formation, therefore affecting the evolution of the physical properties of the host galaxy (e.g. Silk & Rees 1998; Granato et al. 2004; Di Matteo, Springel & Hernquist 2005; Springel, Di Matteo & Hernquist 2005; Ciotti, Ostriker & Proga 2009; Hopkins & Elvis 2010; Zubovas & King 2012). Moreover, negative quasar feedback is also required in theoretical models of galaxy evolution to reproduce the space density and properties of old passive and massive galaxies, observed in the local Universe up to redshift $z \sim 2$ (e.g. Cimatti et al. 2004; Saracco et al. 2005).

Observational indications of feedback associated with quasar-driven massive outflows come from the detection of broad wings of molecular (CO and HCN) emission lines (e.g. Feruglio et al. 2010; Alatalo et al. 2011), P Cygni profiles of FIR OH transitions (e.g. Fischer et al. 2010; Sturm et al. 2011), high-velocity neutral gas in absorption and high-velocity ionized gas (e.g. Nesvadba et al. 2010; Rupke & Veilleux 2011) and from the measurement of absorption column densities (Arav, Korista & de Kool 2002; Arav et al. 2008) in local quasars (but see also Chelouche 2008). High-velocity and broad [O III] emission observed at $z \simeq 2$ (e.g. Alexander et al. 2010; Harrison et al. 2012) also trace large-scale gas outflows. Moreover, direct observational evidences of quasar feedback quenching star formation at high redshift have recently been presented (e.g. Cano-Diaz et al. 2012; Trichas et al. 2012).

Quasar-driven outflows have also been observed up to $z \sim 6$; however, until recently these were identified only through broad absorption lines in their rest-frame UV spectrum (Maiolino et al. 2001, 2004), tracing winds in the vicinity of the accreting BH and accounting only for a tiny fraction of the amount of gas in the whole host galaxy.

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**Table 1.** Observed and inferred physical properties of the $z = 6.4$ QSO J1148 and its host galaxy. See V11 for details.

| Quantity | Description | Value | Reference |
|---|---|---|---|
| $M_{1450\,\text{Å}}$ | Continuum rest-frame AB magnitude | $-27.82$ | Fan et al. (2003) |
| $M_\mathrm{h}$ | Mass of the host dark matter halo | $10^{13}\,\mathrm{M_\odot}$ | Fan et al. (2004), V11 |
| $M_\mathrm{BH}$ | Mass of the supermassive black hole | $3^{+3.0}_{-1.0} \times 10^9\,\mathrm{M_\odot}$ | Barth et al. (2003), Willott, McLure & Jarvis (2003) |
| $L_\mathrm{FIR}$ | Far-infrared luminosity | $(2.2 \pm 0.3)\,\mathrm{L_\odot}$ | V11 and references therein |
| $M_\mathrm{dyn}$ | Mass of the dynamical gas for an inclination angle $i = 65°$ | $(5.5 \pm 2.75) \times 10^{10}\,\mathrm{M_\odot}$ | Walter et al. (2003) |
| $M_{\mathrm{H}_2}$ | Mass of the molecular gas from the CO observations | $1.6 \times 10^{10}\,\mathrm{M_\odot}$ | Walter et al. (2003) |
| $M_\mathrm{star}$ | Stellar mass computed as $M_\mathrm{dyn} - M_{\mathrm{H}_2}$ | $(3.9 \pm 2.75) \times 10^{10}\,\mathrm{M_\odot}$ | Walter et al. (2003) |
| $M_\mathrm{star}$ | Stellar mass from $M_\mathrm{BH}/M_\mathrm{star} \sim 0.002$ | $\sim 2.14 \times 10^{12}\,\mathrm{M_\odot}$ | Marconi & Hunt (2003) |
| SFR | Star formation rate | $(3.8 \pm 0.57) \times 10^3\,\mathrm{M_\odot\,yr^{-1}}$ | Bertoldi et al. (2003) |
| $Z$ | Metallicity from the observations of the narrow-line regions in QSOs | $1.32^{+1.57}_{-1.10}\,\mathrm{Z_\odot}$ | Matsuoka et al. (2009) |
| $M_\mathrm{dust}$ | Mass of dust | $3.4^{+1.38}_{-1.54} \times 10^8\,\mathrm{M_\odot}$ | V11 and references therein |
| $\dot{M}_\mathrm{outfl}$ | Quasar-driven gas outflow rate | $>3500\,\mathrm{M_\odot\,yr^{-1}}$ | Maiolino et al. (2012)[a] |

[a]The gas outflow rate has been inferred from the observations of J1148 only after the model presented in V11 was published (see text).

In a previous work (Valiante et al. 2011, hereafter V11) we have presented a semi-analytical model, GAMETE/QSODUST, for the formation and evolution of high-redshift quasars. This model has enabled us to constrain the star formation history (SFH) and the nature of the stellar populations (e.g. the stellar initial mass function, IMF) of the well-studied high-redshift quasar SDSS J1148+5251 (hereafter J1148) at $z = 6.4$, by linking the evolution of the nuclear BH with the chemical properties of the host galaxy. The main observed and inferred physical properties of J1148 are summarized in Table 1. In V11, we have found that the evolutionary scenarios that allow us to reproduce the physical properties of the quasar J1148 and of its host galaxy, such as the mass of the nuclear BH, the dynamical gas and dust masses, are tightly constrained. More specifically, if stars are assumed to form according to a *standard* IMF, such as a Larson IMF with a characteristic mass of $m_\mathrm{ch} = 0.35\,\mathrm{M_\odot}$, the total stellar mass exceeds the upper limit set by the observed dynamical mass by a factor of 3–10, depending on the adopted star formation model (see V11 for further details). Alternatively, the total stellar mass can be accommodated within the dynamical mass limit if a *top-heavy* IMF is assumed for all stellar populations formed in the host galaxy, with a characteristic stellar mass of $m_\mathrm{ch} = 5\,\mathrm{M_\odot}$.

More important, for the purpose of the present investigation, a fundamental prediction of the model was that '*a powerful outflow is launched by the quasar during the latest ∼(100–200) Myr of the evolution*'. This is a natural consequence of continuous negative feedback that operates along the merger history of the host galaxy and it is required to regulate BH growth, star formation and to reproduce the observed dynamical and chemical properties in all of the evolutionary scenarios presented in V11.

Recently, Maiolino et al. (2012) have detected, for the first time, a massive gas outflow, ascribed to strong quasar feedback, through IRAM PdBI observations of the [C II] 158 μm transition in the host galaxy of J1148. They have revealed broad extended [C II] wings which indicate a large mass ($7 \times 10^9\,\mathrm{M_\odot}$) of outflowing atomic gas. Assuming a spherical outflow and that maximum velocity observed in the wings, $v = 1300\,\mathrm{km\,s^{-1}}$, is the de-projected velocity of the outflow, they obtain a conservative lower limit on the outflow rate of $3500\,\mathrm{M_\odot\,yr^{-1}}$, which represents the highest outflow rate ever detected (see Maiolino et al. 2012, for further details on the observations). The associated kinetic power is barely consistent with the kinetic power that can be produced by a starburst-driven wind, even assuming a star formation rate (SFR) of $\sim 3000\,\mathrm{M_\odot\,yr^{-1}}$ as inferred from the strong FIR thermal emission detected by (sub)mm observations of J1148 (Bertoldi et al. 2003; Beelen et al. 2006). On the other hand, the kinetic energy is about 0.6 per cent of the bolometric luminosity of the quasar, meaning that the observed outflow is more likely to be powered by the active galactic nucleus (AGN).

Here we show that this observational result is a strong confirmation of the theoretical models presented in V11. In fact, in all of the evolutionary scenarios that successfully reproduce the observed properties of J1148, the outflow rate at $z = 6.4$ is largely dominated by the AGN and it is consistent with the observed lower limit.

In what follows, we adopt a Λ cold dark matter (ΛCDM) cosmology with $\Omega_\mathrm{m} = 0.24$, $\Omega_\Lambda = 0.76$, $\Omega_\mathrm{b} = 0.04$ and $H_0 = 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The age of the Universe at a redshift $z = 6.4$ is 900 Myr.

## 2 MODEL DESCRIPTION

Through a binary Monte Carlo algorithm with mass accretion based on the EPS theory, we have simulated 50 hierarchical merger histories of a $10^{13}\,\mathrm{M_\odot}$ dark matter (DM) halo at $z = 6.4$. As discussed in V11, a $[10^{12}–10^{13}]\,\mathrm{M_\odot}$ host DM halo is required to match the observed space density of $z \sim 6$ QSOs. The dependence of the results on the DM halo mass will be discussed in Section 5. Using the code GAMETE/QSODUST, we have followed in a self-consistent way the build-up of the J1148 central SMBH and of its host galaxy along these formation paths (V11).

The nuclear SMBH forms starting from $10^4\,h^{-1}\,\mathrm{M_\odot}$ seed BHs hosted in very high redshift haloes. Along each merger tree, the assembly of the host galaxy and its SFH are driven by binary mergers and mass accretion. Similarly, seed BHs grow by coalescences with other BHs and by gas accretion. The co-evolution of these two components, the SMBH and its host galaxy, is mostly controlled by quasar feedback in the form of a galactic-scale wind, which self-regulates the BH growth and eventually halts star formation.

The evolution of the mass of gas, stars and metals in the interstellar medium (ISM) is followed by taking into account infall and outflow processes from/to the external medium. Metal and dust enrichment is implemented in all progenitor galaxies by considering the contribution from stars of different masses, such as asymptotic giant branch stars and supernovae (SNe), taking into account the proper stellar lifetimes. Moreover, subsequent dust grain reprocessing in the ISM, namely destruction by interstellar shocks and grain growth in molecular clouds, is also taken into account.

Finally, different SFHs for the QSO host galaxy are explored: *quiescent* models, where the efficiency of star formation is independent of galaxy mergers, and *bursted* models, in which the star formation efficiency is enhanced during major mergers between progenitor galaxies.

## 3 MODEL RESULTS

In this section, we present the models that in V11 have been identified to reproduce the available observational constraints on J1148. In all models, the free parameters, namely the efficiency of star formation, BH accretion and quasar-driven wind, have been chosen to reproduce the BH and gas mass of J1148.

As discussed in V11, the inferred stellar mass, a crucial information for the evolutionary models, is affected by large uncertainties. This is the reason why two different values are given in Table 1 and the models that we have explored adopt progressively higher star formation efficiencies and therefore larger final stellar masses. We thus investigate the corresponding effects on the evolution of the chemical properties of host galaxy (metal and dust content).

Four out of the several models presented in V11 have been found to successfully reproduce the properties of the QSO J1148: Q1 t.h., B1 t.h., Q2 and B3. The first two are quiescent (Q1 t.h.) and bursted (B1 t.h.) star formation models where stars form according to a top-heavy IMF, while the quiescent (Q2) and bursted (B3) models assume a standard IMF.

### 3.1 BH–$M_{\rm star}$ relation

For convenience, we report in Fig. 1 the evolution of the $M_{\rm BH}$–$M_{\rm star}$ relation predicted by the four models introduced above. The location of J1148 on the $M_{\rm BH}$–$M_{\rm star}$ plane is indicated by the solid circle (with $M_{\rm star}$ given by the observations, see Table 1) and is compared with the $M_{\rm BH}$–$M_{\rm star}$ relation observed in local quasars and galaxies (open squares) and the empirical fit taken from Marconi & Hunt (2003). A detailed discussion can be found in V11. By construction, all models reproduce the mass of the SMBH in J1148 at $z = 6.4$, but predict different final stellar masses going from the value inferred from the observations, $\sim 3.9 \times 10^{10}\,{\rm M}_\odot$ (models Q1 t.h. and B1 t.h.), up to values progressively closer to the observed local relation, $\sim(1–4) \times 10^{11}\,{\rm M}_\odot$ (Q2 and B3, respectively).

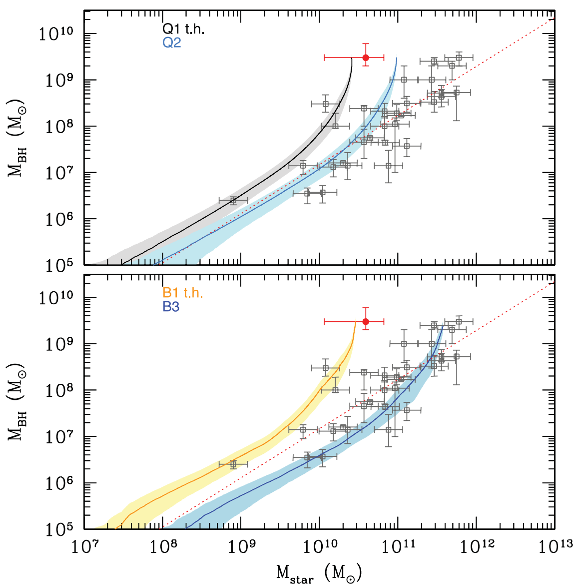


**Figure 1.** The evolution of the J1148 BH mass as a function of the stellar mass for quiescent (upper panels, Q1 t.h. with black line and Q2 with azure line) and bursted models (lower panel, B1 t.h. gold line and B3 blue line). The filled circle and open squares are the J1148 and local QSOs and galaxies observed $M_{\rm BH}$–$M_{\rm star}$ relations, respectively. The dashed line is the Marconi & Hunt (2003) empirical fit to the local relation. Solid lines are the four different models that in V11 have been selected to reproduce the available observations of J1148 (see text), averaged over 50 different merger tree realizations. The shaded areas represent the $1\sigma$ dispersion.

### 3.2 Chemical properties and SFH

By using the chemical evolutionary model with dust described in V11, we have analysed the dependence of the predicted J1148 chemical properties (in particular of metals and dust) on both the SFH (quiescent versus bursted SFRs) and IMF (standard versus top-heavy). The results of the four selected models are shown in Fig. 2. In this plot, we present the predicted evolution of the mass of gas, stars, metals and dust compared with the available observations for J1148. As it can be seen from the figure, independently of the SFH and IMF, both the masses of gas and metals grow up to a maximum value, reached at redshift $z \sim 8$, *and than decrease due to the strong effect of the quasar feedback*.

The SFR of high-redshift quasars is usually estimated from the FIR luminosity, adopting the $L_{\rm FIR}$–SFR relation derived by Kennicutt (1998) under the assumption that the dominant dust-heating mechanism is radiation from young stars. The conversion factor usually adopted to convert $L_{\rm FIR}$ to SFR, $\sim 5.8 \times 10^9\,{\rm L}_\odot$, has been derived assuming a 10–100 Myr old burst of star formation and a Salpeter IMF (see Kennicutt 1998). Following this prescription, the FIR luminosity estimated for J1148 (see Table 1) gives an SFR $\sim (3.8 \pm 0.57) \times 10^3\,{\rm M}_\odot\,{\rm yr}^{-1}$ (Bertoldi et al. 2003). However, it has been pointed out that the inferred SFR would be about an order of magnitude lower ($\sim 180\,{\rm M}_\odot\,{\rm yr}^{-1}$) if the Schmidt–Kennicutt law is instead adopted (Dwek, Galliano & Jones 2007; Li et al. 2008; V11).

In this work, we have further revised the SFR inferred from the observations, by taking into account the different IMFs adopted in our models, and we rescale the $L_{\rm FIR}$–SFR conversion factor for

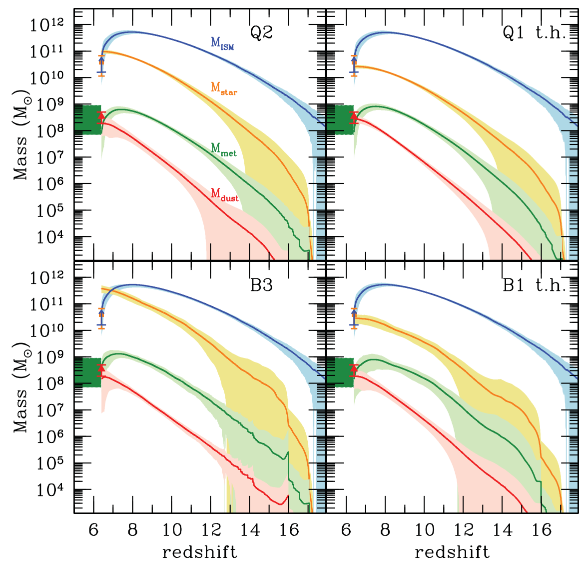


**Figure 2.** The ISM chemical evolution of the J1148 host galaxy in the four different models which best reproduce the observed properties. Solid lines are the evolution of the mass of gas (blue), stars (yellow), metals (green) and dust (red) averaged over 50 hierarchical merger histories with the $1\sigma$ dispersion given by the corresponding shaded areas. The blue arrow indicates the molecular gas mass ($M_{\rm H_2}$), considered as a lower limit for the total gas mass, the yellow solid square is the stellar mass computed as the difference between the dynamical and molecular gas mass, the red triangle is the mass of dust and the green region represents the mass of metals ($Z \times M_{\rm H_2}$).

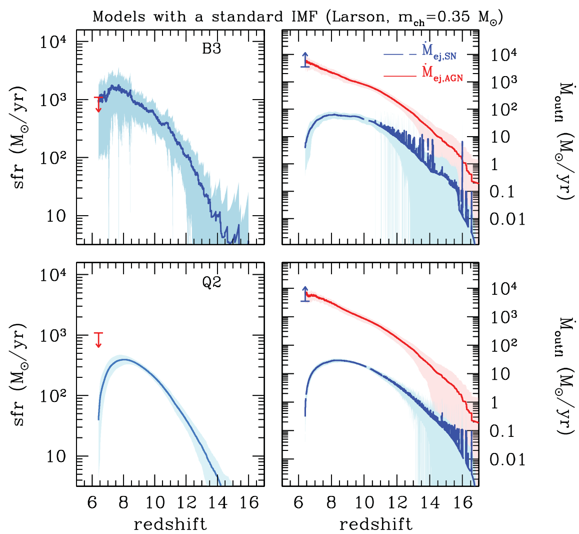


**Figure 3.** The star formation (left-hand panels) and the gas outflow (right-hand panels) rates as a function of redshift, predicted by models B3 and Q2. In both models, a Larson IMF with a characteristic mass $m_{ch} = 0.35\,M_\odot$ has been adopted. All the curves are the averages over 50 random merger tree realizations of the quasar host galaxy, with shaded areas representing the $1\sigma$ dispersion. Blue dashed and red solid lines in right-hand panels represent the mass of gas ejected per unit time by SN and quasar-driven winds, respectively. The arrows indicate the upper limit to the SFR of J1148, corrected for our adopted IMFs, or to the gas outflow rate, obtained by Maiolino et al. (2012).

a Larson IMF with $m_{ch} = 0.35\,M_\odot$ (standard IMF models) and $5\,M_\odot$ (top-heavy IMF). With this correction, we obtain SFRs ~3 to 30 times lower, more specifically SFR ~ $(1087 \pm 163)\,M_\odot\,yr^{-1}$, for a standard IMF, and SFR ~ $(113 \pm 17)\,M_\odot\,yr^{-1}$, for a top-heavy IMF. These values are still consistent with results quoted in previous works (Maiolino et al. 2005; Dwek et al. 2007; Li et al. 2008). Yet, as discussed in V11, we use these values as an upper limit to the effective rate of star formation in J1148, since the active quasar itself may give a non-negligible contribution to dust heating (Bianchi, Valiante & Schneider, in preparation). The quiescent and bursted SFHs for the four selected models are shown in the left-hand panels of Figs 3 and 4.

## 4 QUASAR AND SN-DRIVEN GAS OUTFLOW

In GAMETE/QSOdust, galactic outflows can be driven by SN explosions and by the AGN. Both stellar and quasar feedback are consistently modelled in the form of energy-driven winds sweeping the surrounding material away from the galaxy. The total gas outflow rate is given by $dM_{ej}(t)/dt = dM_{ej,SN}(t)/dt + dM_{ej,AGN}(t)/dt$, with

$$\frac{dM_{ej,AGN}}{dt} = 2\epsilon_{w,AGN}\epsilon_r\left(\frac{c}{v_e}\right)^2\dot{M}_{accr} \quad (1)$$

and

$$\frac{dM_{ej,SN}}{dt} = \frac{2\epsilon_w E_{SN}}{v_e^2}R_{SN}(t), \quad (2)$$

where $v_e^2$ is the escape velocity of the galaxy, $R_{SN}(t)$ is the SN explosion rate, $\dot{M}_{accr}$ is the BH gas accretion rate, $\epsilon_r$ is the radiative efficiency, fixed to be 0.1, and $E_{SN}$ is the average SN explosion energy, assumed to be $2.7 \times 10^{52}$ erg for PISNe and $1.2 \times 10^{51}$ erg for core-collapse SNe. The efficiency of SN winds ($\epsilon_w = 2 \times 10^{-3}$) has been calibrated by the chemical evolution model applied to the Milky Way and its dwarf satellites (Salvadori, Schneider & Ferrara 2007; Salvadori, Ferrara & Schneider 2008). The AGN-wind efficiency ($\epsilon_{w,AGN} = 5 \times 10^{-3}$) and the BH accretion efficiency ($\alpha$ = [180–200], according to the particular model) have been instead chosen to reproduce at the same time the gas and BH mass of J1148.

The right-hand panels of Figs 3 and 4 show the redshift evolution of the gas outflow rate predicted by the selected models, as labelled in the figures, by showing the separate contribution of SNe and the quasar. As it can be seen from these figures, for $z < 12$ the QSO outflow rate exceeds by more than two orders of magnitude the SN outflow rate in all the different models.

For all models, the predicted outflow rate at $z = 6.4$ is fully consistent with the lower limit to the gas outflow rate inferred by Maiolino et al. (2012). With this large outflow rate, the host galaxy should be rapidly cleared of its gas content and star formation should be quenched. Indeed, the predicted SFRs systematically show a downturn at redshifts $z <$ 7–8, when the effect of the quasar-driven wind on the evolution of the ISM gas mass becomes dramatic (see blue lines in Fig. 2). Such a decline is reflected also into the SN rate and, therefore, in the SN-driven outflow rate, which is orders of magnitude lower than the quasar-driven one.

The formulation adopted in V11 for the BH accretion rate ensures that the quasar feedback is active over almost the entire lifetime of the host halo. This feedback results into efficient gas ejection at $z < 8$, when the BH mass and accretion rate are higher (see V11 for a detailed discussion).

## 5 CONCLUSIONS

In this work, we have shown that the formation history of SMBH at the centre of high-redshift quasars is strongly linked to the properties of their host galaxies.

We use a state-of-the-art model (V11) that allows us to simulate a large number of independent hierarchical histories of quasar host galaxies, following at the same time the SFHs, chemical evolution and the gradual build-up of the nuclear BH by mergers and gas accretion.

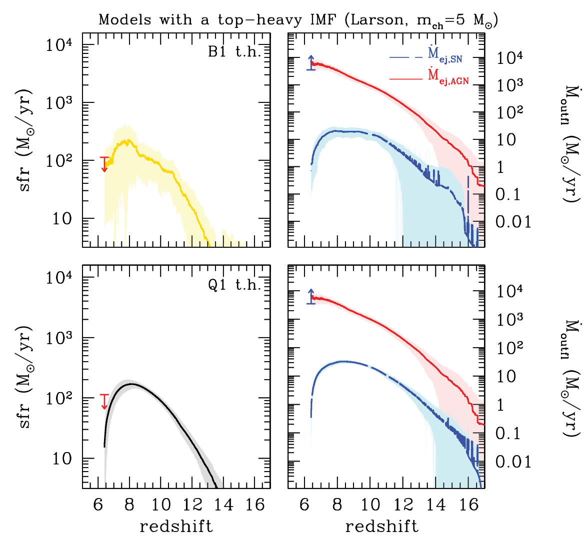


**Figure 4.** The same as in Fig. 3 but for models B1 and Q1. In these two models, a Larson IMF with $m_{ch} = 5\,M_\odot$ has been adopted.

We have recently applied this numerical model to one of the most distant quasars, SDSS J1148, at $z = 6.4$ and we have shown that the joint constraints provided by the dynamical gas and dust masses together with the mass of the nuclear SMBH allow us to reconstruct the SFHs and the nature of the dominant stellar populations in these systems. *A robust prediction of these models is that the evolution of the nuclear BH and of the host galaxy are tightly coupled by quasar feedback in the form of strong galaxy-scale winds*.

The recent detection of broad wings in the [C II] 158 μm line associated with SDSS J1148 by Maiolino et al. (2012) is a strong evidence of clear quasar feedback in the early Universe.

The comparison between model predictions and observational data shows that the gas outflow rates predicted by the models are fully consistent with the lower limit ($3500\,M_\odot\,yr^{-1}$) inferred from the observations. In addition, it lends strong support to the interpretation that the dominant driving mechanism is quasar feedback. According to the physical prescriptions and parameter values adopted in the models presented here, the outflow rate has already significantly affected the gas content of the galaxy, leading to a downturn in the SFR at $z < 7$–8.

It is important to stress that the theoretical findings have been derived independently, well before the observations. Therefore, strong quasar feedback has been a natural byproduct of models that have been identified to reproduce the observed dynamical and chemical properties of the host galaxy. In all models, the SN rate is constrained by the SFR inferred by the observations and by the chemical properties of the host galaxy. The associated SN-wind efficiency has been calibrated using the same chemical evolution model to reproduce the global properties of the Milky Way Galaxy (Salvadori et al. 2008). To be at least comparable with the observed outflow rate, the SN-wind efficiency should be higher by about three to four orders of magnitude. There are no physical motivations to justify such an enormous efficiency.

All the proposed scenarios, i.e. different combinations of SFHs and IMFs, provide consistent results for the quasar-driven gas ejection rate. Thus, the recent observation reported by Maiolino et al. (2012) does not help to break the degeneracy between the proposed models: accurate observations of the stellar mass are necessary to further constrain the properties of the J1148 host galaxy, therefore helping in the identification of the most appropriate IMF and SFH.

Finally, the comparison of our predicted gas outflow rate with that observed for J1148 by Maiolino et al. (2012) allows us to put additional constraints on the mass of the DM halo hosting the SMBH. With a DM halo mass equal to $10^{12}\,M_\odot$, both the BH accretion and feedback efficiencies need to be reduced in order to reproduce the observed BH and gas masses at $z = 6.4$. In fact, a smaller DM halo mass implies a reduced gas mass available at each redshift along the hierarchical history. As a result, the final outflow rate is more than one order of magnitude smaller than for the reference model with DM halo mass of $10^{13}\,M_\odot$ and inconsistent with the observed lower limit.

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