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Metals and dust in high redshift AGNs

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Abstract. We summarize some recent results on the metallicity and dust properties of Active Galactic Nuclei (AGN) at high redshift. By using the spectra of more than 5000 QSOs from the SDSS we find no evidence for any metallicity evolution in the redshift range 2<z<4.5, while there is a significant luminosity-metallicity dependence. These results are confirmed by the spectra of a smaller sample of narrow line AGNs. The lack of metallicity evolution is interpreted both as a consequence of the cosmic downsizing and as a selection effect resulting from the joint QSO-galaxy evolution. The luminosity-metallicity relation is interpreted as a consequence of the mass-metallicity relation in the host galaxies of QSOs. The lack of metallicity evolution is observed even in the spectra of the most distant QSOs known (z∼6). This result is particularly surprising for elements such as Fe, C and Si, which are subject to a delayed enrichment, and requires that the hosts of these QSOs formed in short bursts and at z>10. The properties of dust in high-z QSOs are discussed within the context of the dust production mechanisms in the early universe. The dust extinction curve is observed to evolve beyond z>4, and by z∼6 it is well described by the properties expected for dust produced by SNe, suggesting that the latter is the main mechanism of dust production in the early universe. We also show that the huge dust masses observed in distant QSOs can be accounted for by SN dust within the observational constraints currently available.

Key words. ISM: evolution – ISM: dust – Galaxies: quasars: emission lines – Galaxies: active – Galaxies: evolution

1. Introduction

Quasars and Active Galactic Nuclei (AGNs) in general are powerful tools to investigate the properties of the interstellar medium (ISM) in distant galaxies. Indeed, the huge luminosities characterizing such galactic nuclei, excite large masses of gas in their host galaxies, which as a consequence emit strong atomic (and molecular) lines that can be observed even in very distant systems. These lines can be used to study in detail the ISM properties, such as metal abundances. Moreover, the strong nuclear continuum can be used to investigate in detail reddening effects and, therefore, study the dust properties. Since large samples of AGNs are

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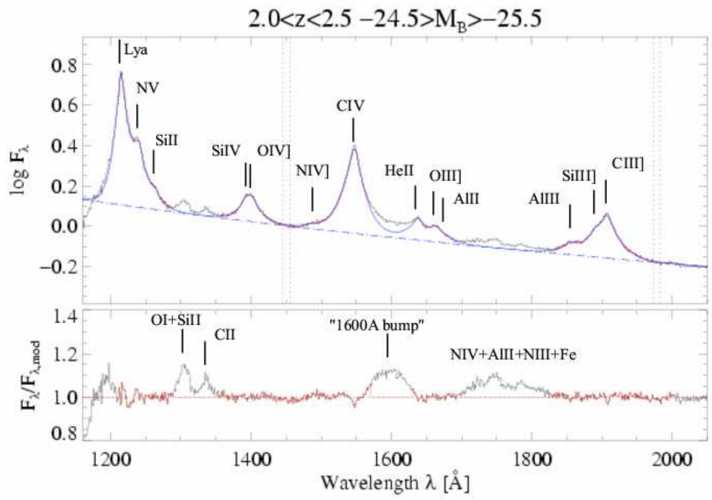

Fig. 1. One of the QSO composite spectra obtained by stacking a few hundreds SDSS spectra. In the upper panel the continuous smooth line shows the best fit to the main spectral lines. The bottom panel shows the residuals of the fit with the identification of additional spectral lines.

now available over large redshift intervals, they can be used to trace the evolution of the ISM as a function of the cosmic age. Since metals and dust are products of the stellar evolution, the ISM investigation through AGNs can be regarded as a powerful tool to constrain the scenarios of galaxy evolution. In this paper we summarize some recent results obtained by us on the metal abundances and dust properties of AGNs spanning a wide redshift range (1<z<6.4), including some preliminary results based on ongoing work.

2. The metallicity of the BLR at 2<z<4.5

We have used more than 5000 QSO spectra from the Sloan Digital Sky Survey (SDSS) data release 2 (DR2) to investigate the metallicity of the Broad Line Region (BLR) across the redshift range 2<z<4.5 and over the luminosity range $-24.5 < M_B < -29.5$ (Nagao et al. 2006a). The huge number of objects allow us to break the degeneracy between redshift and luminosity dependence of the metallicity, which plagued most of the previous studies. In particular, the number of objects is large enough that within each redshift bin we can investigate the metallicity-luminosity dependence and, viceversa, within each luminosity bin we can study the metallicity-redshift dependence. To improve the signal-to-noise ratio we have stacked the spectra within each redshift-luminosity bin, resulting in a grid of 22 high quality, composite spectra. Fig. 1 shows one of these composite spectra with a wealth of broad emission lines. In each spectrum the emission lines were deblended by using an algorithm described in Nagao et al. (2006a) and delivering accurate fluxes for individual lines. A clear, empirical result is that most line ratios depend significantly on luminosity, but do *not* vary significantly with redshift.

The several line ratios available for each composite spectra were compared with detailed photoionization models, presented in Nagao et al. (2006a), to infer the metallicity of the BLR (here abundances are assumed to scale proportionally to solar, except for nitrogen that is assumed to scale quadratically). The first important result is that the metallicities turn out to be super-solar in all cases. The trends as a function of redshift and luminosity are summarized in Fig. 2, which

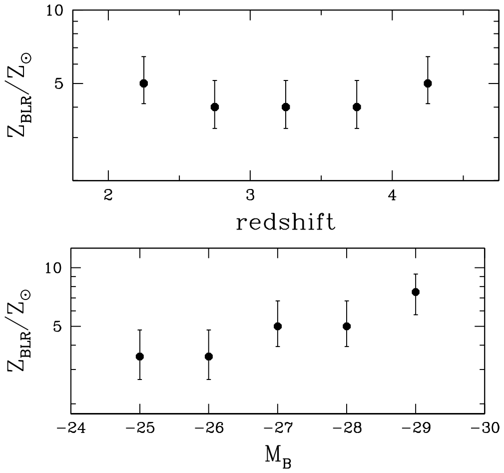

Fig. 2. Average metallicity as a function of redshift (upper panel) and average metallicity as a function of luminosity (lower panel). No evidence is found for a metallicity evolution in redshift, while there is a significant luminosity-metallicity dependence.

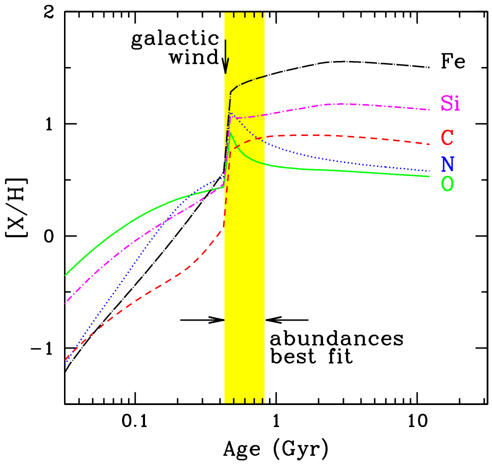

Fig. 3. Abundances evolution for an elliptical galaxy including feedback effects. The downward arrow indicates the onset of the galactic wind. The shaded area indicates the abundance sets which best fit the line ratios observed in the QSO spectra.

shows the metallicities averaged in redshift bins (top panel) and in luminosity bins (bottom panel). The striking result from the top panel of Fig. 2 is that the metallicities in the nuclear region of these quasars are insensitive to redshift, although the QSO sample spans about 90% of the age of the universe. The additional result is that the average metallicity is an increasing function of the QSO luminosity. The latter result can be interpreted as a consequence of the mass-metallicity relation in galaxies (e.g. Tremonti et al. 2004), due to the tendency of more massive galaxies to retain metals more effectively. Indeed, if the QSO luminosity is proportional to the black-hole mass (i.e. the Eddington ratio is on average constant for QSOs with different luminosities), then the $M_{BH} - M_{bulge}$ relation (e.g. Marconi & Hunt 2003) yields a relationship between QSO luminosity and galaxy mass, and therefore a dependence on metallicity. Although this scenario can qualitatively explain the luminosity-metallicity relation in QSOs, there are problems when a *quantitative* comparison is performed with the mass-metallicity relation observed in galaxies. Another possibility is that the luminosity–metallicity relation actually reflects a relationship between metallicity and accretion rate (in terms of L/L_{Edd}), as suggested by Shemmer et al. (2004). Unfortunately we cannot test the latter scenario, since the information on the black hole mass, and therefore on L/L_{Edd}, was lost in the process of stacking the spectra.

Much more puzzling is the lack of any metallicity evolution over the wide redshift range covered by our sample. Indeed, most galaxies at redshift larger than 2 should be undergoing (or have undergone) strong star formation, and therefore should be characterized by a differential chemical enrichment as a function of redshift (specifically, higher metallicities at lower redshifts). In the following we discuss three possible effects or scenarios that may explain the lack of evolution for the quasars BLR.

2.1. Selection effects associated with the QSO-galaxy co-evolution

The lack of metallicity evolution may be a consequence of QSOs being selectively observed at specific epochs, and in particular when they are already aged and chemically mature. Such an effect can be understood within the context of the recent models of QSO-galaxy co-evolution (e.g. Granato et al. 2004; Di Matteo et al. 2005). According to these models, during the early stages of galaxy and black hole growth the AGN is embedded in gas and dust and it is difficult to identify it as a QSOs, due to obscuration. At later times the combined energy released by SNe and by the QSO wind sweeps away large quantities of dust and gas, quenching star formation, and allowing the direct observation of the QSO. At this stage the ISM has already been heavily enriched. We are in the process of investigating this issue more quantitatively (Nagao et al. in prep). More specifically, instead of using constant abundances ratios as discussed above, we are using results of realistic, detailed abundances patterns based on evolutionary models including SNe and AGN feedback. For each abundance pattern at any stage, we infer the expected line ratios and compare them with those observed in the composite QSO spectra. A preliminary result is shown in Fig. 3, where the abundances evolution is shown for the case of a massive elliptical galaxy (Pipino & Matteucci 2004,this one only includes feedback from SNe, a version including QSO feedback is in preparation). The discontinuity in the slope at about 0.5 Gyr is a consequence of the onset of the galactic super-wind. The shaded area shows the range of abundances pattern that best match the line ratios observed in the composite spectra. The most interesting result is that the best matches are obtained at the wind onset, or shortly after that. On the one hand, this result nicely supports models of QSO-galaxy co-evolution involving feedback. On the other hand, the fact that QSOs can be selectively (or preferentially) observed only when they are (chemically) evolved, because their circumnuclear region has been cleared, may explain the apparent lack of metallicity evolution in QSOs.

However, selection effects due to joint QSO-galaxy evolution cannot be the only explanation for the observed lack of metallicity evolution. Indeed, in Sect. 3 we will show that the lack of evolution applies also to narrow line radio galaxies, which are obscured systems, hence presumably observed before the onset of the wind (although radio galaxies are known to be hosted in massive, evolved systems).

2.2. Antihierachical evolution and chemical downsizing

Recent observational studies have reported the detection of a number of high-z massive galaxies significantly larger than expected by classical hierarchical models (e.g. Fontana et al. 2004), suggesting that massive systems evolve faster and at higher redshift than less massive galaxies. This effect is also observed in AGN/QSO surveys, where more luminous systems (hence probably more massive) are seen to peak their evolution at redshift significantly higher than less luminous systems (Hasinger et al. 2005). This effect is known as "anti-hierarchical" growth or "downsizing", and it has been explained theoretically through the SN/QSO feedback effects, which reverse the hierarchical baryonic growth with respect to the dark matter haloes (Di Matteo et al. 2005; Granato et al. 2004). Savaglio et al. (2005) found a chemical version of the downsizing phenomenon, by investigating the mass-metallicity relation at high redshift ($z\sim1$). They found that the M–Z relation evolves, from z=0 to z=1, very rapidly at low galactic masses (in the sense that the metallicity decreases rapidly from z=0 to z=1), while the chemical evolution at high masses ($M_* \approx 10^{11} M_\odot$) is only marginal, and probably remains constant within uncertainties. This result indicates that more massive system evolve, from the chemically point of view, at higher redshift and faster than less massive systems. All the SDSS QSOs used in Nagao et al. (2006a) are very luminous systems, which are probably hosted in very massive galaxies ($M_* > 10^{11} M_\odot$) that, within the context of the downsizing scenario, represent very extreme cases, being already fully evolved and mature already at very high redshift. A more quantitative analysis of the chemical downsizing applied to QSOs will be presented in a forthcoming paper.

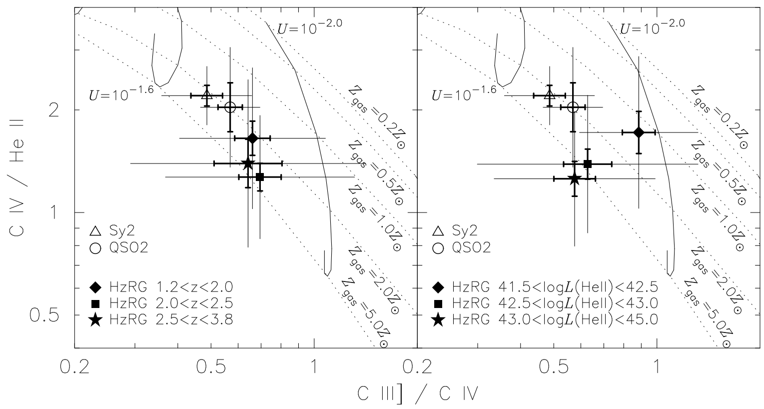

Fig. 4. Diagram showing the average line ratios CIVλ1549/HeIIλ1640 and CIII]λ1909/CIVλ1549 for radiogalaxies grouped in bins of redshift (left) and of HeII luminosity (right). These diagrams are a useful diagnostic to investigate the metallicity of the Narrow Line Region. In particular the dotted lines indicates the loci of the line ratios at constant gas metallicity, while solid lines show loci at constant ionization parameter. An increasing metallicity tends to decrease both line ratios. The observed average line ratios indicate no evolution of the gas metallicity as a function redshift, but there is a significant dependence on luminosity.

2.3. BLR not representative of the host galaxy

The BLR is contained in a very small nuclear region (less than a parsec in size), which could be subject to a much more rapid evolution than the rest of the galaxy. The gas mass of the BLR is small enough that a relatively small number of SNe is enough to rapidly enrich it. Summarizing, the BLR may not be representative of the metallicity in the host galaxy. This issue can be tackled by estimating the metallicity of the Narrow Line Region (NLR), which extends on sizes comparable with the host galaxy, as discussed in the following section.

3. The metallicity of the NLR at 1<z<4

We have used a sample of about 60 high-redshift narrow-line AGN (radio galaxies and type 2 QSOs, which are both AGNs where the BLR is obscured) to investigate the metallicity of the Narrow Line Region (NLR) in the redshift range 1<z<4 (Nagao et al. 2006b). Although this is the largest sample of narrow line AGNs available in this redshift range, it is certainly much smaller than the huge sample available from the SDSS for broad line QSOs. Moreover, the faintness of these objects restricts the use of their observed spectra only to a few (narrow) emission lines. Even with these caveats, the narrow lines probe a region much more extended than the BLR (in luminous objects the NLR extends over several kpc), and therefore they are more suited to probe the host galaxy. Details of this investigation are provided in Nagao et al. (2006b). Fig. 4 summarizes the main results through the diagram involving the UV line ratios CIV/HeII vs. CIII]/CIV, which is a powerful diagnostic diagram to probe the metallicity of the NLR. The dotted curves indicate the loci at constant metallicity, which moves from the top-right towards the bottom-left part of the diagram with increasing metallicity. In the left-hand side panel black symbols indicate the line ratios observed in radio galaxies, averaged in redshift bins. The most interesting result is a lack of evolution, in terms of line ratios (and therefore in terms of metallicity), from z~1.6 to z~3.2, as previously found for the BLR. In the right-hand side panel black symbols indicate the line ratios observed in radio galaxies, averaged in bins of HeII luminosity, where the HeII line is assumed to be a fair indicator of the intrinsic luminosity of these systems. These diagrams display a significant dependence of

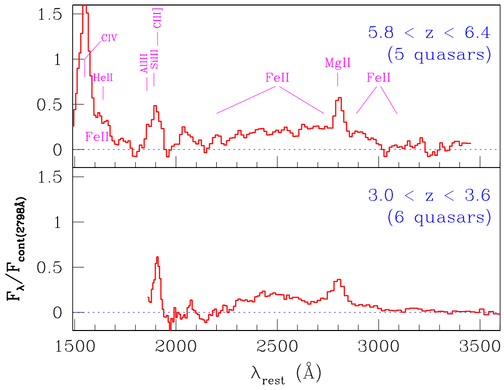

Fig. 5. UV rest-frame average spectra of 5 QSOs at 5.8<z<6.4 (top) showing a prominent iron bump, similar to that observed in lower redshift QSOs (bottom), suggesting a large abundance of Fe even at an epoch when the age of the universe was less than 1 Gyr.

the metallicity on luminosity, as found for the BLR. Summarizing, the trends observed for the BLR are also observed for the NLR, suggesting that the lack of metallicity evolution cannot be entirely ascribed to the small volume probed by the former, nor to obscuration effects associated with evolutionary effects.

4. The chemical evolution of QSOs beyond z>5

The SDSS have now delivered a sizeable sample of quasars even at redshift z>5, the most distant of which currently being at z=6.4 (Fan et al. 2003). Such high redshifts are extremely interesting to investigate within the context of the chemical evolution. Indeed, at z>5 the age of the universe is comparable with the minimum timescale required by stellar processes to enrich the ISM and therefore, regardless of selection effects and galactic evolutionary scenarios discussed above, some chemical evolution is expected to occur. In particular, some elements such as iron and carbon are mostly enriched by type Ia supernovae (SNIa) and AGB stars, which require about 1 Gyr to evolve in classical models, while at z=6.42 the age of the universe is about 800 Myr.

At such high redshift many of the most prominent QSO emission lines are shifted into the near-IR band. Our and other groups have employed deep near-IR spectroscopic observations to investigate the metallicity and abundances in the most distant quasars known. The most surprising result is the evidence for high chemical enrichment already at these early epochs and, again, the lack of any evolution with respect to QSOs at lower redshift. Fig. 5 shows the (continuum-subtracted) average spectrum of 5 QSOs at 5.8<z<6.4 in the UV rest frame (from Maiolino et al. 2003). The prominent bump at $2200 < \lambda_{rest} < 3000$Å, produced by Fe multiplets, suggests a large abundance of iron (probably super-solar) in these objects. The quantitative determination of the iron abundance through these spectra is not trivial and highly uncertain (Verner et al. 2004). However, the similarity of the Fe-bump–to–MgIIλ2798 ratio between intermediate redshift and z~6 QSOs (Fig. 5) strongly suggests little or no evolution in terms of iron abundance relative to the α-elements (which are expected to be produced on much shorter time scales by SNIIe). Similar results were obtained by several other authors (Iwamuro et al. 2004; Freudling et al. 2003; Dietrich et al. 2003; Barth et al. 2003). The analysis of other (broad) line ratios involving other important elements (C, N, Si) have also provided no clear evidence for any chemical evolution up to z~6 (Pentericci et al. 2002,Maiolino et al. in prep.).

The criticism, as discussed in 2.3, that these broad lines used originate from a small region and that may not be representative of the host galaxy, is addressed by recent millimetric and radio observations. Indeed, Walter et al. (2003) and Bertoldi et al. (2003) reported the detection of CO emission lines in the most distant QSO SDSSJ1148+52 at z=6.4. This line is certainly emitted in the host galaxy of the QSO and, beside tracing a large quantity of molecular gas, suggests the presence of large amounts of carbon. However, CO lines are optically thick and may be intense even if the carbon abundance is reduced. A more decisive observation was the detection of the [CII]158μm in the same object (Fig. 6, Maiolino et al. 2005). In contrast to CO, this [CII] line is optically thin,

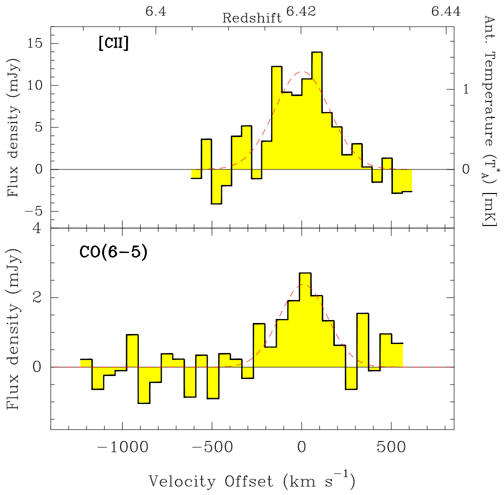

Fig. 6. [CII]158μm (top) and CO(5–6) (bottom) emission lines detected in the host galaxy of the most distant QSO SDSSJ1148+52 at z=6.4 (Maiolino et al. 2004).

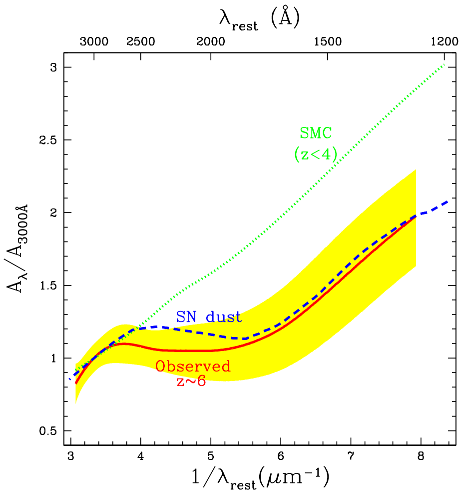

Fig. 7. Extinction curve observed in the QSO SDSSJ1049+46 at z=6.2 (solid curve and shaded area) compared with the SMC curve (dotted line), which applies to QSOs at z<4, and with the extinction curve expected for dust produced by SNe (dashed line, adapted from Maiolino et al. 2004)

and its intensity indicate a strong carbon enrichment in the host galaxy of SDSSJ1148+52 at z=6.4. However, more observations are required to quantitatively determine the carbon abundance, and in particular the C/O ratio, as discussed in Maiolino et al. (2005).

Altogether these results on the metal enrichment of the most distant QSOs are surprising, but not yet in striking contrast with models of chemical evolution. Indeed, in the extreme scenario of a very rapid and very efficient formation of massive elliptical galaxies (and occurring at very high redshift, z>10), recent models can account for a strong enrichment of critical elements, such as Fe, C, N, Si, on time scales as short as a few 100 Myr (Matteucci & Recchi 2001; Pipino & Matteucci 2004; Venkatesan et al. 2004,see also Fig. 3). Within this context, it is important to note the recent finding by Mannucci et al. (2005) and Mannucci et al. (2006) that a population of "fast" SNIa can enrich the ISM on time scales shorter than 100 Myr.

5. Dust evolution at high redshift

Dust, which plays a crucial role in the formation of galaxies and on their observability, is also affected by evolutionary issues and time scales associated with stellar processes. More specifically, according to the classical scenario dust is mostly formed in the envelopes of AGB stars (and late giant in general) which take about 1 Gyr to evolve (Morgan & Edmunds 2003; Marchenko 2006). As a consequence, little dust is expected to be present at z>5, when the universe was younger than 1 Gyr. However, a recent unexpected and puzzling result, obtained through deep mm and submm observations, is the detection of far-infrared thermal emission in several QSOs at z>5, tracing huge masses of dust (Bertoldi et al. 2003; Robson et al. 2004).

5.1. SN dust in the early universe

One possible explanation is that dust is produced in the ejecta of core-collapse supernovae, which evolve on short time scales and therefore provide a rapid mechanism of dust enrichment. The observational evidence for dust production in SNe comes from the observation of SN1987A (e.g. Moseley et al. 1989;

Lucy et al. 1989; Roche et al. 1993; Spyromilio et al. 1993; Colgan et al. 1994), and theoretically modelled by various authors (e.g. Todini & Ferrara 2001; Nozawa et al. 2003). The scenario of SN dust in the early universe has been recently tested by our group through the observation of the reddened QSO SDSSJ1048+46 at z=6.2 (Maiolino et al. 2004). In particular, we found that the extinction curve of the dust responsible for the reddening is different with respect to that observed at z<4 (which is SMC-like, Hopkins et al. 2004), but it nicely matches the extinction curve expected for dust produced by SNe (Fig. 7). This result strongly suggests that most of the dust in the early universe, at z∼6, is produced by SNIIe. Similar results have been obtained by Hirashita et al. (2005). This investigation has been extended to a larger number of QSOs at 4<z<6.2. Preliminary results indicate that the extinction curve evolve gradually from the SMC-like curve characterizing most QSOs at z<4, to the SN dust-dominated extinction curve at z=6.2 (Maiolino et al. in prep).

Recent Spitzer observations have detected only small amounts of dust in Galactic supernova remnants (SNRs), much smaller than expected by models (Hines et al. 2004; Krause et al. 2004), thus questioning theories ascribing to SNe most of the dust production at high redshift. However, Spitzer observations are mostly sensitive to the warm component of dust, which probably accounts for a minor fraction of the dust present in SNRs. Millimetric and submillimetric data are, in principle, suited to detect the cold component of the dust, which may account for most of the dust mass in SNe. So far only upper limits have been reported for mm/submm cold dust emission in SNRs, once non-thermal and foreground components are subtracted (Wilson & Batrla 2005; Krause et al. 2004). Yet, Fig. 8 illustrates that the current observational constraints on the dust production in SNe are still consistent with the scenario where most of the dust in QSOs at z∼6 is produced by SNe. The curved lines show the total dust mass produced by SNe as a function of the age of the galaxy, assuming a star formation rate equal to that observed in the most distant QSO at z=6.4, SDSSJ1148+52 (3000 $M_\odot$ yr^{-1}, Bertoldi et al. 2003) and a constant dust mass produced per each supernova (M^{SN}_{dust}). The two bottom curves show the dust produced assuming M^{SN}_{dust} equal to the dust mass observed in CasA and in the Crab Nebula through Spitzer and ISO observations (Hines et al. 2004; Green et al. 2004). Since such observations sample only the warm component of dust and miss the cold component, these curves should be considered as a lower limit on the total dust mass produced. The two upper curves show upper limits on the total dust mass assuming a M^{SN}_{dust} equal to different upper limits inferred for the cold dust in CasA, based on submm data (lower curve from Krause et al. (2004), upper curve from the later value obtained by Wilson & Batrla (2005)). The solid symbol with errorbars indicate the dust mass in the most distant QSO SDSSJ1148+52 inferred from various mm and submm data (Bertoldi et al. 2003; Carilli 2004; Beelen 2005), including the uncertainty on the emissivity (Dasyra et al. 2005), and assuming a formation epoch in the range 7.5<z<15. The important result is that the observed dust mass is consistent with the maximum dust mass production which is allowed for SNe, based on observational constraints. However, if the host galaxy is as young as a few times 10^7 yr, as tentatively suggested by Walter et al. (2004), then even SNe may not have time to produce enough dust. The uncertainties are however still very large, and more observational data are certainly required to further investigate this issue.

5.2. QSO–dust in the early universe

An alternative mechanism for dust production in the early universe was proposed by Elvis et al. (2002). They show that the physical conditions (and in particular temperature and density) in the outflowing clouds of QSOs are similar to the conditions of AGB stellar envelopes, and therefore may provide sites of dust formation. The interesting feature of this possible mechanism is that it is not subject to specific time scales, and therefore it may provide a fast enrichment mechanism in the early universe, when AGB stars had not time to evolve.

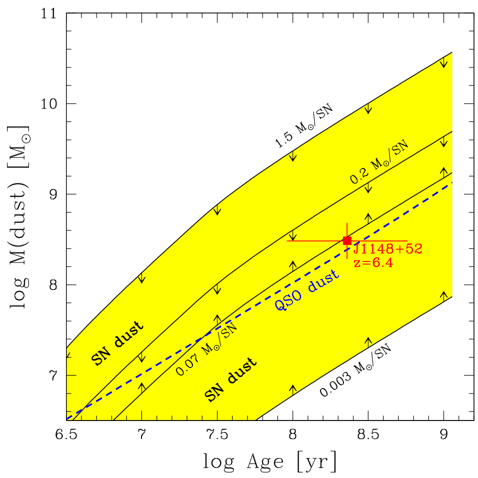

Fig. 8. The solid curved lines show the constraints on the dust mass produced by SNe as a function of age for the most distant QSO SDSSJ1148+52 at z=6.4, based on the current observational constraints on the dust mass produced per SN (see text for details). The dashed line is the expected dust produced in QSO winds, according to the model of Elvis et al. (2002), and under the assumptions discussed in the text. The solid dot with errorbars indicates the dust mass observed in SDSSJ1148+52, assuming a formation redshift between 7.5 and 15, which appear consistent with both the scenarios of SN-dust and QSO-dust production.

A possible caveat of this process is that it must await for the production of metals (in particular C and Si) from the stellar evolutionary processes. However, we have seen in the previous section that these elements may be produced even on relatively short time scales, and therefore this may not be a real problem preventing the formation of dust through QSO winds in the early universe. Unfortunately, Elvis et al. (2002) do not provide predictions for the extinction curves to be compared with our observations, as in Sect. 5.1. However, it is at least possible to check whether QSO winds can produce enough dust to account for the dust mass observed in high-z QSOs. We have developed a simple model by assuming that a QSO has always been accreting at the Eddington rate, that the outflow rate is $\dot{M}_{\rm wind}$ [$M_\odot$/yr] = 0.5×10^{-8} $M_{\rm BH}/M_\odot$ (Proga & Kallman 2002), that the metallicity of the nuclear region has always been Z = 10 $Z_\odot$, and a depletion of metals into dust as observed in the diffuse ISM of our Galaxy. These assumption are somewhat extreme, and therefore the results should be regarded as upper limits. However, our assumptions are probably not very far from reality for such rare and extreme QSOs as those found by the SDSS at z~6. The dashed line in Fig. 8 indicates the total dust mass produced by QSO winds under such assumptions, and shows that the huge dust mass observed in SDSSJ1148+52 at z=6.4 can be produced even through this mechanism. Possibly, both SNe and QSO winds may contribute to the dust enrichment in the early universe. A more thorough analysis will be presented in a forthcoming paper.

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