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THE ORIGIN OF DUST IN THE EARLY UNIVERSE: PROBING THE STAR FORMATION HISTORY OF GALAXIES BY THEIR DUST CONTENT.

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ABSTRACT

Two distinct scenarios for the origin of the $\sim 4 \times 10^8 M_\odot$ of dust observed in the high-redshift ($z = 6.4$) quasar J1148+5251 have been proposed. The first assumes that this galaxy is much younger than the age of the universe at that epoch so that only supernovae could have produced this dust. The second scenario assumes a significantly older galactic age, so that the dust could have formed in lower-mass AGB stars. Presenting new integral solutions for the chemical evolution of metals and dust in galaxies, we offer a critical evaluation of these two scenarios. We show that the AGB scenario is sensitive to the details of the galaxy's star formation history (SFH), which must consist of an early intense starburst followed by a period of low stellar activity. The presence or absence of massive amounts of dust in high-redshift galaxies can therefore be used to infer their SFH. However, a problem with the AGB scenario is that it produces a stellar mass that is significantly larger than the inferred dynamical mass of J1148+5251, an yet unresolved discrepancy. If this problem persists, then additional sites for the growth or formation of dust, such as molecular clouds or dense clouds around active galactic nuclei, must be considered.

Subject headings: galaxies: formation, evolution, high-redshift, starburst, AGN
– infrared: galaxies, general –
ISM: interstellar dust – individual (SDSS J114816.64+525150.3)

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1. INTRODUCTION

Determining the origin of the massive amount of dust present in SDSS J1148+5251 (hereafter J1148+5251), a hyper-luminous quasar at $z = 6.4$ presents a special challenge. The dust mass inferred from far-infrared and submillimeter observations is $\sim (1-5) \times 10^8 M_\odot$ depending on dust composition (Dwek et al. 2007, and references therein), about ten times larger than the mass of dust in the Milky Way (Sodroski et al. 1997). The total infrared (IR) luminosity is about $2 \times 10^{13} L_\odot$, giving a star formation rate (SFR) of $\sim 3400 M_\odot \text{ yr}^{-1}$ for a Salpeter initial mass function (IMF). Since the universe was only ~ 890 Myr old at that redshift, and the galaxy perhaps much younger, it has been suggested that only core-collapse supernovae (hereafter SNe) can produce the observed amount of dust in this object (Morgan & Edmunds 2003; Dunne et al. 2003; Nozawa et al. 2003; Maiolino et al. 2004; Rho et al. 2008; Sibthorpe et al. 2009). Another argument made in favor of SNe as the most important dust sources in the early universe, was based on observations of unmixed ejecta of young remnants, primarily Cas A. The inferred dust mass in this remnant, ranging from $\sim 0.1 - 0.2 M_\odot$, was considered sufficiently large for SNe to account for the observed dust mass in J1148+5251 (Rho et al. 2008; Sibthorpe et al. 2009; Barlow et al. 2010). We consider the $\sim 1 M_\odot$ of dust mass claimed by Dunne et al. (2003, 2009) to have formed in Cas A as an unreasonable amount of dust. The total ejecta mass is $2 - 4 M_\odot$, of which only $\sim 0.2 M_\odot$ consists of condensible elements [e.g. Nozawa et al. (2010), and references therein].

None of these assertions, that SNe are significant dust sources in the early universe, were substantiated by detailed calculations. Specifically, the role of supernovae as destroyers of dust during the remnant phase of their evolution was completely ignored. Furthermore, these claims tacitly assume that the epoch of intense star formation spanned the entire age of the galaxy, which requires an excessively large reservoir of interstellar gas. All these considerations point to the need of more detailed calculations to ascertain the role of SNe as dust sources in the early universe. In such recent calculations, (Dwek et al. 2007) explored the combined effects of dust formation and destruction on the net amount of dust produced in J1148+5251. They found that SNe cannot be important sources of dust in the early universe unless they produce significantly more, and destroy significantly less dust than implied by current observations or theoretical calculations.

In light of these difficulties, Valiante et al. (2009) suggested that AGB stars could be the source of dust in J1148+5251. Their model is based on the numerical simulations of the formation and growth of this galaxy through a series of successive mergers that resulted in repeated intense bursts of star formation (Li et al. 2007). Associated with these mergers is the growth of its central black hole (BH) which at $z \approx 6.4$ has reached a mass of about $\sim 10^9 M_\odot$. In this scenario, star formation commenced at $z \approx 15$, when the universe was

merely 250 Myr old. Consequently, the progenitors of the more numerous and efficient dust producing AGB stars had time to evolve off the main sequence (see Table 1), and produce the observed mass of dust in J1148+5251.

This paper takes a critical look at the these two proposed dust formation scenarios, hereafter referred to as the SN- and AGB-scenarios. We start by introducing some basic definitions of the various quantities that govern the chemical evolution of galaxies, and present new integral solutions for the chemical evolution of galaxies (§2). In §3 we discuss the yields of the main stellar dust sources. These include the explosive SN ejecta, the fast winds created during the Wolf-Rayet (WR) stage of the evolution of stars with masses in excess of $\sim 40 M_{\odot}$, and the quiescent winds from AGB stars. In §4 we calculate the contribution of SNe and AGB stars to the production of dust in young galaxies. We also calculate the evolution of the stellar mass, the stellar luminosity, and the galaxy’s final spectral energy distribution (SED). In §5 we illustrate the sensitivity of the dust evolution to the galaxy’s SFH and the dust lifetime by following the evolution of dust generated in discrete bursts of star formation. Finally, in §6 we explore two additional dust sources: molecular clouds, which have always been considered as an environment for the growth and processing of interstellar dust grains in the Galaxy (Dwek & Scalo 1980; Liffman & Clayton 1989; Dwek 1998; Greenberg & Li 1999; Zhukovska et al. 2008), and AGN winds, which were recently suggested as potential producers of interstellar dust in quasars (Elvis et al. 2002; Maiolino et al. 2006). The results of the paper are briefly summarized in §7.

2. EQUATIONS FOR THE EVOLUTION OF DUST

2.1. Basic Definitions

We define the stellar IMF, $\phi(m)$, so that $\phi(m)dm$, is the number of stars with masses between m and $m + dm$, and normalize it to unity in the $\{m_l, m_u\}$ mass interval, where m_l , and m_u are, respectively, the lower and upper mass limits of the IMF. The IMF-averaged stellar mass, $\langle m \rangle$, is then:

$$\langle m \rangle = \int_{m_l}^{m_u} m \phi(m) dm \quad , \quad (1)$$

The SFR, $\psi(t)$, is the mass of stars formed per unit time, and is related to the stellar birthrate, $B(t)$, by:

$$B(t) = \frac{\psi(t)}{\langle m \rangle}. \quad (2)$$

We assume that all stars in the $[m_l, m_w]$ mass range end their life quiescently, whereas all stars with masses $m_w \leq m \leq m_u$ become core-collapse supernovae (CCSNe), where

$m_w = 8 M_\odot$, is their lower mass cut.

A useful quantity is m_\star , the mass of all stars born per SN event, given by:

$$m_\star \equiv \langle m \rangle / \int_{m_w}^{m_u} \phi(m) dm \quad (3)$$

The SN rate, R_{SN} , is then given by:

$$R_{\text{SN}}(t) = B(t) \int_{m_w}^{m_u} \phi(m) dm = \frac{\psi(t)}{m_\star} \quad , \quad (4)$$

In all our calculations we will use a mass-heavy ISM characterized by a power law: $\phi(m) \sim m^{-\alpha}$ in the $\{m_l, m_u\} = \{1 M_\odot, 100 M_\odot\}$ mass interval, with $\alpha = 2.35$. For this IMF we get:

$$\langle m \rangle = 3.1 M_\odot \quad \text{and} \quad m_\star = 53.0 M_\odot \quad (5)$$

2.2. Equations for the Evolution of Dust or Elements

We first describe the equations for the evolution of the mass of dust in the ISM. Let $M_g(t)$ be the mass of the gas in the ISM at a given time t . The evolution of $M_d(t)$, the mass of dust in the ISM, is governed by the equation:

$$\frac{dM_d(t)}{dt} = - \left[\frac{M_d(t)}{M_g(t)} \right] \psi(t) - \frac{M_d(t)}{\tau_d(t)} + \mathcal{S}(t) \pm \left[\frac{dM_d(t)}{dt} \right]_{\text{inf/out}} \quad (6)$$

where the first term represents the rate at which the dust is removed from the ISM by star formation; the second is the rate at which the mass of elements locked up in dust is returned to the gas phase of the ISM by sputtering or evaporative grain-grain collisions. The parameter $\tau_d(t)$ is the timescale for the combined effect of these processes which are launched by SN blast waves; the third term represents the rate of increase/decrease in the dust mass as a result of infall/outflow from the galaxy, and the fourth term, $\mathcal{S}(t)$, is a source function representing the rate of dust formation in the different astrophysical environments.

The timescale for grain destruction in supernova shock waves is given by:

$$\tau_d \equiv \frac{M_d}{\langle m_d \rangle R_{\text{SN}}} \quad (7)$$

The parameter $\langle m_d \rangle$ is the total mass of the refractory elements, initially locked up in dust, which are returned back to the gas phase of the ISM throughout the evolution of a single

SNR. For the MW galaxy, Jones (2004) found a dust lifetime of $\tau_d \approx 500$ Myr. Adopting a total dust mass $M_d \approx 3 \times 10^7 M_\odot$, and a Galactic SN rate $R_{\text{SN}} \approx 0.02$ (Diehl et al. 2006), gives a value of about $3 M_\odot$ for the grain destruction efficiency in the Galaxy. Since $\langle m_d \rangle$ scales linearly with the mass of ISM dust, we can write:

$$\langle m_d \rangle = \left[\frac{M_d(t)}{M_g(t)} \right] \frac{\langle m_d \rangle_{mw}}{Z_{d,mw}} = \left[\frac{Z_d}{Z_{d,mw}} \right] \langle m_d \rangle_{mw} \quad (8)$$

where $\langle m_d \rangle_{mw} = 3 M_\odot$ is the Milky Way value of $\langle m_d \rangle$, and $Z_{d,mw} \approx 0.007$ is the average dust-to-gas mass ratio in the Milky Way (Zubko et al. 2004). Equation (8) introduced the definition of the dust-to-gas mass ratio, Z_d :

$$Z_d(t) \equiv \frac{M_d(t)}{M_g(t)} \quad , \quad (9)$$

The grain destruction rate can then be written as:

$$\frac{M_d(t)}{\tau_d(t)} = Z_d \left[\frac{\langle m_d \rangle_{mw} R_{\text{SN}}}{Z_{d,mw}} \right] \quad (10)$$

The source function $\mathcal{S}(t)$ represents the rate at which the dust mass in the ISM increases by the nucleation in the different dust sources, or by growth in the ISM, which is an important process responsible for the differential depletions in its different phases. Considering only stellar sources, the source function can then be written as:

$$\begin{aligned} \mathcal{S}(t) = & \int_{\tilde{m}}^{m_w} \left[\frac{\psi(t - \tau_{ms}(m))}{\langle m \rangle} \right] Y_{d,agn}(m) \phi(m) dm & (\text{AGB stars}) \\ & + \int_{m_{wr}}^{m_u} \left[\frac{\psi(t - \tau_{ms}(m))}{\langle m \rangle} \right] Y_{d,wr}(m) \phi(m) dm & (\text{WR stars}) \\ & + \int_{m_w}^{m_u} \left[\frac{\psi(t - \tau_{ms}(m))}{\langle m \rangle} \right] Y_{d,sn}(m) \phi(m) dm & (\text{SNe}) \\ & + \mathcal{A}_{Ia} \int_0^t \left[\frac{\psi(t - \tau)}{\langle m \rangle} \right] Y_{d,Ia} f_{Ia}(\tau) d\tau & (\text{SNIa}) \end{aligned} \quad (11)$$

where the different terms represent the net contribution of the different stellar sources to the dust mass in the ISM. For each stellar mass, the SFR, $\psi(t')$, is calculated at the epoch $t' = t - \tau_{ms}(m)$, where $\tau_{ms}(m)$ is the main sequence lifetime of a star of mass m (Table 1). For AGB stars, the lower limit of the integral, \tilde{m} , is given by: $\max\{m_l, m'(t)\}$, where $m'(t)$ is the mass of a star with a main sequence lifetime t . The lower limit, m_{wr} is the limiting mass above which stars undergo extensive mass loss and become WR stars. $Y_{d,agn}(m)$, $Y_{d,wr}(m)$,

$Y_{d,sn}(m)$, and $Y_{d,Ia}$ are the dust yields in the quiescent winds of AGB and WR stars, and in the explosive ejecta of core-collapse and Type Ia SNe, respectively. In the last term, \mathcal{A}_{Ia} is a normalization constant that can be determined from the ratio between the observed frequency of Type II and Type Ia SNe, and $f_{Ia}(\tau)$ is the distribution function of the delay time, τ , between the birth of the stellar system and the SNIa event (Greggio 2005, 2010). For stellar masses above $\sim 8 M_{\odot}$, $\tau_{ms}(m) \ll t$ for most times of interest, so that the yield from SNe and WR stars can be set equal to $R_{SN} \tilde{Y}_{d,sn}$, and $R_{WR} \tilde{Y}_{d,wr}$, respectively, where R_{WR} is the rate of WR stars, and $\tilde{Y}_{d,sn}$ and $\tilde{Y}_{d,wr}$ the respective IMF-averaged yields of dust in SN and WR stars.

The term describing the rate of change in the dust mass caused by the exchange of gas with the intergalactic medium depends on whether the gas is flowing in or out of the galaxy. In an outflow, the dust-to-gas mass ratio in the outflowing gas is about equal to the galaxy's value, Z_d , and the term is given by:

$$\left[\frac{dM_d(t)}{dt} \right]_{out} = Z_d(t) \left(\frac{dM_g(t)}{dt} \right)_{out} \quad \text{for outflows} \quad (12)$$

In the case of infall, the dust-to-gas mass ratio of the infalling gas, Z_d^{inf} , is generally different from Z_d , and the term becomes:

$$\left[\frac{dM_d(t)}{dt} \right]_{inf} = Z_d^{inf}(t) \left(\frac{dM_g(t)}{dt} \right)_{inf} \quad \text{for infalls} \quad (13)$$

Finally, equation (6) can also be used to describe the evolution of any metal or radioactively unstable nuclei in the ISM by using the appropriate yields in eq. (11), and by exchanging the dust lifetime, τ_d , with the radioactive decay time of the unstable element.

2.3. The Evolution of the Gas

The evolution of the ISM gas is given by the equation:

$$\begin{aligned} \frac{dM_g(t)}{dt} &= -\psi(t) + \int_{m_l}^{m_u} \left[\frac{\psi(t - \tau_{ms}(m))}{\langle m \rangle} \right] M_{ej}(m) \phi(m) dm \pm \left[\frac{dM_g(t)}{dt} \right]_{inf/out} \\ &\approx -(1 - R) \psi(t) \pm \left[\frac{dM_g(t)}{dt} \right]_{inf/out} \end{aligned} \quad (14)$$

where the first term in the top line represents the conversion rate of the ISM mass into stars, the second term represents the rate of stellar mass loss, where $M_{ej}(m)$ is the total mass returned back to the ISM by a star of initial mass m , and the third term represents the rate

of change in the ISM mass as a result of gas infall or outflows. The second line represents the behavior of $dM_g(t)/dt$ in the instantaneous recycling approximation, where the returned mass fraction, R , is approximately 0.7.

The evolution of the gas mass is only weakly coupled to its chemical evolution. The returned mass, M_{ej} , is almost independent of metallicity (Karakas & Lattanzio 2007) and the stellar MS lifetimes are only weakly dependent on metallicity for values above 0.001. So with reasonable accuracy, the evolution of the gas mass can be solved independently of the evolution of the dust and metals in the ISM.

2.4. Integral Solutions

When the evolution of the ISM gas is decoupled from its chemical evolution, eq. (6) can be readily solved with the aid of an integration factor, to yield a convenient functional form for the evolution of the dust or any element in the ISM.

Changing variables (Audouze & Tinsley 1976):

$$\frac{dM_d(t)}{dt} = M_g(t) \frac{dZ_d(t)}{dt} + Z_d(t) \frac{dM_g(t)}{dt} \quad , \quad (15)$$

eq. (6) can be rewritten as:

$$\frac{dZ_d(t)}{dt} + Z_d(t) F(t) = G(t) \quad (16)$$

where $F(t)$ and $G(t)$ are dimensionless functions given by:

$$F(t) \equiv \frac{\psi(t)}{M_g(t)} \left[1 + \frac{\langle m_d \rangle_{mw}}{m_\star Z_{d,mw}} + \frac{1}{\psi(t)} \frac{dM_g(t)}{dt} + \frac{1}{\psi(t)} \left(\frac{dM_g(t)}{dt} \right)_{out} \right] \quad (17)$$

and

$$G(t) \equiv \frac{1}{M_g(t)} \left[\mathcal{S}(t) + Z_d^{inf} \left(\frac{dM_g(t)}{dt} \right)_{inf} \right] \quad (18)$$

Equation (16) can be solved with the aid of an integration factor, giving:

$$Z_d(t) = \exp[-F(t)] \int_0^t \exp[F(t')] G(t') dt + \mathcal{C} \quad (19)$$

where \mathcal{C} is an integration constant. Given M_g , the mass of dust is simply given by: $M_d(t) = Z_d(t) M_g(t)$. The solution applies for calculating the evolution of the metallicity, Z_A , of any element A as well. For stable elements the solution is obtained by the formal substitution of Z_d with Z_A , by setting $\langle m_d \rangle_{mw} = 0$ in eq. (17), and by using the appropriate yields in eq. (11).

3. STELLAR SOURCES OF INTERSTELLAR DUST

In the following we examine the yields and relative importance of the dust formation in SNe, WR, and AGB stars. In all our calculations we adopt a mass-heavy IMF, defined below, which for the observed far-IR luminosity gives a SFR of XXXX $M_{\odot} \text{ yr}^{-1}$.

3.1. Supernovae

Consider a constant SN rate, R_{SN} . The dust production rate is simply given by $S_0 = \tilde{Y}_{d,sn} \times R_{SN}$. Without grain destruction and with a SN rate of 20 yr^{-1} , SN need to condense only $0.03 M_{\odot}$ of dust over a period of $\sim 500 \text{ Myr}$ in order to produce an observed dust mass of $\sim 3 \times 10^8 M_{\odot}$. When grain destruction by SN is taken into account, the amount of dust produced by SNe is given by: $M_d \approx \tilde{Y}_{d,sn} R_{SN} \tau_d$, giving the trivial solution: $\tilde{Y}_{d,sn} \approx \langle m_d \rangle$, that is, in a steady state SNe must produce a dust mass that is equal to the amount they destroy during their lifetime. However, the required value of $\tilde{Y}_{d,sn}$ can be lower before the system reaches a steady state. For example, the first SNe expand in a dust-free medium and therefore are net producers of interstellar dust. Detailed chemical evolution and population synthesis models are therefore needed to fit the observational constraints imposed by the inferred stellar, gas, and dust masses, as well as the stellar and radiative output of the galaxy.

Simple analytical models have shown that even in the absence of grain destruction, SNe must produce at least $\sim 0.3 M_{\odot}$ of dust to account for the observed dust-to-gas mass ratio in J1148+5251 (Dwek et al. 2007; Figure 8). The reason that this number is not lower and equal to the value of $\sim 0.03 M_{\odot}$ derived in our simple estimate above, stems from the fact that in these models the SFR is proportional to $\Sigma_{gas}^{1.5}$, where Σ_{gas} is the mass surface density of the gas (Kennicutt 1998). Σ_{gas} evolves with time, so that the effective timespan over which star-formation takes place is therefore much shorter than the age of the galaxy. It is determined by either the buildup of the ISM in infall models, or by the depletion of the ISM in closed box models. For J1148+5251 the situation is exacerbated by the fact that the IR-inferred SFR for a mass-heavy IMF is $\sim 1500 M_{\odot} \text{ yr}^{-1}$. This SFR can therefore only be sustained for about 20 Myr , if the reservoir of gas is comparable to the dynamical mass or the CO mass of the galaxy.

Do SNe actually produce this much dust? The most detailed information on the amount of dust formed in supernovae comes from IR observations of the young supernova remnant of Cas A. *Spitzer* observations of the remnant have revealed the presence of $\sim 0.02 - 0.04 M_{\odot}$ of hot (Rho et al. 2008) and $\sim 0.08 M_{\odot}$ of cool dust (Sibthorpe et al. 2009; Barlow et al.

2010). The total mass of dust, about $0.1 - 0.12 M_{\odot}$, is still not sufficient to account for the mass of dust observed in J1148+5251 even when grain destruction is almost nonexistent in that galaxy. Furthermore, detailed calculations, using a chemical kinetic approach to follow the transformation of gas phase molecules into small clusters of dust precursors, show that only $\sim 0.1 - 0.15 M_{\odot}$ of dust is created in the explosive ejecta of a Population III $20 M_{\odot}$ SN (Cherchneff & Dwek 2010). Such yield may be typical of SNe of similar masses, regardless of the initial metallicity of the progenitor star.

3.2. Wolf-Rayet Stars

Of the stars that become core-collapse supernovae (CCSNe), only those with masses above $m_{wr} \approx 40 M_{\odot}$ will become WR stars, a stage during they will experience extensive mass loss. The formation of carbon dust becomes feasible during the latest phases of this mass loss phase, when the stellar surface becomes carbon enriched, and the star evolves into a WC star (Crowther 1997). For an IMF with a Salpeter slope of $\alpha = 2.35$, the fraction of CCSNe that become WR stars is:

$$f_{wr} \approx (m_{wr}/m_w)^{1-\alpha} \approx 0.11 \quad (20)$$

So WR stars have to produce about 10 times more dust than SNe to account for the dust mass in J1148+5251. There is observational evidence that most of WR stars are part of a binary system with an OB companion and that the dust formation locus is located in the region where the two winds collide as exemplified by the archetypical systems WR104 and WR140. For the Pinwheel Nebula WR 104, a dust mass loss of $\sim 8 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ is derived by Harries et al. (2004). A typical $60 M_{\odot}$ WR star is characterized by a WC phase lasting about $2 \times 10^5 \text{ yr}$ (Prantzos et al. 1986). We can thus approximate the amount of dust formed by WR stars as $\sim 0.2 M_{\odot}$ over their lifetime. This number is of the same order of magnitude and not 10 times larger than the dust mass formed in the ejecta of a CCSN. Therefore, WR stars are certainly contributing to the dust budget of J1148+5251 but no more than 10% of all dust makers.

3.3. AGB Stars

In the Milky Way, a significant fraction of dust is produced in AGB stars (Dwek 1998; Tielens 1998). Dependent of their evolutionary stage on the AGB, red giants have either a oxygen-rich stellar photosphere characterized by a C/O ratio < 1 , or a carbon-rich photosphere resulting from thermal pulses and 3rd dredge-up and characterized by a C/O ratio

> 1 . The former stars form silicate and metal oxide dust whereas the latter essentially form carbon dust and silicon carbides. At present, there exist no satisfactory models explaining the chemical formation of dust in AGBs and the impact of dust on accelerating the outflow through radiative pressure. Dynamical models often use the classical nucleation theory to describe dust synthesis and derive dust yields (Ferrarotti & Gail 2006), an approach that has been proved to be inadequate when applied to circumstellar outflows (Donn & Nuth 1985; Cherchneff & Dwek 2010).

For the purpose of the present study, we ignore the chemical and physical complexity of the dust formation processes and assume a condensation efficiency of unity to calculate the dust yields as described by Dwek (1998). The calculations assume that carbon dust forms when the C/O number ratio exceeds 1, and that silicate dust forms when this ratio is less than unity. This approach provides upper limits for the dust mass. For illustrative purposes, Figure 1 (left panel) depicts the mass of dust produced during the AGB phase from 1-8 M_{\odot} stars with an initial metallicity of 0.008. Yields were taken from Karakas & Lattanzio (2007). Also shown in the figure are the carbon and oxygen yields (in units of M_{\odot} and divided by their atomic mass), to illustrate the range of stellar masses that produce either silicate or carbon dust. Yields similar to those presented in this figure were adopted by Valiante et al. (2009) based on the models of Ferrarotti & Gail (2006). These models give different dust compositions, a distinction which is not important for the purpose of this paper.

The right panel of the figure shows the IMF-weighted yield of dust from these stars, where the IMF is characterized by a power-law in mass with a Salpeter index of 2.35. The figure shows that the most efficient dust producers are $\sim 3 M_{\odot}$ stars, which have a MS lifetime of about 350 Myr. For AGB stars to be significant contributors to the reservoir of dust in a galaxy, its age has to be significantly older than ~ 400 yr.

3.4. Relative Importance

The rate of dust production by SNe, WR stars, and AGB stars is given by: $\psi \times \tilde{Y}_{d,sn}/m_{\star}$, $0.11 \times \psi \times \tilde{Y}_{d,sn}/m_{\star}$, and $\psi \times \tilde{Y}_{d,agb}/\langle m \rangle$, respectively. Taking 0.15, 0.2, and 0.04 M_{\odot} as the respective yields of dust in these sources, we get that in a steady-state, their relative dust production rate is: 1.0 : 0.11 : 4.6. AGB stars are therefore the most important sources of interstellar dust. However, this steady state is not immediately realized because of the delayed injection of AGB-condensed dust into the ISM. In the local group of galaxies, this delayed injection is manifested in the observed trend of the abundance of polycyclic aromatic hydrocarbons (PAHs) with galactic metallicity, which is taken as a proxy for galactic age (Galliano et al. 2008). The trend shows the existence of a threshold metallicity below which

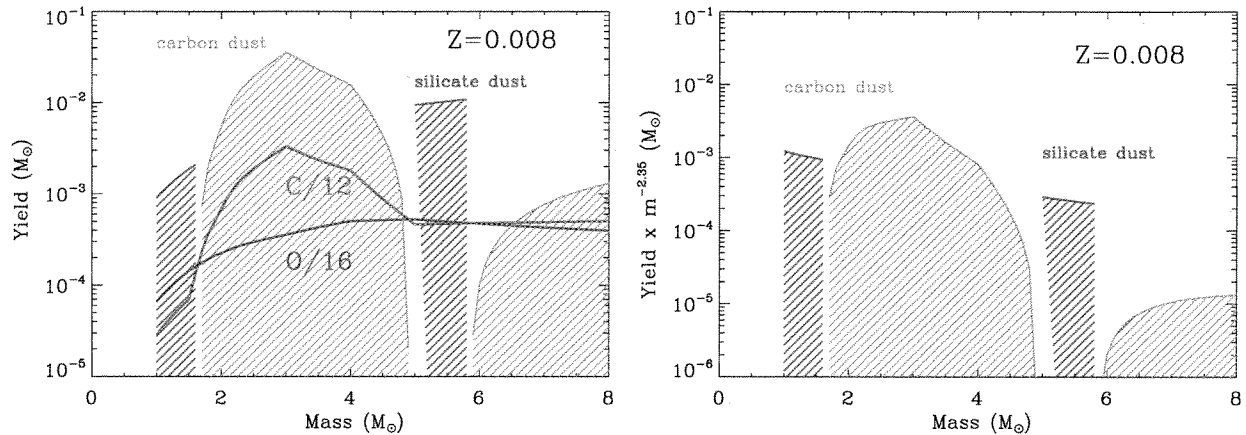


Fig. 1.— **Left panel:** The dust yield from AGB stars with an initial metallicity of 0.008. The red and blue lines depict the carbon and oxygen yields from these stars, divided by their atomic number. Carbon dust (hatched orange regions) is formed when the C/O ratio > 1 , whereas silicate dust (hatched green region) is formed when that ratio is < 1 . **Right panel:** The IMF-weighted yield of dust from these stars. The $\sim 3 M_{\odot}$ stars, which have a MS lifetime of ~ 350 Myr (see Table 2) are the dominant contributors to the production of dust.

the abundance of PAH is very low. PAHs condense in the atmospheres of AGB stars, and therefore represent AGB-condensed dust. So at early times, the mass of dust in galaxies is dominated by SN-condensed dust. The dust evolution models presented in (Galliano et al. 2008) suggest that the steady state when AGB sources are the dominant dust producers may only be reached after about $\sim (1 - 2)$ Gyr of stellar evolution. PAHs can also be produced by shock processing of AGB-condensed carbon dust. However, both mechanisms, stellar condensation and shocks, need AGB stars as the source of dust, so the PAH-metallicity trend manifests the delayed injection of dust by AGB stars, even if most of the PAHs are formed in interstellar shocks.

4. THE QUASAR J1148+5251

4.1. The Evolution the ISM Gas and Dust Masses

In the following we will apply our new mathematical formalism to calculate the evolution of the mass of the ISM and the dust in J1148+5251. For AGB stars to be an important source of interstellar dust, star formation must have commenced at least 500 Myr before the epoch of observations which is about 900 Myr. In their paper, Valiante et al. (2009) adopted

the SFH derived by Li et al. (2007) from simulations of hierarchical galaxy mergers taking place at redshifts $z \gtrsim 6.5$. Their SF history, reproduced from Figure 7 of Li et al. (2007), is reproduced as a bold solid line in the left panel of Figure 6.

An important ingredient of chemical evolution models is the evolution of the gas mass. We adopted two different prescription for calculating this quantity. In the first, we adopted a closed box model with an initial gas mass of $5 \times 10^{11} M_{\odot}$, and used eq. (14) to calculate its evolution. In the second approach we assumed that the SFR derived from the galaxy simulation follows the Schmidt-Kennicutt law in which $\psi(t) = A M_{gas}^{1.5}(t)$, where A is a proportionality constant chosen here to reproduce the model's SFR of $60 M_{\odot} \text{ yr}^{-1}$ at $t = 900 \text{ Myr}$ with the observed gas mass of $\sim 4 \times 10^{10} M_{\odot}$.

In the calculations we adopted an IMF-averaged dust yield of $\tilde{Y}_{d,sn} = 0.15 M_{\odot}$, the yield derived by Cherchneff & Dwek (2010) for a $20 M_{\odot}$ primordial core-collapse supernova. The yield of dust in AGB stars was calculated as in Dwek (1998) using the stellar elemental yields of Karakas & Lattanzio (2007). The stellar IMF was chosen to be a power law: $\phi(m) \sim m^{-\alpha}$ between 1 and $100 M_{\odot}$, with a spectral index of $\alpha = 2.35$.

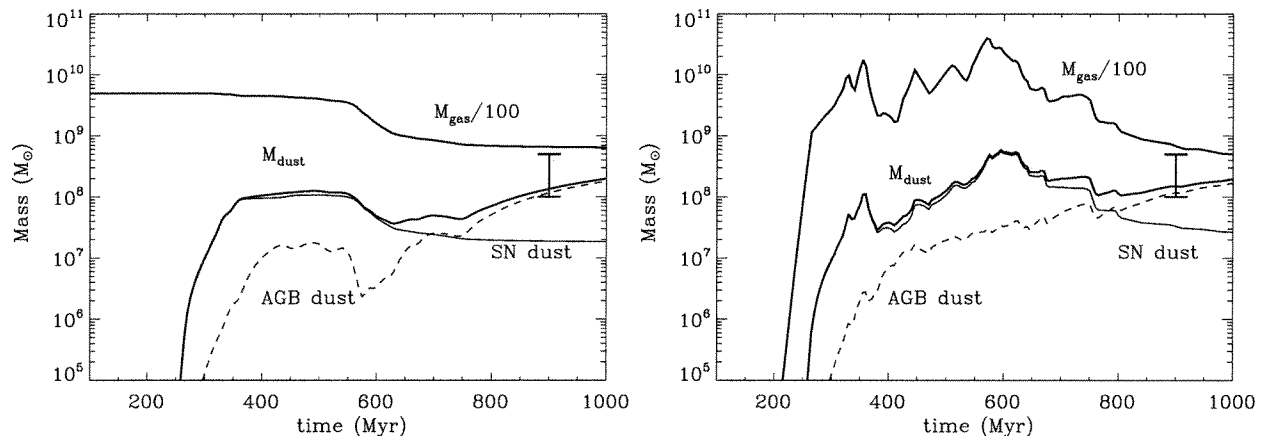


Fig. 2.— The evolution of the mass of the SN-condensed dust, AGB dust, total dust mass, and the mass of the ISM gas in J1148+5251, for the SF scenario of Li et al. (2007), depicted here in Fig. (6). **Left panel:** Results for the closed box model. **Right panel:** Results for the Schmidt-Kennicutt SF law. The vertical line at $t = 900 \text{ Myr}$ is the observed dust abundance.

Figure 2 depicts the evolution of dust and gas masses for the two adopted evolutionary histories of M_g : the closed box model (left panel), and the Schmidt-Kennicutt SF law (right panel). The vertical line at $t = 900 \text{ Myr}$ is the observed dust abundance, the length of the bar reflecting the range of dust masses for the different dust compositions (Dwek et al. 2007). The results of our calculations are in very good agreement with those of Valiante

et al. (2009). Not surprising, the detailed evolution differs from theirs, since it depends on their adopted evolutionary history of M_g , the grain destruction efficiency, and AGB yields, quantities that differ in details from the ones used in this work. However, the main results, the final masses produced by SN- and AGB-condensed dust, are essentially identical. The figures show that AGB stars can readily produce the observed amount of dust with the proposed SFR, and that SN can only be important dust sources only if their IMF-averaged yield is $\sim 1 - 3 M_\odot$, confirming the results of the simpler analytical model of Dwek et al. (2007).

4.2. The Evolution the Stellar Luminosity and Mass

Figure 3 depicts the evolution of the stellar masses and remnants (left panel) and the bolometric stellar luminosity (right panel) of J1148+5251. Calculations were done for the hierarchical SF history depicted in figure 6, using the PÉGASE population synthesis code (Fioc & Rocca-Volmerange 1997). The merger history was proposed by Li et al. (2007) to account for the presence of a supermassive black hole (BH) of mass $\sim 3 \times 10^9 M_\odot$ (Willott et al. 2003). Assuming that the relationship between the BH mass and its spheroidal component is still valid at redshifts $\gtrsim 6$, gives a stellar bulge mass of $\sim \text{few} \times 10^{12} M_\odot$ [e.g. review by (Kormendy & Gebhardt 2001)]. While the stellar mass derived here agrees with that estimate, it is in excess of the dynamical mass of $\approx (5.0 \pm 2.5) \times 10^{10} M_\odot$ that is enclosed within a 2.5 kpc radius of J1148+5251 (Walter et al. 2004). Walter et al. (2004) proposed several solutions to this discrepancy, including an overestimate in the mass of the BH, and a breakdown in the assumption that the CO gas is gravitationally bound. Also, there may be evidence that at high redshifts BHs may grow very rapidly without the corresponding increase in the mass of the host galaxy (Shields et al. 2006). It is therefore premature to rule out the AGB dust formation scenario while the origin of this discrepancy is still unresolved.

4.3. The Nature of its Spectral Energy Distribution

An important distinction between the SN and AGB scenarios for the origin of dust in J1148+5251 is the origin of the far-IR emission. In the SN scenario, the far-IR emission originates from dust that is heated by stellar radiation. The AGN contributes only to the heating of the hotter dust that gives rise to the mid-IR emission [see Fig 11 in Dwek & Arendt (2007)]. In contrast, in the AGB scenario most of the far-IR emission is emitted from dust that is heated by the AGN, with only $\sim 25\%$ heated by stars. Figure 4 depicts the stellar SED calculated for the hierarchical merger SFR at the galactic age of 900 Myr.

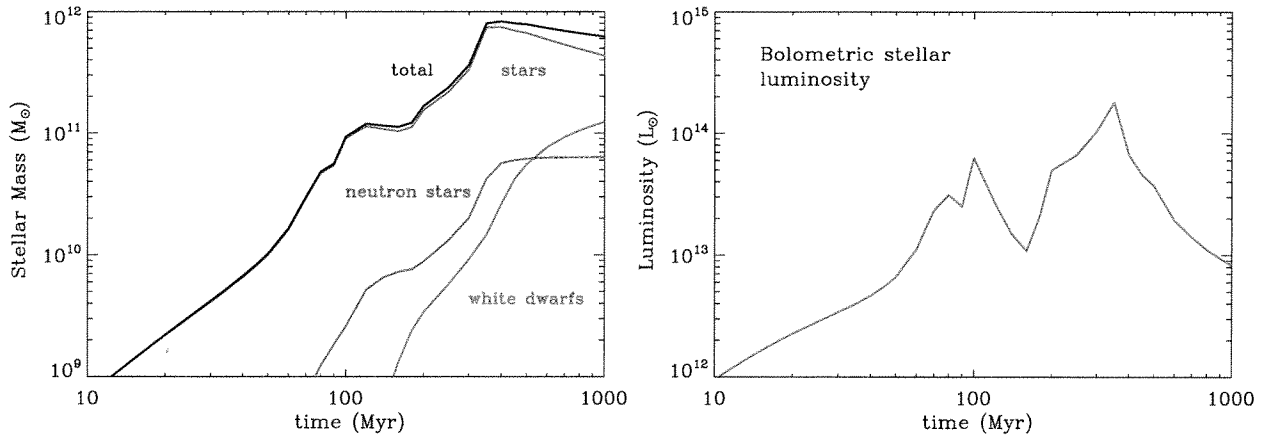


Fig. 3.— **Left panel:** The evolution of the stellar mass content (left panel) and luminosity (right panel) calculated with the population synthesis code PÉGASE using the hierarchical SF history depicted in Figure 6.

In this model, all of the optical to near-IR flux is emitted by the AGN, and only a small fraction, depicted by the shaded area, is stellar. In the absence of any discriminating line emission, can one distinguish between the two scenarios on the basis of the continuum 0.1 to 1 μm continuum emission? This question is addressed in the right panel of the figure which depicts the probability distribution of photometric spectral indices α_p derived from the observed magnitudes of quasars Richards et al. (2003). The spectral index of the spectrum of J1148+5251 is $\alpha_\nu \approx -0.35$ (left panel) which corresponds to a value of $\alpha_p \approx -1.65$. This value is near the median value of -1.6. The optical to near-IR spectrum of J1148+5251 has therefore an equally high probability of being that of an AGN as that of a starburst galaxy.

5. CAN THE STAR FORMATION HISTORY BE DETERMINED FROM THE DUST CONTENT OF GALAXIES?

Can all high-redshift galaxies produce these large amounts of dust? To address this question we will consider the production of dust in a single burst of star formation. Figure 5 depicts the evolution of the mass of dust produced by AGB stars in a 100 Myr burst of star formation characterized by a constant SFR of $1000 M_\odot \text{ yr}^{-1}$. The bold solid lines depicts the evolution of the dust when no grain destruction is taken into account. The thinner lines depict the dust evolution in the presence of grain destruction. Grain destruction was assumed to be constant and to commence only after the cessation of the burst. The different lines are labeled by the lifetime of the dust in units of Myr. An old burst releases $\sim 1 \times 10^8 M_\odot$ of dust 600 Myr after its onset if no destruction has taken place in the intervening period since the end of the burst and the time of observation. The surviving mass of dust is significantly

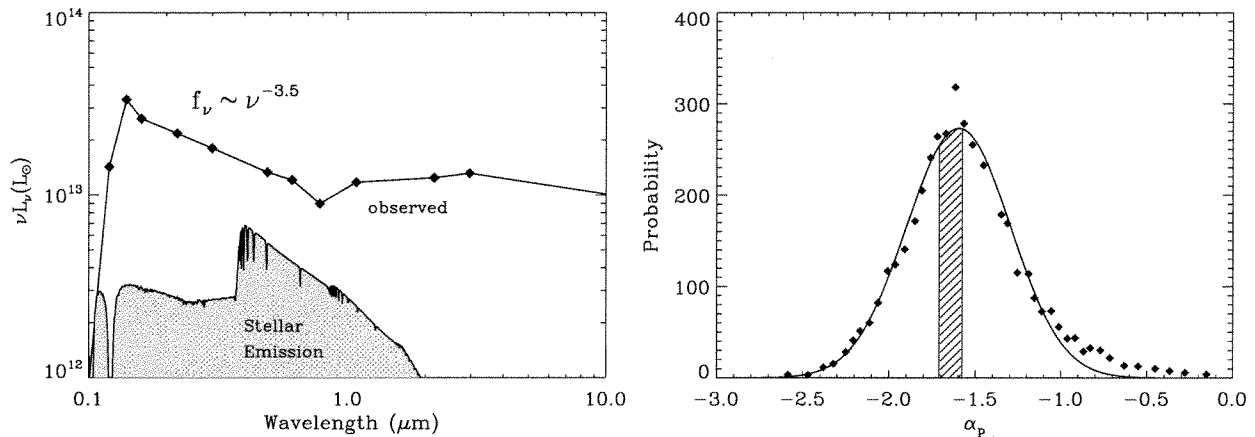


Fig. 4.— **Left panel:** The stellar SED calculated for the hierarchical merger SFR. In this scenario, all of the optical to near-IR flux is emitted by the AGN. In contrast, in the SN model model for the origin of the dust, most of this emission originates from stars [see Fig 11 in (Dwek et al. 2007)]. **Right panel:** The probability distribution of photometric spectral indices α_p derived from the observed magnitudes of quasars Richards et al. (2003). The spectral index of $\alpha_\nu \approx -0.35$ (left panel) corresponds to a value of $\alpha_p \approx -1.65$.

smaller when grain destruction is taken into account. A young burst produces after 200 Myr the least amount of dust, about $10^7 M_\odot$ with no grain destruction, but is also least affected by grain destruction. The figure shows that a single burst of star formation, for example burst 1 with an intensity of $\sim 3000 M_\odot \text{ yr}^{-1}$, or burst 4 with an intensity of 10,000 Myr, can produce the observed $\sim 3 \times 10^8 M_\odot$ of dust in J1148+5251.

Deconstructing the complex SFH of a galaxy undergoing a series of hierarchical mergers can be very illustrative for understanding the origin of dust in such systems. In Figure 6 (left panel) we approximate the SFH of J1148+5251 used by Valiante et al. (2009) by five discrete bursts of star formation. The right panel depicts the cumulative contribution of each of the bursts to the total mass of dust in the galaxy. The oldest burst (number 1) releases the most amount of dust since all stars above $2.1 M_\odot$ contributed to its production. However, grain destruction by the subsequent bursts reduces the mass of dust that survives until 900 Myr to only $\sim 2 \times 10^6 M_\odot$. Almost all of the surviving dust was produced by the third burst. It has a main sequence turnoff mass of $\sim 3 M_\odot$, but it had the largest SFR, and it was followed by a period of relatively low star formation activity and grain destruction.

The formation of about $\sim 3 \times 10^8 M_\odot$ of dust at $z \gtrsim 6$ can therefore be achieved for different SFH. As illustrated in Figure 5, single burst of star formation with the appropriate intensity can produce the required amount of dust, since no grain destruction takes place after the cessation of all star formation activities in the galaxy. Massive amounts of dust can

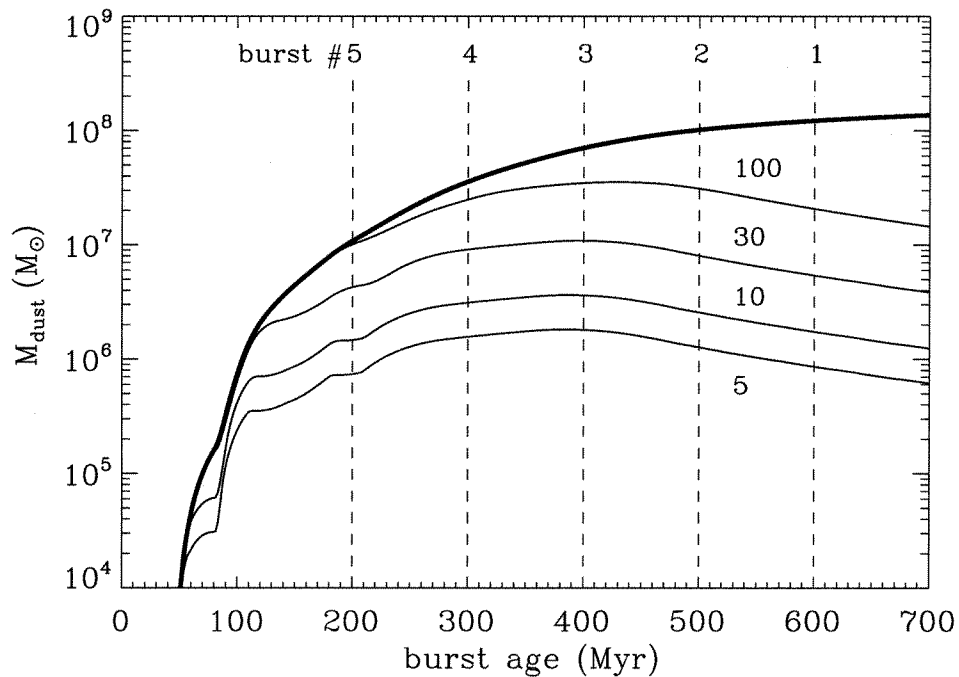


Fig. 5.— The evolution of the mass of dust released by AGB stars a bursts of star formation as a function of the age of the burst, measured from the onset of the burst. The burst duration is 100 Myr, and its intensity is $1000 M_{\odot} \text{ yr}^{-1}$. The top bold line represents the evolution of the dust mass without any grain destruction. Other lines depict the evolution of the dust when it is destroyed by a constant ongoing destruction mechanism, assumed to have started after the end of the burst. The lines are marked by the dust lifetime in units of Myr. The vertical dashed lines mark the age of the burst at epochs that correspond to the burst ages in Fig. 6.

also be produced by a complex SFH such as that presented in Figure 6, provided that the epochs of intense star formation are followed by a period of very low, $\psi \lesssim 50 M_\odot \text{ yr}^{-1}$ rate of star formation, so that the dust lifetime, given by $\sim M_d m_*/(mde\psi)$ will be over 100 Myr. The discriminating factor between the different scenarios capable of producing large amount of dust are the cumulative products, such as the metals or stellar masses, resulting from the star formation activities. Recent observations suggest that not all quasars with redshifts above 6 show evidence of dust (Jiang et al. 2010). While this result may still proven to be premature, our models suggest that this may be a manifestation of the different star formation histories in these objects.

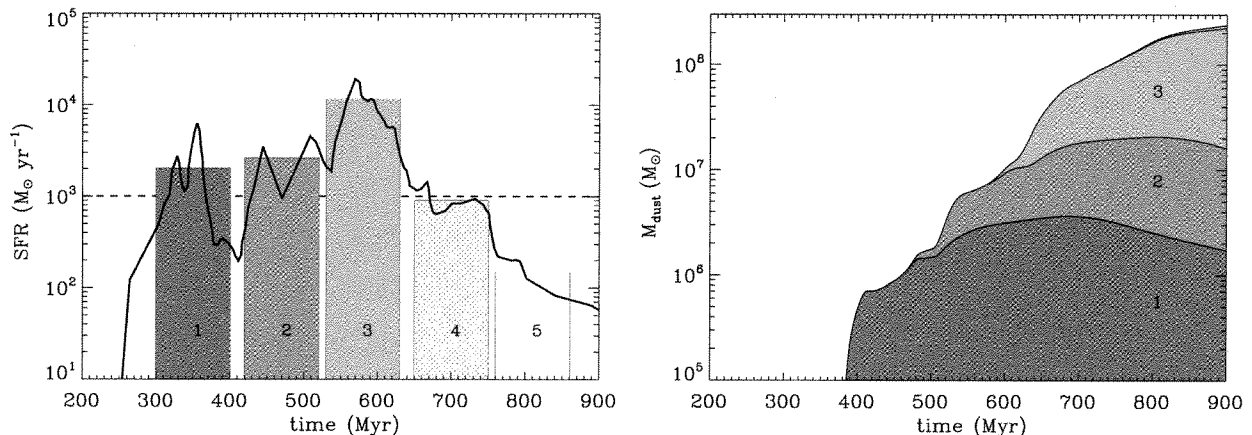


Fig. 6.— **Left panel:** The star formation rate of a galaxy going through hierarchical merger episodes (Li et al. 2007, 2008) (solid red curve), can be approximated by a series of 5 discrete 100 Myr duration bursts (shaded bars). **Right panel:** The contribution of each of the five bursts depicted in the left panel to the total dust mass observed at the galactic age of 900 Myr. Most of the dust is that created by the third burst which had the largest star formation rate, followed by a period of relatively low rates of star formation and grain destruction. The figure illustrates the sensitivity of the dust mass to the SFH of the galaxy.

6. ALTERNATIVE DUST SOURCES

The large and still unresolved discrepancy between the stellar masses predicted by the AGB scenario and the inferred dynamical mass of J1148+5251, raises the possibility that alternative sources may be needed to explain the large amount of dust in this object. In the following we consider the growth of dust in molecular clouds and their formation around AGN as such sources.

6.1. Molecular Clouds

Numerous observations and theoretical considerations support the notion that dust grains are processed and grow in dense molecular clouds (MCs). Observationally, extinction measurements show that the value of $R_v \equiv A_v/E(B - V)$, an indicator of grain size, increases with hydrogen column density [e.g. Kandori et al. (2003), and references therein]. Similarly, interstellar depletions of refractory elements increase with average line of sight gas density (Savage & Sembach 1996) and infrared spectroscopy of molecular clouds show the presence of ices, expected to have condensed out on interstellar grain cores (van Dishoeck 2004). Theoretically, the discrepancy between the relatively short lifetime of interstellar dust (Jones 2004) and the longer lifetime for their replenishment by SNe or AGB stars has been attributed to their growth in molecular clouds (Dwek & Scalo 1980; Dwek 1998; Tielens 1998; Zhukovska et al. 2008).

For grain growth in clouds to play a significant role in replenishing the mass of heavy elements that have been returned by shocks from the solid to the gaseous phase of the ISM, the accretion time has to be shorter than the lifetime of the clouds in which this process is taking place.

Let $\rho_{gr} = n_{gr} \times m_{gr}$ be the mass density of grains in the MC, where n_{gr} is their number density and m_{gr} their mass. Assuming that all grains have the same radius a , the growth rate of ρ_{gr} due to accretion of a heavy element A with a molecular weight μ_A and number density n_A is given by:

$$\frac{d\rho_{gr}}{dt} = \alpha \pi a^2 \mu_A n_A \tilde{v} \quad (21)$$

where α is the sticking coefficient in the collision, and $\tilde{v} = (8kT/\pi\mu_A)^{1/2}$ is the mean thermal velocity of A at temperature T .

The accretion time, τ_{acc} , is defined as follows:

$$\begin{aligned} \tau_{acc}^{-1} &\equiv \frac{1}{\rho_{gr}} \frac{d\rho_{gr}}{dt} = \alpha \left(\frac{\pi a^2}{m_{gr}} \right) \mu_A n_A \tilde{v} \\ &= \alpha \left(\frac{3}{4\rho a} \right) \left(\frac{\mu_A}{m_H} \right) \left(\frac{n_A}{n_{H_2}} \right) m_H n_{H_2} \tilde{v} \end{aligned} \quad (22)$$

Taking the mass of an oxygen atom to represent that of a colliding specie, so that $\mu_A/m_H = 16$, and $n_A/n_{H_2} \approx 5 \times 10^{-4}$, we get that:

$$\tau_{acc}(sec) = \frac{2 \times 10^{18}}{\alpha} \rho \left(\frac{a}{\mu m} \right) \left(\frac{n_{H_2}}{cm^{-3}} \right)^{-1} \left(\frac{T}{K} \right)^{-1/2} \quad (23)$$

For a grain density of 3 g cm^{-3} , radius of $0.1 \text{ } \mu\text{m}$, a cloud density of 10^3 cm^{-3} , and cloud temperature of 20 K , the accretion time becomes $\sim 3 \times 10^6 \text{ yr}$.

The lifetime, τ_c , of the molecular clouds is given by:

$$\tau_c = \frac{M_c}{\psi} \approx \frac{2 \times 10^{10}}{3000} \approx 7 \times 10^6 \text{ yr} \quad (24)$$

where M_c is the MC mass, and where we used the observed H_2 mass and SFR to calculate the average lifetime of the molecular gas. The two timescales, τ_{acc} and τ_c , are comparable, within the uncertainties of the chosen values of the various parameters, suggesting that grain growth in the dense ISM plays an important role in determining the observed dust mass.

If MCs are the main source of the dust in J1148+5251, then the observed IR emission should emanate from the dust in these clouds. In the Milky Way, most (60–75%) of the IR emission is radiated by dust in the diffuse ISM, with only 15–30% radiated from MCs (Sodroski et al. 1997). Likewise, the IR emission from J1148+5251 could arise either from the dust in the MCs, or from dust in the diffuse ISM, including H II regions. Simple arguments suggest that the ISM in J1148+5251, must be clumpy, consequently most of the IR emission must originate from the clumpy medium. The global visual optical depth, $\tau(V)$, of the galaxy is approximately given by $L_{IR}/L_{tot} \approx 2 \times 10^{13}/1 \times 10^{14} = 0.2$. The angular size of J1148+5251 is $\sim 0.2''$ (Walter et al. 2004), which translates into a transverse size of $\sim 1 \text{ kpc}$ at $z = 6.4$. Spread out uniformly over a $R = 1 \text{ kpc}$ radius sphere, the mass surface density of the dust would be $\Sigma_d = 3 M_d/4\pi R^2 \approx 6 \times 10^{-3} M_\odot \text{ cm}^{-2}$. A disk-like geometry will produce similar results. Dust mass absorption coefficients, $\kappa_d(V)$ in the V band ($0.54 \text{ } \mu\text{m}$) are $\sim 3 \times 10^3 \text{ cm}^2 \text{ g}^{-1}$ for silicate dust, and $\sim 5 \times 10^4 \text{ cm}^2 \text{ g}^{-1}$ for carbon dust. The visual optical depth is given by $\tau(V) = \Sigma_d \kappa_d(V)$, so that a uniform distribution of the inferred dust mass over the galaxy will render it completely opaque. Most of the dust must therefore reside in diffuse or dense molecular clouds.

The clumps themselves are most likely to be opaque, so that the IR emission indeed reflects that emanating from the reconstituted grains in the MCs. The surface density of molecular clouds in normal galaxies exhibits a narrow spread in values, ranging from about 10 to $100 M_\odot \text{ pc}^{-2}$ (Inoue & Kamaya 2000). In luminous IR galaxies (LIRGs) star formation seems to take place in clouds with higher surface densities of about 10^3 to $10^4 M_\odot \text{ pc}^{-2}$ (Sakamoto et al. 1992). Adopting a dust-to-gas mass ratio of 0.01, we see that even the lowest density MCs are visually opaque. Therefore, a possible scenario for the origin of the dust and the IR emission from J1148+5251 is one in which the IR emission arises predominantly from MCs, in which the surviving cores of dust grains that formed in SNe or AGB stars, had sufficient time to grow to the currently observed dust mass.

6.2. “Smoking Quasars”

The concept of “smoking quasars”, that is, the possibility that quasars may be producers of interstellar dust was first put forward by Elvis et al. (2002). In his scenario, the broad emission line clouds (BELCs), confined by the centrifugally driven outflowing wind Kartje & Königl (1996), go through the same density and temperature conditions that characterize the dusty winds in stellar outflows. It is therefore naturally to postulate that if the conditions in the stellar winds are ripe to form dust, a similar process will be taking place in the BELCs. This idea was further discussed by Maiolino et al. (2006).

The main issue, not addressed in these papers is whether the BELCs were dusty to start with (Elitzur & Shlosman 2006). If so, then the IR emission observed in the vicinity of the AGN is not the signature of radiation from newly-formed dust, but that of reprocessed dust. This dust could have formed previously in SNe or dusty stellar winds. If so, quasars cannot be considered as net producers of interstellar dust. The issue of quasars as dust sources can therefore only be settled once we have a clearer understanding the origin of the BELCs, and of the dust formation process in these objects.

7. DISCUSSION AND SUMMARY

Using our new integral solutions for the chemical evolution of the ISM gas and its metal and dust contents, we examined the origin of the large amount of dust discovered in the high- z quasar J1148+5251. We have shown that an average $20 M_{\odot}$ supernova needs to make at least $\sim 2 M_{\odot}$ of dust in order for SNe to be a viable source of dust at this high redshift. AGB stars can produce the required amount of dust in a merger scenario in which the assembled galaxy undergoes a period of intense star formation at $z \approx 15$, followed by a period of significantly lower stellar activity. However, many issues regarding the properties of this quasar and the various physical processes that affect the evolution and survival of the dust need still to be addressed before any definitive conclusions about the origin and nature of its dust can be reached. The main issues raised here are:

1. **The mass and gas content of J1148+5251** - The stellar mass offers an important integral constraint on the duration and intensity of the burst of star formation. These place integral constraints on the total amount of dust that could have formed in the quasar. The mass of stars produced in the SN scenario is significantly smaller than that required in the AGB scenario. The mass produced in the latter is much larger than the inferred dynamical mass of the galaxy. Resolving this discrepancy is a crucial step in determining the origin of the dust in J1148+5251.

2. **The star formation history** - Knowing the onset of the starburst is important for determining if the most numerous and prolific dust producing AGB stars had time to evolve off the main sequence. The galaxy must be at least 400 Myr old for AGB stars to have made a significant contribution to its reservoir of dust. At any given epoch, the intensity of the starburst must be at least $2000 M_{\odot} \text{ yr}^{-1}$ in order to produce the inferred amount of dust, and the star formation rate must have dropped to less than $\sim 50 M_{\odot} \text{ yr}^{-1}$ so that the dust that is injected at the epoch of observations will not be significantly destroyed.
3. **Dust production in supernovae** - If the conditions above are not fulfilled, can supernovae produce the observed amount of dust? Our current state of knowledge, observationally and theoretically, suggest that the explosive ejecta of a progenitor $\sim 20 M_{\odot}$ star produces about $0.1 - 0.15 M_{\odot}$ of dust. Such progenitors are the most common metal producing SNe, and fall short of meeting the production requirement. Our knowledge here is based on limited number of observations and calculations, so that the state of our knowledge may change with future observations.
4. **The efficiency of grain destruction in the ISM** - Our current state of knowledge is predominantly based on the simulations that were performed for a homogenous ISM. These calculations need to be expanded for a 2-phase ISM, taking also the spatial distribution of dust sources and sinks into account. For example, one can easily envision an intense starburst producing large amount of dust in one location in the galaxy, followed sometime later by another physically isolated starburst that will have little effect on the evolution of the dust created in the first. Spatially isolated starburst may therefore circumvent the currently estimated short grain lifetime in the ISM.
5. **Dust growth in the ISM** - Studies of Dwek & Scalo (1980) have first suggested that accretion in molecular clouds must play an important role in explaining the origin of the Galactic pattern of interstellar depletions. Numerous other works have since then considered the evolution of dust in a two-phase medium (Dwek 1998; Liffman & Clayton 1989; Zhukovska et al. 2008). A necessary condition for this solution in J1148+5251 is that the IR emission, on which the estimated dust mass is based, must mostly originate from the dust in the molecular clouds. Otherwise, the accreted mantles must survive the harsher conditions that prevail in the more tenuous ISM. In our Galaxy, most of the IR emission originates from the diffuse ISM Sodroski et al. (1997). If grain growth in clouds plays an important role in determining the mass of dust in the Milky Way, then these composite grains must also be able to produce the interstellar extinction curve, the diffuse IR emission, and the interstellar abundance constraints. Zubko et al. (2004) have shown that such composite grains can meet these observational constraints

as well as the bare silicate graphite grains commonly use in interstellar dust models (Li & Draine 2001; Zubko et al. 2004).

6. **Dust formation in around AGN** - Suggested by (Elvis et al. 2002; Maiolino et al. 2006) as a potential source of dust, its effectiveness remains unclear. The origin of the dense broad-line-emitting clouds, and whether they were initially dusty so that the AGN merely reformed pre-existing dust, are questions that need to be addressed to ascertain their role as dust sources in quasars.

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Table 1. Main-sequence Lifetimes of AGB Progenitor Stars¹

Mass (M_{\odot})	redshift				
	0.0001	0.001	0.008	0.0100	0.02
1.0	4998	6774	8634	8846	9516.
1.5	1474	2022	2415	2446	2528.
2.0	663	914	1047	1054	1062.
2.25	486	670	756	759	757.
2.5	371	512	570	570	565.
2.75	292	404	444	443	436.
3.0	236	326	355	354	346.
3.25	195	270	291	290	282.
3.5	164	227	243	241	234.
3.75	140	194	206	204	197.
4.0	121	168	177	175	168.
4.5	94	129	135	134	128.
5.0	75	104	107	106	100.
5.5	62	85	87	86	81.
6.0	52	72	73	72	68.
6.5	45	61	62	61	57.
7.0	39	53	53	53	49.
7.5	34	47	47	46	43.
8.0	31	42	41	41	38.

¹ Lifetimes in Myr, calculated using the analytical formulae from Raiteri et al. (1996).