NANODIAMOND DUST AND THE FAR-ULTRAVIOLET QUASAR BREAK
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ABSTRACT
We explore the possibility that the steepening observed shortward of 1000 Å in the energy distribution of quasars may result from absorption by dust, being either intrinsic to the quasar environment or intergalactic. We find that a dust extinction curve consisting of nanodiamonds, composed of terrestrial cubic diamonds or with surface impurities as found in carbonaceous chondrite meteorites, such as Allende, is successful in reproducing the sharp break observed. The intergalactic dust model is partially successful in explaining the shape of the composite energy distribution but must be discarded in the end, as the amount of crystalline dust required is unreasonable and would imply an improbable fine-tuning among the dust formation processes. The alternative intrinsic dust model requires a mixture of both cubic diamonds and Allende nanodiamonds and provides a better fit of the UV break. The gas column densities implied are of the order 10^{20} cm^{-2}, assuming solar metallicity for carbon and full depletion of carbon into dust. The absorption only occurs in the ultraviolet and is totally negligible in the visible. The minimum dust mass required is of the order ~0.003 M_☉, where r_pc is the distance in parsecs between the dust screen and the continuum source. The intrinsic dust model reproduces the flux rise observed around 660 Å in key quasar spectra quite well. We present indirect evidence of a shallow continuum break near 670 Å (18.5 eV), which would be intrinsic to the quasar continuum.

1. INTRODUCTION
The spectral energy distribution (SED) of active galactic nuclei (AGNs) contains a significant feature in the optical–ultraviolet region, known as “the big blue bump.” As for the emission lines in AGN spectra, it is generally believed that photoionization is the excitation mechanism of the emission lines superimposed in AGN spectra, it is generally believed that photoionization is the excitation mechanism of the emission lines. Photoionization calculations that reproduce the SED that peaks (in the continuum. Photoionization calculations that reproduce the excitation mechanism of the emission lines superimposed in AGN spectra, it is generally believed that photoionization is the excitation mechanism of the emission lines. Photoionization calculations that reproduce the excitation mechanism of the emission lines superimposed in AGN spectra, it is generally believed that photoionization is the excitation mechanism of the emission lines superimposed in AGN spectra.

Subject headings: galaxies: active — intergalactic medium — large-scale structure of universe — radiative transfer — ultraviolet: general

Scott et al. (2004) performed a similar compilation for “nearby” AGNs with redshifts z_q < 0.7 and report the lack of any evidence of a steepening in the FUV! Furthermore, the FUSE composite spectrum for nearby AGNs is significantly harder than that of TZ02, with α_v = -0.56^{+0.38}_{-0.28} in the FUV. Arguably, since nearby AGNs are on average less luminous, they may possess an intrinsically different SED. However, a detailed optical–UV study of a subset of the FUSE sample by Shang et al. (2005) fails to reveal any correlation between the FUV index and black hole mass. Therefore, even though the HST FOS and FUSE samples do not represent equivalent AGN populations, the absence of steepening in the FUV for the nearby sample cannot be explained alone by difference in AGN populations. A plausible explanation for the onset and increasing importance of the break in distant AGNs can be provided by intergalactic absorption, since it would scale with distance. In an earlier paper, Binette et al. (2003) explored the possibility that the break might be the result of H I scattering by a tenuous intergalactic component that the authors associated with the warm-hot intergalactic medium. The models, however, predicted a significant flux discontinuity in the region 1050–1190 Å (λ_obs), which is not observed in quasar spectra, as shown by FUSE (e.g., Kriss et al. 2001). Furthermore, the warm-hot intergalactic medium is too ionized to produce the amount of H I absorption needed to reproduce the break. In this paper we explore an alternative interpretation that is based on a different opacity vector, namely, dust, either intrinsic to the quasar environment or intergalactic. The vector responsible for the absorption will consist of grains made of carbon atoms, a major constituent of the interstellar medium (ISM) dust, albeit here in crystalline form (nanodiamonds). We assume that the intrinsic quasar SED consists of a simple power law and that deviations from the power law are caused by absorption from crystalline carbon dust, either as pure cubic diamonds or of the type observed in carbonaceous chondrite meteorites (e.g., Allende, Orgueil, and Murchison). Many mechanisms have been proposed to explain the formation...
of diamond nanocrystallites (see § 7). About half of them require intense UV irradiation. Interestingly, a significant UV flux is present in the two Herbig Ae/Be objects, for which nanodiamond emission bands have been confirmed first (Van Kerckhoven et al. 2002). Processes that form nanodiamonds by UV irradiation are particularly relevant, since quasars are UV powerhouses and their environment might lead to physical conditions that favor the emergence of carbon-based nanocrystallite grains.

The paper is structured as follows: Following the introduction in § 1, we describe in § 2 the dust models and the algorithm used to compute the transmission function. The methodology and classification of the spectra are described in § 3. In §§ 4 and 5 we present the intrinsic and intergalactic dust absorption models, respectively, and compare them with the observed spectra. In § 6 we decide which of the two models is to be preferred, and we discuss a possible final model. In § 7 we focus on the formation and physical properties of nanodiamonds, and we follow with the conclusions in § 8.

2. PROCEDURE AND CALCULATIONS

2.1. Dust Extinction Curves

In order to account for the sharp SED break by way of dust absorption, we looked for an absorption vector that peaks in the FUV (λ < 1000 Å) and yet causes negligible absorption at wavelengths longer than 1200 Å. Ideally, as it is the case with the ISM dust, the grain particles should be composed of the most abundant elements. In both aspects, the crystalline form of carbon is the most appealing candidate and is the basis of this paper. We consider two types of materials: the terrestrial cubic (pure) diamonds and the nanodiamonds as found in meteorites.

A comparison of the UV extinction properties of the terrestrial diamonds and the meteoritic nanodiamonds can be found in Mutschke et al. (2004). The authors separated the nanodiamonds from the Allende6 meteorite sample and determined their optical constants. The meteoritic nanodiamonds differ in their optical properties from the cubic diamond as a result of chemical impurities (e.g., H, N) and of restructured or unsaturated bonds at their surface.

Following a standard procedure, we calculated a set of dust extinction curves. We assumed that the grains are spherical and that a power law describes the differential distribution of grain sizes, dn gr(a)/da = Cgrn gr(a), where n gr is the volume density of grains, n gr that of hydrogen, a the grain radius, the power-law index, and Cgr the normalization constant, such that the density of grains becomes normalized to the abundance of the dust constituents with respect to hydrogen. We adopted the tabulated complex refraction indices n + ik of Mutschke et al. (2004) for the Allende meteorite nanodiamonds and of Edwards & Philipp (1985) for the cubic (terrestrial) nanodiamonds. The Mie theory was used to compute the extinction cross section Q ext(a, λ, n, k), using a modified version of the published subroutine BHMIE of Bohren & Huffman (1983). The extinction cross section is normalized with respect to the gas density nH, using the following integrals:

$$n_H \sigma_H^N = n_H C_{gr} \int_{a_{min}}^{a_{max}} \pi a^3 \kappa Q_{ext}(a, \lambda, n, k) \, da,$$

$$V_{gr} = \frac{4}{3} \int_{a_{min}}^{a_{max}} \pi a^4 \kappa \, da,$$

where a min and a max are the minimum and maximum values of the grain radii considered. The gas opacity is given by the integration of dτ ext/τ ext = nHσ_H^H dr. Neglecting the contribution of elements other than carbon to the composition of the nanodiamonds, we adopt a mean molecular weight of μ gr = 12 for the grains. The value of the normalization constant C gr is obtained by solving the following:

$$Z_C \mu_{gr} m_H = \rho_{gr} C_{gr} V_{gr},$$

where Z C is the carbon abundance by number with respect to H, m H is the hydrogen atom mass, and μ gr is the density of the grain material. The values adopted for ρ gr are 2.3 (Lewis et al. 1989) and 3.51 g cm$^{-3}$ for the Allende and the cubic nanodiamonds, respectively. For the grain size exponent, we adopted ζ = −3.5. Since we know neither the gas metallicity nor the dust-to-gas mass ratio, we assume that all carbon is locked in dust and adopt the solar value of 3.63 × 10$^{-4}$ for the C abundance, for the sole purpose of procuring a convenient normalization.

The solid lines in Figure 1 represent the extinction curves adopted in this paper. The curves labeled D1 and A1 represent the “small size regime” extinction curves for terrestrial diamonds (red line) and for meteoritic nanodiamonds (blue line), respectively. In both extinction models, a min = 3 Å and a max = 25 Å. In this regime, decreasing further a max would not alter the extinction curve. Our extinction curve A1 (blue line) is very similar in shape to the mass absorption coefficient curve determined by Mutschke et al. (2004; see their Fig. 7 or our scaled version of it, the green dotted line in Fig. 1). A third dust model, which is also useful, is the Allende curve labeled A3 (orange line), whose grain sizes extend up to 200 Å. The peak cross sections for the curves D1, A1, and A3 occur at wavelengths 640, 741, and 787 Å, respectively. Meteoritic nanodiamonds are known to possess a median radius a 0 of ~15 Å. When increasing a max to a value of ~50 (75) Å for the Allende (terrestrial cubic) nanodiamonds, one finds that the peak absorption starts shifting noticeably to the right and the absorption profile widens somewhat. This is illustrated by the two long-dashed lines in Figure 1, both calculated with a max = 100 Å. The above-mentioned curve A3 further extends the grain size range to a max = 200 Å, which significantly shifts the broad absorption peak toward longer wavelengths.

As shown in § 4, the extinction curves D1 and A1 (or A3 in § 5) can reproduce the wide range of continuum steepening observed in the FUV in quasar SEDs. Both types can induce a sharp absorption break, although the cubic diamond is more extreme in this respect. This does not occur with ISM dust extinction. For comparison, we plot an ISM dust model from Martin & Rouleau (1991) (with ζ = −3.5) in Figure 1, which consists of silicate and graphite grains of sizes comprised between a max = 2500 Å and a min = 50 Å (black short-dashed line). It is evident that the customary ISM extinction curve, while reaching a maximum in
the UV, still absorbs significantly longward of the peak, which gives rise to a shallow change of index, rather than a sharp break. Grain size is not the main cause for such differences in relation to nanodiamonds, but rather the type of material being considered. To illustrate this, we show a small grain extinction curve used by Martin & Rouleau (1991). The “small grains” dotted line is the same model, but with \( a_{\max} \) reduced (from 2500 Å to 500 Å (Binette et al. 1993)).

Using optically known materials, one could have treated the absorption hypothesis as an inverse problem, working out the extinction curve that succeeds best. Considering that the current study is mostly exploratory in nature, we consider that it confers a higher degree of plausibility to use an empirical curve such as that of the Allende meteorite, rather than an invented cross section.

2.2. Calculation of the Transmission Curve

The basic assumption behind the current work is that the break observed in the spectra is a manifestation of dust absorption and is therefore not an intrinsic feature of the SED. A key aspect in evaluating how well the dust absorption hypothesis fares is to assume that we can extrapolate the power law observed in the NUV to the region underlying the break. Any departure of the observed spectrum from the extrapolated power law will be modeled as “absorption.” Only in § 6.3 is a broken power law considered for the FUV. In our notation, the “true” or intrinsic quasar SED is described by either one of the following expressions:

\[
F_q^\nu = A \left( \frac{\nu}{\nu_0} \right)^{\alpha_\nu},
\]

\[
F_q^\lambda = B \left( \frac{\lambda}{\lambda_0} \right)^{\beta_\lambda} = B \left( \frac{\lambda}{\lambda_0} \right)^{-(2+\alpha_\nu)},
\]

where \( \nu_0 \) and \( \lambda_0 \) (=912 Å) are the ionization thresholds of hydrogen in frequency and in wavelength units, respectively, while \( \alpha_\nu \) and \( \beta_\lambda \) are the corresponding power-law indices. \( A \) and \( B \) are normalization constants, one of which is set to unity according to whether \( F_q^\nu \) (i.e., \( A \)) or \( F_q^\lambda \) (i.e., \( B \)) is plotted, respectively. In keeping with the tradition in AGN literature, the index that we quote in the text is always \( \alpha_\nu \). On par with the work of TZ02 and Zheng et al. (1997), we prefer to plot \( F_q^\lambda(\lambda) \) for most figures. The FUV region beyond the break is better represented using \( F_q^\lambda \) than \( F_q^\nu \), as can be appreciated by comparing the two panels of Figure 2.

2.2.1. Intrinsic Dust Absorption

The (modeled) transmitted flux in the one-dimensional case is given by \( F_T^{\text{mod}} = T_\nu F_q^\nu \), where \( T_\nu \) is the transmission function, which for a point source is simply the exponential \( e^{-\tau_\nu} \). To compute the opacity \( \tau_\nu \) in the case of dust at the redshift of the quasar, all that is required is to specify the absorption column \( N_H \) and select one, or a combination, of the extinction curves described in § 2.1.

2.2.2. Intergalactic Dust and the Simulation of the Composite Spectrum

If the dust is intergalactic, it is necessary to integrate the transmission along the line of sight to the quasar. Because we also intend to simulate the process of constructing a composite spectrum from synthetic quasar SEDs, we developed the following numerical procedure. Briefly, the simulation of the composite will consist in multiplying each synthetic quasar spectrum by the appropriate transmission function and then co-adding them in the quasar rest frame. The synthetic spectra, before dust absorption, share the exact same SED but differ in redshift and in spectral coverage. In the simulation, we adopted the same set of quasar redshifts as those in the TZ02 sample, as well as the same set of wavelength limits for the synthetic spectra as those characterizing the TZ02 archived spectra. Each synthetic spectrum

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No. 2, 2005

NANODIAMOND DUST AND FUV QUASAR BREAK

663

Fig. 1.—Extinction cross sections for nanodiamonds of radii in the range 3–25 Å from the Allende meteorite (blue solid line labeled A1) and for dust grains consisting of terrestrial cubic diamonds (red solid line labeled D1). The two long-dashed lines illustrate the effect of increasing \( a_{\max} \) to 100 Å, corresponding to dust models A2 and D2 (labels not shown). Finally, the curve A3 corresponds to the case of increasing \( a_{\max} \) to 200 Å (orange solid line). The dotted section of the terrestrial diamond curves shortward of 413 Å corresponds to an extrapolation, as the refraction indices are not available. The green dotted line is the Mutschke et al. (2004) mass absorption coefficient curve, which is renormalized so that its maximum coincides with the A1 curve. The two curves barely differ, except longward of 1200 Å. The black dashed line corresponds to a model of the ISM dust by Martin & Rouleau (1991). The “small grains” dotted line is the same model, but with \( a_{\max} \) reduced (from 2500 Å to 500 Å (Binette et al. 1993)).

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The extinction curves D1 and A1 (or A3) as defined above will suffice to test the dust absorption hypothesis. Instead of
corresponding to a given quasar at redshift $z_q$ is divided into energy bins, and for each rest-frame bin $\lambda_j$, we calculate the (modeled) transmitted flux $F_{\nu}^{\text{mod}} = F_{\nu}^0 T_j = F_{\nu}^0 e^{-\tau(\lambda_j)}$, making use of the integrated opacity along the line of sight up to $z_q$:

$$\tau(\lambda_j) = \int_0^{z_q} n_H(z) \sigma_H^I \left( \frac{\lambda_j}{1 + z} \right) \frac{dl}{dz} dz,$$

where $\sigma_H^I$ is the dust extinction cross section evaluated at wavelength $\lambda_j/(1 + z)$ and $n_H(z)$ is the intergalactic dust density expressed in terms of the hydrogen density.

For the calculations of distances, $dl/dz$, and baryonic densities, we assume the concordance $\Lambda$CDM cosmology with parameters derived from the WMAP experiment (Spergel et al. 2003), that is, $\Omega_lambda = 0.73$, $\Omega_M = 0.27$, $h = 0.71$, with $h = H_0/100$ and a baryonic mass of $\Omega_b h^2 = 0.0224$ corresponding to a hydrogen density at zero redshift of $n_{\text{bar}} = 2.06 \times 10^{-7}$ cm$^{-3}$.

3. METHODOLOGY

3.1. The Initial Database

The spectral database adopted in this work is that of TZ02, which was kindly lent to us by R. C. Telfer. It comprises 332 spectra, mostly HST FOS, of 184 quasars, already reduced and corrected for Galactic dust extinction. The spectra furthermore have been corrected by TZ02 for the presence of Lyman limit absorbers (down to $\tau > 0.3$) and of the Lyα absorption valley (caused by the cumulated absorption from unresolved Lyα forest lines).

3.2. NUV and FUV Spectral Indices

We define the FUV as the wavelength region shortward of the break from 300 to 1000 Å, the NUV as the 1000–3200 Å region longward of the break, and the optical–UV as the 3200–4200 Å region.

Throughout this paper we refer to the power-law index longward of the break as $\alpha_{\text{NUV}}$ and that shortward as $\alpha_{\text{FUV}}$. We assume that the intrinsic SED power-law index, $\alpha_{i}$, has the same value in the region of the break as in the NUV, hence $\alpha_{\text{NUV}} = \alpha_{i}$. Whenever possible, the adopted value for $\alpha_{\text{NUV}}$ will be the value that we estimate empirically, using the adjacent NUV region of the HST FOS spectrum. This value is to be preferred over published values, which correspond to a forced fit of the combined optical–UV region. The HST FOS $\alpha_{\text{NUV}}$ indices are usually significantly harder. They are more appropriate for the exercise at hand, which relies on having a dependable SED description immediately longward of the break that can be extrapolated one octave shortward, in the region of the break itself.

3.3. Preanalysis of the HST FOS Sample

Following a preliminary analysis of the TZ02 sample and of the properties of dust models, we established the following:

1. Individual quasar spectra provide stronger constraints to the models than a single composite spectrum. The process of co-adding varied spectra to construct the composite inevitably leads to a loss of valuable information. Modeling the composite spectrum is probably an essential exercise but does not constitute a determinant proof of the validity of any model. For these reasons, we concentrate here on fitting individual quasar SED.

2. Since combined multigrating spectra extend over a larger wavelength domain, they provide stronger constraints for the models than single-grating spectra. For this reason, this work considers only those 106 spectra of the TZ02 sample that correspond to a combination of two or three HST FOS gratings.\(^{10}\)

3. In the process of looking for patterns among the numerous spectral shapes encountered, we found it beneficial to classify these according to the signs by which dust absorption apparently manifests itself. The proposed classification is nothing more than a convenient and simplified characterization of the big blue bump phenomenology found among the archived HST FOS spectra. By no means does it imply that the quasars themselves are

\(^{9}\) Note that the TZ02 sample includes three HST Space Telescope Imaging Spectrograph (STIS) and six HST Goddard High Resolution Spectrograph (G HRS) spectra.

\(^{10}\) Of particular interest are quasars in the redshift range 0.9–2, for which the spectrum corresponds to a combination of three gratings. In these, the break is in full view and, in most cases, there is sufficient wavelength coverage, longward of the break, to infer the spectral index $\alpha_{\text{NUV}}$ and, shortward of the break, to distinguish absorption features that the models must reproduce.
intrinsically different as a result of their spectra belonging to one class or another.

3.4. Classification of Multigrating Spectra into classes A–D

A physical insight on how dust can alter the continuum shape and account for the break has led to the classification of the multigrating spectra into four groups. The three most relevant groups are qualitatively described in Figure 2a. The four classes are defined as follows:

1. The spectra that show a continuum steepening near 1000 Å ($\lambda_{\text{rest}}$) belong to class A. The NUV spectrum is hard in these spectra and the FUV shows a moderately steepened continuum. PG 1148+549 ($z_q = 0.969$) can be considered the archetype of this class (see Fig. 5). We tentatively assign the seven spectra (usually high-redshift quasars), whose NUV FOS spectrum is not available longward of 1300 Å, to class A. HS 1700+6416 ($z = 2.722$), for instance, is classified as class A (Fig. 13). More than 60% of quasars, whose spectra extended sufficiently into the FUV to determine $\alpha_{\text{NUV}}$, belong to class A alone. This may explain why the spectra of this class individually resemble the TZ02 composite shape, since the composite is after all the result of averaging spectra that more often than not belong to class A.

2. The spectra that show a sharp break near 1000 Å, followed by an extremely steep continuum drop shortward of the break, belong to class B. The NUV spectrum is hard in these spectra. PG 1248+401 ($z_q = 1.03$) in Figure 3 can be considered the archetype of this class. Another example is PKS 0122−00 ($z_q = 1.07$) in Figure 4. Objects in this class are not that common (only six) yet striking by their lack of a significant flux in the FUV.

3. The spectra that show a continuum that is already soft longward of the break, that is, up to $\approx 1600$ Å, belong to class C. The soft region of the continuum now extends to include the continuum beneath the C iv $\lambda 1549$ doublet (or even down to C iii $\lambda 1909$ in some cases). A representative class C spectrum is the quasar 1130+106Y in Figure 11 ($z_q = 0.54$). In many cases a single power law does not fit the NUV part well, and in other cases the index is very steep ($< -1$) throughout the whole spectrum, as exemplified by 3C 279 in Figure 11 (green spectrum). In the FUV, these objects show characteristics of either class A or B; that is, they are either flat in $F_{\lambda}$ or very steeply declining, as illustrated by MC 1146+111 ($z_q = 0.863$; cyan spectrum), which exhibits a class B–like break. We found eight objects with the above characteristics.

4. The high-redshift quasars (three objects) that we could not make sense of belong to class D. They are objects that show an inflection or wide trough in the FUV. HE 1122−1649 is one example (see Fig. 18, blue spectrum). We do not rule out that the troughs could be associated in some cases with one or more Lyα absorption systems.

Only 61 of the available 106 multigrating spectra extended sufficiently shortward of the break, that is, down to at least 900 Å, to ensure proper classification. Therefore, only this subset of 61 quasars has been analyzed in detail and modeled. Of these, 44 are class A, 6 class B, 8 class C, and 3 class D. We mainly focus on class A and B spectra. These two groups together represent 82% of the classified objects and will suffice for the purpose of testing the dust absorption hypothesis. Many interesting spectra that could not be shown in this paper will appear elsewhere (e.g., Binette et al. 2005a, 2005b, 2005c). As for class C, dust appears to be related to some of the observed characteristics of at least a fraction of them (§ 4.3), but further work will be needed to reach definite conclusions. The few objects that form class D are puzzling and will not be modeled with dust absorption in this paper.

3.5. Absorption Models Considered: Intergalactic versus Intrinsic

In order to explore how dust absorption might be the real cause of the observed break, a decision must be made on where the dust is located. The answer to this question defines two basic types of absorption models: (1) the dust is intrinsic to the environment of the quasars, and (2) the dust fills the intergalactic space. In case 1, the transmission function is derived directly from the extinction curve in the rest frame of the quasar, as mentioned in § 2.2.1. With this category of models, we may reasonably expect the amount of dust to vary more or less at random from object to object. In case 2, the dust distribution is intergalactic and fills large volumes of space. We therefore expect that such a dust distribution should be, to first order, homogeneous, since the dust becomes a cosmological component unrelated to the quasars. With case 2, the models predict the same transmission for objects of comparable redshifts, independently of class. The dust density, $n_d(z)$, a function of redshift as mentioned in § 2.2.2, has to be determined, requiring extra constraints. Intergalactic models imply enormous amounts of dust, since it is cosmological. We first study the intrinsic dust case and then proceed to the intergalactic case.

In all figures, when overlaying a dust absorbed model to the rest-frame spectrum of a particular quasar at redshift $z_q$, we follow the following coding: the solid line part depicts the wave-length region corresponding to an idealized FOS spectrograph window extending from 1250 to 3600 Å ($\lambda_{\text{obs}}$), while the dashed line represents an extension into the FUV down to 915 Å ($\lambda_{\text{obs}}$), as would be available using the FUSE satellite. A dotted line is used outside these two observer-frame windows.

4. THE CASE FOR INTRINSIC DUST

The case in favor of intrinsic dust absorption is best made by going through each class in order of increasing complexity of the dust model that it requires, that is, in the order B, A, and C.

4.1. Class B Spectra

Although class B objects are not numerous, they give us an important clue on how to disentangle various effects resulting from dust absorption. What characterizes this class is the very steep drop of the UV flux shortward of 1000 Å ($\lambda_{\text{rest}}$). Class B objects can easily be accounted for by simply using the extinction curve D1 consisting of terrestrial cubic nanodiamonds and adjusting as needed the absorption column $N_{\text{H}}$. This is illustrated

\footnote{Since the spectra have already been corrected for Galactic reddening, there is no reason to be concerned by Galactic dust absorption.}

\footnote{It is likely that only a small fraction of carbon is actually locked into nanodiamond grains. Supposing we independently knew the dust-to-gas ratio due to nanodiamonds $\Delta_{\text{DTG}}$ and that it was smaller than 0.0031, which corresponds to depleting all the carbon onto dust, then the absorption columns quoted in this paper would have to be multiplied by the factor 0.0031/$\Delta_{\text{DTG}}$. The Galactic ISM dust is characterized by a much larger $\Delta_{\text{ISM}} \approx 0.009$, since it contains many other atomic species than C.}
in Figure 3, which shows the spectrum of the archetype class B quasar, PG 1248+401. The red line corresponds to a model using the curve D1 and an absorption column density $N_H$ of $3.2 \times 10^{20}$ cm$^{-2}$ (hereafter the notation $N_{20}$ = 3.2 is used). The assumed underlying power-law index is $\alpha_V = \alpha_{NUV} = 0.0$, which is the index that best fits the emission-line–free continuum longward of Ly$\alpha$. In all our plots, it is the quasar spectrum that we scale, until an overlap with the model is obtained in the NUV. The resulting spectrum scaling factor, $M_{14}$, is listed in each caption in units of $10^{14}$ erg$^{-1}$ cm$^{-2}$ s$^{-1}$ Å. Since we assume the intrinsic SED to be described by a simple power law (until $\lambda >$ 6.3Å), the plotted models in all figures correspond to the function $I_{\nu, \lambda}^{\odot} = T_{\nu, \lambda} (\lambda/912)^{-2\alpha_{\nu}}$, and the $y$-axis can be used to infer the transmission value $T_{\lambda}$ for any value of $\lambda$.

The only free parameter of the above D1 dust model is the column $N_{20}$. The position of the peak in transmission overlaps surprisingly well with that of the observed spectrum. This is the result of the very sharp drop in cross section of curve D1 longward of $\sim$1000Å (see Fig. 1, red line), a property unique to cubic diamonds among dust grains composed of pure carbon. It is important to note that class B objects cannot be accounted for by making use of the Allende extinction curves A1 or A3 because these are characterized by a broader absorption peak and the peak itself is shifted toward higher $\lambda$-values. The blue line in Figure 3 illustrates the case of using curve A1. The relative success of the D1 dust model is telling us that if dust were indeed responsible for the break in class B objects, it must mostly consist of cubic diamonds. This does not rule out that a small fraction of the dust may be of the Allende type. This is demonstrated by the green line, which corresponds to a model with $N_{20} = 2.8$ and a linear dust mixture of 85% of D1 grains and 15% of A1 grains. Hereafter we use the notation of $f_{D1} = 0.85$ to represent the fraction of D1 grains, with $1 - f_{D1}$ being the fraction of A1 grains.

Other class B quasars are PKS 1229–02 and PKS 1424–11, which are quite similar to PG 1248+401. They require models with dust columns of $N_{20} = 3.6$ and 2.0, respectively, and an extinction curve consisting totally or mostly of cubic diamond type D1. In Figure 4 we show another B-type spectrum, quasar PKS 0122–00, which requires somewhat less dust. For this object, the green line model has $N_{20} = 2.0$ and consists of a dust mixture with $f_{D1} = 1.0$. It appears that the model with a mixture of dust types D1 and A1 results in a fit superior to that of the blue line model with pure cubic diamond extinction (with $f_{D1} = 1.0$ and $N_{20} = 2.3$).

In summary, class B spectra require dust that predominantly consists of cubic diamonds. The particular absorption characteristics of cubic diamonds fit the observed FUV steep drop particularly well. Due to the large dust opacities implied, there subsists little or no FUV flux to be observed in these objects shortward of 800Å. If photoionization by high-energy UV photons is the excitation mechanism of the emission lines, it is puzzling to find that the same high-excitation emission lines are observed in class B quasars, devoid of hard UV, as in other objects that do have a hard continuum (e.g., HS 1700+6416 with $\alpha_{FUV} = -0.55$; Reimers et al. 1989). A possibility is that the dust lies outside the
three emission lines: O\textsubscript{iii}, Ne\textsubscript{v}, and O\textsubscript{ii}. A mixture of the two nanodiamond grain types provides a satisfactory fit of the continuum underlying the extinction curve consisting of a mixture with N\textsubscript{D1} = 1.05 and an SED with $\alpha_{\text{FUV}} = -0.2$. The blue line represents the same model but assuming the extinction curve A1 (Allende nanodiamonds), while the green line corresponds to a dust mixture model with $f_{\text{D1}} = 0.6$. This mixed dust model provides a satisfactory fit of the continuum underlying the three emission lines: O\textsubscript{iii}, Ne\textsubscript{v}, and O\textsubscript{ii}.

broad-line region (BLR). In this case, the emission-line BLR clouds would be exposed to an ionizing continuum that is not absorbed.

4.2. Class A Spectra

4.2.1. A Mixture of the Two Nanodiamond Grain Types

Class A spectra show a continuum break that is far less pronounced. The FUV continuum is often flat\textsuperscript{15} in $F_{\lambda}$, with an index $\alpha_{\text{FUV}}$ of order $-1.7$ shortward of 1000 Å. One may reasonably expect that the absorption dust columns are simply smaller than in the previous case. This is confirmed by models. Unlike class B objects, where one species of dust is clearly favored, class A objects generally require an extinction curve that combines the extinction from Allende nanodiamonds with that of cubic diamonds, that is, nanodiamonds with and without surface impurities (§ 2.1). The spectra of PG 1148+549 in Figure 5 serve to illustrate this point. All models shown have the same column of $N_{\text{D1}} = 1.05$ and the same SED with $\alpha_{\text{FUV}} = -0.2$. Either extinction curve D1 or A1 can give rise to a flat continuum immediately longward of the break, but the onset of the break turns out to be inappropriate for both the D1 extinction curve (red line) and the Allende A1 curve (blue line), as seen in Figure 5. An extinction curve consisting of a mixture with $f_{\text{D1}} = 0.6$ (60\% D1 and 40\% of A1 grains), on the other hand, provides quite an acceptable fit to the break (green line). We found that, by using a proper mixture of the two grain types, one can fit all class A objects. Three prominent emission lines stand out above the FUV continuum in PG 1148+549, shortward of 900 Å (the line identifications shown in the figures follow those proposed by TZ02). It is interesting to note that extinction by pure cubic diamonds (red line) gives rise to a narrow dip near 700 Å, a feature not observed in this particular quasar.

4.2.2. Applying the Intrinsic Dust Model to Class A Spectra

A mixture of the two nanodiamond types is very successful in reproducing the break in all class A spectra. More specifically, we can fit all observed 1000 Å breaks assuming one of the four following values of $f_{\text{D1}}$: 0, 0.3, 0.6, or 1.0. A finer subdivision in most cases is not warranted by the data because the spectra very rarely extend sufficiently in the FUV for the fit to be sensitive to small changes in $f_{\text{D1}}$. In a few cases, only the onset of the break is seen, and we could not determine with certainty whether the value of 0.3 or 0.6 is more appropriate. At any rate, the value of $f_{\text{D1}} = 0.3$ appears to be the most frequent as indicated in the histogram of Figure 6, but there remains a substantial fraction of objects that require a different dust mixture.

In Figure 7 we present the distribution of gas columns derived from fitting class A and class B spectra. The mean $N_{\text{D1}}$ value for class A is 1.02 with a standard deviation of 0.29. There are two high-redshift spectra, for which there is no evidence of dust, with an upper limit of 0.1, which are HS 1700+6416 and HE 2347–4342 (they have not been included in the average). If we combine class A and B spectra into a single group and assume that they are part of the same population, we derive $N_{\text{D1}} = 1.20$ and a standard deviation of 0.60. The distribution shows that the presence of nanodiamond dust is the rule in quasars rather than the exception. In many quasars, the amount of dust inferred is comparable. For instance, 39 quasars have a column 0.6 ≤ $N_{\text{D1}}$ ≤ 1.4, which represents 78\% of the 50 class A+B spectra.

As for the distribution of $\alpha_{\text{FUV}}$, describing the NUV continuum, we obtain a mean value for class A of $\overline{\alpha_{\text{FUV}}} = -0.44$ with a dispersion of 0.21. This average considers only the 21 objects for which a reliable estimate of $\alpha_{\text{FUV}}$ could be determined directly from the HST spectra. It is significantly harder than the mean value of $-0.69$ reported by TZ02 and the median value of $-0.83 \pm 0.04$ for local AGNs reported by Scott et al. (2004).
presumably because the softer class C spectra are not included in our average.

4.2.3. Dust Models Predict a Rise Shortward of $\sim$700 Å

Due to the rapid decrease in the dust extinction cross section in the FUV, shortward of the cross section peak (see Fig. 1), an inescapable feature of dust absorption is that a rise in transmitted flux always occurs in the FUV, shortward of $\sim$700 Å. Of the seven multigrating spectra that extended down to 600 Å and showed evidence of dust absorption, we found evidence of a sharp flux rise in four of them. This test was not conclusive for the remaining three spectra. The observation of a steep rise in the FUV is the strongest evidence in favor of dust absorption and is presented in more detail below.

The first spectrum with a sharp rise is PG 1008+1319, which is shown in Figure 8. We adopt the value of $+0.13$ as NUV index, as determined by Neugebauer et al. (1987). The green line corresponds to an intrinsic dust model with $f_{D1} = 0.3$, while the gray line corresponds to $f_{D1} = 0.6$. The column in both models is $N_{20} = 1.2$. Clearly the model with an extinction dominated by Allende nanodiamonds (red line) gives a better fit to the break. Reducing $f_{D1}$ further would cause the break’s onset to occur at too long a wavelength (e.g., the $f_{D1} = 0$ model in Fig. 5).

A second example is PKS 0232−04 of Figure 9. A fit of the NUV continuum favors $c_{\alpha}$ indices in the range $−0.2$ to $−0.4$. To be definite, we adopt the steeper SED with $−0.4$. We verified that the same conclusions are reached when using the harder index. The red line model, which is more satisfactory, corresponds to pure D1 dust with $f_{D1} = 1.0$ and $N_{20} = 0.90$, while the green line model corresponds to $f_{D1} = 0.8$ and $N_{20} = 0.93$. Due to the predominance of cubic diamonds, a narrow dip at 650 Å stands out in models with $f_{D1} \gtrsim 0.7$. This dip appears to be saddened by two prominent emission lines, O vii and Ne viii, both of which are also visible in the composite SED of TZ02, but not as prominently. Interestingly, Scott et al. (2004) discuss the nature of a narrow dip seen blueward of the Ne viii emission in their near-AGN composite. The interpretation they favor is that of blueshifted absorption by Ne viii. Another explanation might be that absorption by cubic nanodiamonds is responsible for this feature. Even though the D1
A third example is provided by the much higher redshift quasar, HS 1307+4617, at \( z = 2.129 \), which is plotted in Figure 10. There is no \textit{HST} FOS spectrum that covers the NUV. Instead, we adopt the value of \( \alpha_{\text{NUV}} = 0.0 \) as inferred from a spectrum of D. Reimers and reproduced in Koratkar & Blaes (1999). The three models superimposed to the spectrum in Figure 10 have the same column \( N_{20} = 1.3 \) and differ only by their proportion of the D1 and A1 dust, as follows: \( f_{\text{D1}} = 0.8 \) (\textit{green} line), 0.6 (\textit{purple} line), and 0.8 (\textit{gray} line). The green line model with \( f_{\text{D1}} = 0.6 \) provides a better fit. It is interesting to note that the disjoint part (\textit{yellow segment}) of the GHRS spectrum (taken with grating G140L) is not consistent with the FUV extrapolation of the models. A solution to this problem is found in \( \text{MC 1146+111} \) (\textit{cyan line}), 3C 279 (\textit{green line}), and 1130+106Y (\textit{black line}). The notation is the same as in Fig. 3. Both MC 1146+111 and 3C 279 have been suitably scaled so as not to overlap with the quasar 1130+106Y, which is being modeled. 3C 279 is flat in \( F_{\nu} \), hence \( \alpha_{\nu} \approx -2 \). Yellow line: Dust absorption model of 1130+106Y assuming \( \alpha_{\nu} = -0.25 \) and an extinction curve corresponding to pure Galactic ISM extinction with \( N_{20} = 9.0 \). (This last model has been multiplied by 1.3 before plotting.) The magenta line represents a dust mixture of ISM-type grains (80%) and terrestrial diamond grains D1 (20%). The \( V \)-band extinction implied by this model is \( A_{V} = 0.4 \) mag.

Evidence of reddening by ISM dust appears to be present in class C spectra, but nanodiamond dust is nevertheless required to explain the break when it is present. A few class C spectra show a steep drop shortward of 1000 Å as in class B spectra. We have not explored the possibility of a combination of the three extinction curves A1, D1, and ISM. It is possible that some class C spectra possess an SED (from NUV to FUV) that is intrinsically steeper than in other classes, with \( \alpha_{\nu} \) in the range \(-2 \) to \(-1.2 \).

5. THE CASE FOR INTERGALACTIC ABSORPTION

The fact that the absorption columns take on similar values in the intrinsic case for the numerous class A spectra invites us to explore the hypothesis that the dust pervades the intergalactic space instead of being confined to the environment of each quasar. Following this hypothesis, the distribution of the dust bears no relation to the quasars but is a function of distance (i.e., \( z \)). By
the same token, we expect the grain composition to be more uniform in the intergalactic case than in the intrinsic case. The intergalactic model does not, however, imply that there cannot be an additional intrinsic dust component local to some quasars, as appears to be the case for class B and C spectra. On the other hand, the case for intergalactic dust will be more convincing if a minority of class A spectra require additional absorption above the one provided by the intergalactic model.

The predictive value of the intergalactic model resides in the function chosen to describe the dust density with redshift. Such a function will allow not only the modeling of the break in individual quasars but also the simulation of the composite SED. The one provided by the intergalactic model, as appears to be the case for class B and C spectra. On the other hand, the case for intergalactic dust will be more convincing if a minority of class A spectra require additional absorption above the one provided by the intergalactic model.

5.1. Constraining the Dust Behavior with Redshift

As a working hypothesis, let us assume that the dust is intergalactic and for now consider only class A spectra. Since the absorption occurs along the line of sight to each quasar, its impact can extend over the whole FUV domain as a result of the redshift effect and cosmological expansion. In a universe that evolves and expands, any cosmological quantity such as the density of the Lyα absorbers, the density of quasars, the star-forming rate, etc., is known to evolve strongly with redshift, that is, with time. The same must apply to the hypothesized intergalactic dust.

There should exist an epoch (z_p) at which the dust density reaches a peak. To describe such a peak, we adopt a parametric form for the dust density n_H(z), similar to that used by Baldry & Glazebrook (2003) to describe the cosmological star formation rate. It consists of a broken power law joining at redshift z_p:

\[ n_H(z) = \begin{cases} 
 n_H^0 (1 + z)^\epsilon, & z \leq z_p, \\
 n_H^0 (1 + z_p)^{-\epsilon} (1 + z)^\gamma, & z > z_p,
\end{cases} \]

(1)

where n_H^0 is the density at zero redshift, 0 < \epsilon < 1, and \gamma are the low- and high-redshift indices, respectively, and z_p is the intersection of the two truncated power laws. Hereafter we use n_H^0 in units of 10^{-8} \text{ cm}^{-3} to express the density at zero redshift.

To constrain the parameters describing the function n_H(z), we proceeded as follows. Since Scott et al. (2004) did not find evidence of a continuum break in nearby AGNs (z < 0.7), this suggests that the peak in absorption occurred at an earlier epoch rather than in the local universe. A positive index for \epsilon, in which absorption increases with look-back time, will have the effect of reducing the importance of the 1000 Å break within the local universe. Another indication of the increase in the importance of the break with redshift can be appreciated in Figure 12, where we plot H_FUV as measured for each quasar by TZ02. To derive the mean values represented by the squares, we distributed the measured indices into five redshift bins and then calculated the average H_FUV within each bin. (The solid line simply connects the five mean values.) After trial and error and varying \epsilon, we found that similar fits to the break could be obtained, using any value within the interval 1.5 < \epsilon < 3.5. To constrain \epsilon more effectively, we adopted the value \epsilon = +2.

To determine the behavior of n_H(z) at the other redshift end, we can compare the very high redshift quasar spectra (z \geq 2.5) with those at intermediate redshifts. As it turns out, most high-z HST FOS spectra are single grating and cannot be used for that purpose. Fortunately, there exist two quasars with high signal-to-noise ratio (S/N) and wide spectral coverage that we could analyze in greater detail, HS 1700+6416 and HE 2347–4342, which are plotted as F_z in Figure 13. The power-law indices for HS 1700+6416 and HE 2347–4342 that we adopt are \alpha_z = −0.55 (from Reimers et al. 1989) and +1.70 (inferred from the best model), respectively. The missing parameter values defining n_H(z) were arrived at using various constraints, as described below.

Because of the redshift effect, the HST FOS spectra of both HS 1700+6416 and HE 2347–4342 do not cover the typical break region at 1000 Å (\lambda_{\text{break}}). Viewed from the perspective of intergalactic dust, however, the absorption break should have shifted to shorter wavelengths (with z), as demonstrated below in § 6.2. As a consequence, the continuum shape’s departure from that of a pure power law must be the result of the hypothesized intergalactic dust, if such a model is to be of any use. Despite the ragged appearance of both continua in Figure 13, caused by the many absorption systems along the line of sight, it is clear that both show a general curvature or change of index, which intergalactic absorption must be able to explain. It turns out that such a curve can be reproduced by intergalactic dust models using either of the extinction curves, A1 or D1. To select the appropriate extinction, we required that the dust model successfully reproduced the break observed in the lower redshift spectrum of PG 1148+549, which is the archetype of class A. This second constraint effectively rules out cubic diamonds as shown by the

Note that if we attempt to fit the above curvature using intrinsic dust, the absorption actually goes the wrong way, making the transmitted spectrum appear even harder, as illustrated by the green line model calculated with N_{20} = 0.5 and f_{01} = 0.3.

17 Because of the hardness of HE 2347–4342 (\lambda_{\text{break}} \sim 3), using F_{\lambda_{\text{break}}}^\text{obs} is much more convenient than F_{\lambda_{\text{break}}}^\text{intrinsic}.

18 The density \rho_{\text{H}} as defined in this work is not a comoving but rather a local quantity.
red line model of PG 1148+549 in Figure 14. In the case of intergalactic models with dust curve A1, the break occurs at somewhat too short a wavelength (see Fig. 14, blue line). To compensate for the redshift smearing effect, we extended the grain size range of the Allende nanodiamonds, extending it up to $a_{\text{max}} = 200 \text{ Å}$. This defines the new extinction curve A3 (see Fig. 1, orange line) used in all our intergalactic calculations. This extinction curve A3 was found to provide an overall better fit to class A objects, in the intergalactic case.

Having selected the optimal extinction curve, strong constraints on $z_p$ and $n_{\text{D}}^{\text{A3}}$ can now be derived by varying these parameters until an acceptable fit of the two high-$z$ quasars is found. We found that $\gamma$ is loosely constrained to negative values $\leq -1.4$. To further constrain the function $n_{\text{D}}(z)$ and $\gamma$, we made use of the composite quasar SED of TZ02 (shown in Fig. 15). We simulated this composite by co-adding synthetic dust-absorbed SEDs of the same redshifts and spectral widths as those in the actual TZ02 sample, following the procedure described in § 2.2.2. This exercise indicated a preference for somewhat larger values of $\gamma$ than the range favored above using the two high-$z$ quasars. To be definite, we adopted the value of $\gamma = -1.5$, which corresponds to the overlap between the two types of constraints. The result of combining these different constraints in an iterative fashion has been that an acceptable fit to the broad curvature of both high-$z$ quasars of Figure 13 occurs when using the value $z_p \simeq 0.4$ for the peak dust redshift. The resulting orange line model, which requires $n_{\text{D}}^{\text{A3}} = 3.4$, now overlays both continua in Figure 13, as well as the outline of the break in PG 1148+549 (Fig. 14). In conclusion, the intergalactic dust model can account for the progressive steepening of the power-law index observed shortward of 500 Å in HE 2347–4342.

5.2. Applying the Intergalactic Model

A reasonable expectation of the intergalactic dust model is that it should apply to all the classes defined in § 3.4. This is not to say that additional absorption by a local dust component cannot take place in some quasars. For instance, class B quasars, although dominated by intrinsic dust, as shown in § 4.1, can also be modeled as the sum of intergalactic absorption and absorption by intrinsic D1 dust. An example of such complementarity is given by class B quasar PKS 0122–00 in Figure 4. An orange line model is plotted, which includes absorption by both intergalactic A3 dust and intrinsic D1 dust of column $N_{\text{D}1} = 1.0$. Except toward the FUV, this orange line model (mostly hidden by the foreground red line!) is almost identical to the previously described green line model (§ 4.1), which consisted of an intrinsic dust mixture with $f_{\text{D1}} = 0.8$ and column $N_{\text{D1}} = 2.0$. A similar comparison can be established with the intergalactic orange line model of PG 1248+401 (Fig. 3).

When attempting to simulate the composite SED of Figure 15, it turns out that $n_{\text{D}}^{\text{A3}}$ must be increased, from 3.4 to 4.7. If not, the model lay significantly above the composite. Such a model with $n_{\text{D}}^{\text{A3}}$ increased to 4.7 is shown by the purple solid line in Figure 15. This simulation, although imperfect, is encouraging, if we consider that our simulation assumed a single power-law index $\alpha_{\nu} = -0.6$ while the TZ02 composite sampled widely different energy distributions. Furthermore, TZ02 have combined spectra of classes A–D, while the pure intergalactic model is intended for class A objects. It is presumably for that reason that
Is it possible to simulate the TZ02 composite assuming only intrinsic dust? One difficulty is that the intrinsic model is mute about how other parameters like \( N_{20}, f_{D1}, \) or \( \alpha_v \) might vary with increasing \( z \). However, since each class A spectrum can be fitted quite well by varying \( f_{D1} \) and \( N_{20} \), which is an approach that we consider superior to that of simply fitting the TZ02 composite, it can then be argued that not being successful in the simulation of the composite is of secondary importance. Although we consider this to be true, we nevertheless attempted to simulate the composite because it reveals real trends in quasar SEDs. The fact that the TZ02 composite remains very soft at very short wavelengths instead of showing an FUV rise must be explained somehow.

The silver dashed line in Figure 15 illustrates our initial attempt to simulate\(^1\) the composite SED, assuming \( \alpha_v = -0.6 \) and keeping all the input parameters constant with \( z \). The column is \( N_{20} = 1.0 \) and \( f_{D1} = 0.3 \). The FUV flux is obviously predicted too strong. This happens because the extinction cross section falls off too rapidly at very short wavelengths, and a steep rise in \( F_{\lambda} \) becomes unavoidable shortward of 600 Å. The simulated composite simply tends toward the slope given by the index \( \alpha_v \). If we vary the column with redshift, by defining a function \( N_{20}(z) \), we obtain the absurd result that, in order for the simulated composite to overlap the TZ02 composite, the dust column would have to increase sharply with redshift. This is not only an ad hoc dust behavior, but it is also contradictory to the absence of any increase with \( z_q \) of the columns determined in § 4.2. In addition, it is at odds with the lack of absorption in the two high-redshift spectra of HS 1700+6416 and HE 2347–4342, for which we determined absorption upper limits of \( N_{20} \leq 0.1 \). Attempts to model the curvature in these two spectra with intrinsic dust result in absorption features at the wrong end of the spectrum. In effect, local dust makes both spectra appear even harder than they already are, as illustrated by the green line model in Figure 13 calculated with \( N_{20} = 0.5 \) and \( f_{D1} = 0.3 \).

6.2. The Intergalactic Dust Hypothesis

The few shortcomings mentioned above for the intrinsic case disappear with intergalactic dust. By construction, the continuum of the two high-redshift quasars, HS 1700+6416 and HE 2347–4342, can be reproduced. On the other hand, the break can be fitted only for a qualified majority of class A spectra, while the other spectra usually require intrinsic dust to be added to the model. The TZ02 composite can be reproduced, albeit with a density \( n_h^* \) increased by 40% (for which we have no satisfactory explanation to propose). The FUV index \( \alpha_{FUV} \), when evaluated at the fixed wavelength of 800 Å, exhibits the correct trend with redshift, as shown by the long-dashed line in Figure 12. One may argue that the amount of dust implied by the intergalactic model is excessive if not plainly unreasonable, but it is not an impossible amount. The fraction of the baryonic mass that the value \( n_h^* = 3.4 \) corresponds to is 17% (see § 6.3), assuming that the mean cosmic carbon metallicity is about solar and that the dust is intergalactic, because it was expelled from galaxies by radiation pressure (Ferrara et al. 1991) or through Type II supernovae.

The intergalactic model, on the other hand, makes stringent predictions about how the break ought to shift (and soften) with increasing redshift. This is shown in Figure 16, in which the transmission function is plotted at representative \( z_q \) values. The

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\(^1\) In a situation in which none of the parameters defining the intrinsic model vary with redshift (as for the silver dashed line model in Fig. 15), all the absorbed SEDs are identical and there is no need to co-add the spectra in order to simulate the composite.
continuous part of each $T_i$ curve corresponds to the fiducial spectrograph window of 1250–3600 Å ($\lambda_{\text{obs}}$; see § 3.5) and shows what part of the break is visible at a given redshift $z_q$. Notice that when the redshift exceeds values of $\sim 1.5$, the break is markedly shifted toward shorter wavelengths. Of the three spectra presented in § 4.2.3, which showed a clear flux rise in the FUV, only one is of sufficiently high redshift to test this, HS 1307+4617 with $z = 2.129$. Its spectrum is shown again in Figure 17 and can be compared with the pure intergalactic model with $n_H = 3.4$, which is represented by the brown dashed line. The SED is the same as earlier, that is, $n_H = 3.4$.

![Image 1](image1.png)

**Fig. 16.**—Transmission functions $T_i(\lambda)$ for $z$ values of 0.1, 0.2, 0.5, 1.0, 1.5, 2.0, 2.8, 3.5, and 5.0, assuming the standard intergalactic dust model and the extinction curve A3. The parameters used to define the function $\eta(z) = 0.4, \epsilon = +2$, and $\gamma = -1.5$ (eq. [1] in § 5.1). The solid part of each line corresponds to the fiducial spectrograph window of 1250–3600 Å ($\lambda_{\text{obs}}$) at the corresponding quasar redshift. The thick gray dashed line is a fit of the $z_q = 2.8$ transmission curve using the cutoff function $C_\sigma$ defined in eq. (2), with $\lambda_{\text{brk}} = 670$ Å, $\delta = -1.6$, and $f = 2.8$.

The gradual break (or curvature) seen in the brown dashed line model in Figure 17 not only occurs at very short wavelengths ($\sim 550$ Å) but is extremely shallow. Obviously, in order to fit the sharp break characterizing the HS 1307+4617 spectrum, additional intrinsic absorption must be considered. A model is represented by the orange line, which is a model that combines intergalactic with intrinsic dust. The local dust column is $N_H = 0.8$ with a dust composition $f_{\text{D1}} = 0.6$. The fit to the observed flux rise is surprisingly good, much better even than with the pure intrinsic case represented by the green line in the previous Figure 10 of the same quasar. Even more suggestive is the disjoint spectrum obtained with GPHS grating G140L (Fig. 17, yellow spectrum), which despite its lower S/N appears to prolong the FUV rise of the multigrating spectrum (black line). The intergalactic model is marginally consistent with the continuum level set by this spectrum segment, in contrast with the pure intrinsic model, which rises too steeply (see Fig. 10, green line).

The green dashed line in Figure 17 represents the contribution of intrinsic dust absorption that is present in the orange line mixed model. In summary, even though intrinsic dust is the main contributor to the sharp break observed in HS 1307+4617, the signature at the shortest wavelengths expected in high-z spectra as a result of intergalactic dust appears to be independently confirmed in this quasar.

Is the intergalactic hypothesis vindicated? It turns out not to be the case. In effect, a rather poor fit is provided for the two other quasar spectra that showed an FUV flux rise, PG 1008+1319 and PKS 0232–04. As is the case for HS 1307+4617, these two quasars require additional intrinsic absorption, with dust columns ($N_H$) of 0.5 and 0.25 and dust mixtures ($f_{\text{D1}}$) of 0.0 and 1.0, respectively. However, even when combining this additional absorption with intergalactic dust, the FUV rise cannot be reproduced at all, as shown by the corresponding orange lines in Figure 8 of PG 1008+1319 and in the new Figure 18 of PKS 0232–04. The FUV continuum level is predicted too low in the PKS 0232–04 model and, in both figures, the flux rise (orange lines) occurs at too short a wavelength.

### 6.3. Evidence of a Higher Energy Break?

As indicated above, the discrepancy of the intergalactic model for reproducing the FUV rise in PG 1008+1319 and PKS 0232–04 could not be resolved. This inadequacy of the model is sufficiently significant to reject the intergalactic dust hypothesis at the assumed density.20 Moreover, in more than one aspect, the intergalactic model is implausible. Assuming that the mean metallicity of matter (stars and interstellar gas) in galaxies at current epochs is near solar, as derived by Calura & Matteucci (2004a, 2004b), would not contribute in an essential way to explaining the break and would have to be discarded on account of Occam’s razor principle.

20 If we adopt an intergalactic model that uses significantly less dust than $n_H = 3.4$, it would be at the cost of having more intrinsic dust present and this in a larger fraction of class A spectra, if not the majority of them. Hence, such a model would not contribute in an essential way to explaining the break and would have to be discarded on account of Occam’s razor principle.
We find that for an object at $z = 0.7$, the selective extinction is $E_{B-V} = 0.022$ ($A_{obs}$), much in excess of the value of 0.002 inferred from cosmological supernovae by Perlmutter et al. (1999).
1000 Å break, which we believe is entirely due to nanodiamond dust absorption.

7. NANODIAMONDS:
THE INFRARED-UV CONNECTION

Nanodiamonds are, to date, the most abundant presolar grains, in both mass and numbers, that have been extracted from primitive carbonaceous meteorites (Mutschke et al. 2004 and references therein), but their detection in the ISM has been elusive. Diamond crystallite emission bands in the 3.3–3.6 μm region due to surface C–H stretching modes of hydrogenated nanodiamonds have been established with confidence for a few Herbig Ae/Be objects and one carbon-rich post-AGB star HR 4049 (Guillois et al. 1999; Van Kerckhoven et al. 2002; Acke & van den Ancker 2004). Van Kerckhoven et al. (2002) presented a detailed analysis of the Infrared Space Observatory SWS spectra of the two Herbig objects, HD 97048 and Elias I, as well as of the post-AGB HR 4049. They applied a physical model to the emission profile of the 3.53 μm band and inferred a temperature of 950 and 1000 K for HD 97048 and Elias I, respectively. Assuming radiative equilibrium between photoheating and far-infrared cooling for the grains, the authors could estimate the UV radiation flux impinging upon the diamonds in these three objects. The diameter range they inferred for the crystallite diamonds is 2a ~ 10–100 Å. Interestingly, the multiwavelength data for both HD 97048 and Elias I, as well as for the post-AGB star HR 4049, indicate that the 3.53 μm emission takes place within a disklike structure. The distance between the star and the emission region is ≤9 and ≤22 AU in HD 97048 and Elias I, respectively. The formation site that these authors favor for the crystallite diamonds is in situ formation within the disk rather than within the ISM or via ejection from stars. In the field of AGNs, subarcsecond VLT observations by Rouan et al. (2004) using NAOS+CONICA revealed wavelike structures in the mid-infrared, which the authors propose might be due to emission by nanodiamonds at a temperature close to sublimation.

To explain the predominance of nanodiamond grains in primitive meteorites, several formation mechanisms have been proposed, such as (1) chemical vapor deposition from stellar outflows (Lewis et al. 1987), (2) impact shock metamorphism driven by supernovae (Tielens et al. 1987), (3) energetic ion bombardment by a supernova (Daulton et al. 1995), (4) UV annealing of carbonaceous grains (Nuth & Allen 1992), (5) nucleation in organic ice mixtures by UV photolysis (Kouchi et al. 2005), and (6) chemical conversion of PAH clusters to nanodiamonds in the presence of UV radiation (Duley & Grishko 2001). It is interesting to note that the last three processes involve UV radiation. The above post-AGB and the two Herbig Ae/Be stars emit UV radiation (Van Kerckhoven et al. 2002), a fact that is possibly related to the formation of the observed nanodiamonds.

Could a similar formation process operate within the UV-intense environment of quasars? The indication that cubic diamonds dominate in class B quasars might be related to an evolutionary sequence of the grains. A possible scenario might be the following. Via the process of dehydrogenation of PAH clusters by quasar UV radiation, hydrogenated nanodiamonds form, with optical properties similar to the Allende type. If the UV radiation heats up the nanodiamonds beyond 1300 K, a process of surface dehydrogenation begins, which may cause the grain optical properties to become more similar to that of cubic diamonds. Finally, the disappearance of H stretch cooling may result in a runaway heating, followed by graphitization and eventually sublimation of the grains.

To confirm the existence of nanodiamond grains in AGNs, one could attempt to detect the far-infrared emission bands caused by hydrogenated nanodiamonds (Van Kerckhoven et al. 2002; Jones et al. 2004). However, AGNs are intrinsically very strong far-infrared emitters, and the signature of any narrow emission band will certainly be diluted. For instance, the dust silicate feature at 9.7 μm predicted by calculations (Laor & Draine 1993) is not observed as often as expected in AGNs. The UV radiation absorbed by nanodiamonds represents at most 10% of the energy integrated over the whole SED. Let us assume the AGN unification picture with a bi-cone opening angle of 45°. If the nanoparticles are located outside the BLR, then a fraction of only 0.10[1 – cos (45°/2)] ≤ 0.01 of the quasar bolometric luminosity will be reprocessed into far-infrared emission by nanodiamonds. Assuming a uniform covering factor of unity within the radiation bi-cone, the minimum dust mass required by the intrinsic model is given by 0.044N_{20}r_{ps}^2[1 – cos (45°/2)] M_{⊙}, where r_{ps} is the distance in parsecs separating the dust screen from the central UV source. For an arbitrary distance of 1 pc and N_{20} of unity, the dust mass implied is 0.0033 M_{⊙}, a value independent of the assumed dust-to-gas ratio (see footnote 14).

To the extent that Allende-type nanodiamonds might be a candidate carrier (see Jones & d’Hendecourt 2004) for the extended red emission observed in nebulae between 5400 and 9500 Å, it is conceivable that a fraction of the UV flux absorbed by dust might be reemitted by photoluminescence.

8. CONCLUSIONS

We have presented evidence that indicates that dust absorption by nanodiamonds is successful in reproducing the 1000 Å
break, as well as the FUV rise seen at shorter wavelengths. Could the agreement between the intrinsic dust models and the spectra be simply the result of a coincidence between the break location and the FUV extinction properties of nanodiamonds? To rule out such a possibility will require that an independent confirmation of the presence of nanodiamonds be found. Detection of grain emission in the far-infrared, at 3.43 and 3.53 μm, is one possibility, although this emission mechanism works only with surface-hydrogenated grains (see § 7). Another possible route would be to observe selected quasars in order to extend the UV coverage in objects for which only the onset of the break is seen so far. The idea would be to look for a confirmation of a flux rise shortward of 700 Å in as many quasars as possible. This would require high-quality observations using a satellite with FUV sensitivity. One possibility might be the R = 1000 spectrometer on board the projected World Space Observatory satellite, which is expected to offer a sensitivity window covering the range 1100–3500 Å (λ_{rest}) (Barstow et al. 2003).

We have ruled out that the dust causing the 1000 Å break is predominantly intergalactic on the basis that it is not required per se and that the FUV rise could not be modeled satisfactorily using intergalactic dust. Furthermore, the amount of crystalline carbon that is needed turns out to be impossibly large. Since intergalactic dust is not responsible for the continuum rollover observed in HS 1700+6416 and HE 2347–4342, at z ≈ 2.8, we have proposed that this feature is a manifestation of a higher energy break, near 18.5 eV, which is presumably intrinsic. Including the same break in the other quasar SEDs markedly improves the simulation of the composite, as well as the detailed modeling of the FUV rise in PG 1008+1319 and PKS 0232–04. At any rate, such a break is bound to take place somewhere in the FUV so that the quasar SED connects smoothly with the soft X-rays. In effect, the optical–X-ray index, α_{opt}, which relates the monochromatic continuum flux at 2500 Å to that at 2 keV, is characterized by values in the range 1.3–1.6 (equivalent to an α_{opt} between −1.3 and −1.6). Given that our mean α_{opt,UV} index for class A is much harder, with −0.44, a continuum turnover must take place somewhere in the FUV. Our results suggest that such turnover occurs at 18.5 eV. We are currently in the process of studying how the FUV and the soft X-rays may join together (S. Haro-Corzo et al. 2005, in preparation).

Intrinsic dust models require gas columns of the order 10^{20} cm^{−2}, assuming solar C abundance and full depletion onto nanodiamond grains. For comparison, in the solar neighborhood, a V-band extinction of a tenth of a magnitude by ISM dust corresponds to a gas column of 1.9 × 10^{20} cm^{−2} (Whittet 2003). Larger columns (but the same dust masses) would be implied for our models, if we assumed smaller dust-to-gas ratios. To the extent that the nanodiamond dust lies in the vicinity of the AGN, the minimum dust mass required by intrinsic models is small, ≃0.003 M_{\odot} c^{2} M_{\odot}, (see § 7). This value is independent of the assumed dust-to-gas ratio because the absorption gas columns scale inversely with it (see footnote 14).

We have shown evidence that ISM-like dust might be playing a role in explaining the continuum appearance of a fraction of quasars, the so-called class C quasars. To confirm this suggestion will require more complex models than presented here, in which more extinction components might have to be contemplated (ISM, SMC, nanodiamonds, SiC, etc.). An alternative is that class C quasars emit with an intrinsically much softer SED.

How does the intrinsic dust hypothesis fare in relation to the result of Scott et al. (2004), in which the break is apparently absent in local universe AGNs? An interesting scenario comes to mind. An inspection of the 45 multigrating spectra, which could not be classified because their spectra did not extend down to 900 Å (λ_{rest}; see § 3.4), reveals that the softer class C spectra are more frequent at lower redshifts. Interestingly, a fraction of class C quasars do not show any break (see spectrum of 3C 279 in Fig. 11). A possibility might be that there is a secular evolution of the dust properties, with nanodiamonds being absent in quasars with z_q ≳ 2.5, later becoming predominant at z_q < 2, and, finally, being progressively replaced by ISM-like dust for z_q ≲ 0.7.

Interpreting the 1000 Å break in terms of dust absorption may contribute to resolving the following issues in the AGN field:

1. The continuum rise in the 650–700 Å region, seen in a few individual quasar spectra, is not predicted by any accretion disk model or any other continuum emission model known to the authors. Such a rise, on the other hand, is expected with nanodiamond dust absorption.

2. If the 1000 Å break is intrinsic to the ionizing continuum of quasars, the mean ionizing photon energy turns out rather small, making it difficult to account for the observed luminosities of the high-excitation lines (e.g., Korista et al. 1997). With the alternative interpretation of dust absorption, the SED turnover is pushed to higher energies and the break is an artifact of line-of-sight dust absorption.

3. The puzzling fact that the high-excitation emission lines in UV-deficient quasars (e.g., class B quasars such as PG 1248+401 in Fig. 3) are comparatively as luminous as in other quasars. This is easily explained by dust absorption provided that the dust lies outside the BLR or under any geometry, in which dust only affects the observer’s line of sight and not the BLR lines of sight to the UV source.

4. The FUV rise observed in a few quasars, HS 1307+4617, PG 1008+1319, and PKS 0232–04, must be followed by a SED turnover at higher energies. A detailed modeling of this flux rise, assuming dust absorption, and the shallow rollover seen in HS 1700+6416 and HE 2347–4342 (as well as the sharper cutoff in class D object HE 1122–1649; Fig. 18) are both consistent with the presence of a continuum cutoff at 18.5 eV. Even if such a cutoff is not directly perceptible in individual spectra in the rest of the sample, it is consistent with the FUV slope seen in the TZ02 composite.

5. The narrow continuum dip shortward of the Ne viii emission line in the composite spectra of TZ02 and Scott et al. (2004) is not accompanied by a similar absorption dip blueward of O vi in emission, as one might expect if the trough was due to absorption by an outflowing ionized wind. Instead, the Ne viii trough could be the result of the narrow absorption peak that characterizes the cubic diamond (D1) extinction curve.

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