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SMOKING QUASARS: A NEW SOURCE FOR COSMIC DUST

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ABSTRACT

Although dust is widely found in astrophysics, *forming* dust is surprisingly difficult. The proper combination of low temperature (<2000 K) and high density is mainly found in the winds of late-type giant and supergiant stars that, as a result, are the most efficient sources of dust known. Dust ejected from these stars into the interstellar medium has multiple important effects, including obscuring background objects and enhancing star formation. We show here that quasars are also naturally copious producers of dust, if the gas clouds producing their characteristic broad lines are part of an outflowing wind. This offers an explanation for the strong link between quasars and dust and for the heavy nuclear obscuration around many quasars and introduces a new means of forming dust at early cosmological times.

Subject headings: dust, extinction — galaxies: abundances — intergalactic medium — quasars: general

1. INTRODUCTION

It is widely believed that the quasar environment is hostile to dust, so it is striking that quasars contain large amounts of dust, even at high redshifts ($z > 4$; Omont et al. 2001; Priddey & McMahon 2001) when the universe is only 1–2 Gyr old ($H_0 = 65$ km s^{-1} Mpc^{-1}). How dust can form so early is a significant problem (Edmunds & Eales 1998). Normally the dust in quasars is assumed to arise from independent processes unconnected with the quasar. However, an intrinsic origin is hinted at: the outer radius of the region producing the strong broad emission lines (BELs) is typically coincident with the dust sublimation radius (Clavel, Wamsteker, & Glass 1989). We show that the free expansion of the clouds producing the quasar BELs produces conditions conducive to the formation of dust, making quasars one of the few sources of cosmic dust.

Carbon-rich dust does form in similarly unfavorable-seeming environments, such as the UV-bright Wolf-Rayet and R Corona Borealis stars. These hot giants have effective photospheric temperatures and wind densities that are strikingly similar to the initial conditions of the BEL clouds (BELCs; $T_{\rm eff} \geq 2 \times 10^4$ K; Sedlmayr 1997).

The gas producing the BELs lies in a large number of small "clouds" at temperatures of 10^4 K and densities of 10^9–10^{11} cm^{-3} (Osterbrock 1989). BELs are Doppler-broadened to a few percent of the speed of light (~3000–15,000 km s^{-1}). As yet though, the kinematics of the BELCs—whether they are infalling, in bound orbits, or in an outflowing wind—is not well established (Peterson 1997). Moreover, the issue of how to prevent these clouds from dispersing has been problematic. Pressure confinement by a hotter surrounding medium would seem straightforward but appeared to suffer insurmountable problems in a simple spherical geometry (Mathews 1986).

Outflowing winds of highly ionized material are common in quasars (Arav, Shlosman, & Weymann 1997), so a similar flow pattern for BELCs is a reasonable possibility. Elvis (2000) showed how such a wind, if highly nonspherical, can solve the confinement problems of the BELCs by assuming that they are a cool phase in equilibrium with a warmer (10^6 K) wind medium. With this model, a large number of other puzzling features of quasar phenomenology seem to fall into place. The fate, however, of the outflowing BELCs constantly being ejected from the quasar were not considered by Elvis. We examine that fate here in a manner that in fact applies to any model in which the BELCs move outward. We find that dust creation is a natural consequence.

In any outflow model that begins with the BEL region initially in pressure equilibrium with a surrounding warmer medium, the divergence of the outflowing warm wind (even if only at the sound speed of the warm confining medium, ~100 km s^{-1}) will rapidly take the system out of pressure balance.[1] The BELCs will then begin to expand, limited by their sound speed (initially ~10 km s^{-1}), and will cool to temperatures at which dust will form, if the pressure is still sufficiently high and if the dust-forming species are available. This process resembles that which makes smoke in terrestrial settings. Quasars are then dusty because they themselves create dust, which may resemble soot; they are "smoking quasars."

A full treatment of dust formation generally requires coupling the dust-forming medium hydrodynamics with the full set of dust condensation chemistry equations (Sedlmayr 1997). Such an exercise is limited by our knowledge of the highly nonlinear dust condensation chemical paths and by the uncertainties related to the role of nonequilibrium chemistry. We therefore use a simple comparison between active galactic nucleus and cool star atmospheres to derive reasonable estimates for the conditions of dust formation in the BELCs.

2. THE DUST FORMATION WINDOW

The general scenario for dust formation is based on the concept of the "dust formation window." Effective dust condensation seems to take place whenever a chemically enriched medium has a sufficiently low temperature, and a large enough density, to allow dust grain condensation. The amount of dust produced, the chemical composition, and the final size of the grains depend on the length of time over which the conditions remain favorable.

The typical dust grains encountered in the interstellar medium have condensation equilibrium temperatures in the range

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[1] Evidence from reverberation mapping currently suggests that the BEL region is not in overall expansion (Peterson 1997). This is expected in the Elvis (2000) picture, where the BEL region is initially rotating and rising in a cylinder and is only later blown outward, e.g., by radiation pressure, to form a radial wind; the BEL gas is shielded in the radial wind region from much of the quasar-ionizing continuum.

of 600–1400 K or somewhat higher (Frenklach & Feigelson 1989; Frenklach, Carmer, & Feigelson 1989). These conditions are generally met in the cool atmospheres of late-type giants and supergiants, which are the main Galactic sources of dust (Sedlmayr 1994). The location of the dust formation window in these stars is given by the temperature gradient in the circumstellar environment that is determined by radiative transfer ($T \propto R^{-0.4}$; Ivezić & Elitzur 1997). For a typical red giant on the asymptotic giant branch (AGB), this region is a shell (with a thickness of $5–10R_*$) lying a few stellar radii (R_*) from the stellar photosphere. The density at the inner edge of this shell is $n \sim 10^9$ cm^{-3}, and the pressure $P \sim 10^{-4}$ dyn cm^{-2}. Shock waves induced by radial pulsations in long-period variables can raise the value of the pressure by a factor of 10^2, up to $P \sim 10^{-2}$ dyn cm^{-2} (Höfner 1999). This greatly increases the dust grain production (Fleischer, Gauger, & Sedlmayr 1991, 1992) and thus the total dust-driven mass loss (from 10^{-7} up to 10^{-4} $M_\odot$ yr^{-1}). The time spent by the newly formed grains in the dust-growing region depends on the stellar wind velocity (10–20 km s^{-1}) and is typically a few years.

Figure 1 shows the dust formation window in pressure-temperature space for the chemical species that lead to the formation of dust in an O-rich (*top panel*) or a C-rich (*bottom panel*) cool star circumstellar envelope. The thin solid lines mark the phase transition region below which the most important dust precursor molecules can be formed (adapted from Lodders & Fegley 1999). The hatched area is the dust-forming region in the circumstellar envelope of a cool giant star. The region is limited on the right by the thermodynamical path of a static outflowing wind typical for an AGB star. The left side is obtained by increasing the maximum pressure in the envelope by a factor of 100, as during the propagation of pulsational shocks in the atmospheres of long-period variables. Dust formation in the envelopes of evolved giants occurs in the region between the two tracks, below the phase transition lines for each chemical species. The formation of any individual species depends on there being sufficient time available.

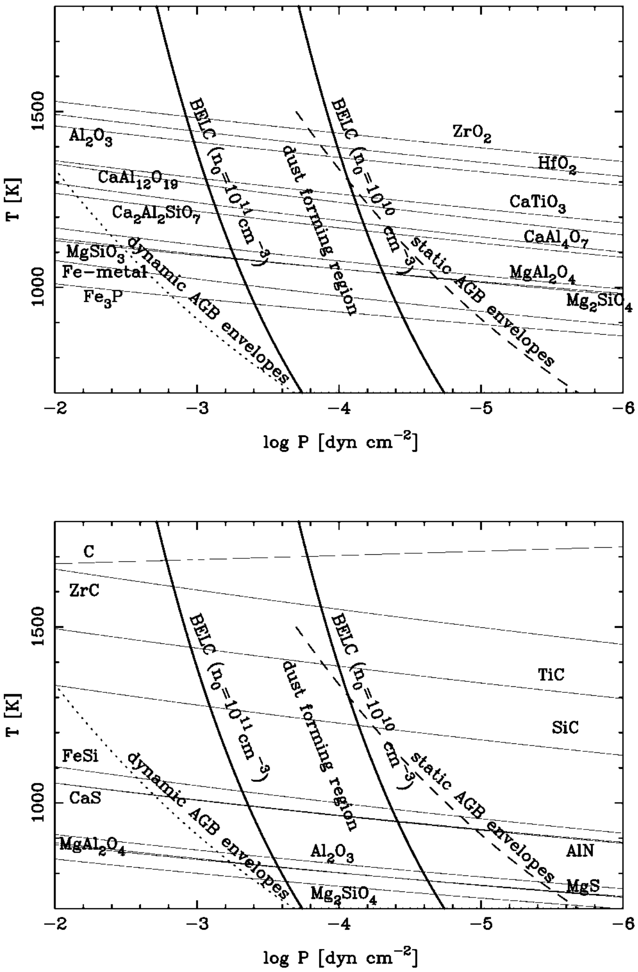

FIG. 1.—Phase transition lines for O-rich (*top panel*) and C-rich (*bottom panel*) dust precursor molecules (adapted from Lodders & Fegley 1999). The hatched area is the dust formation region in the circumstellar envelopes of evolved cool giant stars, delimited by the two cases of static and dynamic (pulsating) AGB atmospheres. The thick solid line is the path of BELCs as they expand, for two different values of their initial density.

3. DUST FORMATION AND BELCs

The parameters described in the previous section define the dust formation window in a setting where dust condensation is known to occur copiously. We want to compare these conditions with the ones encountered by the BELCs as they expand in the quasar outflow, in order to evaluate their own chances of condensing dust. The initial conditions of the BELCs are very different from the ones in a cool star atmosphere. The temperature is far higher ($T_{0,\,\mathrm{BELC}} \sim 10^4$ K; Osterbrock 1989), and such a high temperatures are hostile to dust formation. However, the density of BELCs is also high ($P_{0,\,\mathrm{BELC}} \sim 0.1$ dyn cm^{-2}; Osterbrock 1989) compared with the dust condensation region of cool star atmospheres. So if the BELCs expand and cool as part of an outflowing wind, this cooling could lead them through the dust formation window.

We will simplify the situation by assuming that the BELC material is an ideal gas obeying polytropic adiabatic scaling and further that the gas is monoatomic with index $\gamma = 5/3$. This assumption is initially good and will hold at least until the gas undergoes a phase change of H into H_2, which will not occur before dust begins to form. With this assumption, we can estimate the expansion factor required for cloud cooling below the dust condensation equilibrium temperature:

$$\left(\frac{r}{r_0}\right)_{\mathrm{BELC}} = \left(\frac{T_{\mathrm{cond}}}{T_{0,\,\mathrm{BELC}}}\right)^{1/3(1-\gamma)}. \qquad (1)$$

Since $(T_{\mathrm{cond}}/T_0)_{\mathrm{BELC}} \sim 0.1$, $(r/r_0)_{\mathrm{BELC}} \sim 3$, which tells us that BELCs reach a dust formation temperature once they have expanded by a factor of 3.

Unless and until the clouds start to interact with one another, we can approximate their pressure with the polytropic $P \propto r^{-3\gamma}$, which gives $P_{\mathrm{BELC}} \sim 10^{-3}$ to 10^{-4} dyn cm^{-2} for clouds expanded by a factor of 3. A more accurate analysis of the cloud expansion process, taking into account cloud interactions and the hydrodynamics of the surrounding medium, will find a larger value of the pressure. Furthermore, if we relax the hypothesis of adiabatic expansion, allowing thermal equilibrium between the clouds and the ionizing radiation, then the cloud temperature will drop even faster since the cloud ionization parameter will rapidly decrease with the cloud expansion (see § 5).

The above estimates show that the BELCs do reach the same values of temperature and pressure encountered in the dust formation window of cool giant stars (Lodders & Fegley 1999), as shown in Figure 1 (the thick solid lines show the limiting case of adiabatic expansion; the lines become more vertical as expansion is reduced). However, the actual formation of dust and its precursors and the amount of grains that are condensed depend on the time spent by the clouds in the region favorable to grain condensation and growth. This is given by the cloud expansion timescale $\tau_{\rm BELC} = r_0/c_0 \sim 3$ yr, where $c_0 \sim 10$ km s^{-1} is the initial sound speed of the cloud and $r_0 \sim 10^{14}$ cm (Peterson 1997) their initial average size. Since their sound speed is similar to the wind speed of red giant branch stars, this timescale is comparable to the time spent by *circumstellar* grains in the region where dust growth is most active, suggesting that the efficiency in dust production in the BEL region and late-type giant winds may be similar.

Radiatively driven winds seem to be characteristically unstable, producing highly structured winds in stars with "P Cygni" profiles, OB stars and Wolf-Rayet stars (e.g., Stahl et al. 1993; Owocki 2001), that suggest that shocks may be common. In AGB winds, these intermittent pressure enhancements boost dust production, starting a nonlinear "avalanche" effect, as observed in Mira variables and other long-period variables (Fleischer, Winters, & Sedlmayr 1999 and references therein). Quasars show similar structures (Turnshek 1988), which are predicted by hydrodynamic modeling (Proga 2000), indicating that pressure fluctuations could greatly enhance the quasar dust creation rate.

Where is the dust made? To estimate how far the clouds are from the quasar center when the dust condensation processes turn on, we need to couple the cloud expansion rate with their equation of motion. We assume that the BELCs comove with a warm confining medium. With this assumption, the clouds will be accelerated from an initial velocity of $v_0 \simeq 5 \times 10^8$ cm s^{-1} to an asymptotic value of $v_\infty \simeq 5 \times 10^9$ cm s^{-1}. Note that the BELCs are moving supersonically at velocities ∼100 times larger than their free expansion rate. The ratio $u = d/d_0$ between the clouds' distance at a given time, compared with the clouds' initial distance when they detach from the quasar accretion disk, is then large. In the limit $\beta^2 = (v_0/v_\infty)^2 \ll 1$ and $u \gg 1$, the equation of motion of the expanding clouds can be solved analytically, which gives the following relation between the expansion factor $x = (r/r_0)_{\rm BELC}$ and the cloud position u:

$$x \sim \beta \frac{\tau_0}{\tau_{\rm BELC}} \left(u + \frac{1}{2} \ln u \right), \qquad (2)$$

where the logarithmic term is due to the variation of the sound speed caused by the expansion of the cloud, $\tau_0 = d_0/v_0 \simeq 24$ days is the time required for the cloud to double the initial distance from the quasar, and $\tau_{\rm BELC} \simeq 3$ yr is the cloud expansion timescale. For $u \gg 1$, we have

$$\frac{x}{u} \sim \beta \frac{\tau_0}{\tau_{\rm BELC}} \simeq 2 \times 10^{-3}, \qquad (3)$$

which means that for $x \sim 3$ (the expansion factor at which dust begins to condense), $u \sim 10^3$. Given an initial distance from the quasar center of $d_0 \simeq 10^{16}$ cm (for moderate luminosities; Peterson 1997; Sabra & Hamann 2001), BELCs will start to be dust bearing when they are ∼3 pc from the quasar center. This result also shows that the ionization parameter $U = n_{\rm ph}/n_e$ of the clouds becomes very small as the clouds reach the dust-forming region. Since $n_{\rm ph} \sim u^{-2}$ and $n_e \sim x^{-3}$, by the time the clouds are 3 pc from the central black hole, U will have decreased by a factor $3^3/(10^3)^2 \simeq 3 \times 10^{-5}$. This rapid decrease of the ionization parameter will cause an even faster drop in the cloud temperature, assuming an initial equilibrium between the clouds and the ionizing radiation rather than pure adiabatic expansion. As explained before, this will favor an earlier dust condensation in the clouds, with even higher efficiency due to the higher local gas pressure.

4. DUST SURVIVAL IN THE BELCs

Can the dust survive the radiation field from the quasar black hole? The quasar luminosity is of order 10^9 times higher than the $10^4\ L_\odot$ of a typical giant star. The large flux of energetic photons from the quasar continuum may then in principle overheat the newborn dust grains above their sublimation temperature. This could delay the occurrence of dust condensation until it becomes impossible because of the ever-decreasing gas density. However, due to the much larger geometrical dilution in quasars, the radiative flux reaching the BELCs' interior is actually lower than the stellar flux in the dust-forming region of the giant's wind. For a quasar of luminosity of 10^{46} ergs s^{-1}, the flux density 3 pc from the quasar center is ∼10^7 ergs cm^{-2} s^{-1}. This is at least 1 order of magnitude less than the ∼2×10^8 ergs cm^{-2} s^{-1} in the stellar case. For this reason, the dust formation window of the BELCs is determined by the polytropic expansion of the clouds' gas, as we have assumed, and not by radiative transfer, as in the case of circumstellar envelopes (Ivezić & Elitzur 1997).

The actual flux penetrating the interior of the BELCs is in fact even lower since the neutral hydrogen and the dust precursor molecules expected to exist in the interior of the BELCs are very efficient at absorbing the quasar radiation. In the radial flow of Elvis (2000), the BELCs will stack up radially to give a mean covering factor of unity, given their initial 0.1 value, and so provide additional self-shielding. The interior of BELCs a few parsec from the quasar center seems to be a safe place for dust formation, and we can conclude that even for the most luminous quasars, dust sublimation is prevented in the BELCs.

Other destruction mechanisms, such as dust sputtering by electrons and ions or chemical sputtering, are not very effective at the rather low ($T_K \lesssim 10^4$ K) kinetic temperature of the cloud medium. Kinetic sputtering by the surrounding medium becomes effective (Draine & Salpeter 1979) only for $T_K \gtrsim 5 \times 10^5$ K. By the time the BELCs start forming dust, they will be surrounded by a warm medium having a temperature $T \sim T_0 u^{2(1-\gamma)} \sim 2 \times 10^5$ K, which is already low enough to prevent the immediate destruction of the nascent dust grains by sputtering.

5. DISCUSSION AND CONCLUSIONS

The composition of dust depends on the element abundances in the originating material. If the number ratio of C/O is above unity, then almost all the oxygen is tied up in CO, which does not react to form solids, leading to carbon-rich dust; conversely, if C/O is less than unity, carbon grains are almost nonexistent, and oxides (e.g., SiO_2) dominate (Whittet 1992). Carbon is overabundant in quasars at high redshifts (Hamann & Ferland 1999), so carbonaceous dust may be dominant. Quasar oxygen abundances, however, have not been well measured (Hamann & Ferland 1999). Carbonaceous dust formation in stars is similar to that of smoke or soot from combustion (Frenklach & Feigelson 1989; Cadwell et al. 1994), hence our term smoking quasars.

Because dust condensation is highly nonlinear (Frenklach & Feigelson 1989), the amount of dust formed in any particular quasar is hard to predict and will depend on subtle variations of wind conditions, including the initial density. Heavily obscured quasars (Sanders et al. 1988) may be easily formed this way. A comparison with unobscured quasars may pinpoint optimal conditions for dust condensation.

If dust creation is a consequence of the quasar activity itself, then some issues of early cosmological epochs are affected:

1. Quasar winds ($v > 1000$ km s^{-1}) readily exceed the escape velocity from a galaxy ($v_{\rm esc} \sim 200$ km s^{-1}) or even a rich cluster of galaxies ($v_{\rm esc} \sim 1000$ km s^{-1}). Hence, unless there is a retarding force, the dust they produce will be ejected into the intergalactic medium (IGM). Dust in the IGM may affect measurements of cosmological parameters, including acceleration (Aguirre 1999), alter the gaseous IGM composition via selective depletion of elements onto dust grains, contribute to the far-infrared background, changing galaxy evolution models (Dwek 1986; Dwek, Rephaeli, & Mather 1990; Aguirre & Haiman 2000), or possibly alter the Sunyaev-Zeldovich effect (Sunyaev & Zeldovich 1972) in clusters of galaxies (Marengo 2000). The potential for such effects must be enhanced with quasars as an additional source for dust.

2. At low redshift, the quasar will effectively be recycling dust from the host galaxy interstellar medium out into the IGM, while changing the dust size distribution and the dust-to-gas ratio. At high redshifts, the matter entering the quasar accretion disk is likely to contain very little dust since creating large amounts of dust (10^8–10^9 $M_\odot$; Omont et al. 2001) at $z > 5$ is difficult to arrange (Edmunds & Eales 1998), in part because there is only 1 Gyr available to form red giant stars. Quasars can provide an additional path for dust formation, adding to the original stock. Assuming the dust-to-gas mass ratio measured in long-period variables (Knapp 1985), and noting that a quasar of luminosity 10^{46} ergs s^{-1} can eject up to 1 $M_\odot$ yr^{-1} (Sabra & Hamann 2001), a dust production rate of ~0.01 $M_\odot$ yr^{-1} follows.

The most luminous quasars, in which the highest dust masses are found (Omont et al. 2001), have luminosities over 10^{47} ergs s^{-1} and so may have mass-loss rates of greater than 10 $M_\odot$ yr^{-1}, leading to ~10^7 $M_\odot$ of dust over a nominal 10^8 yr lifetime. This mass approaches the amounts detected, although the assumed dust-to-gas ratio is merely illustrative. As a result, the infrared emission of quasars may not require the normally assumed large associated burst of star formation (Sanders et al. 1988).

This is an economical explanation. If the only dust at high z is manufactured in quasars, then far less dust (in units of Gpc^{-3}) is implied by infrared/submillimeter detections of quasars than if quasars simply illuminated the preexisting dust, which would then need to be more widely distributed.

In summary, dust will be created from the free expansion of quasar broad emission line clouds in an outflowing wind. The association of dust with quasars is then not necessarily linked with intense star formation around quasars but is a consequence of the quasar activity itself. The inevitable creation of dust in quasar winds may solve the puzzle of where the first dust comes from and, in doing so, suggests a new importance for quasars in cosmology.

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