Recycling Intergalactic and Interstellar Matter
IAU Symposium Series, Vol. 217, 2004
Pierre-Alain Duc, Jonathan Braine and Elias Brinks, eds.

Quasar Winds as Dust Factories at High Redshift

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Abstract. Winds from AGN and quasars will form large amounts of dust, as the cool gas in these winds passes through the (pressure, temperature) region where dust is formed in AGB stars. Conditions in the gas are benign to dust at these radii. As a result quasar winds may be a major source of dust at high redshifts, obviating a difficulty with current observations, and requiring far less dust to exist at early epochs.

1. Introduction: Dust in High Redshift Quasars

Dust is common in high redshift (z=4–6) quasars (Omont et al. 2001, Priddey & McMahon 2001), apparently implying that dust is widespread by this epoch. This presents a puzzle: how can so much dust be formed in the short time available? WMAP cosmology (Spergel et al. 2003) puts the age of the universe at z=6 to be only 0.95 Gyr, and the age of first reionization (and so the first stars) at an age of ~0.2 Gyr (z~20). In our galaxy the primary source of dust lies in the winds of red giant stars, specifically Asymptotic Giant Branch (AGB) stars. Only stars with masses greater than 2 $M_{\odot}$ can reach the AGB in the less than ~1 Gyr available. Another source of dust is thus required.

Normally this extra source is taken to be type 1 (massive star) supernovae. Recent SCUBA results (Dunne et al. 2003) show that the 300 year old type 1 supernova remnant (SNR) Cas A is rich in dust, lending credence to this picture. However, the possible destruction of SNR formed dust in their shocks may not be fully resolved. Here we point out another, seemingly inevitable, path for dust formation up to at least z=6: *quasar winds.*

The fate of outflowing broad emission line (BEL) quasar gas constantly being ejected from quasars had previously not been considered. We examined that fate (Elvis, Marengo & Karovska 2002) in a manner that applies to any model in which the BEL clouds move outward. We find that dust creation is a natural consequence.

2. Quasar Winds

Outflowing winds of highly ionized material are common in quasars [see Arav, Shlosman & Weymann (eds) 1997]. The gas emitting the prominent Broad Emission Lines (BELs) may well participate in these winds. The BELs, which produce e.g. Lyα, Hα, Hβ , CIV, NV (e.g. Krolik 1999) are Doppler broadened

https://doi.org/10.1017/S0074180900197906 Published online by Cambridge University Press

to a few percent of the speed of light ($\sim 3000 - 15,000$ km s^{-1}). The gas producing these lines lies at temperatures of 10^4 K and at the strikingly high densities of 10^9-10^{11} cm^{-3} (Osterbrock 1989). These densities are comparable to chromospheric values (Allen 1975, Korista 1999). The kinematics of this BEL gas - infalling, bound, or outflowing - is not well established (Peterson 1997). Moreover, the issue of how to prevent this high density gas from dispersing has been problematic. Pressure confinement by a hotter surrounding medium would seem straightforward and a 2-phase medium is even predicted for gas irradiated by a hard quasar-like continuum (Krolik, McKee & Tarter 1981). However this model appeared to suffer unsurmountable problems (Mathews 1986). Most obviously the any BEL 'clouds' would be ripped apart by shear forces in less than one orbital time. As a result this model was abandoned.

A BEL wind has advantages. Elvis (2000) showed how such a wind can include the BEL gas as a cool phase in pressure equilibrium with the warmer (10^6 K) wind medium. With this model a large number of other puzzling features of quasar phenomenology seem to fall into place. A wind in which both BEL gas and the hotter confining gas are co-moving solves the cloud survival problem, and if the wind is non-spherical also solves the problem of the confining medium being Thomson thick, which cannot be the case as rapid X-ray variability is essentially universal in AGNs.

But a wind requires us to ask what happens to the gas as it flows outward. In any outflow model 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, $\sim$100 km s^{-1}) will rapidly take the system out of pressure balance. The BEL clouds will then begin to expand, limited by their sound speed (initially $\sim$10 km s^{-1}), and will cool to below 1000 K, at which temperatures dust will form *if* the pressure is still sufficiently high. Could quasar BEL gas then be the source of quasar dust at high redshift?

3. Smoking Quasars

A full treatment of dust formation 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 non-linear dust condensation chemical paths, and by the uncertainties related to the role of non-equilibrium chemistry. We therefore use a simple comparison between AGN and cool star atmospheres, to derive reasonable estimates for the conditions of dust formation in the BEL clouds.

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.

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 cool star circumstellar envelope. The thin solid lines mark the phase transition region

https://doi.org/10.1017/S0074180900197906 Published online by Cambridge University Press

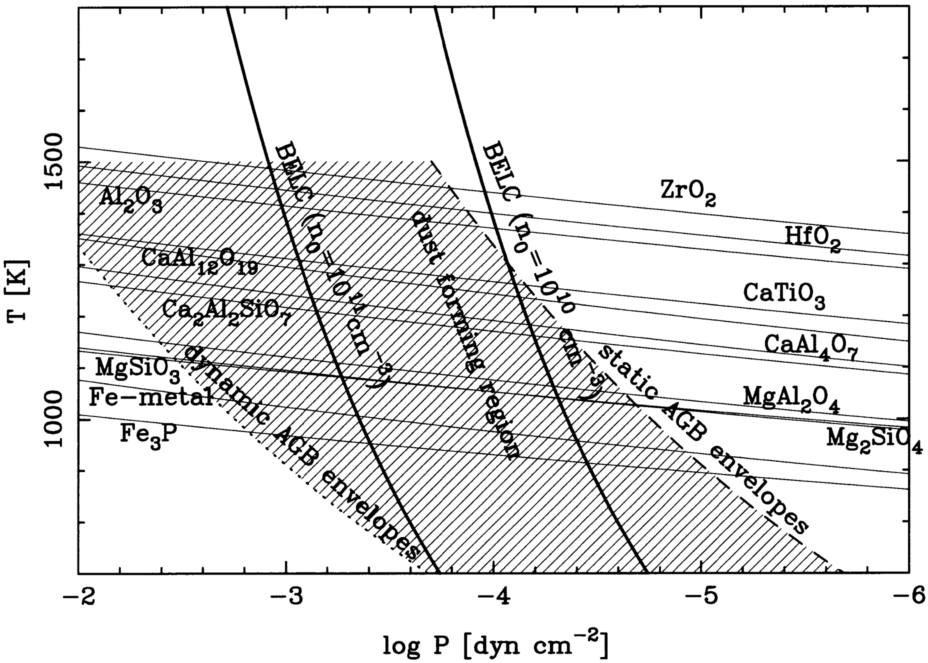

Figure 1. Phase transition lines for O-rich dust precursor molecules (adapted from Lodders & Fegley 1999). The hatched area is the dust formation region in the circumstellar envelopes of evolved cool giant stars, delimited by the two cases of static and dynamic (pulsating) AGB atmospheres. The thick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

below which the most important dust precursor molecules are formed. 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 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. A closely similar diagram can be drawn for C-rich gas.

Figure 1 shows adiabats for BEL gas, assuming $\gamma = 5/3$. Clearly they pass through the dust formation window for plausible initial densities. The BEL gas enters the dust formation window after expanding by a factor of three. This process resembles that which makes smoke in terrestrial settings. Quasars are then dusty because they themselves create dust which, since carbon may be overabundant in quasars, may resemble soot. Hence we called them 'smoking quasars'.

If quasar winds are driven by line radiation then the characteristic instability of such winds suggests that shocks may be common. In stars with 'P Cygni'

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profiles (OB stars and Wolf-Rayet stars) such winds produce highly velocity-structured opacity (e.g. Stahl et al., 1993, Owocki 2001). Quasars show similar structures (Turnshek 1988), and are suggested by hydrodynamic modeling (Proga 2001). In AGB star winds these intermittent pressure enhancements boost dust production (figure 1), starting a nonlinear "avalanche" effect, as observed in Miras and other Long Period Variables (Höffner 1999). This suggests that pressure fluctuations could greatly enhance the quasar dust creation rate.

Can the dust survive the radiation field from the quasar BH? Surprisingly a quasar wind provides a *more benign* environment for dust than an AGB star wind, despite the quasar luminosity being much higher than the 10^4 $L_\odot$ luminosity of a typical giant star. The large flux of energetic photons from the quasar continuum might have overheated the newborn dust grains above their sublimation temperature, delaying the occurence of dust condensation, perhaps until it becomes impossible due to the ever decreasing gas density. However, due to the much larger geometrical dilution in quasars, the radiative flux reaching the BEL clouds interior is actually lower than the stellar flux in the dust forming region of the giant's wind. For a quasar of luminosity 10^{46} erg s^{-1} the flux density 3 pc from the quasar center is $\sim 10^7$ erg cm^{-2} s^{-1} . This is at least one order of magnitude less than the $\sim 2 \cdot 10^8$ erg cm^{-2} s^{-1} in the stellar case. So the dust formation window of the BEL clouds 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).

Other destruction mechanisms, such as dust sputtering by electrons and ions, or chemical sputtering, are not very effective at the rather low ($T_K < 10^4$ K) kinetic temperature of the cloud medium. Kinetic sputtering by the surrounding medium becomes effective (Draine & Salpeter 1979) only for $T_K > 5 \times 10^5$ K. By the time the BEL clouds 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 their immediate destruction by sputtering.

4. Quasar Dust Masses

The total amount of dust that is formed, however, depends on the time spent by the clouds in the region favorable to grain condensation and growth. This is given by the cloud expansion time-scale $\tau_{(BELC)} = r_0/c_0 \sim 3$ 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. This timescale is comparable with the time spent by circumstellar grains in the region where dust growth is most active, suggesting that the efficiency in dust production of BEL region and late type giant winds may be similar.

The most luminous quasars, in which the highest dust masses are found (Omont et al. 2001), have luminosities over 10^{47}erg s^{-1} and so may have mass loss rates >10 $M_\odot$ yr^{-1}. Assuming the same dust fraction as in AGB stars gives $\sim 10^7$ $M_\odot$ of dust over a nominal 10^8 yr lifetime. This approaches the amounts detected but is still short by about an order-of-magnitude. However, super-solar abundances are common in high redshift quasars, certainly in carbon (Hamann & Ferland 1999), providing a higher density of raw material for the formation of precursor molecules. Dust condensation is highly nonlinear (Frenklach &

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Feigelson 1989), the amount of dust formed in any particular quasar is hard to predict, but the dependence on abundance is likely to be an n^2 process initially, allowing for more dust to be produced than in our simple estimate. As a result the infrared emission of quasars may not require the normally assumed large associated burst of star formation (Sanders et al. 1988).

5. Consequences of Quasar Dust Creation

Quasar winds provide an economical explanation for high z dust. Dust at z$\sim$4 is observed primarily from observations of quasars and of sub-mm sources. If dust is everywhere and quasars illuminate this pre-existing dust then the total dust mass at z=4 is large.

If the only dust at high z is manufactured in quasars, then far less dust is implied than if quasars simply illuminate pre-existing dust, which would then need to be distributed among all high z galaxies, active or not. The metals in the dust must, of course, have been created by an earlier generation of massive stars, that go supernova quickly. To establish high quasar BEL abundances, the star formation must be local to the quasar nucleus, again suggesting a more limited amount of high z star formation.

High z counterparts to sub-mm SCUBA sources seem to imply enormous starbursts, but conclusively distinguishing between a starburst and a quasar as the root power source heating the dust seen by SCUBA is extraordinarily difficult, leaving open the quasar option.

In this picture dust can be formed as soon as quasars form. Quasar winds (v >1000 km s^{-1}) readily exceed the escape velocity from a galaxy (some v_{esc} $\sim$200 km s^{-1}), or even a rich cluster of galaxies (v_{esc} $\sim$1000 km s^{-1}). Hence the dust they produce will be ejected into the intergalactic medium. Dust is an important catalyst of star formation, as dust provides both shielding from ambient ultraviolet radiation and an efficient cooling path for the surrounding medium. The early creation of dust by quasars may then be important for seeding star formation at slightly later times.

6. Conclusions

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

Acknowledgments. We thank Eric Feigelson for alerting us to the problem of dust formation at high redshift, and both he and Fabrizio Nicastro for valuable discussions. This work was supported in part by NASA contract NAS8-39073 (Chandra X-ray Center).

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