The Fate of Dust and the Alignment Effect in HZRGs

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Abstract

The alignment of optical emission along the axis of radio emission in high redshift radio galaxies is now a common phenomenon. In many cases this aligned component can be shown to be significantly polarized, a result that has led to models for the emission that employ scattering of light emitted from the AGN. Both electron scattering and dust scattering have been proposed, and both mechanisms have positive and negative attributes. One aspect of dust scattering that has not been explored previously is the response of the dust grains to the passage of the strong shock associated with the radio source. The scattering medium must be distributed over many tens of kiloparsecs, and it must survive for a time comparable to the age of the radio source. Analogs with emission line conditions suggest that the dust is contained in gas clouds of high density contrast and small filling factors embedded in a more diffuse medium. The survival of dust grains in such an environment after the passage of a 10,000 km/s shock associated with the radio jet is calculated for a wide range of parameters. It is found that for almost all cloud configurations the grains are destroyed by sputtering processes in a time much less than the minimum radio source lifetime of 10 million years. Thus, polarization due to an in situ population of grains seems somewhat problematic. Two alternate methods for grain production are explored, namely the transport of grains outward from the galaxy in the mixing layer associated with the radio jet, and the production of grains by a population of stars whose formation was triggered by the passage of the radio jet.

1 Introduction

A decade has passed since the initial observations were made that showed alignment of the extended optical emission with the associated radio source axis, and although this phenomenon has now been seen in many additional instances, the specific mechanism of how this emission is produced is not yet clear. The alignment of optical continuum radiation has been suggested to be either scattering of AGN radiation by electrons or dust (Tadhunter, Fosbury and di Serego Alighieri 1989) or the occurrence of jet induced star formation (De Young 1989; Rees 1989; Begelman and Cioffi 1989).

The view of these objects changed dramatically with the discovery that in many cases the optical continuum is polarized. Polarization of the blue continuum has been observed to be a common phenomenon in high redshift radio galaxies that display the alignment effect. Most of these observations confirm that the *extended* emission is polarized, which provides a critical constraint on models of these objects. It is important to note that not ALL high redshift radio galaxies showing the alignment effect also show measurable polarization; some of the exceptional cases are at very high redshift and display rather dramatic characteristics (e.g., Dey, these proceedings).

It is clear that in those alignment effect radio galaxies with significant polarization, a large fraction of the aligned blue continuum must be due to light scattered from the AGN. The two viable processes for producing the required scattering are Thompson scattering from electrons or Mie scattering from a population of dust grains. There are problems and uncertainties associated with both of these mechanisms, but electron scattering seems to encounter the most severe difficulties. Because of this, scattering by a population of dust grains seems to have emerged as the favored mechanism for producing the polarized light observed in high redshift radio galaxies, and it is this process that is examined here. Cimatti et al. (1993) showed that for many objects the data could be reproduced reasonably well by a spherical distribution of dust grains in an optically thin, single scattering environment, using Mie scattering from a population of dust grains similar to that found in our own interstellar medium; i.e., with a grain size distribution that follows the power law prescription of Mathis, Rumpl, and Nordsieck (1977; hereafter MRN). Total grain masses required are usually of order 10^8 solar masses, which is not an unreasonable constraint and is consistent with the dust masses derived from millimeter and sub-millimeter observations. Another important constraint is the spatial distribution of the grains. The extent of the polarized emission implies the grains extend many tens of kiloparsecs from the center of the parent galaxy, and in principle this distribution could extend all the way out to the radio hotspots, implying an overall distribution extending up to 100 kpc.

The specific problems addressed here are the related issues of the dust longevity and the dust environment, and thus indirectly the origins of the dust as well. The polarized emission lies in the "alignment region" between the radio source hotspots and the parent galaxy. Thus this emission, and by assumption the population of scattering centers, must have survived the passage of the radio source. Moreover, this survival must continue long enough for the radio source leading edge to have moved from the location of the innermost scattering regions to its presently observed position. If this were not the case, then the grains would either have to be created after the radio source passage or be replenished in some way.

2 Initial and Boundary Conditions

The jet of outflowing material that creates the radio source is moving supersonically relative to the ambient medium for almost all choices of jet and environment parameters that are consistent with observations. Jet propagation may even be weakly relativistic in the inner few kiloparsecs near the nucleus. Thus the radio jet will be accompanied by a strong shock, and any pre-existing population of grains will feel the effects of this shock and may in some circumstances be destroyed by it.

Assuming a spherical distribution of grains requires a few hundred million solar masses in grains to produce enough scattering centers to match the observations (Cimatti et al. 1993). Thus, the minimum grain mass which must be present is that which is directly illuminated by the AGN in the alignment region, and this implies $M_{gr,tot} \sim 10^7 M_\odot$. As previously noted, this material must be distributed over a large spatial scale extending many tens and perhaps hundreds of kiloparsecs from the active nucleus. The composition of the grains is taken to be primarily silicates and graphite in analogy with the Galactic grains. The focus here will be on the graphite grains because this population is the most robust of the common grains. If graphite grains are destroyed, then silicates and the much more delicate ices will also not survive. Because nothing is known about the size distribution of grains at high redshift, the MRN distribution $n(a) = K_a a^{-3.5}$ will be used here, where $n(a)$ is the number density of grains and a is the grain radius. Upper and lower limits on a will be taken as 2500 Å and 100 Å respectively. It is important to note that this distribution provides an almost flat distribution in grain mass as a function of grain radius. Thus there are many more small grains than large, with the vast majority of scattering centers located at the low end of the grain size distribution. This will have important consequences when considering the survival of the overall grain population.

The environment in which the grains find themselves is also largely unknown, though some logical inferences can be made from emission line observations of these objects. This information, together with analogies drawn from our own ISM, would suggest that the grains are probably located in clouds imbedded in a multiphase medium. If the origin of the grains is due to a wind from the parent galaxy at early epochs or to infall of primordially enriched material, survival of the grains against evaporation in a hot wind phase or in an initially hot cooling flow would also suggest placing them in clouds. If the grains are co-located with the emission line regions, then observations suggest that number densities are around $10 - 100$ cm^{-3}, temperatures are near $T \simeq 10^4$ K, and filling factors are about 10^{-4}. The cloud masses must be less than the Jeans mass, and cloud sizes and the cloud-intercloud density and temperature ratios must be such as to give long evaporative lifetimes. In addition, the clouds must not be so dense or large that a major fraction of the grains are not able to act as scattering centers; the total dust masses of $\sim 10^8 M_\odot$ obtained from observations assume that all grains scatter light and scatter it only once. An optimal cloud configuration does not "hide" a large mass of grains from the UV light that needs to be scattered. In general, intercloud (and circumgalactic) densities and temperatures of $10^{-2} - 10^{-3}$ cm^{-3} and $T \sim 10^7 - 10^8$ K respectively, together with cloud number densities of $1 - 100$ and cloud sizes of order 100 pc will satisfy the above conditions.

Other initial conditions arise from considering the outflowing jet that powers the radio source and gives rise to the shock impinging on the ambient grain population. Propagation speeds are poorly constrained, but a nominal average jet propagation speed of $\sim 10^9$ cm s^{-1} will produce a radio source of $\sim$ 100 kpc in extent over a period of 10^7 years. These numbers fit well within the overall sizes and age estimates for the high redshift radio sources. Thus if the nominal age of the radio source is 10^7 yr, then this must also be about the minimum lifetime of the aligned continuum emission, and hence the grain population must survive for a comparable time if it is not created after the passage of the radio jet or replenished by some means. With these propagation speeds, jet radii of order 100 pc and jet number densities of order 1 will produce energy fluxes consistent with the radio powers observed for these objects, assuming the usual (and arbitrary) energy conversion factor of about ten percent. Again, these jet parameters are consistent with the nominal values used in modeling jets that power the luminous radio sources.

3 Evolution of Grain Populations

The processes that can result in grain destruction are then initiated when the shock wave associated with the radio jet hits a cloud containing grains. Cloud-shock encounters have been considered in detail through numerical simulations by Klein, McKee and Colella 1994 (KMC). The results of these calculations will be employed here. In particular, the shock speed in the cloud will be reduced from its initial value by a factor proportional to the square root of the cloud/intercloud density ratio, as found by KMC. As the shocked cloud gas is compressed it will begin to cool, and the cooling will be calculated as a function of time using polynomial fits to the standard cooling curve, assuming standard abundance ratios. Use of the KMC prescription for the shock velocity in the cloud ensures that pressure equilibrium is maintained between the post shock cloud material and the post shock intercloud medium, and thus the cooling will be taken to be isobaric. The metallicity of the gas in the clouds will be taken as one half solar in almost all cases.

The effects of shock waves on grains have been treated by many authors; e.g., Draine and Salpeter (1979), Seab and Shull (1983), McKee et al. (1987), Tielens et al. (1994). As a grain crosses the shock front, its velocity does not change as fast as that of the gas, and hence this differential velocity will cause non-thermal sputtering of the grain until drag forces bring it to the same speed as the surrounding gas. The drag forces arise from purely hydrodynamic drag and also from Coulomb drag because the grains carry a net electric charge and are moving in an ionized medium. In addition to this non-thermal sputtering, thermal sputtering can also remove material from the grain in the hot post-shock gas. This process will continue until radiative cooling causes a significant temperature drop in the gas. If magnetic fields are present in the clouds, then the non-thermal sputtering can be enhanced by the "betatron process". Because the charged grains are moving though the cloud magnetic field, they execute gyromotion. As the gas cools, if the cooling time is much longer than the gyroperiod of the grain, the grain will approximately conserve its magnetic moment in the increasing magnetic field that accompanies the increasing gas density. This will serve to increase the grain speed for a short time and thus enhance the ablation of grain material due to nonthermal sputtering. This process ceases when the gas cooling is essentially completed and the gas temperature is of order 10^4 K. Another process influencing the grain population is the effect of grain-grain collisions. This process can occur during the betatron phase, and it can have an important effect on the smaller grains. Grain-grain collisions have been recently treated in detail by Tielens et al. (1994), and the results of those calculations will be incorporated here. The ablation of grain material by photons is less than that due to gas sputtering for the UV radiation fields arising from the AGN, and thus it will not be considered here.

A final process that must be considered is the effect of thermal conductivity. If there are no magnetic fields in the clouds, then the betatron effect is absent, but in this case the effects of thermal conductivity may serve to reheat the clouds and inhibit cooling. For a very hot intercloud medium and/or small clouds, the conductivity may become saturated. The effects of thermal conductivity on interstellar clouds have been considered in some detail by McKee and Begelman (1990), and the results of these calculations will be used here to see if conductivity is significant should the magnetic fields in the clouds be negligible. It is important to note that although the physical processes occurring in the clouds that drive the evolution of the grain population are similar to those occurring in the interstellar medium, the conditions in the high redshift radio sources are very different. In particular the shock velocity associated with the radio jet is much higher than interstellar shocks, and in addition the inferred cloud densities may also be higher than typical interstellar values.

3.1 Calculation of Grain Evolution

The distribution of grain sizes ranges from grain radii of 100 Angstroms to 2500 Angstroms; the grains are assumed to be spherical graphite particles in all cases. The evolution of the grain population is followed by calculating the fate of grains with four logarithmically equally spaced initial grain radii, namely 100, 300, 1000 and 2500 Å. The effects of interaction of grains of different size arises only when considering grain-grain collisions; a treatment of these interactions is described when the grain-grain collision times are calculated.

The evolution of the grains is then found by following the time development of a single grain of a specific initial size under the influence of hydrodynamic and Coulomb drag, thermal and non-thermal sputtering, betatron acceleration, grain-grain collisions, and gas cooling, with the possibility of conductive reheating.

The hydrodynamic drag on a grain due to grain-gas collisions is given by (e.g., Draine and Salpeter 1979)

$$\frac{dv_g}{dt} = -\frac{3\rho {v_g}^2}{4a\rho_g} + \frac{v_o}{2{n_o}^{1/2}n^{1/2}}\frac{dn}{dt}.$$

The second term of this equation gives the acceleration due to the betatron effect. Here ρ_g is the grain density, v_g the grain speed, a the grain radius, and

ρ is the density of the gas. The drag due to multiple Coulomb interactions is a diffusive process essentially the same as dynamical friction, and it can be represented as (Draine and Salpeter 1979)

$$\frac{dv_g}{dt} = -\frac{3nkT\phi^2}{2a\rho_g} ln(\lambda) G(s).$$

Here $\phi = Z_g e^2/akT = eU/kT$ where a is again the grain radius and U is the grain potential, while T is the gas temperature. $G(s) \simeq s(1.5\pi + 2s^3)^{-1}$, where $s = (m{v_g}^2/2kT)^{1/2}$. The thermal and non-thermal sputtering yields are taken from the recent work of Tielens et al. (1994), and the resulting change in grain radius is given by

$$\frac{da}{dt} = -\frac{m_{sp} v_g n A Y(v_g)}{2\rho_g} - C_{th} n R(T).$$

Here m_{sp} is the mass of a grain atom, A is the abundance of the most effective ion for non-thermal sputtering, and Y is the yield per impact for non-thermal sputtering. Tielens et al. show that helium is the most effective species for non-thermal sputtering, and the data from Tielens et al. for that ion are used here. C_{th} is a normalizing factor used to provide the same units for both terms, and R is the thermal sputtering rate given by Tielens et al. as a function of gas temperature, while n is the gas number density. Finally, the cooling of the gas is given by

$$\frac{dT}{dt} = -\frac{n\Lambda(t)}{k},$$

and the number density evolves as

$$\frac{dn}{dt} = -\frac{n}{T}\frac{dT}{dt}.$$

These simultaneous differential equations are then integrated numerically to follow the evolution of the grains.

4 Results

Calculations were done for cloud number densities of $1 - 100$ cm^{-3} and ICM densities of 0.01 and 0.001 cm^{-3}. Initial cloud temperatures were taken to be 10^4 K in all cases, and the shock speed associated with the radio jet was set at 10^9 cm s^{-1}. A given grain is considered to be destroyed if it is reduced in radius by a factor of 10 in less than the jet propagation time of 10^7 yr. Grain - grain collision times were calculated as a function of time, and the grain destruction as a function of relative grain velocity was taken from the detailed calculations of Tielens et al.

In no cases calculated were grain-grain collisions more effective in destroying grains than were the thermal and non-thermal sputtering processes. The results of the calculations are summarized in Table 1. An "S" entry indicates grain survival after 10^7 yr, while and "*" indicates grain destruction.

n	a_o=100	a_o=300	a_o=1000	a_o=2500
ICM	*	*	S	S
1	*	*	*	*
10	*	*	*	S
100	S	S	S	S
100C	*	*	S	S

Table 1. Grain survival for a number of cloud densities (see text).

The run denoted by "100C" indicates the case where it is assumed no magnetic fields are present and that thermal conductivity can take place. The "ICM" run calculates evolution when the grains are not assumed to be in clouds but are instead uniformly distributed in the rarefied circumgalactic medium surrounding the parent galaxy out to of order 100 kpc. As noted above, with the MRN grain distribution almost all the grains are at the small radius end of the size distributions, less than 1000 Angstroms. Hence the above table shows that almost all the grains are destroyed in almost all the circumstances. Grain populations whose grains survive only at initial radii greater or equal to 1000 Angstroms, are essentially destroyed as a scattering population. Figure 1 shows two samples of the evolution of the grain radius as a function of time for different conditions, while Figure 2 shows a sample of the evolution of the grain velocity and demonstrates the "betatron effect".

Thus it can be seen that only under very special circumstances, occupying a small section of parameter space, do enough grains survive the passage of the radio source shock to remain as effective scattering centers and to give rise to a polarized continuum radiation as observed.

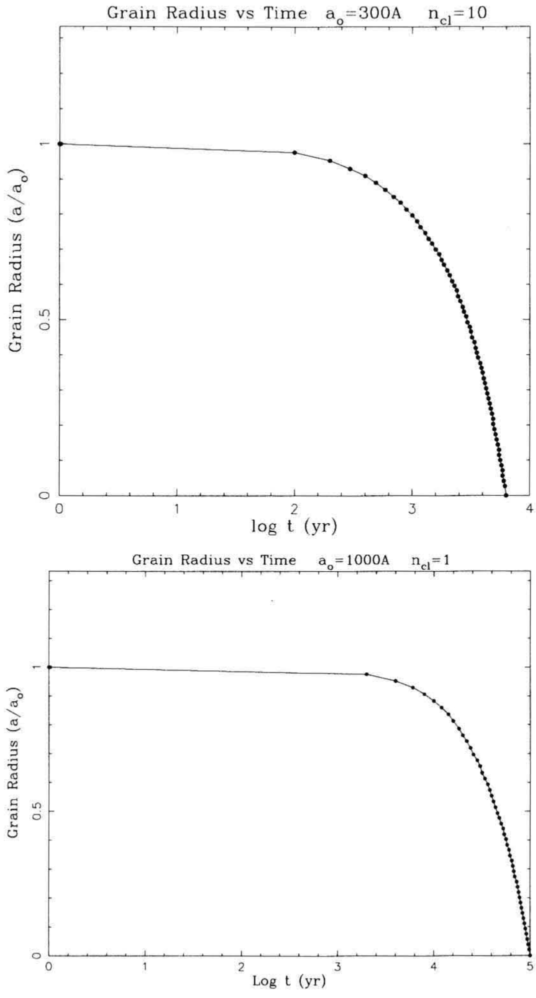

Figure 1. The evolution of the grain radius as a function of time for two sets of initial conditions.

5 Conclusions

While these calculations show that under some circumstances grains can survive the passage of the radio jet, the small volume of parameter space where this is allowed makes the use of a pre-existing grain population as a scattering medium somewhat problematic. Given the rather easy destruction of the grains, other options might be to carry them out of the galaxy with the radio jet or to create them in situ after the jet passage. Calculations of mass entrainment in the mixing layers of radio jets show that sufficient mass, enriched with grains, could be moved from the galaxy ISM to distances where the alignment effect occurs. However, once again it is not clear that grains in this environment can survive long enough; the above calculations also apply to any grain containing clouds entrained in the mixing layer, and once again the allowed parameter space is discouragingly small.

A final possibility is that the requisite grains are produced by a population of stars whose formation was triggered by the passage of the radio jet. Dwek (1997)

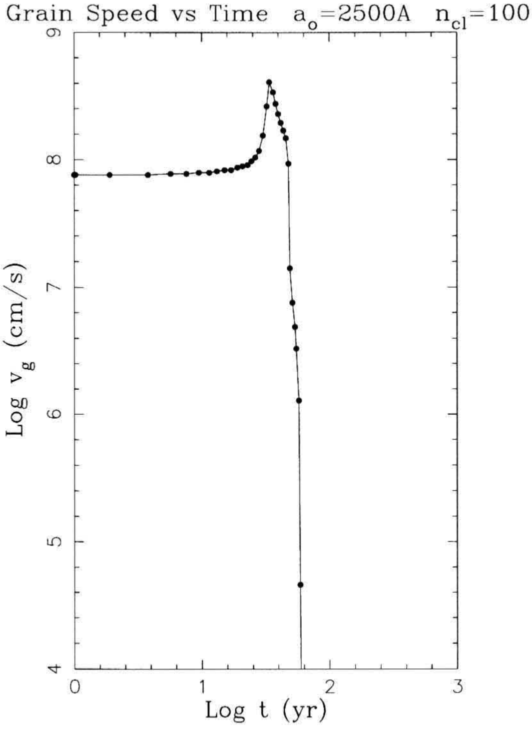

Figure 2. The evolution of the grain velocity, showing the "betatron" effect.

has recently shown that a major source of dust grains is found in supernova events, and such events occurring only a million years after the jet passage could provide an origin of the dust grains. Dwek estimates that each supernova produces roughly one solar mass in dust grains, hence 10^7 supernovae could provide the necessary total dust mass. Although the IMF resulting from jet induced star formation is unknown, use of a Salpeter IMF with upper and lower cutoffs of 100 and 0.1 solar masses shows that a total star production of $\simeq 2 \times 10^9 M_\odot$ will give rise to the required number of supernovae. Assuming a ten percent conversion of ambient gas into stars, this requires a total mass of gas in the circumgalactic region out to 100 kpc of 2×10^{10} solar masses, which is not an unreasonable value.

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