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ENRICHMENT OF THE INTERGALACTIC MEDIUM BY RADIATION PRESSURE DRIVEN DUST EFFLUX

Anthony Aguirre,[a,b] Lars Hernquist,[b] Neal Katz,[c] Jeffrey Gardner,[d] & David Weinberg[e]

[a]Institute for Advanced Study, School of Natural Sciences, Princeton NJ 08540
[b]Department of Astronomy, Harvard University 60 Garden Street, Cambridge, MA 02138
[c]Department of Physics and Astronomy, University of Massachusetts, Amherst, MA 98105
[d]Department of Astronomy, University of Washington, Seattle, WA 98195
[e]Department of Astronomy, Ohio State University, Columbus, OH 43210

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ABSTRACT

The presence of metals in hot cluster gas and in Lyα absorbers, as well as the mass-metallicity relation of observed galaxies, suggest that galaxies lose a significant fraction of their metals to the intergalactic medium (IGM). Theoretical studies of this process have concentrated on metal removal by dynamical processes or supernova-driven winds. Here, we investigate the enrichment of the IGM by the expulsion of dust grains from galaxies by radiation pressure. We use already completed cosmological simulations, to which we add dust assuming that most dust can reach the equilibrium point between radiation pressure and gravitational forces. We find that the expulsion of dust and its subsequent (partial) destruction in the IGM can plausibly account for the observed level of C and Si enrichment of the $z = 3$ IGM. At low-z, dust ejection and destruction could explain a substantial fraction of the metals in clusters, but it cannot account for all of the chemical species observed. Dust expelled by radiation pressure could give clusters a visual opacity of up to $0.2 - 0.5$ mag in their central regions even after destruction by the hot intracluster medium; this value is interestingly close to limits and claimed observations of cluster extinction. We also comment on the implications of our results for the opacity of the general IGM. Finally, we suggest a possible 'hybrid' scenario in which winds expel gas and dust into galaxy halos but radiation pressure distributes the dust uniformly through the IGM.

Subject headings: cosmology: theory — intergalactic medium — galaxies: abundances — dust: extinction

1. INTRODUCTION

Several independent sets of observations indicate that galaxies must lose a substantial fraction of the metals they produce during their lifetimes. First, metal lines in hot X-ray emitting gas in clusters and groups indicate that as much metal lies outside of galaxies in these objects as inside them (e.g., Mushotsky et al. 1996; Renzini 1997; Davis, Mulchaey & Mushotsky 1999; Buote 2000). Second, quasar absorption line studies imply that the intergalactic medium (IGM) at $z \lesssim 3$ is enriched to metallicity $Z \gtrsim 10^{-2.5}\,Z_\odot$ (e.g., Songaila & Cowie 1996; Cowie & Songaila 1998; Ellison et al. 2000; Penton, Sticke & Schull 2000). Cosmological simulations indicate that this seems to require at least $\sim 10\%$ of galactic metals to be ejected (Aguirre et al. 2001a,b). Third, the strong positive correlation between galaxies' masses and metallicities (e.g., Zaritsky, Kennicutt & Huchra 1994) is naturally explained by the efficient escape of metals from low-mass galaxies (Dekel & Silk 1986; Lynden-Bell 1992).

Most theoretical studies addressing this ubiquitous presence of intergalactic metals have focused on the removal of metal enriched gas from galaxies; the gas may be removed by ram-pressure stripping, during dynamical encounters between galaxies, or as an outflow driven by supernovae and stellar winds. While dynamical removal undoubtedly occurs at some level (especially in rich clusters), it is not clear that it can account for the level of metallicity in the $z = 3$ IGM or the mass-metallicity (M-Z) relation of galaxies (Aguirre et al. 2001a; but see Gnedin 1998). Metal ejection by galactic winds can explain the M-Z relation (winds escape low-mass galaxies more easily) and may account for the observed level of IG enrichment (e.g., Cen & Ostriker 1999; Aguirre et al. 2001b), but it is unclear whether they can do this without overly disturbing the thermal or structural properties of the high-z IGM.

A third metal removal mechanism, which has not previously been treated in a cosmological context, is the ejection of dust grains by radiation pressure. As first pointed out by Pecker (1972) and Chiao & Wickramasinghe (1972), bright galaxies can exert a radiation pressure force on nearby grains that exceeds their gravitational attraction, forcing the grains into the galaxies' halos or beyond. Subsequent studies involving realistic model galaxies have confirmed this idea, showing also that gas drag is insufficient to confine grains unless they start at small galactic scale-height (e.g., Ferrara et al. 1990; Shustov & Vibe 1995; Davies et al. 1998; Simonsen & Hannestad 1999).

All of these studies support the idea that much of a galaxy's dust may be ejected during its lifetime, so it is interesting to assess the possible IG enrichment that would ensue. Unlike winds, enrichment by dust (partially destroyed in transit or by the IGM) would not impact the thermal/structural properties of the IGM or galaxies. In this Letter, we assess the amount and distribution of metals transferred to the IGM as dust driven by radiation pressure, using two smoothed-particle hydrodynamics (SPH) simulations. The first has 128^3 dark matter particles and 128^3 SPH particles in a $(17\,\mathrm{Mpc})^3$ box, and ends at $z = 3$. The second, ending at $z = 0$, has 2×144^3 particles in a $(77\,\mathrm{Mpc})^3$ box. Both assume $\Omega_\Lambda = 0.6$, $\Omega_b = 0.047$, $\Omega_m = 0.4$, $h = 0.65$ and $\sigma_8 = 0.8$. The simulations are described in more detail in Aguirre et al. (2001a) and in Weinberg et al. (1999). Section 2 describes the method of adding metals and dust to the already completed simulations. Section 3 gives results pertaining to the enrichment of the $z = 3$ IGM and the $z = 0$ intracluster medium, in several representative models. We discuss these results and their implications in § 4.

2. METHOD

The method by which we calculate IGM enrichment is discussed in detail in Aguirre et al. (2001a). Briefly, our method post-processes a limited number of outputs from already completed SPH cosmological simulations that include star formation. We assume that each unit of forming stellar mass instantaneously generates y_* units of metal mass. We then deposit this metal mass in gas particles near the forming star particle as follows:

1. A fraction $(1 - Y_{\rm ej})$ of the metal is distributed in the nearest 32 gas particles, using the SPH smoothing kernel (see Hernquist & Katz 1989). Half of the locally-distributed metal is added in the form of dust, the other half as gaseous metal.

2. The remaining mass is tallied for a given galaxy,[1] for which we also compute the mean metallicity $\langle Z \rangle_{\rm gal}$ and the UV-optical-NIR luminosity, using the models of Bruzual and Charlot[2] and a Scalo or Salpeter initial mass function (IMF).

3. Using $\langle Z \rangle_{\rm gal}$ we apply a dust correction to the luminosity from Heckman et al. (1998; see Aguirre et al. 2001a), normalized to give the observed ratio at $z = 0$ in the cosmic UV-optical-NIR and FIR backgrounds (which are also output by the simulations).

4. We assume a grain size distribution (GSD) in mass $dm(a)/da$ and opacity (per unit mass) law from Kim, Martin & Hendry (1994) and Laor & Draine (1993), respectively, for either graphite or silicate grains.

5. The fraction $Y_{\rm ej}$ of metal formed in a galaxy is distributed as dust spherically about the center of star formation. A dust mass proportional to $dm(a)/da$ is placed in a shell where the radiation pressure on a grain of radius a balances the galaxy's gravitation.

The process is repeated for each galaxy at each time step. New stars are formed with the metallicity (including dust) of the gas from which they form. Each gas particle has an accumulated mass of gaseous metals and dust, and we track the GSD for each particle using a 9-point piecewise power law fit (see Aguirre et al. 2001a for details). The GSD is modified as the dust is converted to metals by thermal sputtering by the IGM (using the yields of Jones et al. 1994), or as new (unsputtered) dust is added to the particle.

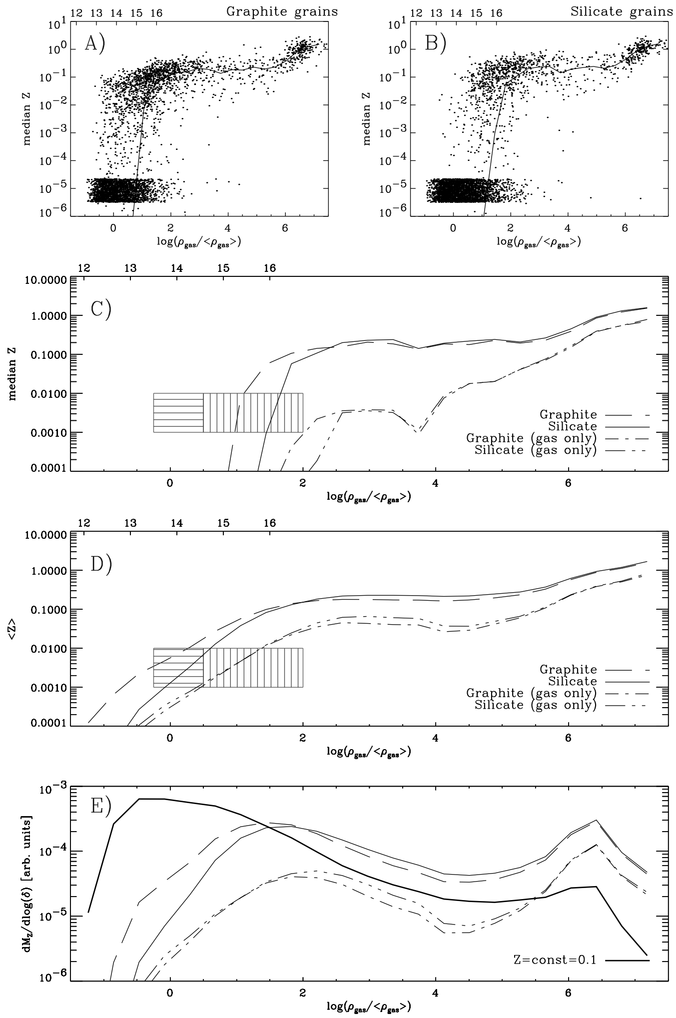

Fig. 1.— Enrichment of the IGM plotted in four ways. **Panel A:** Random subsample (1 in 500) of particle metallicities for the fiducial model with graphite grains, versus overdensity $\delta \equiv \rho_{\rm gas}/\langle \rho_{\rm gas} \rangle$. Top axis (here and in all panels) gives approximate $\log N(H\ I)$, using the relation of Davé et al. (1999). The solid line shows the median metallicity versus δ. **B:** As for panel A, for silicate grains. **C:** Median metallicities versus δ for models with graphite and silicate grains, but for total (dust+gas) metal content, and for gaseous metals only. The shaded box roughly indicates the metallicity of low-column density Lyα absorbers (Ellison et al. 2000). **D:** As for panel C, but *mean* metallicities are plotted. **E:** As for panel C, but gives mean metallicities times the fraction of baryons at a given δ, showing the contribution by components with different δ to the cosmic metal density. The thick line shows the distribution assuming constant metallicity (with the same total metal mass).

3. RESULTS

Our basic model assumes graphite grains, a 1:1 ratio between the cosmic UV-optical-NIR and FIR backgrounds at $z = 0$ (c.f. Madau & Pozzetti 2000), a Scalo IMF with cutoffs at $0.1\,\mathrm{M}_\odot$ and $100\,\mathrm{M}_\odot$, $y_* = Z_\odot$, and $Y_{\rm ej} = 0.5$. The last assumption is maximal, as only $\sim 1/2$ of a typical

[1]By 'galaxy' we mean a group of bound particles found using the SKID package, publicly available at http://www-hpcc.astro.washington.edu/tools.

[2]The models are available via anonymous FTP from ftp.noao.edu.

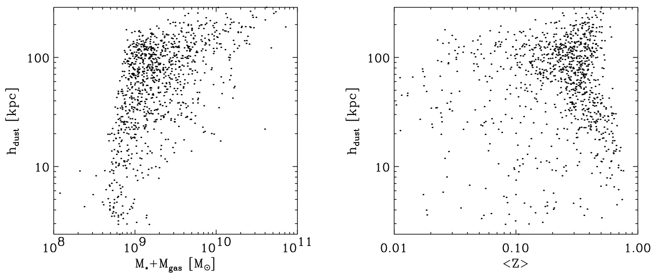

FIG. 2.— **Left:** Maximal dust ejection radius $h_{\rm dust}$ vs. galaxy mass for $z = 3$. **Right:** $h_{\rm dust}$ vs. mean metallicity.

galaxy's metals are in dust. We also give corresponding results for silicate grains.

Figure 1 shows the key results at $z = 3$, using the 128^3 simulation. The top two panels give a sparse sampling of individual particle metallicities, versus the gas overdensity δ. The stellar yield y_* is uncertain by perhaps a factor of two, and all of the curves could be scaled vertically for a higher assumed value. The metallicity at $\delta \lesssim 10^4$ could also be (roughly) scaled by $Y_{\rm ej}$ for lower assumed values. The bar at the bottom of each panel shows the zero metallicity particles and indicates that the distribution is rather inhomogeneous, especially for silicate grains (Panel B). This can also be seen by comparing panels C and D, which show the median and mean metallicity vs. δ. The latter shows that dust ejection can provide *enough* metals to account for the Lyα observations (indicated by the hatched rectangle), though the enrichment may not, in these models, be uniform enough. It is important to note, however, that (assuming grains decouple from the galactic gas) our method always *under*estimates the radius to which the grains can escape, because they would inevitably reach the force balance radius with some velocity and overshoot it. Thus the distribution should probably be more uniform than shown here. (The ejection radius should also be limited by the average dust velocity $\bar{v}_d$ times the available time, but introducing this limit does not change the fiducial model results unless $\bar{v}_d \lesssim 100\,{\rm km\,s^{-1}}$, slow compared to velocities seen in more detailed studies of dust ejection.)

Figure 1 gives results for both the *total* metal enrichment (dashed and solid lines), and for the gas-phase enrichment (single- and triple-dot-dashed lines), where grains have been converted to gas by thermal sputtering only. Because destruction by both thermal and nonthermal sputtering during grain ejection would destroy more dust, true gas-phase abundances should lie above the latter two curves (although if grains are destroyed *very* efficiently at small radii they will not survive to pollute the low-density regions).

The models with different dust corrections (e.g. changing the 1:1 ratio in cosmic backgrounds to 1:2 or 3:1) give differences in $z = 3$ enrichment comparable to the

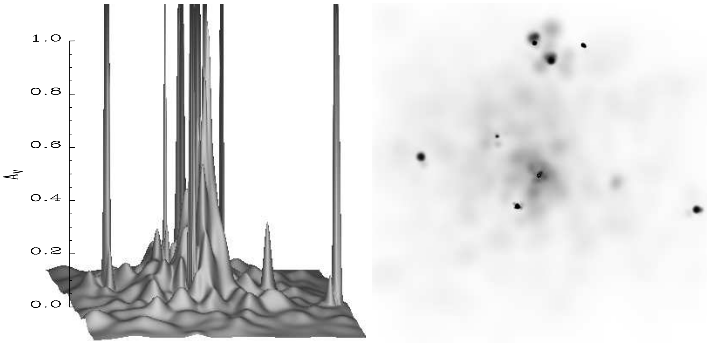

FIG. 3.— Dust extinction for a simulation cluster at $z = 0$ in the fiducial model, with graphite grains. Both images are $1.2\,{\rm Mpc}\times 1.2\,{\rm Mpc}$, projected through a $1.2\,{\rm Mpc}$ cube. The left surface gives visual extinction, assuming $\kappa_V = 4 \times 10^4\,{\rm cm^2\,g^{-1}}$. The right panel simulates what a sheet of white paper would look like through the dust of the cluster.

differences between the silicate and graphite models (which differ in dust opacity by a factor of a few). Similar changes are induced by different assumed IMFs (see Aguirre et al. 2001a).

Quantities pertaining to the galaxies ejecting dust at $z = 3$ are shown in Fig. 2. The left panel, giving the maximal dust ejection radius vs. the galaxy (baryon) mass, shows that ejection is most effective from the larger galaxies. This, and a correlation between mass and metallicity (resulting from more efficient star formation in larger galaxies), largely washes out the anti-correlation between ejection radius and metallicity one would expect from the metallicity-dependent dust correction (as shown in the right panel). At low redshift, the balance reverses, and high mass galaxies eject metals slightly less efficiently due to their large dust corrections.

The 144^3 simulation (which runs to $z = 0$) allows us to assess the enrichment of the low-z IGM by dust ejection. This simulation only resolves galaxies of baryon mass $\gtrsim 10^{10.7}\,{\rm M_\odot}$, but these galaxies dominate the observed $z = 0$ mass function, and the more efficient ejection of grains from large galaxies at high-z (when small galaxies contribute relatively more mass), so we capture the bulk of the metal enrichment. In the fiducial model described above, the ICM of the most massive groups/clusters is enriched to $\approx 1/5\,Z_\odot$.

Dust is destroyed efficiently in the hot ICM, but enough remains that some extinction can occur. Figure 3 shows the optical depth through a simulation group/cluster of baryonic mass $2 \times 10^{13}\,{\rm M_\odot}$ in the fiducial graphite model, assuming a dust visual opacity of $\kappa_V = 4 \times 10^4\,{\rm cm^2\,g^{-1}}$ (reasonable for a more realistic silicate-graphite mixture). Except along paths through galaxies, the cluster optical depth is typically $\lesssim 0.2$ mag; the central region has $A_V \sim 0.5$ mag. Poorer groups show less opacity. We note also that the same model predicts a general 'diffuse' extinction to $z = 0.5$ of $\approx 0.05 - 0.1(\kappa_V/4 \times 10^4\,{\rm cm^2\,g^{-1}})$ mag, which is comparable to the difference between Hubble diagrams for different cosmological models at $z = 0.5$ (Aguirre 1999) and could potentially be important in observational cosmology.[3]

4. DISCUSSION AND IMPLICATIONS

[3]The far-infrared emission from such dust would not violate constraints from the observed far-infrared or microwave backgrounds; see Aguirre & Haiman (1999).

In § 1 we argued that dust ejection is an interesting alternative to dynamical or wind enrichment of the IGM because it may be efficient, yet not disturb the IGM or galaxies in a way incompatible with observations. Our simulations, which produce reasonable predictions for the masses, luminosities, and spatial distribution of galaxies, support this possibility by indicating that most galaxies at high z have properties that would tend to repel dust grains, out to a radius large enough that the low-density IGM can be significantly polluted. The chief uncertainties in our calculation are *not* the detailed choices of dust opacity, IMF, dust correction, cosmological parameters, etc. (all of which are probably uncertain only at a level which does not significantly affect our results), but rather in the physics of dust ejection itself. We assume that most dust reaches the point of equilibrium between radiation pressure and graviational forces, but realistically dust might be destroyed in transit, or confined to galaxies by other forces. Gas drag can confine grains at small galactic scale-heights, but this still allows a large dust outflow when the circulation of gas in the galaxy is considered (Shustov & Vibe 1995). But magnetic fields (not included in our treatment) might be extremely important, since charged grains in a microgauss field would oscillate about field lines with a Larmor radius significantly smaller than the galaxy scale. To escape, dust may diffuse along a vertical component of the magnetic field (Shustov & Vibe 1995), perhaps enhanced by low-level winds or by Parker instabilities (Chiao & Wickramasinghe 1972; Ferrara et al. 1991). Magnetic fields may also be much weaker at high-z if they have been amplified by a dynamo since then.

If dust *can* escape magnetic fields, our calculations show that it could significantly pollute the IGM. A unique signature of enrichment by dust is that while dynamics or winds would pollute the IGM with chemical abundances similar to those of the galaxies, dust ejection can only enrich the IGM with elements such as C, Si, and Mg, which solidify as grains. Elements such as N, Zn, and the noble gases, which are very lightly depleted onto grains, should only be ejected in trace amounts. Thus by measuring the relative ratio of N to C or Si in Lyα lines, one could constrain the pollution by dust. Presently N is detected only in absorbers of fairly high ($N(H\,I) \sim 10^{16}\,\mathrm{cm}^{-2}$) column density (Songaila & Cowie 1996), but pushing these observations to lower H I columns could give strong constraints on (or evidence for) dust enrichment.[4] At low redshifts the significant abundances of Ne and Ar in cluster gas (e.g., Mushotsky et al. 1996) indicates that dust cannot be the sole pollutant of the ICM and that some enrichment by other mechanisms must occur. Higher quality data from *Chandra* should allow a much more interesting test of the importance of dust ejection.

Our calculations also give a fairly accurate assessment of the expected opacity of rich clusters if about half of the observed enrichment were due to dust ejection (unless the grain opacities are significantly higher than we have assumed). Our estimate of $\sim 0.2-0.5$ mag in the central few hundred kpc of clusters is roughly comparable to both claimed detections of cluster dust using extinction of background quasars (e.g., Boyle et al. 1988; Romani & Maoz 1992) or IR emission (Stickel et al. 1998), and to upper limits based on reddening (e.g. Maoz 1995).[5] This indicates that the general picture of substantial dust ejection from galaxies might provide an interesting level of extinction through the IGM, but would not violate any current constraints on cluster dust density.

The primary difficulty with dust ejection as an explanation for the Si and C enrichment of the low-density IGM is that it is not at all clear – theoretically or observationally – that dust really can decouple from galactic gas; but if it can, there appears to be no reason why it would not escape to large radii. Galactic winds, on the other hand, are clearly observed both locally and at high-z, and they should certainly be able to pollute (at least) the halos of their progenitor galaxies. But spreading the metals to large distances may disrupt the IGM more than observations allow (e.g., Theuns, Mo & Schaye 2000; Aguirre et al. 2001b). This suggests a possible 'hybrid' scenario in which gas and dust are expelled into a diffuse mixture in the halos of galaxies. But while gas remains there, the dust could continue, driven by radiation pressure, to large distances.

For example, imagine a representative $z = 5$ galaxy of baryonic mass $5 \times 10^9\,\mathrm{M}_\odot$ and UV-optical-NIR luminosity $2.5 \times 10^{10}\,L_\odot$ driving a wind of velocity $v = 200\,\mathrm{km\,s}^{-1}$ at small radii. Such a galaxy could reasonably drive a wind to $\sim 1-100$ kpc (using the results discussed in Aguirre et al. 2001b), but our calculations show that radiation pressure could exceed gravitational attraction out to 100-200 kpc. If $0.1\,\mu$m graphite grains were to decouple from the gas near the disk (say at 10 kpc), they could reach $(100-200)$ kpc after $\approx (0.2-0.4)$Gyr, with velocity $\approx 470-500\,\mathrm{km\,s}^{-1}$ (in calculating this we assume here that the enclosed mass is proportional to the radius). After ~ 1 Gyr (i.e. at $z = 3$) the grains could reach up to ~ 420 kpc; silicate grains could reach up to ~ 280 kpc during the same time. This is an upper limit since we have neglected gas drag; adding gas drag appropriate for $\delta = 100(10)$ gas reduces the graphite distance to 250(385) kpc and the silicate distance to 220(270) kpc.[6] but indicates that radiation pressure can quite plausibly eject dust far enough to pollute the IGM quite uniformly while disturbing the IGM only near the galaxy.

In summary, our calculations indicate that galaxies at high redshift tend to repel rather than attract dust grains. If a substantial fraction of dust can reach at least the equilibrium radius between gravitational and radiation pressure forces, then the ensuing enrichment can account for the mean level of C and Si observed in the IGM at $z \sim 3$. Dust ejection would also enrich groups and clusters substantially, though radiation pressure cannot account for *all* of the metals observed. The resulting dust extinction would be $\lesssim 0.5$ mag through the cores of rich clusters. Dust ejection and the ejection of metals by winds are, in some sense, complementary. Winds almost certainly drive

[4]Unfortunately (for this application), N might also be lacking if it is underproduced in the massive (perhaps low-metallicity) stars responsible for the enrichment at high-z; see Arnett (1995).

[5]The conclusions of reddening studies are vulnerable to changes in the dust grain-size distribution by dust destruction; see Aguirre (1999).

[6]For this estimate we use a drag force $\sigma\rho v^2$ where σ and v are the dust geometrical cross section and velocity, and ρ is the density of the medium. This neglects Coulomb drag and is good in the limit of highly supersonic grains.

gas into the halos of galaxies, but may overly-disturb the IGM if the gas travels to very large radii. Dust may be confined to galaxies by magnetic fields or gas drag but should leave unimpeded if first moved into the halo. Radiation pressure acting on dust can therefore help enrich the IGM more uniformly than winds alone. Because only certain elements form dust, the possibility of intergalactic enrichment by dust can be robustly tested – in principle – by measuring ratios between refractory and non-refractory elements in the IGM.

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