The dynamics of charged dust in magnetized molecular clouds

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ABSTRACT
We study the dynamics of large, charged dust grains in turbulent giant molecular clouds (GMCs). Massive dust grains behave as aerodynamic particles in primarily neutral dense gas, and thus are able to produce dramatic small-scale fluctuations in the dust-to-gas ratio. Hopkins & Lee directly simulated the dynamics of neutral dust grains in supersonic magnetohydrodynamic turbulence, typical of GMCs, and showed that the dust-to-gas fluctuations can exceed factor $\sim 1000$ on small scales, with important implications for star formation, stellar abundances and dust behaviour and growth. However, even in primarily neutral gas in GMCs, dust grains are negatively charged and Lorentz forces are non-negligible. Therefore, we extend our previous study by including the effects of Lorentz forces on charged grains (in addition to drag). For small-charged grains (sizes $\ll 0.1 \mu m$), Lorentz forces suppress dust-to-gas ratio fluctuations, while for large grains (sizes $\gtrsim 1 \mu m$), Lorentz forces have essentially no effect, trends that are well explained with a simple theory of dust magnetization. In some special intermediate cases, Lorentz forces can enhance dust–gas segregation. Regardless, for the physically expected scaling of dust charge with grain size, we find the most important effects depend on grain size (via the drag equation) with Lorentz forces/charge as a second-order correction. We show that the dynamics we consider are determined by three dimensionless numbers in the limit of weak background magnetic fields: the turbulent Mach number, a dust drag parameter (proportional to grain size) and a dust Lorentz parameter (proportional to grain charge); these allow us to generalize our simulations to a wide range of conditions.

Key words: accretion, accretion discs – instabilities – turbulence – planets and satellites: formation – stars: formation – galaxies: formation – cosmology: theory.

1 INTRODUCTION
Dust is crucial for a diverse array of phenomena in astrophysics. Dust plays an important direct role in planet and star formation, and also in ‘feedback’ processes during star cluster and galaxy formation. Dust is also vital for radiative cooling of gas, attenuation and absorption of light in the interstellar medium (ISM) and the evolution of heavy-element abundances and phases in galaxies. It is also a key observational tracer of the ISM in nearby regions and high-redshift galaxies. This broad importance of dust means that it is critical to understand dust dynamics and grain clustering, in the ISM and star-forming regions.

It has long been known that dust grains do not necessarily move with gas in astrophysical fluids. In protoplanetary discs, in particular, a wide variety of conditions have been identified where different fluid conditions can produce orders-of-magnitude variations in the local dust-to-gas ratio, including ‘pressure’ traps, local ‘vortex traps’ or ‘turbulent concentration’ in turbulent discs, the streaming instability, ‘zonal flows’ in magnetically active discs and more (see e.g. Bracco et al. 1999; Cuzzi et al. 2001; Youdin & Goodman 2005; Johansen & Youdin 2007; Carballido, Stone & Turner 2008; Bai & Stone 2010a,b; Pan et al. 2011; Dittrich, Klahr & Johansen 2013; Jalali 2013; Hopkins 2014a). Large fluctuations in the density of aerodynamic particles relative to gas have also long been observed in terrestrial turbulence (Squires & Eaton 1991; Fessler, Kulick & Eaton 1994; Rouson & Eaton 2001; Gualtieri, Picano & Casciola 2009; Monchaux, Bourgoin & Cartellier 2010).

More recently, several studies have suggested that dust grains in GMCs or neutral galactic discs should exhibit similar fluctuations (Padoan et al. 2006; Hopkins 2014b; Hopkins & Conroy 2017) – in terms of the aerodynamic drag equations, a grain of diameter $\sim 0.1–1 \mu m$ in a typical GMC is analogous to a metre-sized boulder in a protoplanetary disc. And observations have identified small-scale ($\sim 0.01–1 \text{ pc}$) fluctuations in the local dust-to-gas ratio of large grains in a number of nearby molecular clouds (Thoraval, Boisse & Duvert 1997; Thoraval, Boissé & Duvert 1999; Abergel et al. 2002; Flagey et al. 2009; Boogert et al. 2013). Across different regions in the ISM, variations in extinction curves and emission/absorption features similarly suggest there may be large fluctuations in the...
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2 METHODS

The methods here exactly follow Paper I with the addition of Lorentz forces, so we briefly summarize here and refer to that paper for details. Hopkins & Lee (2016, hereafter Paper I) presented a first numerical study of dust as aerodynamic particles under these conditions, and showed that indeed similar, dramatic fluctuations are expected in supersonic, isothermal, magnetohydrodynamic (MHD) turbulence, on scales that could be important for star formation, dust grain growth and a wide variety of other phenomena. However, that study considered only neutral dust grains — i.e. while the gas was magnetized, the grains felt no Lorentz forces. But real grains in GMCs are expected to be charged, and the Lorentz forces should dominate over aerodynamic (drag) forces for sufficiently small grains, or for large grains in sufficiently low-gas-density regions. This is yet another, perhaps critical, way that dust dynamics are different in GMCs and the ISM from terrestrial or protoplanetary disc turbulence.

In this paper, we therefore extend the study of Paper I, to include explicit, self-consistent Lorentz forces on grains, with realistic charges. We will show this does indeed have effects in the regimes expected, but these are generally subdominant to the effects of modest changes in the grain size.

relative abundance of large grains (Miville-Deschênes et al. 2002; Gordon et al. 2003; Dobashi et al. 2008; Paradis et al. 2009). The solar neighbourhood, in particular, appears to exhibit an anomalous large-grain abundance (Krüger et al. 2001; Meisel, Janches & Mathews 2002; Frisch & Slavin 2003; Althobelli, Grün & Landgraf 2006; Althobelli et al. 2007; Poppe et al. 2010). And Hopkins (2014b) suggested that this could explain some (but not all) of the variations in abundances observed within some star massive clusters.¹

But there are some important differences between dust dynamics in GMCs, as compared to the more well-studied terrestrial and planetary disc cases: most obviously, that the turbulence in GMCs is highly supersonic, approximately isothermal (because the gas is rapidly-cooling), magnetized and self-gravitating. Hopkins & Lee (2016, hereafter Paper I) presented a first numerical study of dust as aerodynamic particles under these conditions, and showed that indeed similar, dramatic fluctuations are expected in supersonic, isothermal, magnetohydrodynamic (MHD) turbulence, on scales that could be important for star formation, dust grain growth and a wide variety of other phenomena. However, that study considered only neutral dust grains — i.e. while the gas was magnetized, the grains felt no Lorentz forces. But real grains in GMCs are expected to be charged, and the Lorentz forces should dominate over aerodynamic (drag) forces for sufficiently small grains, or for large grains in sufficiently low-gas-density regions. This is yet another, perhaps critical, way that dust dynamics are different in GMCs and the ISM from terrestrial or protoplanetary disc turbulence.

In this paper, we therefore extend the study of Paper I, to include explicit, self-consistent Lorentz forces on grains, with realistic charges. We will show this does indeed have effects in the regimes expected, but these are generally subdominant to the effects of modest changes in the grain size.

¹ Specifically, Hopkins (2014b) argue grain–gas dynamics may be relevant for certain abundance variations in large, low-density clusters (see e.g. Carretta et al. 2009; Carraro 2014), where the grain-decoupling parameter $a$ (introduced below) is maximized, as opposed to low-mass clusters which appear to exhibit smaller abundance spreads (Pancino et al. 2010; Bragaglia et al. 2012; Carrera & Martínez-Vázquez 2013).
Here, $\alpha$ is the dimensionless ‘drag’ or ‘size’ parameter from Paper I.

\footnote{We will, for convenience, define the number density $\langle n_{\text{gas}} \rangle \equiv \langle \rho_{\text{gas}} \rangle / \mu m_p$ with $\mu = 2.3$ (appropriate for solar metallicity, molecular gas), but $\mu$ never enters the dynamics.}

where the tilde-superscript $\tilde{\mathcal{M}}$ denotes the value of $x$ in code units.\footnote{We will, for convenience, define the number density $\langle n_{\text{gas}} \rangle \equiv \langle \rho_{\text{gas}} \rangle / \mu m_p$ with $\mu = 2.3$ (appropriate for solar metallicity, molecular gas), but $\mu$ never enters the dynamics.}
Thus, aside from the initial mean field (energetically important in the saturated state only for run ‘n1’), the saturated dynamics of the problem are governed by $M_A$, $\alpha$ and $\phi$, greatly simplifying our parameter survey. All runs use here 256$^3$ gas and $2 \times 256^3$ dust particles and a variety of convergence studies in Paper I (appendix B, fig. B1) demonstrate that this is sufficient for converged results in quantities studied here. Table 1 presents the list of simulations we study. For each run, we select $M_A$, $\alpha$, $\phi$ by initially selecting a representative temperature $T$ and simulation results. (see Section 4), we find reasonable agreement between the theory assuming a basic supersonic turbulence model. Although qualitative, these arguments aid in understanding when dust charging should significantly modify its density distribution. As discussed below (see Section 4), we find reasonable agreement between the theory and simulation results.

3 DUST MAGNETIZATION

In this section, we estimate the influence of the magnetic field on dust-grain dynamics. A convenient way to parametrize this is through the ratio of the dust gyroradius $r_{gy,d}$ to its free-streaming length in the gas $L_{stream}$. If $r_{gy,d} > L_{stream}$, then the dust is effectively unmagnetized (it is stopped before undergoing a gyro-orbit), while if $r_{gy,d} < L_{stream}$ the magnetic field will have a strong influence on dust dynamics (Lazarian & Yan 2002). Here, we estimate $r_{gy,d}/L_{stream}$ assuming a basic supersonic turbulence model. Although qualitative, these arguments aid in understanding when dust charging should significantly modify its density distribution. As discussed below (see Section 4), we find reasonable agreement between the theory and simulation results.

The dust free-streaming length may be estimated as $L_{stream} \sim \langle |u_d - u_{gas}| \rangle t_s$, where the stopping time $t_s$ is given by equation (2) and the relative velocity $\langle |u_d - u_{gas}| \rangle$ may be estimated as the ‘eddy velocity’ $v_{\lambda} \sim \langle |u_{gas}(r + \lambda) - u_{gas}(r)| \rangle$ (with $\lambda = |\lambda|$) of the turbulence on scale $\lambda = L_{stream}$. We then assume the standard hydrodynamic velocity scalings $v_{\lambda} \sim M_A (\lambda/L_{box})^{1/2}$ for $v_{\lambda} > c_s$, $v_{\lambda} \sim c_s (\lambda/R_{\text{sonic}})^{1/4}$ for $v_{\lambda} < c_s$, where $R_{\text{sonic}} \sim L_{box} M_{\lambda}^{-2}$ is the scale at which the turbulence transitions from supersonic to subsonic. This scaling assumes that the influence of the magnetic field on the flow should be relatively unimportant until at, or below, the subsonic scales ($\sim R_{\text{sonic}}$). Otherwise – i.e. in the case of strong mean fields – the turbulence would be Alfvénic in character and anisotropic at large scales (Lithwick & Goldreich 2001; Cho & Lazarian 2003). Our analysis is thus restricted to turbulence where $M_A > 1$ and the field is tangled on supersonic scales (this is the opposite regime to Yan et al. 2004). This appears to be satisfied for most of the simulations detailed in Table 1 (an exception is ‘n1’, which has a relatively strong mean field).

Assuming the force on dust from the magnetic field will not strongly alter the streaming length, one can estimate (see Paper I)

$$L_{stream} \sim \frac{\alpha^2 M_A}{\phi} \left( \frac{n_{gas}}{(\sigma_{gas})} \right)^{-1/2} \frac{L_{stream}}{L_{box}} \frac{\langle u_d - u_{gas} \rangle}{\langle u_{gas} \rangle} L_{stream} > R_{\text{sonic}}$$

$$L_{stream} < R_{\text{sonic}}$$

The transition between the two regimes occurs when $n_{gas} / (\sigma_{gas}) \sim \alpha M_A^2$. Noting that the density contrast in an isothermal shock is $n_{gas} / (\sigma_{gas}) = M^{2}$ (Passot & Vázquez-Semadeni 1998; Konstandin et al. 2012), we see that there are three regimes (see Paper I, section 3.1 for further discussion): (i) if $\alpha \gtrsim 1$, $L_{stream} > R_{\text{sonic}}$ everywhere (including the shocks) and the dust is weakly coupled to the gas; (ii) if $M^{2} \lesssim \alpha \lesssim 1$ the dust is trapped in the highest density shocks but can cluster on scales larger than the sonic length; (iii) if $\alpha \ll M^{-2}$ the dust is strongly coupled to the gas down to scales below the sonic length.

To estimate the ratio $r_{gy,d}/L_{stream}$, we assume $B/\rho_{gas}^{1/2} \sim c_s \sqrt{M_A}/M_A \propto \text{constant}$, everywhere in the turbulence. This estimate is supported by observations (Crutcher 1999; Crutcher et al. 2010) and numerical simulations (Banerjee et al. 2009; Burkhart et al. 2009; Molina et al. 2012) in the regime of interest where the fields dynamically unimportant on supersonic scales (i.e. we again require $M_A > 1$). Note that the dust feels the total ‘large-scale’ magnetic field (in contrast to the velocity field, where only $v_\lambda$ is important), so we do not need the magnetic field spectrum. Using the dust gyroradius $r_{gy,d} = m_d u_{gy,d} / B$, and equations (5)–(6), one obtains

$$r_{gy,d}/L_{stream} \sim \frac{\alpha}{\phi} \left( \frac{n_{gas}}{(\sigma_{gas})} \right)^{-1/2} \frac{L_{stream}}{L_{box}} \frac{\langle u_d - u_{gas} \rangle}{\langle u_{gas} \rangle} \frac{\langle u_d - u_{gas} \rangle}{\langle u_{gas} \rangle}$$

Inserting equation (7) into equation (8) leads to the estimate

$$r_{gy,d}/L_{stream} \sim \frac{\alpha^{1/2} M_A}{\phi} \frac{\langle u_d - u_{gas} \rangle}{\langle u_{gas} \rangle} \frac{L_{stream}}{L_{box}} M_A \frac{\langle u_d - u_{gas} \rangle}{\langle u_{gas} \rangle} L_{stream} > R_{\text{sonic}}$$

$$L_{stream} < R_{\text{sonic}}$$

Equation (9) illustrates that the dust magnetization, $r_{gy,d}/L_{stream}$, is governed by the parameters

$$\Theta_1 = \frac{\alpha^{1/2}}{\phi} M_A \text{ and } \Theta_2 = \frac{1}{\phi} M_A.$$

5 We focus on large grains $a_d \sim 0.1–10$ μm because (1) these contain most of the dust mass, and (2) smaller grains are tightly-coupled to the gas and therefore exhibit less extreme dust-to-gas fluctuations.

6 Drain & Sutin (1987) estimate grain charges based on a pure collisional model for large grains and a polarization model for small grains. Shull (1978) show that accounting for higher-order effects can lower the charge by a factor $\sim 2$ when the dust–gas motion is highly supersonic. Since this is uncertain, we remind the reader that the parameter $\phi$ is what actually enters the dynamical equations solved here.

7 This is because velocities on smaller scales do not strongly perturb the dust, while those on larger scales simply advect dust and gas together; see Voelk et al. (1980), Lazarian & Yan (2002) and Paper I.

8 Note that we have also assumed a subsonic scaling $v_{\lambda} \sim \lambda^{1/2}$, which only holds perpendicular to the magnetic field in magnetized turbulence (Goldreich & Sridhar 1995; Maron & Goldreich 2001). This estimate is more appropriate than the parallel scaling $v_{\lambda} \sim \lambda^{1/4}$ when the dust gyroradius is larger than the smallest perpendicular scales, since the dust will not be perfectly tied to the field lines (see Lazarian & Yan 2002 and Yan et al. 2004 for further discussion).

9 Crutcher et al. (2010) report a lower density bound, below which the field and density are uncorrelated. This might be expected as the turbulence transitions into an Alfvénic regime, but we ignore this possible change in scaling here for simplicity.
Recalling that the transition between the $L_{\text{stream}} > R_{\text{sonic}}$ and $L_{\text{stream}} < R_{\text{sonic}}$ regimes occurs at $n_{\text{gas}} (n_{\text{gas}}) \sim \alpha M^2$, and noting that $r_{\text{gyd}}/L_{\text{stream}}$ increases monotonically with density, we see that there are three regimes:

- $\Theta_1 > 1$ – unmagnetized: The dust is always ‘unmagnetized’ ($r_{\text{gyd}} > L_{\text{stream}}$ over all scales).
- $\Theta_1 < 1$ and $\Theta_2 > 1$ – mixed: The dust is magnetized at low gas densities $n_{\text{gas}} < n_{\text{gc},\text{crit}}$, but switches to being unmagnetized ($r_{\text{gyd}} < L_{\text{stream}}$) as it streams into high-density regions $n_{\text{gas}} > n_{\text{gc},\text{crit}}$.
- The critical gas density that governs the change is

$$\frac{n_{\text{gc},\text{crit}}}{n_{\text{gas}}} \sim \sigma^2 \left( \frac{M}{M_A} \right)^2,$$

where $\sigma$ is a dimensionless factor.

The simulations presented below cover each of these regimes [see $(\Theta_1, \Theta_2)$ column of Table 1]. Note that our discussion here has been intended to estimate when the magnetic field is important for the dust, as opposed to the influence of the magnetic field on the dust distribution (this is discussed in more detail in the next section).

## 4 RESULTS

In Figs 1–2, we show the bivariate distribution of dust and gas densities in some representative simulations. Here and throughout this paper, all distribution functions are dust-mass weighted. In Fig. 1, we see the effects of increasing $\alpha$ (grain size). As described above (see equation 7) and in Paper I, small grains ($\alpha \ll M^{-2}$) are tightly coupled to gas, very large grains ($\alpha > 1$) are spread closer to uniformly and weakly-coupled to the gas, and grains with intermediate $\alpha (M^{-2} \lesssim \alpha \lesssim 1)$ produce interesting dust–gas distributions. This behaviour is similar to that seen in Paper I without Lorentz forces; for a more detailed analysis of the gas-density dependence of fluctuations, and their dependence on spatial scale (power spectra/correlation functions), we refer interested readers to Paper I.

Fig. 2 shows the effect of adding Lorentz forces at two grain sizes for three different levels of dust charge (no charge, ‘$n20\_noZ$’; ‘standard’ charge, ‘$n20$’; and $10 \times$ charge, ‘$n20\_hiZ$’). The illustrated dust–gas distributions broadly follow our expectations based on the theory of dust magnetization in Section 3. Small grains ($\alpha = 0.001$)

The critical gas density $n_{\text{gc},\text{crit}}$ governing the change from magnetized to unmagnetized dust [see equation (11)] is $n_{\text{gc},\text{crit}} (n_{\text{gas}}) \approx 75$, which is consistent with what is observed in Fig. 2 (of course, the change is gradual and the theory heuristic, so we should not expect obvious quantitative agreement).

Figure 1. Time-averaged bivariate distribution of dust and gas densities, in representative simulations from Table 1. We plot iso-density contours at fixed probability density levels $dP/d\log n_{\text{gas}}$ with $dP/d\log n_{\text{gas}} = 10^{-1}$, $10^{-2}$, $10^{-3}$, $10^{-4}$, $10^{-5}$ (black, green, blue, red, respectively). Dotted lines show $n_{\text{dust}} = n_{\text{gas}}$ (dust at constant density) and $n_{\text{dust}} = n_{\text{gas}}$ (constant dust–gas coupling, i.e. $\delta = 1$). The simulations shown are chosen to reflect increasing value of the ‘drag parameter’ $\alpha$ (equation 5), which determines how tightly coupled the dust and gas are. As explained in Section 3, for $\alpha \ll M^{-2}$, the coupling is near-perfect. For $\alpha \gtrsim 1$, the dust is almost entirely un-correlated with the gas. Intermediate $\alpha$ show dust roughly following gas, $n_{\text{dust}} \approx n_{\text{gas}}$, but with large local fluctuations in $n_{\text{dust}}$ at all $n_{\text{gas}}$. Note that the distribution in $n_{10000}$ is likely affected by Poisson noise and may be even more tightly coupled to the gas than it appears: its distribution resembles the limiting $\alpha = 1$ case (where the dust is perfectly coupled to the gas) as shown in Paper I, fig. C1.

in both ‘$n20$’ and ‘$n20\_hiZ$’ are magnetized everywhere in the gas ($\Theta_1 < 1, \Theta_2 < 1$), and indeed the dust–gas distributions are quite different to the charged case (‘$n20\_noZ$’), with tighter coupling of the dust to the gas. In contrast, the large grains ($\alpha = 0.01$) are either unmagnetized (for standard grain charge, ‘$n20$’) or in the ‘mixed’ regime (for $10 \times$ charge, ‘$n20\_hiZ$’). In agreement with the theory, the standard-charge (“$n20$”) distribution looks similar to the uncharged case, while the ‘$n20\_hiZ$’ distribution is similar at high-gas densities (where the grains are unmagnetized) but exhibits stronger dust–gas coupling at low-gas densities (where the grains are magnetized). For the parameters of this simulation (‘$n20\_hiZ$’ $\alpha = 0.01$), the critical gas density $n_{\text{gc},\text{crit}}$ governing the change from magnitized to unmagnetized dust [see equation (11)] is $n_{\text{gc},\text{crit}} (n_{\text{gas}}) \approx 75$, which is consistent with what is observed in Fig. 2 (of course, the change is gradual and the theory heuristic, so we should not expect obvious quantitative agreement).

The dust-to-gas ratio $\delta \equiv (n_{\text{dust}}/n_{\text{gas}})/(n_{\text{dust}}/n_{\text{gas}})$ (i.e. integrating out one dimension from Figs 1–2) is an interesting quantity for both practical application to GMCs and for theory. We illustrate its distribution in Fig. 3 for each of the ‘standard-charge’ simulations ($n1\_1$, ‘$n20$’, ‘$n1000$’, ‘$n10000$’ and ‘$n1000\_noZ$’). As in Paper I, we find these are approximately log-normal, with power-law tails. More quantitatively, the dispersion of $\delta$ (denoted $\sigma_{\log \delta}$) is illustrated in Fig. 4 for all simulations (see also Table 1). There is clearly a strong increase in $\sigma_{\log \delta}$ with $\alpha$ – i.e. with larger $a_0$ and smaller ($n_{\text{gas}}$) – particularly around $\alpha \sim 0.005$–$0.01$ where $\sigma_{\log \delta}$ increases from $-0.05$ to $-0.35$ dex. This is expected as grains transition from

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being tightly coupled to the gas for $\alpha \ll M^{-2}$ to uniformly filling the box if $\alpha \gg 1$ (see Paper I and equation 7), and is a more quantitative illustration of the effects shown in Fig. 1. Also note that the ‘floor’ at $\alpha \sim 0.015-0.02$ ($\delta \lesssim 0.001$) is not real, but represents the limitations of our numerical method. Fig. 4 also serves to illustrate that the effects of dust magnetization on the dispersion of $\delta$ are subdominant to its variation with $\alpha$, although the magnetized cases mostly show slightly lower $\sigma_{\log \delta}$. In other words, the change to the dust–gas distribution with magnetization seen in Fig. 2 causes only a small modification to $\sigma_{\log \delta}$ in comparison to the variation with grain size. A more detailed discussion of the non-magnetized scaling is given in Paper I.

It is helpful to examine the changes in dust-to-gas ratio distributions with individual parameters, which is done in Fig. 5. The left-hand panel shows the effects of Mach number $M$ on the $\delta$ distribution with otherwise equal simulation parameters. We see that the effect on the $\delta$ distribution is minor, even though the logarithmic dispersion in the gas density in the higher-$M$ run is significantly larger (by $\approx 0.2$ dex, in agreement with the well-studied Mach number-density variance relation; Konstandin et al. 2012). There is none the less some weak effect of $M$ on $\delta$: at the lowest $\alpha$, the tails in $\delta$ are broadened (because dust in the lower-$n_{\text{gas}}$ tails of the gas distribution is, locally, more weakly-coupled), while at large $\alpha$, the distribution actually becomes slightly more narrow (because the grains are already loosely-coupled, this moves the system more towards a ‘uniformly mixed’ distribution).

In a similar vein, the right-hand panel of Fig. 5 compares simulation with neutral grains (‘n20_noZ’), ‘standard-charge’ grains (‘n20’), and 10× charged grains (‘n20_hiZ’), keeping all other parameters fixed. This is another way of examining the data shown in Fig. 2. Similar to the discussion above, we see that the small grains ($\alpha = 0.001$) in both the ‘n20’ and ‘n20_hiZ’ simulations are quite different to the neutral grains (‘n20_noZ’), but similar to each other (aside from an increased dispersion in ‘n20_hiZ’, perhaps due to resonant acceleration; see below). In contrast, large grains ($\alpha = 0.01$) are similar between the neutral and standard-charge grains (since these are unmagnetized), while the 10× charged grains exhibit a substantial decrease in variance compared to the neutral grains because they are magnetized in low-gas-density regions (they are in the ‘mixed’ regime).

Finally, it is worth commenting on an interesting feature of the $\delta$ distributions in Figs 3 and 5 – the flat, high-$\delta$ tail that appears in some simulations (e.g. $\alpha = 0.001$, ‘n20’). A comparison with the parameters in Table 1 shows that this exists only for those parameters at which the dust is magnetized ($\Theta_1 < 1$, $\Theta_2 < 1$), while the comparison to an equivalent neutral dust simulation in Fig. 5(b) shows that it is related to the action of the Lorentz force (the tail appears only for charged grains and is stronger in ‘n20_hiZ’ compared to ‘n20’). We speculate that this effect may be related to resonant acceleration of dust grains, which can occur when multiples of the dust Larmor frequency match the turnover frequency of the turbulence as seen by the dust (Lazarian & Yan 2002; Yan & Lazarian 2003; Yan et al. 2004). The turbulent magnetic field is then stationary in the dust frame and resonantly exchanges energy with the grains through Landau damping and cyclotron damping (as occurs for ions and electrons in weakly collisional plasmas). The higher dust velocities could be particularly important for dust shattering and coagulation (Yan & Lazarian 2003), but we leave further study of this interesting effect to future work.

5 CONCLUSIONS

We study how charged dust grains behave in GMCs by running idealized simulations of isothermal, magnetized, supersonic turbulence, with a population of dust grains of physically interesting

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12 As discussed in Paper I (see also Genel et al. 2013), the mismatch between the EOM for grains, where gas quantities are interpolated to the exact grain location, and gas, where the fluxes are calculated from a Riemann problem and averaged over a finite volume, means there will inevitably be some small, purely numerical dust-to-gas fluctuations even when the two should be perfectly-coupled. There we showed $\alpha \lesssim 0.001$ hits this ‘floor’.

13 There is actually a slight enhancement in variance in ‘n20’ compared to ‘n20_noZ’ for large grains. We speculate that this is because the lowest gas density regions, which would have completely de-coupled from the dust, have weak Lorentz coupling and induce some additional dust concentration.
sizes and realistic charge, which experience both drag and Lorentz forces from the gas. We argue that the dynamics are essentially determined by three dimensionless parameters, the turbulent Mach number $M$, grain size parameter $\alpha \equiv a/\lambda_d$ (equation 5) and Lorentz parameter $\phi \equiv Z_d/\alpha^2$ (equation 6). We show that, when $M \gg 1$, grain dynamics are strongly governed by the parameter $\alpha$. With small $\alpha \lesssim M^{-2}$, dust moves tightly with the gas; with large $\alpha \gtrsim 1$, grains decouple from the gas and spread uniformly, while intermediate cases (expected for large grains in a wide range of typical GMCs) produce interesting local fluctuations in the dust-to-gas ratio $\delta$, with the logarithmic dispersion in $\delta$ increasing from $\sim 0.05$ to $0.35$ dex as $\alpha$ increases. At a given $\alpha$, we show that varying $M$ (within the range expected in GMCs) has weak effects. Comparing simulations without Lorentz forces, we see the Lorentz forces produce a size-dependent effect: smaller grains (larger $\alpha$) have their fluctuations suppressed with non-zero $\phi$, while larger grains show weak effects. This can be understood more quantitatively by considering the ratio of dust gyroradius $r_{gyd}$ to dust streaming length $L_{stream}$, which we examine using the parameters $\Theta_1 = \alpha^{1/2}/M_{1/\phi}$ and $\Theta_2 = M_{1/\phi}$ (for $M_{1/\phi} \gtrsim 1$). In general, $\Theta_1 \lesssim 1$ is required for appreciable effects on the dust clustering statistics, which implies that $r_{gyd} < L_{stream}$ (at least at low densities), meaning the dust dynamics are significantly modified by the presence of the magnetic field.

In Paper I (section 4), we discuss implications of partial dust–gas coupling (and variations in local dust-to-gas ratios) for dust formation, extinction and observed dust clustering, cooling and star formation. Because high-density regions can have enhanced/suppressed dust-to-gas ratios in large grains (which contain a large fraction of the metal mass), this can have interesting implications for stellar abundances. Hopkins & Conroy (2017) use similar simulations, coupled to a specific dust chemistry model, to explore consequences for abundance patterns in metal-poor stars, and suggest that certain observed chemical signatures in these stars may demonstrate...
variable dust-to-gas ratios in their progenitor clouds. Hopkins (2014b) use a simple analytic model to further explore the consequences for stellar abundance variations across present-day star forming clouds. Taking observed scalings of GMC properties (e.g. Bolatto et al. 2008) with size \( R_{\text{GMC}} \), they show the critical parameter \( \alpha/\sqrt{\rho_0} \) should scale \( \alpha R_{\text{GMC}} \) for grains of a fixed size. In physical terms, for sufficiently large clouds \( > 100 \) pc (for 0.1–1 \( \mu \)m grains), \( \alpha \gtrsim M^{-2} \) and grain densities fluctuate on scales greater than the sonic length (the characteristic size of dense star-forming filaments and protostellar cores). All of this work, however, ignored Lorentz forces; our goal here was to explore how this might change the dynamics. Since we find the effects of Lorentz forces are subdominant to grain size variations, none of the key qualitative conclusions from these studies are altered. However, by further suppressing fluctuations in the small-grain regime (while having little effect for large grains), Lorentz forces will make the ‘threshold’ effect above more dramatic (where fluctuations are unimportant below, but significant above, some characteristic grain/cloud size scale).

A major caveat of this study is that we have considered only the cold, dense ISM in GMCs—the values of \( \alpha \) and \( \phi \) here are appropriate when \( T \lesssim 100 \) K. It is interesting to ask what happens to dust in the warm-neutral and warm-ionized medium, with \( T \sim 10^3–10^4 \) K; since the equilibrium grain charge (and \( \phi \)) are expected to scale \( \propto T^{1/2} \), we expect Lorentz forces to rapidly increase in importance. Unfortunately, the numerical method here (explicitly integrating the Lorentz forces) becomes unacceptably expensive for very large \( \phi \) (as the Larmor frequency increases); we are working on a fully-implicit scheme for integrating the Lorentz term that will allow us to extend our simulations into this regime (also implicit schemes for including dust back-reaction; see Yang & Johansen 2016). These simulations will also be interesting from a theoretical standpoint, allowing study of the magnetized, high-\( \sigma \) region of parameter space that is absent from the simulation set presented in the current work (see, for example, Fig. 4). In the mostly ionized medium, we also need to account for Coulomb interactions, but these primarily manifest as a modest correction to the drag term (Draine & Salpeter 1979) so their effect should be straightforward to understand and implement numerically. Radiation pressure and dust-collisional dynamics may also modify the conclusions here, especially in the most dense regions where this is relevant for star formation, and we will explore this further in future work.

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