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Interactions between inertial particles and shocklets in compressible turbulent flow

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Numerical simulations are conducted to investigate the dynamics of inertial particles being passively convected in a compressible homogeneous turbulence. Heavy and light particles exhibit very different types of non-uniform distributions due to their different behaviors near shocklets. Because of the relaxation nature of the Stokes drag, the heavy particles are decelerated mainly at downstream adjacent to the shocklets and form high-number-density clouds. The light particles are strongly decelerated by the added-mass effect and stay in the compression region for a relatively long time period. They cluster into thin filament structures near shocklets. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4896267>]

Advection of inertial particles by turbulent flow, which occurs when the particle density is different from that of the ambient fluid, is of practical significance in various natural and engineering flows. For instance, the interaction between rain droplets and air turbulence is crucial for understanding cloud dynamics.^{1–3} Inertial particles in the incompressible turbulence have attracted intensive investigations through both experiments and numerical simulations.^{4,5} Depending on the level of the inertia, particles concentrate in different regions of the flow domain.⁶ Light particles are trapped in high vorticity region,⁷ while heavy particles tend to be expelled by vortices.^{8–10} Some theoretical studies have been aimed at understanding these intermittent distributions.^{4,11} Particle acceleration plays an important role in such phenomena,¹² and many efforts have been devoted to investigating the acceleration of inertial particles in the past few years, see, for example, Refs. 13–17.

Compressible turbulence has been studied extensively in past. This includes the shock-turbulence interaction^{18–21} and compressible isotropic turbulence,^{22–24} to name a few. However, there are relatively fewer studies on compressible turbulence laden with inertial particles despite its importance in many phenomena. Interaction between heavy particles and gas turbulence is one of the key problems in the inertial confinement fusion, supernova explosions, and interstellar clouds.^{25,26} The interaction between very heavy particles and compressible turbulence has been studied by using the same model as for the incompressible case, i.e., only the Stokes drag is considered.^{27,28} The detailed model for particles in a compressible flow has been developed recently.^{29–31} It has also been shown that for certain particle parameters, the point-particle model can still be used to study the particle-shock interaction.³²

In this study, we will investigate inertial particles with different density advected in a compressible homogeneous isotropic turbulence by using numerical simulations. The background flow is solved in the Eulerian framework, while the inertial particles are tracked simultaneously by solving the dynamic equations for particles. The control parameters for the flow and particles are chosen such that the point-particle model is applicable. We shall focus on the dynamics and spatial distributions

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of particles with different inertia under the influence of shocklets, and ignore for now the backward effects of the particles on the flow.

The three-dimensional compressible turbulence is simulated in a periodic box $(2\pi)^3$ by a WENO-Compact hybrid scheme.³³ The flow is driven by a solenoidal force at the large scales. A uniform cooling is applied to maintain the total internal energy being finite. The resulting Reynolds number Re_λ based on the Taylor microscale is approximately 153. The turbulent Mach number M_t , defined as the ratio of the root mean square (rms) value of velocity magnitude u_{rms} to the mean speed of sound c , is approximately 1.03, which corresponds to a moderate Mach number in astrophysics field. A resolution of 512^3 is used with a mesh size $dx \approx 0.0123$, which is slightly smaller than the viscous length scale $\eta \approx 0.0129$. The large eddy turn over time T^E is around 1.12. The Kolmogorov time scale $\tau_\eta = (\nu/\epsilon)^{1/2}$, where ϵ is the mean energy-dissipation rate and ν the mean kinematic viscosity of the fluid, is about 0.064.

The complete dynamic equation for the inertial particle in compressible flow is more complicated than that for incompressible flow. Parmar *et al.*³² have proposed an outline for numerically simulating particle-shock interaction, and the theoretical model has been compared with experiments and computations. Similar to their work we only retain the added-mass effect and the Stokes drag. If the relative Mach number seen by the particles is small, we may also neglect the compressibility correction. Denote the fluid density by ρ_f , the particle density by ρ_p , the particle radius by r , respectively. We utilise the following simplified model, which is the same as in the incompressible flow⁵

$$\ddot{\mathbf{x}} = \dot{\mathbf{v}} = \beta \frac{D\mathbf{u}}{Dt} + \frac{1}{\tau_p}(\mathbf{u} - \mathbf{v}). \quad (1)$$

Here a dot denotes the Lagrangian derivative with respect to time t , D/Dt is the material derivative, $\mathbf{x}$ and $\mathbf{v}$ are the location and velocity of an inertial particle, respectively. The two terms on the right-hand side are the added mass effect and the Stokes drag, and

$$\beta = \frac{3\rho_f}{\rho_f + 2\rho_p}, \quad \tau_p = \frac{r^2}{2\beta\nu}. \quad (2)$$

Notice that ρ_f and ν are not constants in compressible flow, thus β and τ_p also change as the particle moves.

In practice, for each case after the flow reaches a statistically steady state, a million inertial point particles are seeded into the flow domain uniformly and evolve for $10 T^E$. The dynamic equations for particle are integrated with a time step approximately $\tau_\eta/100$. The statistics are calculated during the last $7 T^E$, during which the data of particles are sampled every $\tau_\eta/10$. Two control parameters of particle dynamics are β and the Stokes number $St = \tau_p/\tau_\eta$ defined by mean fluid density and viscosity. Here, we investigate the inertial particles whose density is either much larger or much smaller than the fluid density. For Case L with light particles $(\beta, St) = (3, 0.1)$, while for Case H with heavy particles $(\beta, St) = (0, 1)$. During simulations we assume the radius and density of particles do not change and compute the instantaneous β and St with the local ρ_f and ν . The results of Case T with passive tracers are also included for comparison.

In order to illustrate the spatial distribution of the particles, we define a local number density $\xi(\mathbf{x})$ in the Eulerian space. $\xi(\mathbf{x})$ is equal to the number of particles in a cubic box which has a center at $\mathbf{x}$ and volume of V_0 . Since we have 1 million particles in our simulations, V_0 is set to be $(2\pi)^3 \times 10^{-6}$. Thus for a perfect uniform distribution $\xi \equiv 1$ and $\xi_{rms} = 1$. If the distribution is non-uniform, ξ_{rms} must be larger than unit. The bigger ξ_{rms} is, the stronger concentration of particles there exists in the field. The ξ fields are computed for three cases at one time step, and we obtain $\xi_{rms} \approx 5.69$ for Case L, $\xi_{rms} \approx 1.44$ for Case T, and $\xi_{rms} \approx 2.09$ for Case H, respectively. Therefore, the light particles have the most intermittent distribution among the three cases and concentrate to certain regions with very high local number density. The heavy particles have stronger non-uniform distribution than the tracers. The distribution of tracers also shows weak non-uniformity. This is expectable since in the compressible flow tracers naturally exhibit high number density at the flow region with larger fluid density. In Fig. 1, we draw the instantaneous iso-surfaces of ξ and dilatation $\theta = \nabla \cdot \mathbf{v}$. For compressible flow θ serves as an excellent indicator of local compression. Large

FIG. 1. Instantaneous iso-surfaces of $\xi/\xi_{rms} = 2$ (green) and $\theta/\theta_{rms} = -5$ (orange) in a π^3 box. For all three panels $Re_\lambda \approx 153$, $M_f \approx 1.03$, and $\theta_{rms} \approx 5.77$. (a) Case L with $\xi_{rms} \approx 5.69$, (b) Case T with $\xi_{rms} \approx 1.44$, and (c) Case H with $\xi_{rms} \approx 2.09$.

negative θ pinpoints the strong compression near the shocklets. The heavy particles develop large clouds with higher number densities downstream of the shocklets, e.g., see the upper-middle part of Fig. 1(c). The light particles form very thin and remarkably long filaments, as shown in Fig. 1(a). It has long been recognised that light particles tend to be trapped in the core regions of intense vortex tubes in the incompressible turbulence.⁶ And the vortices can be enhanced after they pass through the shocklets, e.g., see Ref. 21. However, the long filaments shown here usually locate right on shocklet surfaces in the compression region. Thus, this is more likely caused by shocklets instead of the vortices. Moreover, later we will show that acceleration of light particles is dominated by the added mass effect caused by the intense compression near shocklets.

Since inertial particles distribute non-uniformly and are preferentially located at certain regions of the flow domain, the probability distribution function (PDF) sampled along particle trajectories is actually the so-called “biased sampling.”¹⁶ We calculate the PDFs of dilatation θ by this biased sampling. Figure 2(a) plots the θ -PDFs for three cases. A pronounced peak appears at $\theta < 0$ in the curve of Case L, which strongly suggests that light particles accumulate at high compression region. The probability of finding heavy particles in the strong compression region is slightly smaller than that of tracers. In the expansion region with positive θ , the difference among the three cases is negligible.

The discrepancy between different curves shown in Fig. 2(a) indicates that the three types of particles respond differently to the shocklets. To reveal the difference, we investigate the direction of particle movement relative to the shocklet surface in the compression region. Following Yang *et al.*,³⁴ we define the compression region as the flow region with $\theta < -\theta_{rms}^n$. Here θ_{rms}^n denotes the rms value of all negative θ of the Eulerian field. For the current control parameters, the compression region usually occupies 6.5% of the total flow domain. The normal direction of the shocklet surface can be well approximated by the opposite direction of the pressure gradient $-\nabla p$, which can also be treated as the propagation direction of the shocklets. Let α be the angle between the particle velocity

FIG. 2. (a) The PDFs of θ sampled along the trajectories of inertial particles. (b) and (c) PDFs of $\cos \alpha$ and a_L in the compression region with $\theta < -\theta_{rms}^n \approx -7.46$, respectively. Case H: red dashed-dotted line; Case T: green solid line; Case L: blue dashed line. The PDFs are first computed for every time step and then averaged over time. The error bars are estimated by the standard deviation of the temporal fluctuation. For clarity the error bars are only shown at every other data point.

FIG. 3. Ensemble average along particle trajectories when they encounter shocklets. (a) θ normalized by θ_{rms} , (b) v_n normalized by the rms value of tracer velocity component. Case H: red dashed-dotted line; Case T: green solid line; Case L: blue dashed line. The ensemble average is computed by first averaging over all particles encountering shocklets at fix t_s and then averaging over time. The error bars are estimated by the standard deviation of the temporal fluctuation. For clarity the error bars are only shown at every 3 data point. Notice in (a) the curves for Cases H and T almost collapse with each other.

$\mathbf{v}$ and $-\nabla p$. The PDFs of $\cos \alpha$ in the compression region are plotted in Fig. 2(b). The curves of Cases T and H have peaks at $\cos \alpha = -1$ and approach zero at $\cos \alpha = 1$, which implies that most particles in both cases move against the shocklets from upstream (the lower pressure side). The PDF of Case H has a narrower and higher peak than Case T, indicating that heavy particles are more likely to hit the shocklets vertically. For Case L, the PDF curve has a peak at $\cos \alpha \approx 0.5$. Thus, more light particles move in the same direction as the shocklet propagation direction in the compression regions.

The longitudinal acceleration $a_L = \mathbf{a} \cdot \mathbf{v}/|\mathbf{v}|$, i.e., the acceleration component in the direction of particle velocity, determines the time changing rate of velocity magnitude. Figure 2(c) shows the PDFs of a_L in the compression region for the three cases. The curve of Case H has significantly shorter tails than that of the tracers. The curve of Case L has the longest tail at the positive value, which is almost the same as the one at the negative value; therefore, a significant portion of the light particles are accelerated near the shocklets.

More information about the behavior of particles near shocklets can be obtained by the ensemble average of flow quantities along particle trajectories near shocklets. In our analysis, a particle encounters a shocklet at time t_s when θ is smaller than $-\theta_{rms}^n$ and reaches a local minimum in its time history. The ensemble average, denoted by $\langle \cdot \rangle$ hereafter, is then performed over all time interval $(t_s - 5\tau_\eta, t_s + 5\tau_\eta)$. Figure 3(a) shows such average of θ normalized by θ_{rms} of entire Eulerian field. Near shocklets the local dilatation along all particle trajectories plunges to very large negative values. Then after a small overshoot, which corresponds to the expansion region just behind the shocklets,²⁰ the curves of Cases H and T quickly recover to nearly zero. However, $\langle \theta \rangle$ for Case L remains negative for the entire time interval, which means that light particles can stay in the compression region near shocklets for a very long time.

The same average has also been performed for the velocity component normal to the shocklet surface $v_n = \mathbf{v} \cdot (\nabla p)_s$, where the tilde denotes the normalized vector and the subscript “s” denotes the value at t_s , respectively. $v_n > 0$ indicates that the particle moves from upstream of the shocklets to downstream. The curves of $\langle v_n \rangle$ are plotted in Fig. 3(b). For all three types of particles $\langle v_n \rangle$ slowly increases when $t < t_s$ and starts to decrease at t_s . For Cases T and L $\langle v_n \rangle$ drops very sharply at the shocklet surface. For heavy particles $\langle v_n \rangle$ changes more smoothly. Heavy particles act as a time filter, which is similar to the incompressible case.^{14,16} Remarkably, the inertial effect for light particles can be so strong that the severe adverse pressure gradient near the shocklets may cause the $\langle v_n \rangle$ decreases to zero.

The distinct behaviors of v_n for different particles near shocklets can be understood by the following theoretical analysis. For finite size sphere interacting with a shock, the force experienced by the sphere has been discussed in detail.^{29,30} Here, we shall assume point particle and employ a simple model to explain the behavior of v_n . Starting from Eq. (1) and assuming that τ_p is constant, it is readily to show that

$$\mathbf{v}(t) = \mathbf{v}(t_0)e^{-\frac{t-t_0}{\tau_p}} + \int_{t_0}^t \beta \mathbf{a}_f e^{-\frac{t-\tau}{\tau_p}} d\tau + \int_{t_0}^t \frac{\mathbf{u}}{\tau_p} e^{-\frac{t-\tau}{\tau_p}} d\tau. \quad (3)$$

FIG. 4. Ensemble average along particle trajectories when they encounter strong shocklets. (a) $\langle a_n \rangle$: Case H: red dashed-dotted line, Case T: green solid line, Case L: blue dashed line. (b) $\langle a_n \rangle$: green solid line, $\langle a_{\beta n} \rangle$: blue dashed line, $\langle a_{dn} \rangle$: red dashed-dotted line. All the quantities are normalized by the rms value of tracer acceleration component, and the error bars are estimated by the standard deviation of the temporal fluctuation. For clarity the error bars are only shown at every 3 data points. Note the two panels have different scales in ordinates.

To simplify the discussions, we apply this formula to particles crossing a normal shock, which is a good approximation of the strong shocklets in turbulent flow.³⁵ Assume the flow is steady and denote the quantities upstream and downstream of the shock by subscripts 1 and 2, respectively. Then the fluid acceleration is zero except at the shock surface, which takes a δ -function shape as $a_f = (u_2 - u_1)\delta(t - t_s)$. Moreover, for the two different inertial particles we considered here, β is constant and equal to 3 or 0, respectively. If a light particle and a heavy particle move toward the normal shock with velocity u_1 , they will follow the same fluid tracer perfectly until they hit the shock surface. Then by (3) one has, for $t > t_s$,

$$v(t) = \gamma u_1 + (1 - \gamma)u_2 + \gamma\beta(u_2 - u_1) \quad (4)$$

with $\gamma(t) = e^{-(t-t_s)/\tau_p}$. Thus for Case H with $\beta \equiv 0$, $v(t)$ changes smoothly from u_1 toward u_2 with the relaxation time scale $\tau_p \approx \tau_\eta$, in good agreement with the numerical result shown in Fig. 3(b). For Case L the particle velocity at t_s^+ is $u_1 + \beta(u_2 - u_1)$, which elucidates the sharp change of v_n at t_s as observed in the curve of Case L in Fig. 3(b).

To further clarify how the shocklets affect the dynamics of inertial particles, we plot the ensemble average of $a_n = \mathbf{a} \cdot (\nabla p)_s$ for three cases in Fig. 4(a). Positive a_n represents particle acceleration toward the shocklet from upstream. All the quantities in Fig. 4 are normalized by the rms value of one component of tracer acceleration. Clearly, among three cases the light particles experience the largest acceleration near shocklets. The $\langle a_n \rangle$ curve of Case T is very similar to the $\langle \theta \rangle$ curve of Case T in Fig. 3, which is because that for tracers a_n is directly related to θ in the compression region.³⁴ The $\langle a_n \rangle$ curve of heavy particles, which is solely determined by the Stokes drag, exhibits a negative peak at $t > t_s$. Thus, the heavy particles are decelerated after they penetrate the shocklets. The $\langle a_n \rangle$ curve of light particles shows more interesting behavior. It has a large negative peak at t_s and a small positive peak at $t > t_s$, which indicates that the light particles are first decelerated and then accelerated.

For light particle, the acceleration consists of two parts, i.e., that caused by the added mass effect $\mathbf{a}_\beta$ and that by the Stokes drag $\mathbf{a}_d$. These two parts can be calculated, respectively, from the two terms on the right-hand side of (1). Figure 4(b) plots the ensemble averages $\langle a_n \rangle$, $\langle a_{\beta n} \rangle$, and $\langle a_{dn} \rangle$ for light particles. It can be seen now that the large negative peak of $\langle a_n \rangle$ comes from the added mass effect and the small positive peak from the Stokes drag effect, respectively. The added mass effect is proportional to fluid acceleration, which itself is directly related to local dilatation, thus the $\langle a_{\beta n} \rangle$ in Fig. 4(b) is again very similar to the $\langle \theta \rangle$ curve of Case L in Fig. 3(a).

Based on the above observations, we can now obtain a physical picture of how inertial particles respond to the shocklets. Suppose a heavy particle, a light particle, and a passive tracer start moving toward a shocklet from the same upstream location. The passive tracer will be decelerated because of the large pressure gradient. The light particle will be decelerated more severely because of the added mass effect and the direction of its moving may be reversed temporarily, since some of them may move in the direction of shocklet propagation. The heavy particle is less responsive to the pressure gradient. The light particle lags behind the passive tracer while the heavy particle leads the other two. After they penetrate the shocklet, the heavy particle experiences a Stokes drag pointing upstream

of the shocklet and is decelerated. The light particle can be captured by the shocklets temporarily. After the light particle escapes, it will be pushed away from the shocklet by the Stokes drag. Thus, the light particles will accumulate at the shocklet surface.

In conclusion, we have reported several important and interesting phenomena of particles with different inertia advected by compressible turbulence. We focus on the role of particle acceleration near shocklets and its effect on the formation of different types of non-uniform distributions. Heavy particles are decelerated by the Stokes drag effect after they move through shocklets, and they gather into high-number-density clouds downstream of the shocklets. Light particles cluster into thin filaments adjacent to shocklets because the added mass effect delays the light particles penetrating the shocklets. Downstream of the shocklet, however, light particles are pushed away from the shocklets by the Stokes drag effect. The present results show that even for a moderate Mach number, the shocklets have profound influences on inertial particles; these influences should be more intense for a larger Mach number.

Finally we emphasise that, in this preliminary study we only considered the inertial particles which are passively advected by the background flow. The backward effects of particles may play important roles, which are especially true for the light particles since they accumulate at shocklets and cause large local number density. Thus, the particle-fluid interaction and even the particle-particle interaction must be included in this region. Also for some other particle parameters the particle size effect should be considered, and compressibility corrections of the model must be made for higher Mach number.

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- ¹G. Falkovich, A. Fouxon, and M. Stepanov, "Acceleration of rain initiation by cloud turbulence," *Nature* **419**, 151–154 (2002).
- ²E. Bodenschatz, S. Malinowski, R. Shaw, and F. Stratmann, "Can we understand clouds without turbulence?" *Science* **327**, 970–971 (2010).
- ³S. Balachandar and J. K. Eaton, "Turbulent dispersed multiphase flow," *Annu. Rev. Fluid Mech.* **42**, 111–133 (2010).
- ⁴E. Balkovsky, G. Falkovich, and A. Fouxon, "Intermittent distribution of inertial particles in turbulent flows," *Phys. Rev. Lett.* **86**, 2790–2793 (2001).
- ⁵F. Toschi and E. Bodenschatz, "Lagrangian properties of particles in turbulence," *Annu. Rev. Fluid Mech.* **41**, 375–404 (2009).
- ⁶E. Calzavarini, M. Kerscher, D. Lohse, and F. Toschi, "Dimensionality and morphology of particle and bubble clusters in turbulent flow," *J. Fluid Mech.* **607**, 13–24 (2008).
- ⁷E. Calzavarini, T. van den Berg, F. Toschi, and D. Lohse, "Quantifying microbubble clustering in turbulent flow from single-point measurements," *Phys. Fluids* **20**, 040702 (2008).
- ⁸K. Squires and J. Eaton, "Preferential concentration of particles by turbulence," *Phys. Fluids A* **3**, 1169–1178 (1991).
- ⁹J. Bec, L. Biferale, M. Cencini, A. Lanotte, S. Musacchio, and F. Toschi, "Heavy particle concentration in turbulence at dissipative and inertial scales," *Phys. Rev. Lett.* **98**, 084502 (2007).
- ¹⁰E. Saw, R. Shaw, S. Ayyalasomayajula, P. Chuang, and A. Gylfason, "Inertial clustering of particles in high-Reynolds-number turbulence," *Phys. Rev. Lett.* **100**, 214501 (2008).
- ¹¹I. Fouxon, "Distribution of particles and bubbles in turbulence at a small Stokes number," *Phys. Rev. Lett.* **108**, 134502 (2012).
- ¹²S. Goto and J. Vassilicos, "Sweep-stick mechanism of heavy particle clustering in fluid turbulence," *Phys. Rev. Lett.* **100**, 054503 (2008).
- ¹³S. Ayyalasomayajula, A. Gylfason, L. R. Collins, E. Bodenschatz, and Z. Warhaft, "Lagrangian measurements of inertial particle accelerations in grid generated wind tunnel turbulence," *Phys. Rev. Lett.* **97**, 144507 (2006).
- ¹⁴J. Bec, L. Biferale, G. Boffetta, A. Celani, M. Cencini, A. Lanotte, S. Musacchio, and F. Toschi, "Acceleration statistics of heavy particles in turbulence," *J. Fluid Mech.* **550**, 349–358 (2006).
- ¹⁵R. Volk, E. Calzavarini, G. Verhille, D. Lohse, N. Mordant, J. Pinton, and F. Toschi, "Acceleration of heavy and light particles in turbulence: Comparison between experiments and direct numerical simulations," *Physica D* **237**, 2084–2089 (2008).
- ¹⁶J. Salazar and L. Collins, "Inertial particle acceleration statistics in turbulence: Effects of filtering, biased sampling, and flow topology," *Phys. Fluids* **24**, 083302 (2012).
- ¹⁷J. Martinez Mercado, V. Prakash, Y. Tagawa, C. Sun, D. Lohse, and I. C. T. Res, "Lagrangian statistics of light particles in turbulence," *Phys. Fluids* **24**, 055106 (2012).

- ¹⁸ S. Lee, S. Lele, and P. Moin, "Direct numerical simulation of isotropic turbulence interacting with a weak shock wave," *J. Fluid Mech.* **251**, 533–562 (1993).
- ¹⁹ S. Jamme, J. Cazalbou, F. Torres, and P. Chassaing, "Direct numerical simulation of the interaction between a shock wave and various types of isotropic turbulence," *Flow, Turbul. Combust.* **68**, 227–268 (2002).
- ²⁰ J. Larsson and S. K. Lele, "Direct numerical simulation of canonical shock/turbulence interaction," *Phys. Fluids* **21**, 126101 (2009).
- ²¹ J. Larsson, I. Bermejo-Moreno, and S. Lele, "Reynolds- and Mach-number effects in canonical shock-turbulence interaction," *J. Fluid Mech.* **717**, 293–321 (2013).
- ²² S. Lee, S. Lele, and P. Moin, "Eddy shocklets in decaying compressible turbulence," *Phys. Fluids A* **3**, 657–664 (1991).
- ²³ R. Samtaney, D. Pullin, and B. Kosović, "Direct numerical simulation of decaying compressible turbulence and shocklet statistics," *Phys. Fluids* **13**, 1415–1430 (2001).
- ²⁴ S. Pirozzoli and F. Grasso, "Direct numerical simulations of isotropic compressible turbulence: Influence of compressibility on dynamics and structures," *Phys. Fluids* **16**, 4386–4407 (2004).
- ²⁵ E. Falgarone and J. Puget, "The intermittency of turbulence in interstellar clouds: implications for the gas kinetic temperature and decoupling of heavy-particles from the gas motions," *Astron. Astrophys.* **293**, 840–852 (1995).
- ²⁶ J. Scalo and B. Elmegreen, "Interstellar turbulence II: Implications and effects," *Annu. Rev. Astron. Astrophys.* **42**, 275–316 (2004).
- ²⁷ L. Pan, P. Padoan, J. Scalo, A. Kritsuk, and M. Norman, "Turbulent clustering of protoplanetary dust and planetesimal formation," *Astrophys. J.* **740**, 6 (2011).
- ²⁸ M. Samimy and S. K. Lele, "Motion of particles with inertia in a compressible free shear layer," *Phys. Fluids A* **3**, 1915–1923 (1991).
- ²⁹ M. Parmar, A. Haselbacher, and S. Balachandar, "Generalized Basset-Boussinesq-Oseen equation for unsteady forces on a sphere in a compressible flow," *Phys. Rev. Lett.* **106**, 084501 (2011).
- ³⁰ M. Parmar, A. Haselbacher, and S. Balachandar, "Equation of motion for a sphere in non-uniform compressible flows," *J. Fluid Mech.* **699**, 352–375 (2012).
- ³¹ M. Parmar, S. Balachandar, and A. Haselbacher, "Equation of motion for a drop or bubble in viscous compressible flows," *Phys. Fluids* **24**, 056103 (2012).
- ³² M. Parmar, A. Haselbacher, and S. Balachandar, "Modeling of the unsteady force for shock-particle interaction," *Shock Waves* **19**, 317–329 (2009).
- ³³ J. Wang, L. Wang, Z. Xiao, Y. Shi, and S. Chen, "A hybrid numerical simulation of isotropic compressible turbulence," *J. Comput. Phys.* **229**, 5257–5279 (2010).
- ³⁴ Y. Yang, J. Wang, Y. Shi, Z. Xiao, X. He, and S. Chen, "Acceleration of passive tracers in compressible turbulent flow," *Phys. Rev. Lett.* **110**, 064503 (2013).
- ³⁵ J. Wang, Y. Shi, L. Wang, Z. Xiao, X. He, and S. Chen, "Effect of shocklets on the velocity gradients in highly compressible isotropic turbulence," *Phys. Fluids* **23**, 125103 (2011).