Velocity Distribution of Driven Inelastic One-component Maxwell gas

V. V. Prasad,1,2 Dibyendu Das,3 Sanjib Sabhapandit,4 and R. Rajesh1,2

1The Institute of Mathematical Sciences, C.I.T. Campus, Taramani, Chennai-600113, India
2Homi Bhabha National Institute, Training School Complex, Anushakti Nagar, Mumbai-400094, India
3Department of Physics, Indian Institute of Technology, Bombay, Powai, Mumbai-400076, India
4Raman Research Institute, Bangalore - 560080, India

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I. INTRODUCTION

Granular matter, constituted of particles that interact through inelastic collisions, exhibit diverse phenomena such as cluster formation, jamming, phase separation, pattern formation, static piles with intricate stress networks, etc. [1,2]. Its ubiquity in nature and in industrial applications makes it important to understand how the macroscopically observed behavior of granular systems arises from the microscopic dynamics. A well studied macroscopic property is the velocity distribution of a dilute granular gas. While several studies (see below) have shown that the inherent non-equilibrium nature of the system, induced by inelasticity, could result in a non-Maxwellian velocity distribution, they fail to pinpoint whether the velocity distribution is universal, and if yes, what its form is. In this paper, we focus on the role of driving in determining the velocity distribution within a simplified model for a granular gas, namely the inelastic Maxwell model.

Dilute granular gases are of two kinds: freely cooling in which there is no input of energy [3,5], or driven, in which energy is injected at a constant rate. In the freely cooling granular gas, the velocity distribution at different times $t$ has the form $P(v,t) \sim v_{rms}^{-1} f(v/v_{rms})$, where $v$ is any of the velocity components, $v_{rms}(t)$ is the time dependent root mean square velocity and $f$ is a scaling function. $v_{rms}(t)$ decreases in time as a power law $v_{rms}(t) \sim t^{-\beta}$. To determine the behavior of $f$ for large argument, it was argued that the contributions to the tails of the velocity distributions are from particles that do not undergo any collisions, implying an exponential decay of $P(v,t)$ with time $t$ [12]. Thus, $f(x) \sim \exp(-ax^{1/\theta})$, or $P(v,t) \sim e^{-av^{1/\theta}}$ for large $v$. It is known that at initial times, the granular particles remain homogeneously distributed with $\theta = 1$ [6], leading to $P(v,t)$ having an exponential decay in all dimensions. At late times they tend to cluster resulting in density inhomogeneities with current evidence suggesting $\theta = d/(d + 2)$ [9,12,15].

In dilute driven granular gases, the focus of this paper, the system reaches a steady state where the energy lost in collisions is balanced by external driving. Several experiments, simulations and theoretical studies have focused on determining the steady state velocity distribution $P(v)$. In experiments, driving is done either mechanically through collision of the particles with vibrating wall of the container or by applying electric or magnetic fields on the granular beads. Almost all the experiments find the tails of $P(v)$ to be non-Maxwellian, and described by a stretched exponential form $P(v) \sim \exp(-\beta v^{\alpha})$ for large $v$. Some of these experiments find $P(v)$ to be universal with $\beta = 3/2$ for a wide range of parameters [21,24]. In contrast, other experiments [20,23] find $P(v)$ to be non-universal with the exponent $\beta$ varying with the system parameters, sometimes even approaching a Gaussian distribution ($\beta = 2$) [20].

In numerical simulations, driving is done either through the boundaries [8,27] which leads to clustering, or homogeneously [28,31] within the bulk. In simulations of a granular gas in three dimensions, driven homogeneously by addition of white noise to the velocity (diffusive driving), it was observed that $\beta = 3/2$ for large enough inelasticity [29]. However, similar simulations of a bounded two dimensional granular gases with diffusive driving found a range of distributions in the steady state, with $\beta$ ranging from 0.7 to 2 as the parameters in the system are varied [30,31].

Theoretical approaches have been of two kinds: kinetic theory, or by studying simple models which capture essential physics but are analytically tractable. In kinetic theory [32], the Boltzmann equation describing the evolution of the distribution function is obtained by truncating the BBGKY hierarchy by assuming product measure for joint distribution functions. While it is difficult to solve this non-linear equation exactly, the deviation of the velocity distribution from Gaussian can be expressed as a perturbation expansion using Sonine polynomials [11,32,34]. This approach describes the ve-
velocity distribution can be obtained by linearizing the Boltzmann equation \[11 \text{, } 35 \text{, } 36\]. Notably, for granular gases with diffusive driving, this leads to the prediction \(P(v) \sim C \exp(-b|v|^2)\) with \(\beta = 3/2\) for large velocities, independent of the coefficient of restitution, strongly suggesting that the velocity distribution is universal \[11\].

The alternate theoretical approach is to study simpler model like the inelastic Maxwell gas, in which spatial coordinates of the particles are ignored and each pair of particles collide at constant rate \[10\]. In the freely cooling Maxwell gas, the velocity distribution decays as a power law with an exponent that depends on dimension and coefficient of restitution \[37\, 40\]. In contrast, for a diffusively driven Maxwell gas, in which collisions with the wall and modelled by velocities being modified by an additive noise, it was shown that \(P(v)\) has a universal exponential tail \((\beta = 1)\) for all coefficients of restitution \[11\, 42\]. However, it has been recently shown \[33\, 44\] that when the driving is diffusive, the velocity of the center of mass does a Brownian motion, and the total energy increases linearly with time at large times. Thus, the system fails to reach a time-independent steady state, making the results for diffusive driving valid only for intermediate times when a pseudo-steady state might be assumed. This drawback may be overcome by modeling driving through collisions with a wall, where the new velocity \(v'\) of a particle colliding with a wall is given by \(v' = -r_wv + \eta\), where \(r_w\) is the coefficient of restitution for particle-wall collisions, and \(\eta\) is uncorrelated noise representing the momentum transfer due to the wall \[43\] (diffusive driving corresponds to \(r_w = -1\)). For this dissipative driving \((|r_w| < 1)\), the system reaches a steady state, and the velocity distribution was shown to be Gaussian when \(\eta\) is taken from a normalized Gaussian distribution \[43\]. If \(\eta\) is described by a Cauchy distribution, the steady state \(P(v)\) is also a Cauchy distribution, but with a different parameter \[43\].

Thus, while the velocity distribution for the freely cooling granular gas is universal and reasonably well understood, it has remained unclear whether the velocity distribution of a driven granular gas is universal. Also, if the velocity distribution is non-Maxwellian, a clear physical picture for its origin is missing. Intuitively, it would appear that the tails of the velocity distribution would be dominated by particles that have been recently driven and not undergone any collision henceforth. This would mean the \(P(v)\) cannot decay faster than the distribution of the noise associated with the driving. If this reasoning is right, the noise statistics should play a crucial role in determining the velocity distribution, making it non-universal. How sensitive is \(P(v)\) to the details of the driving? In particular, how does \(P(v)\) behave for large \(v\) for different noise distributions \(\Phi(\eta)\)? We answer this question within the Maxwell model, both for dissipative driving \((0 \leq r_w < 1)\) as well as the pseudo steady state for diffusive driving \((r_w = -1)\). In particular, we show that the tail statistics are determined by the noise distribution for dissipative driving. For the pseudo steady state in diffusive driving, we find that the velocity distribution is universal if the noise distribution decays faster than exponential and determined by noise statistics if the noise distribution decays slower than exponential.

The rest of the paper is organized as follows. In Sec. \[II\] we define the Maxwell model and its dynamics more precisely. In Sec. \[III\] the steady state velocity distribution of the system is determined by studying its characteristic function as well as the asymptotic behavior of ratios of successive moments. In particular, we obtain the velocity distribution for a family of stretched exponential distributions for the noise. The results for dissipative driving may be found in Sec. \[III A\] and those for diffusive driving in Sec. \[III B\]. In Sec. \[V\] the exact solution of the non-interacting problem is presented. Section \[V\] contains a summary and discussion of results.

II. DRIVEN MAXWELL GAS

Consider \(N\) particles of unit mass. Each particle \(i\) has a one-component velocity \(v_i, i = 1, 2, \ldots, N\). The particles undergo two-body collisions that conserve momentum but dissipate energy, such that when particles \(i\) and \(j\) collide, the post-collision velocities \(v_i'\) and \(v_j'\) are given in terms of the pre-collision velocities \(v_i, v_j\) by:

\[
\begin{align*}
v_i' &= \frac{(1 - r)}{2} v_i + \frac{(1 + r)}{2} v_j, \\
v_j' &= \frac{(1 + r)}{2} v_i + \frac{(1 - r)}{2} v_j,
\end{align*}
\]

where \(r \in [0, 1]\) is the coefficient of restitution. For energy-conserving elastic collisions, \(r = 1\). In the Maxwell gas, the rate of collision of a pair of particles is assumed to be independent of their spatial separation as well as their relative velocity. These simplifying assumptions make the model more tractable as the spatial coordinates of the particles may now be ignored.

The system is driven by input of energy, modeled by particles colliding with a vibrating wall \[43\]. If particle \(i\) with velocity \(v_i\) collides with the wall having velocity \(V_w\), the new velocities \(v_i', V'_w\) respectively, satisfy the relation \(v_i' - V'_w = -r_w(v_i - V_w)\), where the parameter \(r_w\) is the coefficient of restitution for particle-wall collisions. Since the wall is much heavier than the particles, \(V'_w \approx V_w\), and hence \(v_i' = -r_wv_i + (1 + r_w)V_w\). Since the motion of the wall is independent of the particles and the particle-wall collision times are random, it is reasonable to replace \((1 + r_w)V_w\) by a random noise \(\eta\) and the new velocity \(v_i'\) is now given by \[43\],

\[
v_i' = -r_wv_i + \eta_i.
\]

In this paper, we consider a class of normalized stretched exponential distributions for the noise \(\eta\),

\[
\Phi(\eta) = \frac{a^\frac{1}{\gamma}}{2\Gamma(1 + \frac{1}{\gamma})} \exp(-a|\eta|^\gamma) a, \gamma > 0,
\]
characterized by the exponent \( \gamma \). Note that there is no apriori reason to assume that the noise is Gaussian as the noise is not averaged over many random kicks.

The system is evolved in discrete time steps. At each step, a pair of particles are chosen at random and with probability \( p \) they collide according to Eq. (1), and with probability \((1 - p)\), they collide with the wall according to Eq. (2). We note that evolving the system in continuous time does not change the results obtained for the steady state.

We also note that though the physical range of \( r_w \) is \([0, 1]\), it is useful to mathematically extend its range to \([-1, 1]\). This makes it convenient to treat special limiting cases in one general framework. For instance, when \( r_w = -1 \), the driving reduces to a random noise being added to the velocities, corresponding to diffusive driving. In this case, the system reaches a pseudo-steady state before energy starts increasing linearly with time for large times [43, 44]. When \( r_w \neq -1 \), the system reaches a steady state that is independent of the initial conditions. In the limit \( r_w \to -1 \), and rate of collisions with the wall going to infinity, the problem reduces to an Ornstein-Uhlenbeck process [44]. The case \( r_w = 1 \)

is also interesting. When \( r_w = 1 \), the structure of the equations obeyed by the steady state velocity distribution is identical to those obeyed by the distribution in the pseudo-steady state of the Maxwell gas with diffusive driving \((r_w = -1)\) [43].

### III. STEADY STATE VELOCITY DISTRIBUTION

We use two diagnostic tools to obtain the tail of the steady state velocity distribution: (1) by directly studying the characteristic function of the velocity distribution and (2) by determining the ratios of large moments of the velocity distribution.

In the steady state, due to collisions being random, there are no correlations between velocities of two different particles in the thermodynamic limit. We note that for finite systems, there are correlations that are proportional to \( N^{-1} \) [43]. The two point joint probability distributions can thus be written as a product of one-point probability distributions. It is then straightforward to write

\[
P(v, t + 1) = p \int dv_1 dv_2 P(v_1, t) P(v_2, t) \delta \left[ \frac{1 - r}{2} v_1 + \frac{1 + r}{2} v_2 - v \right] + (1 - p) \int \eta d\eta \Phi(\eta) P(v_1, t) \delta [\eta - r_w v_1 - v] \tag{4}
\]

where the first term on the right hand side describes the evolution due to collisions between particles and the second term describes the evolution due to collision between particles and wall. In the steady state, the velocity distributions become time independent and we use the notation \( \lim_{t \to \infty} P(v, t) = P(v) \). Equation (4) is best analyzed in the Fourier space. Let the characteristic function of the velocity distribution be defined as

\[
Z(\lambda) = \langle \exp(-i \lambda v) \rangle. \tag{5}
\]

It can be shown from Eq. (4) that \( Z(\lambda) \) satisfies the relation [43]

\[
Z(\lambda) = p Z \left[ \frac{1 - r}{2} \lambda \right] Z \left[ \frac{1 + r}{2} \lambda \right] + (1 - p) Z(r_w \lambda) f(\lambda), \tag{6}
\]

where \( f(\lambda) \equiv \langle \exp(-i \lambda \eta) \rangle_{\eta} \). Equation (6) is non-linear and non-local (in the argument of \( Z \)) and is not solvable in general. But it is possible to numerically obtain the probability distribution for certain choices of the parameters.

When \( r = 0 \) and \( r_w = 1/2 \), Eq. (6) takes the form,

\[
Z(\lambda) = p \left[ Z \left( \frac{\lambda}{2} \right) \right]^2 + (1 - p) Z \left( \frac{\lambda}{2} \right) f(\lambda), \quad r = 0, r_w = 1/2. \tag{7}
\]

Thus, \( Z(\lambda) \) is determined if \( Z(\lambda/2) \) is known. By iterating to smaller \( \lambda \), and considering the initial value

\[
Z(\lambda) = 1 - \lambda^2 \langle \nu^2 \rangle / 2 \text{ for small } \lambda, \text{ one can use this recursion relation to calculate characteristic function for any value of } \lambda. \text{ Here } \langle \nu^2 \rangle \text{ may be calculated exactly [see Eq. (9)]. The velocity distribution may be obtained from the inverse Fourier transform of } Z(\lambda).

When \( r_w = 1 \), Eq. (6) allows the tail statistics of \( P(v) \) to be determined exactly. In this case, the characteristic function satisfies the relation

\[
Z(\lambda) = \frac{p Z \left[ \left( 1 - r \right) \lambda/2 \right] Z \left[ \left( 1 + r \right) \lambda/2 \right]}{1 - (1 - p) f(\lambda)}, \quad r_w = 1. \tag{8}
\]

Equation (8) may be iteratively solved to obtain an infinite product involving simple poles. The behavior of the velocity distribution for asymptotically large velocities is determined by the pole closest to the origin, and has the form \( P(v) \sim \exp(-\lambda^* |v|) \), where \( \lambda^* \) is determined from \( 1 - (1 - p) f(\lambda) = 0 \) [43]. When \( r = 1/2 \), the iterative numerical scheme discussed above for dissipative driving may be followed for determining the characteristic function for the diffusive case.

The dynamics [Eqs. (1,2)] also allows the calculation of the moments of the steady state distribution. For the Maxwell model, it was shown that the equations for the two point correlation functions close [43, 44]. The closure can be also extended to one dimensional pseudo Maxwell models where particles collide only with nearest neighbor particles with equal rates [45]. Using this simplifying
property, the variance of the steady state velocity distribution in the thermodynamic limit was determined to be:

\[ \langle v^2 \rangle = \frac{2\kappa \sigma^2}{1 - \gamma^2 + 2\kappa (1 - \gamma^2)}, \]  

(9)

where \( \kappa = (1-p)/\rho \) and \( \sigma^2 \) is the variance of the noise distribution. On the other hand, the two-point velocity correlations in the steady state vanishes in the thermodynamic limit.

Among the higher moments, the odd moments vanish as the velocity distributions is even. Define 2n-th moment of the distribution to be \( \langle v^{2n} \rangle \). The evolution equation for \( M_{2n} \) may be obtained by multiplying Eq. (4) by \( v^{2n} \), and integrating over the velocities. It is then straightforward to show that they satisfy a recurrence relation,

\[
[1 - \epsilon^{2n} - (1 - \epsilon)^{2n} + \kappa (1 - \gamma^{2n})] \ M_{2n} = 
\sum_{m=1}^{n-1} \left( \frac{2n}{2m} \right) \epsilon^{2m} (1 - \epsilon)^{2n-2m} M_{2m} M_{2n-2m} 
+ \kappa \sum_{m=0}^{n-1} \left( \frac{2n}{2m} \right) \gamma^{2m} M_{2m} N_{2n-2m},
\]

(10)

where \( \epsilon = (1 - r)/2 \) and \( N_i \) is the \( i \)-th moment of the noise distribution. Equation (10) expresses \( M_{2n} \) in terms of lower order moments. Since \( P(v) \) is a normalizable distribution, \( M_0 = 1 \). Also \( M_2 \) is given by Eq. (9). Knowing these two moments, all higher order moments may be derived recursively using Eq. (10).

The ratios of moments may be used for determining the tail of the velocity distribution. Suppose the velocity distribution is a stretched exponential:

\[ P(v) = \frac{b^{1/\beta}}{2\Gamma(1 + 1/\beta)} \exp(-b|v|^\beta), \quad b, \beta > 0, \]  

(11)

where \( \Gamma \) is the Gamma function. For this distribution the 2n-th moment is

\[ M_{2n} = b^{-2n/\beta} \frac{\Gamma(2n+1)}{\beta \Gamma(1 + 1/\beta)}, \]  

(12)

such that that the ratios for large \( n \) is

\[ \frac{M_{2n}}{M_{2n-2}} \approx \left( \frac{2n}{b^2} \right)^{2/\beta}, \quad n \gg 1. \]  

(13)

Though Eq. (13) has been derived for the specific distribution given in Eq. (11), the moment ratios will asymptotically obey Eq. (13) even if only the tail of the distribution is a stretched exponential. This is because large moments are determined only by the tail of the distribution. Thus, the exponent \( \beta \) can be obtained unambiguously from the asymptotic behavior of the moment ratios.

We first evaluate the velocity distribution numerically by inverting the characteristic function \( Z(\lambda) \). For this calculation, \( f(\lambda) \), the Fourier transform of the noise distribution in Eq. (3), is determined numerically using Eq. (7). Figure 1 shows the velocity distributions obtained for \( \gamma = 1/2, 1, 2, 3 \) for different values of \( a = 3 \) (see Eq. (3) for definition of \( a \)) for \( r_w = 1/2 \), corresponding to dissipative driving, the velocity distribution \( P(v) \) approaches the noise distribution for large velocities for all values of \( \gamma \). This suggests that the tail of the distribution is determined by the characteristics of the noise. However, using this method, it is not possible to extend the range of \( v \) to larger values so that the large \( v \) behavior may be determined unambiguously. The range of \( v \) is limited by the precision to which \( f(\lambda) \) can be determined numerically.

The ratios of moments [see Eq. (13)] is a more robust method for determining the tail of the velocity distribution. The moments are calculated from the recurrence relation Eq. (10) where the moments of the noise distribution described in Eq. (3) is given by

\[ N_{2n} = a^{-2n/\gamma} \frac{\Gamma(2n+1)}{\gamma \Gamma(1 + 1/\gamma)}. \]  

(14)

The numerically obtained moment ratios of the steady state velocity distribution for dissipative driving is shown in Fig. 2 for different noise distributions characterized by \( \gamma \). The moment ratios increase with \( n \) as a power law with an exponent \( 2/\gamma \), independent of the value of \( r_w \) and the coefficient of restitution \( r \). Comparing with Eq. (13), we
We now determine the constant $b$ in the exponential in Eq. (11). It may be determined from Eq. (13) once $\beta$ is determined. Rearranging Eq. (13), we obtain

$$b(n) \approx \frac{2n}{\beta} \left( \frac{M_{2n}}{M_{2n-2}} \right)^{-\beta/2}, \quad n \gg 1. \quad (15)$$

Figures 3 (a) and (b) show the variation of $b(n)$ with $n$ for different $\gamma$. We find that for large $n$, $b(n)$ is independent of coefficient of restitution $r$, but may depend on $r_w$. Also, we find that $b - b(n) \propto n^{-1}$ for all values of $\gamma$. Figures 3 (c) and (f) show the variation of $b$ with $r_w$ for different $\gamma$. For $\gamma = 1/2$ and 1, $b$ is independent of $r_w$, while for $\gamma = 2$ and 3, it depends on $r_w$. We have checked that $b$ is independent of $r_w$ for $\gamma$ up to 1. In Figures 3 (c) and (f), the values of $b$ are also compared with that obtained for a non-interacting system in which collisions between particles are ignored. We find that the values of $b$ for both the interacting and non-interacting system coincide. In addition, for $\gamma \leq 1$, we find that the value of $b$ approaches the value $a$ characterizing the noise distribution.

### B. Velocity distributions for diffusive driving

The Maxwell gas with diffusive driving ($r_w = -1$) does not have a steady state in the long time limit, when the total energy diverges. However, it has a pseudo steady state solution that is valid at intermediate times. On the other hand when $r_w = 1$ the system reaches a steady state at large time. It has been shown that the velocity distribution in the pseudo steady state for the case $r_w = -1$ is the same as the velocity distribution in the steady state of the system with $r_w = 1$ [43]. For $r_w = 1$ and $\eta$ taken from a Gaussian distribution, the velocity distribution was shown to have an exponential distribution [39]. In this section, we determine this steady state for other noise distributions.

In Fig. 4 the numerically obtained $P(v)$ is shown for different values of $\gamma$. We find that for $\gamma = 1/2, 1$ the velocity distribution approaches the noise distribution. Interestingly, when $\gamma = 2, 3$ the velocity distribution deviates significantly from the noise distribution. While the data for $\ln P(v)$ appears to vary linearly with $v$, the range
is limited and it is not possible to unambiguously conclude that $P(v)$ is exponential independent of the noise distribution.

As for the dissipative case, the better tool to probe the tail of the distributions is the moment ratios Eq. (13). Figure 4 shows that moment ratios increase with $n$ as a power law. The power law exponent is $2/\gamma$ for $\gamma < 1$ [see Fig. 4(a)] and equal to 2 for $\gamma \geq 1$ [see Fig. 4(b)-(d)]. Thus, we conclude that $\beta = \min(\gamma, 1)$. Thus, $P(v)$ is universal, and has an exponential tail for $\gamma \geq 1$.

The exact form of the universal exponential tail can be analytically obtained as follows. If the velocity distribution has the form $P(v) = (\lambda^*/2) \exp(-\lambda^*|v|)$, the moment ratios in the large $n$ limit behaves as $M_{2n}/M_{2n-2} \approx (4n^2 - 2n)/\lambda^*$. But we have seen in Sec. III that, for dissipative driving Eq. (8) satisfies a solution such that the velocity distribution is determined by the pole nearest to the origin $\pm \lambda^*$ obtained from relation $1 = (1-p)f(\lambda)$. When $\gamma = 1$, the pole has the form given by

$$\lambda^* = \pm a\sqrt{p}, \quad \gamma = 1,$$

$$\lambda^* = \pm \sqrt{-2 \ln(1-p)} / \sigma, \quad \gamma = 2.$$ (16, 17)

When $\gamma = 3$, we obtain complicated Hypergeometric function for $f(\lambda)$ from which $\lambda^*$ may be determined numerically. The moment ratios thus obtained are plotted in Fig. 4(b), (c), and (d) which matches with the numerically calculated moment ratio. It can be seen that when $\gamma < 1$, there is no $\lambda^*$ which satisfies the relation $1 = (1-p)f(\lambda)$.

From Eq. (13), we obtain the coefficient $b$ for the diffusively driven system and is shown in Fig. 5. It is seen that when $\gamma < 1$, the coefficient $b(n)$ approaches that of the noise distribution $a = 3$. For $\gamma \geq 1$, $b$ is calculated by substituting $\beta = 1$ in Eq. (15). One finds in this case that $b$ approaches $\lambda^*$ which is obtained analytically.

**IV. NON-INTERACTING SYSTEM**

We showed in Sec. III that, for dissipative driving, the tail of the velocity distribution $P(v)$ is identical to that of a non-interacting system in which collisions between particles may be ignored. In this section, we determine the velocity distribution of the non-interacting system in terms of the noise distribution. In the non-interacting system, the particle is driven at each time step. If $v_n$ is the velocity after the $n^{th}$ collision, then

$$v_n = -r_wv_{n-1} + \eta_{n-1}.$$ (18)

For a particle that is initially at rest ($v_0 = 0$),

$$v_n = \sum_{m=0}^{n-1} r_w^m \eta_{n-m-1} = \sum_{m=0}^{n-1} r_w^m \eta_m,$$ (19)

where the second equality is in the statistical sense, and follows from the fact that noise is uncorrelated and therefore the order is irrelevant.

Now, consider the moment generating function of the noise distribution $\langle \exp(-\lambda \eta) \rangle \equiv \exp[\mu(\lambda)]$ where $\mu(\lambda)$ is the cumulant generating function,

$$\mu(\lambda) \equiv \sum_{i=1}^{\infty} \frac{\lambda^i}{2i!} C_{2i},$$ (20)

where $C_{2n}$ is the $2n^{th}$ cumulant of the noise distribution. It has been assumed that the noise distribution is symmetric such that only even cumulants are non-zero. The
moment generating function of the velocity after infinite
time-steps is,

\[ \langle \exp(-\lambda \eta) \rangle_{\eta} = \left\langle \exp \left[ -\lambda \sum_{m=0}^{\infty} \eta_m \right] \right\rangle_{\eta} = \exp \left[ -\sum_{m=0}^{\infty} \mu(r_m^\eta) \right]. \] (21)

From the definition of \( \mu(\lambda) \) [see Eq. (20)], we obtain

\[ \mu(r_m^\lambda) = \sum_{n=1}^{\infty} \frac{(r_m^\lambda)^{2n}}{2n!} C_{2n}. \] (22)

Summing over \( m \),

\[ \sum_{m=0}^{\infty} \mu(r_m^\lambda) = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{(r_m^\lambda)^{2n}}{2n!} C_{2n}, \]

\[ = \sum_{n=1}^{\infty} \frac{\lambda^{2n}}{2n!} \left( \frac{1}{1 - \lambda^{2n}} \right) C_{2n}. \] (23)

But, \( \langle \exp(-\lambda \eta) \rangle = \exp[\xi(\lambda)] \) where \( \xi(\lambda) \) is the cumulant generating function of the velocity distribution at large times,

\[ \xi(\lambda) = \sum_{n=1}^{\infty} \frac{\lambda^{2n}}{2n!} D_{2n}, \] (24)

where \( D_{2n} \) is the \( 2n^{th} \) cumulant of the velocity distribution. Comparing with Eq. (23), we obtain

\[ D_{2n} = \frac{C_{2n}}{1 - \lambda^{2n}}. \] (25)

For large \( n \), behavior of the cumulants of the velocity distribution approaches that of the noise distribution. Thus, by knowing all cumulants, the velocity distribution of the non-interacting system is completely determined.

V. DISCUSSION AND CONCLUSION

In summary, we considered an inelastic one component Maxwell gas in which particles are driven through collisions with a wall. We determined precisely the tail of the velocity distribution \( P(v) \) by analyzing the asymptotic behavior of the ratio of consecutive moments. Our main results are: (1) For dissipative driving, the tail of \( P(v) \) is identical to that of the corresponding non-interacting system where collisions are ignored. By solving the non-interacting problem, the cumulants of the velocity distribution may be expressed in terms of the noise distribution and. Thus, \( P(v) \) is highly non-universal. (2) For diffusive driving, \( P(v) \) is universal and decays exponentially when the noise distribution decays faster than exponential. If \( \Phi(\eta) \) decays slower than exponential, then \( P(v) \) is non-universal and the tails are similar to the tail of \( \Phi(\eta) \). These results are summarized in Fig. 6.

These results generalize the results in Ref. [13], where it was shown that for dissipative driving that when the noise distribution is gaussian or Cauchy, the tails of the velocity distribution are similar to that of the noise distribution. The results are also consistent with the intuitive understanding that the tails of velocity distribution are bounded from below by the noise distribution. This is because the tails are populated by particles that have been recently driven and then do not undergo any collision. We expect that more complicated kernels of collision will not change the result. This could be the reason why many of the experimental results [22] see non-universal behavior. However, there are experiments that see universal behavior [21, 24]. In these experiments the \( P(v) \) is measured in directions perpendicular to the driving direction. It may be that the details of the driving are lost when energy is transferred to other directions. Transferring energy in other directions ensures that collisions cannot be ignored, unlike the case of one-component Maxwell gas studied in this paper. The two component Maxwell model is a good starting point to answer this question. Methods developed in the paper will be useful to analyze the same. This is a promising area for future study.

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