Introduction: Recent images of Pluto strongly suggest that dunes are present on the dwarf planet’s surface [1]. This finding opens questions about the movement of loose, sand-sized particles, and the conditions under which this movement can form familiar patterns such as ripples and dunes. We seek to better understand these patterns using physical models.

Fundamentals of Sand Transport. Sand movement occurs via several mechanisms: saltation, suspension, reptation, creep, and granular convection. Saltation refers to a small leap that a particle makes—usually a few centimeters. This can occur either due to the wind velocity exceeding a threshold of motion or due to particles colliding against each other in a chain reaction started by wind. Suspension occurs as the smallest particles are carried large distances through air. Reptation occurs when (generally large) particles move across the surface due to wind forces.

The final two processes, creep and granular convection, are driven primarily by the force of gravity. Creep is often defined to include reptation, but for our purposes, it will be defined exclusively as sand movement at or near the surface. Finally, granular convection, like creep, is caused by gravity, and is the process by which smaller particles seep downward, forcing the larger particles upward. Effectively, it means that larger particles end up near the surface over time.

It is important to note that these processes are a function of three physical forces: gravity, the force of wind, and the static frictional force between the particles (Fig. 1).

A Model of Threshold Velocity. A crucial factor in determining sand transport—and the distinguishing factor between the transport of loose particulate matter and the dynamics of fluids—is the threshold velocity: the minimal velocity at which wind forces exceed frictional forces, and the particle begins to move. Consider the following physical equation:

\[ u_{th} \approx A_N \frac{\rho_p - \rho_a}{\rho_a} gd \] (i)

In this model the threshold velocity, \( u_{th} \), is dependent on the densities of the air and of the particle, \( \rho_p \) and \( \rho_a \) respectively; the acceleration due to gravity, \( g \); the diameter of the particle, \( d \); and a constant \( A_N \), \([e.g., 3]\)

Nishimori’s Model. A model of sand transport developed by Nishimori [4] takes into account saltation and creep to describe the progress of emergent patterns, such as ripples, over time. The key inputs are the saltation length, saltation height, and saltation proportionality constant. Its primary use is in understanding the overarching patterns in dunes and ripples rather than the individual ripples or dunes themselves.

Specifically, the simulations of Nishimori’s model we ran began with a spatial matrix of a sand surface, where the value at each point, \( h \), represented sand height. In each time step, an amount, \( q \), saltated a
length $L$ (a linear function of $h$), as shown in these equations:

$$h_{n'} = h_n(x,y) - q \quad (ii)$$

$$h_{n'}(x + L(h_n(x,y)), y) = h_n(x + L(h_n(x,y)), y) + q \quad (iii)$$

Additionally, creep was modeled by changing the value $h$ at each point as a function of the value $h$ of the points nearest neighbors (NN) and next-nearest neighbors (NNN), as well as of a diffusion constant, $D$ (which depends on the angle of repose):

$$h_{n+1}(x,y) = h_n'(x,y) + D \left[ \frac{1}{6} \sum_{NNN} h_{n'}(x,y) + \frac{1}{12} \sum_{NNN} h_{n'}(x,y) - h_{n'}(x,y) \right] \quad (iv)$$

Using these simulations, the degree of frustration in the pattern was evaluated by counting the frequency of bifurcations after a given amount of time.

**Analysis:** By counting bifurcations in various runs of Nishimori’s model, we have concluded that frustration in the emergence of aeolian patterns correlates much more strongly with the saltation proportionality constant than with the saltation height. This means that for an otherwise perfect transverse wave pattern in sand, interruptions—bifurcations, in particular—occur in part due to a difference in wind velocities as a function of height (the saltation proportionality constant); these interruptions do not, however, appear to depend on the amount of sand transported in a given time frame (saltation height).

This conclusion is significant, because if emergent patterns like ripples or dunes experience high enough levels of frustration, no recognizable pattern will be visible in the disorganization. Therefore, in determining whether dunes will form (and what they will look like if they do) the dynamics of the wind as a function of height (the saltation proportionality constant); these interruptions do not, however, appear to depend on the amount of sand transported in a given time frame (saltation height).

The difference in wind velocities as a function of height has previously been confirmed to contribute to the unstable nature of dunes with respect to along-axis perturbations [5]. Our findings also suggest that for familiar aeolian patterns to form, it is not as important that the atmosphere transports as high a volume of sand in a given period of time as Earth’s atmosphere does.

On Pluto specifically, the atmosphere is much thinner than on Earth, which may mean particulate matter is transported less often than it would be in terrestrial wind conditions. Still, as long as some transport is occurring, and no external forces disturb the area, very similar patterns should form if given enough time. Another implication of these findings is a possible explanation of disparities in the apparent organization of Pluto’s dunes. If we assume that the composition of the dunes is homogeneous on a large scale, and that the underlying geology of Sputnik Planitia is essentially flat (which may or may not be true), then a difference in wind velocities as a function of height may be one important reason that some dune patterns are regular, while others have more defects and discontinuous crests.

**Data of Pluto:** Images of linear features on the surface of Pluto were captured by New Horizons. Evidence strongly suggests that these patterns are transverse dunes that may be composed of sand-sized solid methane particles [1].

Measurements of the average spacing of the dunes and the frequency at which defects occur can be compared with these model outputs to help reveal the conditions under which these features form on Pluto.