In celebration of Peter Kirkland Haff: scholar, mentor, friend
1944 – 2024

A legion of beautiful stars watching over Peter Haff's beloved Mojave Desert twinkled extra last night — a brief spacetime ripple — in celebration of an extraordinary person.

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Peter grew up as a free-range kid. If it was within walking or biking distance before the dinner deadline, it was part of his, and his friends', stomping grounds. A place and time where Peter's parents and his friends' parents could (mostly) not need to worry, and kids inquisitively discovered stuff on their own. Televisions were a thing, but not much a part of Peter's life. Based on Peter's descriptions, I am convinced his free-range adventures were an important part of the source of his unwavering curiosity about natural things, and fundamentally contributed to his deep insights regarding how things work. This was always with him. When walking with Peter, say, in the Duke University Forest, Peter invariably saw natural patterns in need of explanation. Peter was particularly intrigued by any and all things involving capillary waves. And waveforms more generally. And fractals, and... the list is endless.

Peter attended Harvard where he majored in physics. In our many conversations Peter did not say much about his Harvard experience, other than to describe his favorite courses in physics, and that despite doing well, being perplexed by certain aspects of the physics he learned, and commenting on the physics and mathematics he wished he had learned better. That, and his love of discovery when losing himself in reading books — so many books on so many topics — in the Harvard library. Similarly, Peter did not say much about his PhD studies at the University of Virginia, other than to note that when newly minted he applied to every — yes, every — open physics faculty position in the U.S. and Canada. The outcome? Nothing.

Peter landed as a postdoc at Caltech. He loved Pasadena, and relished being in the thick of things in the Physics Department during a golden period of physics, with access to an astonishing number of Nobel Laureates, including Richard Feynman. Peter reminisced fondly about his friendship with Robert Sharp, then chair of the Division of Geological Sciences, and their occasional field adventures together in the desert. Peter described the relentless intensity of years in a soft-money position while raising two youngsters — Tonya and Jesse — with his wife Suzanne. Peter eventually arrived at Duke University, recruited by Robert Behringer, a pioneer in the field of granular physics, as part of the growing efforts in this field that Bob led at Duke. Peter started in Engineering then gravitated to Geology, later absorbed by the Nicholas School of the Environment. That's where I seriously started interacting with Peter in the mid-1990s. The Duke library and the coffee shops tucked away in corners were our favorite places to discuss things. Those and the Duke Gardens and the Duke Forest. And there was the added fun of watching Peter yukking it up in Spanish with the baristas.

While at Caltech, Peter pursued wide-ranging work on the physics of particle sputter-

ing: the ejection of particles from the surface of a solid material due to impacts of energetic ions of a gas or plasma. Peter produced an impressive body of work on this topic, with implications spanning the role of sputtering in atomic mixing to the behavior of planetary bodies, for example: the role of sputtering in the dynamics of the E ring of Enceladus, and ejection of mass from Io; the erosion of planetary atmospheres by energetic particles; and the role of sputtering of the lunar surface by the solar wind as a mechanism of mass fractionation. This work continues to be a starting point for many researchers in planetary science. But Peter wanted to do Earth things, and among his favorite places was the Great Sand Dunes National Park in southern Colorado. Inspired by what he saw there and having interacted with Bob Sharp and read Ralph Bagnold's book, *The Physics of Blown Sand and Desert Dunes*, it was a natural for Peter to aim at this topic, notably the role of sputtering sand grains due to energetic impacts of saltating particles, building on his deep understanding of the physics involved. Peter's contributions to aeolian transport together with those on the physics of granular flows more generally are now widely considered to be foundational landmarks — essential reading — in these fields.

Perhaps you know there is a physics law named in Peter's honor — Haff's cooling law — a foundational element of granular physics, particularly granular gases. This started with a 1983 paper in which Peter did an amazingly difficult and novel thing: he formulated the analogue of the Navier-Stokes equations for granular flows. Because of dissipative (inelastic) particle collisions, Peter recognized the need to add a kinetic energy equation that explicitly treats energy losses during collisions. This led to Haff's law in which, following particle excitation, the kinetic energy E of the system decays with time as $E \sim t^{-2}$ in the homogeneous cooling state. Haff's law has since been carefully tested and confirmed by sophisticated numerical simulations and then in 2020 — 37 years later — using novel microgravity physical experiments. So here is Peter in his intellectual honesty and modesty about my making a big deal of things: "Well... it's not like it's one of Newton's laws; it's more like a Darcy's law or a Fick's law, after all. At most it's a physics law-let." Nonetheless, please know if you do not already: it's a big deal. On this and related topics, the clarity of Peter's thinking and physical insight jumps off the pages of his writing.

On both sides of his retirement to emeritus professor, Peter did something equally amazing and novel. He carefully defined and articulated the idea of Earth's technosphere — the collection of all things physical and otherwise that humans have created — a complex system whose role rivals that of the biosphere or hydrosphere, wherein human behavior, individual and collective, is inextricably bound to its dynamics. Peter asks us to

> "abandon the apparently natural assumption that the technosphere is primarily a human-created and controlled system and instead [consider] the idea that the workings of modern humanity are a product of a system that operates beyond our control and that imposes its own requirements on human behavior. The technosphere is a system for which humans are essential..."

The idea of Earth's technosphere is entirely familiar to social scientists, economists and philosophers, but less so to Earth scientists, which is unfortunate. Because of its far-reaching implications challenginng the naïve perception "that human agency is the driving force of the modern world" — *the Anthropocene illusion* — the idea of Earth's technosphere is a source of continuing debate in several fields. But here is the amazing part. In his efforts to clarify the essential elements of the dynamics of the technosphere, Peter formulated a set of physically based "rules" (Peter carefully avoided any allusion to "laws") that all dissipative systems must

satisfy. Peter purposefully and carefully formulated these rules in a manner such that they are consistent with the laws of physics while accommodating the emergent behaviors of complex systems, including the technosphere, that defy conventional reductionist explanations. These six regulative rules — the rules of inaccessibility, impotence, control, reciprocity, performance and provision — are breathtaking in their clarity. As a consequence, Peter's ideas regarding the technosphere are increasingly emerging in discussions of Earth's future in this critical century.

Peter was intellectually fearless. In pursuing his work, nothing was *a priori* off the table, and he sought out an astonishing breadth of sources for inspiration and insight. Most of us read books and essays occasionally. When Peter was not thinking or writing about his work he was *always* reading books and essays, or listening to podcasts — many topics and all genres. Peter habitually listened to book audiotapes when he drove to and from work. He offered a simple rule: Start reading, and if after a reasonable good-faith effort it does not resonate, move on. There is so much out there that *will* resonate! (I fondly recall when Peter introduced me to the writings of Cormac McCarthy in a coffee shop at Duke.) In our discussions of his work on the technosphere, Peter nimbly navigated and connected ideas from Plato to Kant to Deutsch. Moreover, while pursuing this work he had ongoing conversations with social scientists, economists, physicists, atmospheric scientists, biologists, Earth scientists and so on. Peter's personal library, which he added to continually, was an amazing, eclectic collection — that of a genuinely erudite scholar.

Peter was a special mentor, although throughout the experience I did not view Peter as a mentor per se; that dawned on me later. And I suspect Peter didn't either. That's what made it special; it seemed like an intellectual co-conspiracy. Nonetheless I did a lot of watching, and listening. Peter was quite capable with mathematics — hard stuff. But like Feynman, Peter insisted that any use of mathematics had to have a clear physical interpretation. Peter was a master of dimensional analysis (among other things he first pointed out to me that the Reynolds number is actually a Péclet number) and particularly adept at taking hard problems and reducing them to their barest essence on dimensional grounds. Peter stressed the importance of talking with others — people willing to engage and be honestly critical — about one's ideas and efforts. To Peter, the principles and practice of critical rationalism were essential in doing good science, and, more generally, in achieving clear thinking. Peter emphasized the importance of writing, that you don't actually understand something until you write it, then rewrite it, clearly. Sometimes in our bantering Peter would, in reaction to my (our) work, simply ask questions. The kind that, after a pause, lead to: "Oh... yeah. I need to rethink that." Most importantly, Peter invariably was enthusiastically invested in getting things right. It was just damn great fun to interact with Peter.

Over the years I coached five students to pursue their graduate studies at Duke. Whereas only one of the five worked directly with Peter, I knew they all would be in great hands and thrive at Duke based on what they wanted to do at the graduate level then beyond. Importantly, I banked on knowing the students would have access to Peter — access to a colleague who excelled in engaging with talented students. Students adored Peter — his intellect, his insight and wisdom, his kindness.

On a more personal note, a highlight of my intellectual experience is the fact that Peter and I traded sabbaticals. I launched my own deep thinking about statistical physics at Duke, and then Peter launched his deep thinking on the technosphere at Vanderbilt. Playing with Peter was on the itinerary every day. And we snuck music into the mix. Inspired by his Nashville experience, including the honky-tonks, Peter purchased two guitars at famous shops and learned some serious licks. During the pandemic of 2020,

Peter and I communicated via Skype. This was a time of introspection, and in one of our sessions Peter noted that he had been pondering the items and events in his life that he got right and which made him particularly happy. To wit, Suzanne. Kind, witty, wise Suzanne — with an amazing life story of her own. Spending time with Suzanne and Peter was a movable feast of inveterately delightful engagement.

To say that we now no longer have amongst us a wonderful colleague and friend — one of the great intellects of our time — is factually correct but an understatement in spirit. I got lucky: to joyfully interact with Peter, learn from him, and intellectually co-conspire with him. And now, with loss, I am reminded that Peter once said: If you let it, life is rich and has a knack for getting in the way and helping fill in the holes and divots.

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