This paper is based on my Teller Award lecture, given in September 2017 at the Inertial Fusion Sciences and Applications Conference. A significant aspect of my career, mentioned in the award citation, has been my contribution to education in an area of science relevant to inertial confinement fusion (ICF). The area specifically is high-energy-density physics, in which I published the first textbook and its second edition [1, 2]. In retrospect, it seems remarkable to have ever learned enough to be able to write that book, even in the first 30 years of a career. So I structured my lecture around my intellectual journey through the relevant material. Reflecting that unusual talk, this paper sets out to briefly highlight some areas I worked in, discuss what concerned us at the time, and indicate where subsequent work has gone. This paper is definitely not a review, which would need to be much lengthier and to have much more scope in what it referenced. Instead, it reflects my own journey through high-energy-density physics. I apologize in advance to the many authors whose seminal work on some topic or other, at some point in time, I fail to mention.

Much of my career trajectory can be connected to the sequence of events in a laser target, like those illustrated in figure 1. One or more laser beams creates a ‘coronal plasma’ at the target surface. The laser is absorbed in this plasma, where it also may drive instabilities that scatter the laser light and generate energetic particles. Heat transport carries some of the deposited energy into the ablator, where the resulting ablation pressure drives a shock wave into the matter. After that, the sequence of events may involve hydrodynamics, radiation hydrodynamics, and other physics, depending upon how the target is structured. This sequence of events will set the structure for the next few sections of the paper, moving from the laser irradiation to the hydrodynamic response of a target and eventually to radiative effects.

1. Laser-plasma interactions

When I joined the ‘Laser Program’ at the Lawrence Livermore National Laboratory (LLNL), one manager there told me that
ICF was a dying program. And indeed, the ICF program was in danger of dying out worldwide around 1980. This reflected the utter failure of ICF experiments to perform as predicted during the late 1970s. Those experiments irradiated targets with laser light having a wavelength of 1 micron or longer, which turned out to be very poorly absorbed at surfaces. Instead, they produced large levels of laser-plasma instabilities, which efficiently reflected the laser light, or converted its energy into high-energy electrons that interfered with making fusion work. The program was saved when work in France and the US [3, 4] showed two things: first, one could efficiently convert 1 micron laser light to light at 0.53 µm and 0.35 µm. Second, using such light greatly reduced (but did not eliminate) the electrons produced by the instabilities. As a result, it was clearly important to come to understand the instabilities, with the aim of learning enough to avoid substantial adverse effects in targets aimed at fusion ignition.

It also first became possible in the early 1980s to irradiate surfaces with laser beams having a few kJ of energy, at wavelengths of 0.53 or 0.35 µm. Typically the pulses were about 1 ns in full width at half maximum, sometimes Gaussian in temporal shape but advancing to flat-topped shapes by the end of that decade. In order to produce the energy fluxes appropriate to inertial fusion applications (of order 10^{15} W cm^{-2}), it was necessary to have the beams produce spot sizes of on surfaces of a few hundred µm. The community knew that such beams were not smooth enough to be used for inertial fusion by direct irradiation of fuel capsules. We imagined, wrongly, that they might suffice for the irradiation of hohlraums, to drive direct irradiation of fuel capsules by x-rays. The structure on these beams, illustrated in figure 2, was quite extensive. The beam was not at all uniform, with large areas that differed in energy flux (often called ‘intensity’) by factors of ten. Our job was to understand what happened during the interaction of such beams with the coronal plasmas they produce at material surfaces.

Stimulated Raman scattering (SRS) is of particular concern for ICF, because it can occur over a wide range of densities, and has the potential to produce both scattered laser light and damaging, energetic electrons. For that reason, it was the focus of much of our work and will be the focus here. SRS occurs when laser light scatters from an electron plasma wave (EPW, a compressional modulation of the electron density also known as a Langmuir wave or a Bohm–Gross wave). The scattered light wave can have up to twice the wavelength of the incident, laser light. SRS is an instability. It amplifies both the scattered-light wave and the EPW from thermal levels, and can grow to involve a large fraction of the laser energy. Thus, it can limit inertial fusion using lasers. SRS is one of several instabilities that can reflect the laser light or generate suprathermal electrons [2, 5].

In the sort of experiments just described, SRS produced images like that shown in figure 3. The late Tudor Johnston, a major contributor to such studies, and to the fun one could have doing them, described such spectra as images ‘of one butterfly wing flapping’ The particular spectrum shown is from irradiation of a target using a flat-topped pulse of 350 nm light. The boundary labeled ‘A’ is a result of Landau (kinetic) damping, which greatly reduces the SRS amplification. The boundary labeled ‘B’ is a result of using a thin target that exploded to produce a comparatively large plasma whose maximum density decreases with time [6], as longer SRS wavelengths originate at higher density. When thicker targets were used, the spectrum remained relatively fixed in shape, as indicated by the gray triangle.

The fact that we saw the level of SRS we did from planar targets, and that the maximum SRS intensity did not occur at the density maximum in exploding targets, was not anticipated from simple theory. We published a paper in Physical Review Letters (a PRL), making the case that SRS was transformed by the complexities of the laser beam, and of the plasma it produced, into an ‘absolute instability’, a type of process that would allow growth to large amplitude [7]. We also published PRLs, and often longer papers, on several other aspects of SRS. We showed evidence that SRS produces energetic electrons, a consequence of nonlinear damping of large-amplitude EPWs [8, 9], an important historic result that still appears from time to time today. Even so, among the PRLs cited in the present section, that one was the most difficult to get the journal to accept. We showed that SRS could be quenched by collisions [10–12] and could scatter light in the forward
direction [13]. We showed that stimulated Brillouin scattering (SBS) could interfere with SRS, producing the notch labeled ‘E’ in figure 3 [14]. We showed that when Landau damping is strong, there is still finite amplification of scattered light at the shorter wavelengths indicated by ‘D’ in figure 3. This process is also known as stimulated Compton scattering [15].

As one can see, in those days one could typically get a paper into PRL by explaining any little detail of the physics connected to an important application. Most of the explanations were natural applications of well-known behavior and not a surprise to anyone, but did need to be experimentally observed. This was especially important because we did not trust any of the models then computationally feasible to accurately predict the nonlinear behavior. The best models of that era for understanding nonlinear behavior were particle-in-cell models. They could and did identify important nonlinear mechanisms, and were developed and run by outstanding scientists. But the best they could do was to produce noisy results on short timescales, over small volumes, using large electromagnetic fields and heavy electrons. An example relevant to SRS is that of Estabrook et al [16]. Through improved computational methods made feasible by the enormous increase in available computing power, the models of today are far more capable. Their predictive power may be more limited by our continuing inability to accurately simulate plasma conditions, a bit of which is discussed in the next section, than by their modeling of the LPI.

The aspect of the SRS spectrum that proved the most intractable was known as ‘the gap’. The spectrum in figure 3, and from similar experiments using thick targets, should have theoretically extended to 700 nm, in the absence of strong SBS. But it universally did not. Eventually two of us came up with what proved to be the correct explanation: that the EPW driven by SRS could itself drive an instability, limiting its own amplitude and that of the scattered light wave, and that the limiting EPW amplitude was smaller for the waves that produced longer-wavelength SRS [17]. Although the instability of the EPW had long been known to exist, no one had previously made the connection to the structure of the SRS spectrum. This explanation was controversial and was widely disbelieved at first. But in fact, we had solved the aspect of the SRS problem of that era that was intellectually the most difficult. So naturally, PRL refused to take that paper. It took a few years and advances in experimental technique, but eventually experimental evidence confirmed the explanation [18], which had come to be less controversial by then, and PRL did take that paper. (The most important of the advances was the implementation of Thomson-scattering measurements, but more flexible use of multi-beam laser facilities and the simultaneous use of several diagnostics also contributed.)

As such research moved into the 1990s and beyond, the development of beam-smoothing techniques improved the control of experimental conditions, as well as the prospects for fusion using lasers. The smoothed beams did not have large areas at far above the average energy flux, and produced plasmas having far less internal structure. Diagnostics and experimental technique improved as well. Montgomery [19] extensively reviews the research from this later period. On revisiting the entire history, what is striking to me is that we identified and found experimental evidence for most of the basic effects known today, in that early research under such challenging conditions. SRS is only one aspect of LPI. Others, beyond our scope to discuss here, also were explored in those early years and have been of continuing interest since.

2. Plasma hydrodynamics and equations of state

The heating of the target by the laser, and the resulting shocks, convert the target material into moving plasma. This motion, and various structure that results, is the province of plasma hydrodynamics. This topic first came to my attention when we used ‘exploding foil’ targets to produce large-scale-length plasmas for LPI [6, 20]. To a first approximation [21], the structure of such expanding plasmas can be described as a (spatial) Gaussian, self-similar expansion. More accurately, the plasma corona expands at low density as an isothermal expansion, while the expansion of the rear surface can range from isothermal to adiabatic, depending on details [22].

During the 1980s we came to realize that the codes we used to simulate the conditions in the plasma corona typically overestimated the plasma generation by a significant factor [6]. It is very disappointing that this is still true today, as seen in figure 4 of Fein et al [23]. All the relevant codes evaluated the laser absorption in a sensible way, used standard equations of state, and modeled heat transport using flux-limited diffusion. This discrepancy is seldom mentioned, in part because relevant measurements are not common. But one can also note that the field as a whole is so focused on applications that it has failed to value progress in understanding simple, fundamental behavior. On this specific issue, some experimental work is finally underway by a group using novel diagnostic techniques [24] based on x-ray interferometry. If better computational models of the evolution of the coronal plasma under such conditions have been demonstrated, I am not aware of them.
Most of my experience with hydrodynamics came through the advent of what we now call High-Energy-Density Laboratory Astrophysics (HEDLA). Two related lines of research began to develop in the early 1990s. Researchers began to use lasers to measure properties of matter that were relevant to astrophysics, notably including equations of state and x-ray absorption rates. An early example is that of Springer et al [25]. Soon thereafter, Hideaki Takabe and Bruce Remington developed the specific idea of using lasers to do astrophysically relevant hydrodynamics, and began to promote the general idea of forming a community that used lasers (and soon, other tools) to explore astrophysically relevant topics. I was soon drawn into this area. My own activity since that time has been primarily focused on producing, in laboratory experiments, dynamical processes that are relevant to astrophysics. The first major emphasis, for the community focused on dynamical processes, was on hydrodynamics, where we were able to most readily adapt experiments that had been developed for ICF.

Layered, complex targets can produce combinations of shock waves and expansions that create structures of interest for laboratory astrophysics and other applications. Some examples can illustrate how these have proven to be of use. If the ablator or a subsequent dense layer is sufficiently thick, the laser-driven shock evolves in to a blast wave, having a shock front followed by an expansion. There are other ways to produce blast waves, but this one is relevant here. If the blast wave reaches an interface with lower-density matter, structure at the resulting interface grows by the Rayleigh–Taylor instability. This mechanism also creates structure within supernovae, for which the observations and simulations do not readily agree. This motivated and enabled a long sequence of laboratory astrophysics experiments probing this unstable mechanism (for example, see [26–29]), later extended to experiments relevant to energy transport in supernova remnants [30]. If one introduces a gap between the initial, dense matter and a layer of less-dense matter, one can produce an expanding flow that then impacts a stationary material. Figure 4 shows how this type of flow enabled experiments relevant to supernova remnants [31–35]. Another application of targets with a gap has been to produce gentle (isentropic) compression of matter [36], useful for equation-of-state studies. Other hydrodynamic HEDLA studies that followed our initial experiments included a lot of work on hydrodynamic jets, and some work on clump destruction by shock waves. With time, HEDLA research has broadened into areas far beyond the initial experiments involving hydrodynamics and x-ray absorption.

Structured targets are also used to observe fundamental hydrodynamic behavior and especially hydrodynamic instabilities. They have an advantage over other experimental approaches, in that the initial conditions can be precisely machined on interfaces, which are then converted to plasma by shock waves or other mechanisms. Experiments of this type began in the late 1980s and continue to this day. The Rayleigh–Taylor instability at ablating surfaces is of direct relevance to ICF and has been the focus of experiments since the 1990s [37, 38]. At interfaces embedded within structures, Rayleigh–Taylor is of fundamental interest and has also seen work from the mid-1990s [39] to recent designs [40] and experiments [41, 42] for NIF. My own involvement in this area came as we sought to produce original observations of fundamental hydrodynamic processes in compressible flows, a topic important in both the laboratory and astrophysics. This reflected a partial transition in our HEDLA research, once we realized that the objects of interest to the astrophysicists change from year to year, while it takes several years or more to produce an experimental result on any specific topic. It began with the first experiments to observe the Kelvin–Helmholtz instability [43, 44], followed by much other work on that process. This included work by our collaborative team.
3. Radiation transport and radiation hydrodynamics

My first experience with radiation transport came in our modeling of experiments aimed at plasma hydrodynamics in supernova remnants. We had to use what is known as a discrete-ordinates method, for reasons that are not important here, to accurately calculate the behavior of a laser-shocked target [33]. Soon after, though, we began to seriously engage the problem of doing radiation-hydrodynamic experiments, motivated by the request of our astrophysical colleagues for results against which they could test their codes. This led us to choose to produce and study radiative shocks, a quest that has continued now for 20 years.

We were limited at first by experimental capabilities, and so were able to produce shock waves having shock-produced radiative precursors in low-density foam [72], which followed a less-detailed experiment done much earlier in France [73].

Over the next few years, we saw the advent of techniques for filling targets with a controlled density of gas. As a result of the differing diagnostic facilities, European researchers concentrated on measurements of the radiative precursor that forms ahead of the shock, in xenon at pressures near 0.1 atm, diagnosed using optical techniques. The seminal paper on precursor properties was that of Bouquet et al [74] in PRL. It was followed by quite a few others (a few: [75–77]), including one [78] that corrects a physics error in the first paper. Our own work focused on the properties of the highly compressed dense layer, using xenon at pressures near 1 atm, diagnosed using x-ray radiography. The seminal paper from this work was that of Reighard et al [79], which, naturally PRL declined to accept. (I was so angered by the editorial handling of that paper that I boycotted that journal for a few years.) Extensive further research on this topic produced many publications; here are cited a few [80–83]. Our images of the dense, shocked layer have been used to validate several radiation-hydrodynamic codes. Other work with radiative shocks has included the observation of secondary shocks during the late-time evolution of radiative blast waves [84], the observation of radiative precursors produced when electron energy transport heated a dense shell [85], and the observation of radiative, quasi-spherical, blast waves produced by high-pressure explosions [86].

Figures 5 through 8 illustrate the design, target structure, data, and results from some of these radiative-shock experiments, performed at the Omega Laser Facility and not previously published. In a project focused on testing the predictive capability of simulations, we drove a radiative shock through a nozzle and down an elliptical tube. Figure 5 shows a schematic of these experiments. The tube initially contained 1 atm of Xe gas. The laser-accelerated Be first drove a diverging, curved shock into a circular tube, before the nozzle constricted the motion along one transverse axis. Figure 6 shows a photograph of one of these targets. They are mounted on a stalk, filled by a fill tube, and have a conical shield to protect the diagnostics from signals generated when the laser beams strike the Be ablator. An acrylic superstructure sustains the elliptical shape of the tube, and has access holes through which the x-rays for radiography pass. Figure 7 shows data from one experiment in this configuration. One can see the shock wave...
within the thin, polyimide tube that confines the gas, and can see substantial structure on a wide range of scales. One can also see, by comparison with the radiographic data shown above in figure 4, that the quality of the diagnostic images improved substantially during the decade between these two measurements.

The data of figure 7 are from a project focused on testing the predictive capability of simulations using the multiphysics code [87–89] we call CRASH. CRASH incorporates standard physics and methods. Highlights are that it is an Eulerian code, includes dynamic adaptive-mesh refinement, works with tabular equations of state and opacities, follows electron- and (multigroup) radiation-energy transport by flux-limited diffusion, and has an accurate laser-energy deposition model (for collisional absorption). We ran the code for cases designed to characterize how its output responded to the variation of chosen input parameters across a range of uncertainty, developed probability distributions based on comparisons with data from radiative shocks in circular tubes [90], and used this information to predict the results for the elliptical case. As one can see in figure 8, the distribution of predicted location overlapped with the distribution of observed location but the majority of the shock locations were above the prediction intervals specified by the statistical models. We were disappointed when the sponsor shut down their entire program of related research, leaving us with only speculations about the origins of the discrepancy. It was interesting that the physicists on the team felt that the code plus the statistical model had done pretty well, while the statisticians on the team were quite disappointed.

A cautionary note, for those who develop an interest in them, is that radiative shocks are complicated systems, and can exist in several regimes. Early work, and some more recent, often contains errors that result from an incomplete understanding. By the time we were well into this area, I was actively writing my textbook, and the need to understand and explain these systems led to some theoretical contributions regarding the shocks produced in these laboratory systems [1, 91] and also deep within systems in which the radiation is trapped [92, 93]. One of the more entertaining details of these studies was the discovery that radiation can at times flow ‘uphill’, in the direction opposite of that calculated by a diffusion model [94]. This occurs within very thin hot (or cold) layers, which one often finds in radiative shocks.

Returning to the science, more recent work in radiative shocks has included the observation of radiative reverse shocks [95, 96], colliding radiative shocks [97], and radiative shocks that affect instabilities at a material interface [30].

### 4. ICF and a few other pieces

My career in high-energy-density physics began in the ICF program at the Lawrence Livermore National Laboratory, where my first supervisor, one E. Michael Campbell, insisted I begin by working to understand the basics of how ICF works. Since that time hundreds of papers on ICF progress have been published, and this is not the place to review them. A couple of related items seem worth pointing out. Some new aspects of the behavior of mid-Z and hi-Z targets have come to be understood in the past decade [98, 99]. It also surprised me to find, upon exploring the ICF problem in more detail recently, that the implosions that attempted to produce ignition during the early years of operation of the NIF were significantly more demanding than those that would be needed in an ICF power plant. Specifically, they required much more convergence of the fuel capsule.

In laboratory astrophysics, our astrophysical colleagues also called for work on collisionless shocks in magnetized plasmas. This motivated me to write a design paper laying out conditions for such experiments [100]. It was clearly premature, but eventually helped motivate work that has recently made great progress [101–103]. In the meantime, Kato and Takabe [104] realized that laboratory experiments could explore the mechanisms at work in forming collisionless shocks in initially unmagnetized media, hypothesized to be relevant to gamma-ray bursts [105]. A wide range of work on this and related problems has ensued, of which some examples include [106–109], and [110]. Its culmination so far has been the observation of the Weibel instability thought to initiate the shock formation [111, 112]. Meanwhile, researchers using intense lasers identified an approach to produce collisionless shocks within their very dense, but very strongly heated, targets [113].
It has been known for decades that laser-produced plasmas generate strong magnetic fields in their coronae [114]. Even so, as recently as the early years of this century, one could not find any US agency interested in funding research with magnetized flows produced by high-energy-density facilities. (My own background in this area came from teaching basic plasma physics and space plasmas, and from my early years in magnetic fusion.) Today this has radically changed, which motivated a much expanded discussion of magnetized flows in my second edition [2]. The importance of magnetized flows to the operation of Z pinches came to be appreciated [115–117]; they have since become a key part of an approach to fusion called MagLiF [118, 119]. The group led by Sergey Lebedev at Imperial College London showed the world that Z-pinches could also be used for laboratory astrophysics [120, 121]. Researchers have also developed a number of devices [122–124] that can create magnetic fields in laser facilities which are strong enough to affect the plasma flows they can produce. Among other applications, these have been used extensively for laboratory astrophysics research. Among many others, examples include the excellent paper by Albertazzi et al [125] and the seminal first observations of a turbulent plasma dynamo by Tzerferacos et al [126]. I believe that this last accomplishment would have made any sensible list of grand challenges in plasma physics compiled in recent decades. So it was disappointing, though not surprising, to hear that the authors had a difficult time getting it published in a ‘high-profile’ journal.

5. Conclusion

In concluding I would like to address two issues that seem relevant to the progress of inertial fusion, high-energy-density physics, and related science. The first of these is publications. The world has an obsession with ‘high-profile’ publications, which I have come to conclude is misplaced. Early in my career, the main target of our community was PRL, and as you can see I published there a lot. But reflecting on 40 years of experience, both as an author and as a referee, having excellent work published in PRL is a statistical process, with a bias against truly novel work. More recently, there has been more emphasis on publishing in Science or Nature, to which the publisher of Nature has responded by providing more journals. A colleague noted that it takes an extra year of work, massaging the message and the details, to get a paper into these journals, assuming one manages to get the interest of an editor to start with. In addition, these journals tend to follow fields their editors consider to be ‘hot’. So managing to publish there involves some combination of luck and ambition. Yet neither of these qualities would fit into a proper definition of excellence in science. In the time one spends massaging the

Figure 7. Radiographic images of a single, radiative-shock experiment from orthogonal views. The shock is propagating from left to right. One can see the shock tube walls at the top and bottom by limb-darkening. The other structures at the top and bottom are for spatial and intensity calibration. The radiative shock is moving to the right, within the tube. The minor axis (left) and the major axis (right) of the ellipse were imaged. Both images were taken 26 ns after the initial laser pulse began. Reproduced from [128]. CC BY 4.0.

Figure 8. Posterior prediction intervals for shock location, viewed along the minor axis, versus time. Grey curves show a sample of simulated trajectories at different input settings, green curves are 95% prediction intervals incorporating parameter and input uncertainty, black curves form 95% prediction intervals incorporating parameter and input uncertainty, discrepancy variation and observational uncertainty. The circles are the observations from the experiments. Credit for the statistical analysis and figure: Reproduced from [128]. CC BY 4.0.
message, one could publish two excellent papers in excellent journals, like this one. My own view is that what our field needs, and should honor and support much more, is review papers. It would also be better to see the present-day, high-profile journals evolve to present curated collections of high-impact or high-value results initially published elsewhere, with well-informed commentary.

Considering that the occasion of this paper is the Edward Teller award, I want to take up one final topic on which he spoke strongly. Our work in understanding and simulating [89] radiative shocks in xenon was substantially limited by outdated, though always foolish, classification rules. Edward Teller was vociferous, and right, about the negative impact of classifying research. In an interview with US News and World Report, published on 29 May 1967, Teller said ‘if we insist on keeping secret things that we do keep secret for years, I will say that a considerable fraction of these secrets are secrets only in our imagination, information kept from our own people .... ’. In 1973, Teller urged the US Congress to pass a law requiring that all secret government research be declassified one year after it was completed. I agree with him. It is always a mistake to classify fundamental science, because worldwide science moves forward yet undoing classification is a bureaucratic nightmare. In the end, one harms ones own interests by restricting research in an area once thought important enough to classify, which in turn reduces the ability or interest of academics in training new researchers. The US and some other countries have gone down this path with regard to the properties of materials of high atomic number, such as gold or xenon, at high temperatures. There are now very few scientists under age 60 in the US who understand them well. And nothing practical has been gained. Any potential target of the classification has ample resources, and has had decades, to learn whatever they wanted to know. One senior manager in a major laboratory recently expressed to me his concern about the absence of such people. Well, one reaps what one sows.

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