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Miniature supernova shock waves

A laser–plasma experiment has recreated shock waves in collisionless, weakly magnetized conditions and evidenced electron acceleration to relativistic energies, offering unprecedented insight into a long-standing problem in astrophysics.

Laurent Gremillet & Martin Lemoine

Figure 1: Zooming in on a supernova shock wave: Tycho's supernova remnant, revealing soft X-ray emission from the interior shocked gas (in red), and hard X-rays from electrons accelerated to TeV energies at the shock wave (in blue). The inset shows a zoom (not to scale) on the structure of the collisionless shock. © X-ray: NASA/CXC/Rutgers/K.Eriksen et al.; Optical: DSS; numerical simulation: CALDER/L. Gremillet; photomontage: C. Henneguez.

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In highly rarefied space plasmas, supersonic motion spawns collisionless shock waves, that is, shocks whose dissipative properties proceed from particle scattering in self-generated electromagnetic fields rather than Coulomb collisions. This remarkable feature turns those

structures into efficient particle accelerators *à la* Fermi [1], in which particles gain energy from repeated bounces in the electromagnetic turbulence across the shock front. Accordingly, cosmic phenomena glow with non-thermal radiation from highly relativistic particles and the very origin of cosmic rays can be traced to the collisionless shock fronts of supernova remnants. Evidence for particle acceleration up to energies well above 1 TeV in these objects has accumulated over the years [2] as illustrated in Fig. 1. More generally, collisionless shock waves and their phenomenological consequences are thought to shape much of the high-energy, multi-messenger Universe. Thus, generating a collisionless shock in the laboratory, and one that can give rise to particle acceleration as reported now by Federico Fiuza and co-authors [3] in *Nature Physics* represents an experimental feat.

In itself, the structure of a collisionless shock is a famous problem of plasma physics [4]. It depends on both the shock velocity and the Mach numbers, in particular the so-called Alfvénic Mach number (ratio of the shock velocity to the speed of the incompressible normal modes of the magnetized plasma) that scales inversely to the magnetization degree of the unshocked medium. Shock waves of moderate magnetization (Alfvénic Mach numbers around ten) abound in interplanetary space. For those, spacecrafts have provided a wealth of *in situ* data up to the edge of the Solar system. However, supernova shock waves are not only faster (thousands of kilometres per second), they are also significantly less magnetized (Alfvénic Mach numbers of several hundreds). In this regime, the turbulence that initially sustains the shock transition is believed to result from the electromagnetic Weibel instability [5] that generates microscopic random electromagnetic fields out of momentum space anisotropy. Here, the anisotropy stems from the counterstreaming of the ambient plasma and the particles reflected off the nascent shock surface. Thereon, the Weibel instability fragments the plasma into magnetized filaments whose nonlinear evolution mediates the shock transition [6]. As this process takes place on scales orders of magnitude below what can be resolved from observations, the structure of these shock waves has remained elusive.

How a particle is extracted from the thermal ambient plasma and injected with sufficient energy into shock acceleration represents yet another puzzle, pivotal to our understanding of the radiative properties of collisionless shocks. This problem is more acute for electrons than for ions, as their mean (thermal) energy would scale proportionally to their mass, should both species cross the shock without being influenced by the other. Observations indicate that electrons draw extra energy from the shock but how so remains under debate. This is where the experiment of Fiuza and co-authors finds special importance.

Conducted with the world's largest laser at the National Ignition Facility (NIF), this experiment consisted of irradiating two deuterated carbon foils, placed a few centimetres apart facing each other. More than a hundred laser beams delivered a total energy of about 1 MJ in 3 ns, vaporizing the targets into plasma plumes, which then expanded and interpenetrated at high velocities (of about 2000 km/s). The Weibel instability that ensued in the counterstreaming region generated magnetic fields on sub-millimetric ion skin-depth scales that were strong enough to halt and thermalize the ions, thereby generating a double-shock system representative of supernova remnants. Laser ablation permeated the pre-shock plasmas with a net, large-scale magnetization, but at a level sufficiently low to preserve weakly magnetized conditions with an Alfvénic Mach number of around 400. Shock formation was demonstrated by measuring a fourfold plasma compression around the contact plane, together with bulk electron heating to tens of millions of Kelvins.

Remarkably, the shock was sustained long enough to accelerate electrons to relativistic energies about two orders of magnitude above the thermal shocked plasma.

This achievement builds upon a decade of experimental and theoretical progress in the field [7]. The key to success in the experiment of Fiuza and co-authors was to ensure that the turbulence developed rapidly enough during the interaction, and that the overlapping plasma region remained substantially larger than the scattering length of the ions in the turbulence — yet much smaller than their collisional mean free path. Dense plasmas were thus needed to speed up the turbulence growth, but not excessively so lest collisions affect the system dynamics. The high flow speeds that are desired to hasten the instability also require strong laser heating and sufficient spacing between the targets — conditions attainable with a NIF-class laser drive. It should be noted that collisionless shock waves have been produced before using lower-energy lasers, but at higher magnetization and smaller velocities [8]. While no longer underpinning the shock formation, some Weibel-driven turbulence may then still arise to generate suprathermal electrons as observed recently [9].

Albeit impressive, the study of Fiuza and co-authors remains limited in its ability to diagnose the self-induced fields, the degree of ion heating and the very mechanisms through which electrons are accelerated. The data are interpreted through kinetic numerical simulations but these are forced — as is standard — to use a reduced dimensionality, an artificially low ion mass and scaled-up ion velocities, which precludes direct comparison with the measurements. These simulations indicate that the electron acceleration occurs through repeated encounters with moving structures in the shock transition layer, in general agreement with theoretical views [10]. However, the measured electron spectrum does not exhibit the power-law seen in the simulations, and the reason for this deserves further scrutiny.

Finally, a nagging question regarding such experiments is whether Coulomb collisions, which are neglected in kinetic simulations, may alter the electron dynamics and also, to some extent, the turbulence growth. At stake is the true similarity between the experimental and actual supernova remnant shock waves. While ion–ion collisions between the interpenetrating beams can be safely neglected, electron–ion collisions remain frequent on the experimental timescale, at least for electrons with near-thermal energies. Appraising their impact on the properties of laser-driven shocks, and particularly on the electron energization processes, will undoubtedly spur further experimental and simulation studies.

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