Accelerators and Dinosaurs

Michael S. Turner

Sixty-five million years ago, dinosaurs ruled Earth, and then astrophysics killed them. To be fair, Earth and a 10-km-sized asteroid suffered a collision governed by the laws of Isaac Newton, a physicist, not an astronomer. Since World War II, accelerators have ruled the world of big science, with no less success than the dinosaurs. Bigger and better accelerators probed matter down to the level of its most basic constituents—quarks and leptons—and in the process established the standard model of particle physics, an elegant mathematical description of the deep inner workings of nature. Then—according to some—astrophysics struck accelerators dead as the dinosaurs.

The villains in this apparent replay of the dinosaur tale are advocates (including me) for using the universe as a Heavenly Laboratory to address pressing questions in particle physics. And indeed, there have been some notable successes. Experiments using beams of neutrinos from the Sun and cosmic-ray collisions in Earth's atmosphere have provided us with the first solid evidence for neutrino mass, and telescopes tracking distant supernovae have revealed the presence of the mysterious dark energy that is causing the expansion of the universe to speed up.

Our zeal and these successes may have made accelerators appear to be the dinosaurs of 21st-century science. But far from it, discoveries made in the Heavenly Lab have made accelerators even more important. Not only are accelerators essential to probing the world of elementary particles, but also they can make (and have already made) discoveries that are critical to understanding the cosmos. The two have a yin–yang complementarity: The Heavenly Lab offers enormous dynamical range in energy, density, and other parameters, while accelerators offer repeatable experiments under carefully controlled conditions.

Not just for cosmology anymore

Before explaining why astrophysics has made big accelerators even more important, I remind my readers that only a handful of the more than 15 000 accelerators in operation around the world are used in particle-physics research. This fact would not surprise Ernest O. Lawrence, who saw an importance far beyond physics research. He and his brother John, a physician, pioneered the medical applications of accelerators at Berkeley. Today, one-third of all accelerators are involved in medical applications, such as cancer therapy, imaging, and the production of short-lived isotopes. The other two-thirds are used for industrial applications ranging from micro-machining to food sterilization and for national security applications, which include x-ray inspection of cargo containers and nuclear stockpile stewardship.

In 1946, high-energy accelerator master-builder Robert R. Wilson, the designer of the Harvard University proton cyclotron and later Fermilab, made a strong case that protons have promise in cancer therapy because their range is predictable and because they deposit most of their energy where they stop. Fifteen years later, Harvard physicists and Massachusetts General Hospital doctors began treating cancer patients with a proton beam from the Wilson cyclotron. At Fermilab, Wilson and his colleagues created a special neutron beam for cancer therapy, which has been used to treat patients for almost 30 years, and helped the Loma Linda University Medical Center in California build the first dedicated proton-therapy facility.

In the 1940s, John Blewett, Herbert Pollock, and other General Electric scientists succeeded in detecting synchrotron light from electrons running in circles. Some 20 years later, the first dedicated synchrotron light source started operating at the University of Wisconsin. In 1975, NSF funded the first x-ray light user facility, which operated parasitically off the high-energy SPEAR electron–positron storage ring at SLAC. The success of this and other facilities led to second- and now third-generation synchrotron light sources. These dedicated facilities enable a broad program of science, from surface physics and chemical dynamics to structural biology and semiconductor physics, and are in operation around the world. Fourth-generation machines will feature much brighter beams with much shorter pulses than those currently operating.

Today, accelerators produce beams of all kinds of particles for all kinds of purposes. Neutron scattering has applications ranging from magnetism and superconductivity research to genomic biology and materials engineering. Other accelerators produce and then reaccelerate short-lived nuclear isotopes to carry out fundamental nuclear research, including the study of the nuclear processes in stars that produced the elements in the periodic table. (You just can't get away from astrophysics!)

Accelerators are clearly a highly diversified species, in no danger of extinction.

Sakharov and star stuff

Although the first evidence for neutrino mass came by way of heavenly neutrinos, only by using accelerator-produced neutrino beams of well-determined energy, flux, and flavor content will we be able to sort out the pattern of neutrino masses and get at neutrino *CP* violation. (*CP* is the symmetry operation that relates particles and antiparticles, where *CP* is the product of charge conjugation, *C*, and coordinate inversion, *P*; *CP* violation refers to the small difference in the laws of physics for particles and antiparticles discovered by James Cronin, Val Fitch, and their collaborators almost 40 years ago, with an accelerator.) Doubtless, neutrinos will teach us about the unification of the forces. (Neutrino mass is one of the basic predictions of theories that unify the strong, weak, and electromagnetic interactions.) But we have a more personal stake. It now seems possible, even likely, that neutrino mass and *CP* violation had something to do with creating the matter that became stars, and ultimately, the stuff like us that came from the stars.

The existence of quark-based matter is remarkable, even by cosmological standards. For our quarks to have survived the simmering particle soup that existed during the earliest moments, there must have been a tiny excess of

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quarks over antiquarks—a few extra quarks per billion. Without such a quark–antiquark asymmetry, quarks and antiquarks would have annihilated each other to negligibly small numbers when the universe was microseconds old. With an asymmetry, a few quarks survived and combined into the baryons (neutrons and protons) that are still with us today. So where did the crucial quark excess come from?

The first inklings of a solution came in 1967 when Soviet physicist and dissident Andrei Sakharov gave a seminar that left his colleagues scratching their heads. He explained how *CP* violation, baryon-number nonconservation, and the early rapid expansion of the universe could conspire to produce an excess of quarks over antiquarks. Violation of baryon-number conservation is needed if a symmetric quark–antiquark soup, a state of zero baryon number, is to develop an excess of quarks, a state of positive baryon number, B. (Quarks carry baryon number $\frac{1}{3}$ and antiquarks carry baryon number $-\frac{1}{3}$). A preference in the laws of physics favoring quarks over antiquarks is needed to ensure a uniform excess of quarks, rather than quarks here and antiquarks there. The role of the expansion is more subtle: In thermal equilibrium, the net baryon number is zero even if B and *CP* are violated; the rapid early expansion of the universe leads to a quickly dropping temperature that prevents thermal equilibrium from being established.

The seminar left Sakharov's colleagues befuddled because there was no evidence or even theoretical motivation for B nonconservation and even less appreciation for the cosmological puzzle of the matter–antimatter asymmetry. (The dinosaurs didn't see astrophysics coming either.) Now we have an appreciation of the need for a cosmic quark excess and ample motivation for B violation; for example, B violation is a central prediction of theories that unify the strong, weak, and electromagnetic interactions.

Neutrino mass implies that lepton number is not conserved, provided that neutrino masses are of the Majorana type, as is currently favored. And if neutrino interactions violate *CP* (why not? *CP* violation is a feature of the world of elementary particles), then an excess of neutrinos over antineutrinos could develop in the early universe. Interactions predicted by the standard electroweak theory violate fermion number (the sum of net baryon number and net lepton number) and can transmute a neutrino asymmetry into a quark asymmetry. Voilà—we may exist because of neutrinos. We need accelerator experiments to shed light on neutrino masses and *CP* violation to give us more clues on why we exist!

Quark soup and the dark side

On to darker matters. Cosmologists have put forth a compelling case for a remarkable idea: The dark matter whose gravity holds together all structures in the universe, from our own galaxy to distant superclusters, is composed of elementary particles left over from the earliest moments. Neutrinos are a part of the cosmic mix, but based on what we already know about their masses, they can account for at most 10% of the dark matter. The lightest supersymmetric particle—the neutralino, whose mass is expected to be about a hundred times that of a proton—is the prime dark-matter suspect. Supersymmetry (SUSY) is the hypothetical symmetry that relates fermions and bosons and is at the root of attempts to unify gravity and the other forces and to understand why the Higgs boson is not incredibly heavy. If SUSY is correct, then there is a heavy SUSY partner for every known particle and the lightest of these SUSY partners (the neutralino) is stable.

The race is on. Particle physicists are trying to produce the neutralino at the highest-energy accelerators, Fermilab's Tevatron and, in the future, CERN's Large Hadron Collider. Physicist–astronomers (I am too polite to use the term "half-astrophysicists") have put ultrasensitive "neutralino telescopes" in deep underground labs to detect a few of the swarm of neutralinos believed to be holding our own Milky Way together. The astrophysicist in me is rooting for Milky Way neutralinos to be detected first. But I also know that producing and studying neutralinos with accelerators is an indispensable part of the plan if we are to truly understand how neutralinos fit into the grander scheme of things and if we are to convince the Kansas School Board to include neutralinos in the curriculum. In a similar vein, for more than 20 years in public lectures I have been explaining how the universe began from quark soup; until the Relativistic Heavy Ion Collider at Brookhaven produces evidence for quark–gluon plasma in the lab, I am not on totally firm ground.

Payback time

In the 1970s, when cosmology was stalled, discoveries made at accelerators launched my field into its current renaissance. The discovery of the cosmic microwave background radiation in 1965 had told us the universe began as a hot particle soup; however, not knowing about quarks and gluons erected a brick wall at 10 microseconds. If the fundamental particles are the finite-sized neutrons, protons, and other hadrons, the universe had a confusing beginning with overlapping particles and a maximum temperature of only 100 MeV, due to the exponentially rising number of hadron states.

The emergence of the standard model of particle physics in the late 1970s opened the door to the study of the earliest moments of the universe, with its temperatures as high as 10^{19} GeV. Because quarks, leptons, and gauge bosons are pointlike and weakly interacting, the early universe is then no harder to understand than a dilute, hot plasma. In the 1980s, the driving ideas in cosmology today—inflation, dark matter, and Sakharov's baryogenesis—were developed; all have their roots in the hard-won knowledge about quarks, leptons, and gluons that has come from accelerator experiments.

Further progress in understanding the universe's origin, its evolution to its present state, and its ultimate destiny will involve accelerator experiments that will teach us more about nature's deepest inner workings.

Cosmology has added new urgency to questions that particle physicists are asking. For example:

- Higgs or no Higgs? Inflation is based on a scalar-field cousin of the Higgs.
- SUSY or not? Superpartners, superstrings, and SUSY-breaking all have important cosmological implications.
- Extra dimensions or not? If extra dimensions exist, they may have had important implications for the birth and early evolution of the universe.
- What is the nature of *CP* violation? The origin of quark-based matter—and us—is fundamentally tied to *CP* violation.

I would not even rule out accelerators teaching us something profound about dark energy, that diffuse, mysterious stuff whose only known effects are to cause the speeding up of the expansion of the universe and to keep me awake at night trying to figure out what it is.

Cosmology and particle physics have been drawn together by discoveries made using both telescopes and accelerators. The two fields are now joined at the hip by a new set of profound questions, whose asking and answering cannot be neatly partitioned into physics and astronomy. To realize the grand opportunity to advance our understanding of the universe, of the laws that govern it, and even of our place in it, we will need both accelerators and telescopes. Far from killing off high-energy accelerators, astrophysics has made them more relevant than ever. ■