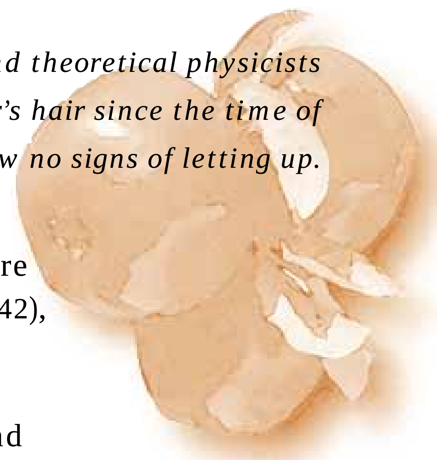
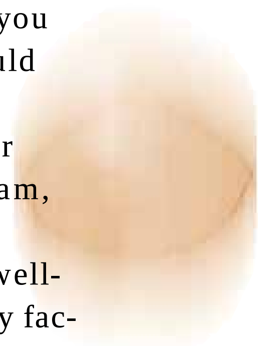
by VIRGINIA TRIMBLE

The Astro-Particle-Cosmo-Connection



Observational astronomers and theoretical physicists have been getting in each other's hair since the time of Newton and show no signs of letting up.

FOR ISAAC NEWTON (1642–1727), though there were laboratory data from the work of Galileo (1564–1642), the British Union of Growers of Poorly-Attached Apples (BUGPAA), and probably others, the real test of universal gravitation was its application to the lunar and planetary orbits that Johannes Kepler (1571–1630) had managed to extract from the observations of his mentor Tycho Brahe (1546–1601). Looking at the various dates, you might reasonably suppose that the planetary orbits would have been somewhat improved by the time *Principia* approached publication (1687), but as the names of other seventeenth-century astronomers will not be on the exam, you are not required to read or remember any of them.



Entering the twentieth century, we find the equally well-known example of Einstein's theory of general relativity facing reality in the form of the advance of the perihelion of Mercury* and the gravitational deflection of light by the sun.** From that day (1919) to this, GR has passed every test astronomy can throw at it, especially the correct description of the changing orbits of binary pulsars (meaning neutron stars in orbits with other neutron stars or massive white

**Meaning that Mercury's elliptical orbit rotates once every 3 million years relative to the distant stars.*

***Meaning that the apparent positions of stars, and radio sources, have been seen to be shifted on the sky when your line of sight passes close to the limb of the sun.*

Russell Hulse, co-discoverer of the binary pulsar 1913 + 16, whose behavior in the decades since has provided the most stringent available tests of general relativity. (It passed; Hulse won a Nobel Prize.) (Courtesy AIP Meggers Gallery of Nobel Laureates)

dwarfs). In the pulsar case, for which Joseph Taylor and Russell Hulse shared the 1993 Nobel Prize in physics, the physical processes include gravitational radiation and other strong-field effects, for which general relativity makes different predictions from those of other theories that would also fit the solar system, weak-field data.

Those pulsar orbits would be getting larger or smaller if the coupling constant, G, were changing with time. Non-zero dG/dt would also affect the lifetimes of stars (whose rate of energy generation scales like G^5), the range of masses possible for old white dwarfs (supported against gravity by degenerate electron pressure) and neutron stars (supported by degenerate neutron pressure), the dynamical evolution of clusters of stars, and distances within the solar system. Curiously, astronomical observations lead to just about the same limits on dG/dt from all of these systems: not more than about 10 percent either way in the 10–20 Gyr age of the universe. Such observations, as well as the Mercurian orbit advance, also tell us that the speed of gravitons is very close to the speed of photons in a vacuum. One always writes the equations with c, but one means c(gravity), not c(light).

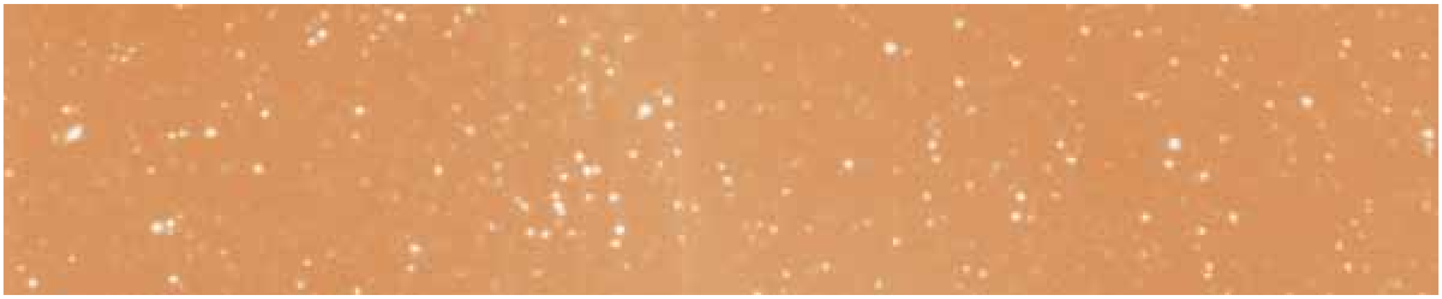
OTHER HISTORICAL EXAMPLES AND FALSE ALARMS

Particle physics can perhaps be said to have begun with the discovery of entities beyond the n, p, and e found in ordinary atoms. The first were the positron, the mu ("Who ordered that?") meson, and the pi (Yukawa particle) meson. All first appeared as upper-atmosphere secondary cosmic rays (ones produced when primary cosmic ray protons hit atmospheric molecules—very hard). A convenient date to remember is 1937, when a shower of papers by people you have heard of in other contexts (Heitler, Oppenheimer, Serber, Homi Bhabha) clarified that these were indeed secondary products but also new particles with well-defined properties.

Astronomical considerations have also made occasional contributions to nuclear physics, most famously in 1953, when Fred Hoyle realized that the carbon-12 nucleus must have a particular excited state, or we would all be made out of pure hydrogen and helium, no further fusion being possible in stars. More recently, the need for lifetimes, energy levels, and cross sections of nuclides likely to form in exploding stars, but most unlikely in the lab, have driven both calculations and experiments.

From time to time, astronomers have concluded that some set of observations simply could not be explained in terms of the (then) standard model of physics and have attempted to invent what they thought was needed. Like many other examples of hubris, this has typically been punished, exile from the community being the most frequent outcome. Some cases are relatively well known, like the Steady State universe, invented to allow stars and galaxies to be older than the apparent cosmic expansion time scale, but requiring the addition of a creation field to general relativity or other theories of gravity. The suggestion that atomic spectral lines can be redshifted by something that is not a Doppler effect, not the expansion of the universe, and not a strong gravitational field, at least when those lines come from quasars, is another well known example.

Less famous, perhaps, are James Jeans' proposal that spiral nebulae represent new matter pouring into the universe, "white hole" explanations of quasars, and the prestellar matter of Viktor Ambartsumian, who believed that clusters of new stars expand out of regions of very



dense, prestellar stuff, perhaps a bit like Gamow's Ylem, but not confined to the early universe, and then in turn expel gaseous nebulae from their surfaces to produce configurations like the stars and gas of Orion. (Conventional stellar evolution tracks do roughly the reverse, beginning with gas and ending with very dense remnants.)

As time goes on, the various possible interactions between astronomy, cosmology, particle physics, and so forth that are discussed in the following sections will move to this one. I am not prepared to guess which will then be seen as "interesting historical examples" and which as "that was an astronomer who thought he was Feynman."*

Leo Goldberg

Academician Viktor Ambartsumian, who died last year, was among the first astronomers to propose a specific mechanism for the formation of expanding clusters of massive, young stars. He later extended the idea (expansion from some kind of very dense, prestellar material, different from known interstellar or laboratory gases) into a possible explanation for quasars. (Courtesy AIP Emilio Segrè Visual Archives)

THINGS THAT DO NOT GO BUMP IN THE NIGHT

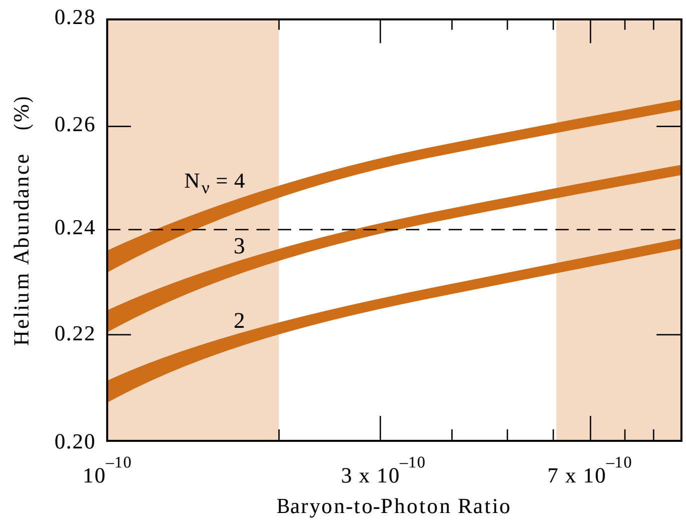
You could write a whole book about the exotic particles, properties, and processes that we know do not exist because they would violate some set of astronomical observations. In fact someone has (Georg Raffelt; see the list of "more reading" on page 51). The general idea is that stars must be allowed to form from the interstellar medium, do their nuclear thing for millions or billions of years, and die as planetary nebulae + white dwarfs (from low mass stars) or as supernovae + neutron stars or black holes (from stars of more than about 8 solar masses), at all times adhering to a set of nonlinear differential equations that describe conservation laws, rates of energy generation and transport, and equilibrium between pressure and gravity. The detection of neutrinos from SN 1987A with very much the temperature, time scale, and flux that had been expected from neutron star formation brought this whole field into considerable prominence. The constraints are sometimes quite tight simply because, on the whole, stars manage pretty well with just the standard-model physics that we are all so tired of.

In addition, any new entities you might want to postulate must not be so numerous and massive as to make the average density of the universe big enough to slow the expansion measurably today (since we see no such slowing). Nor are they (or you) allowed to spoil the set of nuclear reactions at high density and temperature that produce deuterium, helium (3 and 4), and a bit of lithium-7 in the early universe ("big bang nucleosynthesis"). I mention here only a small, representative set of examples and urge you to peruse Raffelt's book for many more and for the corroborative details.

1. There must not be too many magnetic monopoles floating around, or they will short out the large-scale magnetic fields of Jupiter, pulsars, and the interstellar gas. This Parker (for Eugene of Chicago) limit means that such monopoles must have rest masses of at least 10^{16} GeV if they are to be dynamically important in the universe.

2. The magnetic dipole moment of the electron neutrino cannot be more than about 3×10^{-12} of the Bohr magneton, or the neutrinos from SN 1987A would never have

**The original image here was a* New Yorker *cartoon bearing the caption: "That's God. He thinks he's a doctor."*



Plot of some of the consequences of nucleosynthesis during the hot dense (big bang) phase. Observed abundances of lithium-7 and deuterium in gas and stars that have experienced very little nuclear processing require that the real universal density of baryonic material (the baryon-to-photon ratio) fall somewhere in the white stripe—corresponding to a baryon density less than 10 percent of the closure density. Then the fact that the abundance of helium is, at very most, a little more than 24 percent says that there can be at most three neutrino flavors in the early universe. (Courtesy C. Copi and D. Schramm, University of Chicago)

made it out of the parent star and through space to us. This is probably rather smaller than the best laboratory limit, and the 1987A data also set limits to neutrino masses, coupling to right-handed and Majorana neutrinos, and such that are comparable to or better than the laboratory numbers.

3. Quite a few of the things you might think of doing with neutrinos would mess up the early universe, including, in particular, adding to the "known" three flavors. A fourth or fifth neutrino family would speed up the early expansion so much that too many neutrons would survive to form more helium than we see. There is, of course, also a limit of roughly three neutrino flavors from the laboratory width of Z^0 decay, but, because we do not know lifetimes or masses a priori, the two considerations rule out somewhat different volumes of parameter space.

4. Any new bosons or weakly interacting massive particles you might want to dream up must not couple to ordinary or degenerate matter tightly enough to transport much energy in either normal stars or white dwarfs and neutron stars. If they do, you will cool off your WDs and NSs too fast (so we wouldn't see the ones we see) and change the internal density and temperature distribution of nuclear-burning stars away from the ones needed to reproduce known correlations of stellar masses, luminosities, radii, and evolutionary phase.

A cross section of 10^{-36}cm^2 at stellar temperatures borders on being "too big" for a number of these contexts. Another false alarm was the attempt to reduce neutrino emission from the sun by cooling its interior with WIMPs whose cross sections fell in the borderline range. At least two problems resulted. The interior distribution of density no longer matched the one derived from analysis of solar pulsation frequencies, and later stages of evolution, like the horizontal branch phase, became so short-lived that you couldn't account for the large numbers of stars seen in them.

There are also a few cases where something new under the sun might still improve agreement between models and observations. One of these is the possible presence of pion condensate or strange quark matter in the interiors of neutron stars (which we should then call pion stars, quark stars, or some such). Either one will hasten cooling after nuclear reactions stop. This could be useful if existing upper limits on thermal emission from the surfaces of neutron stars should ever get pushed lower than the predictions from conventional cooling curves. In addition, each permits a given mass to be somewhat more compact without collapsing. Thus the star can rotate a bit faster without slinging mud in theorists' faces. At the moment (2:37 p.m. Wednesday, September 25, 1996) the two shortest periods of rotation measured for neutron stars are both quite close to 1.55 msec and are comfortably accommodated by most ordinary equations of state for nuclear matter. The false alarm of a 0.5 msec pulsar reported at the site of SN 1987A several

years ago triggered a considerable flurry of preprints on quark (etc.) stars, some of which made it into print before the report was retracted—and a few afterwards!

Neutron stars remain, of course, the most extreme environment under which we can test pictures of how superfluids and superconductors behave. They also remain awkwardly refractory to experiment.

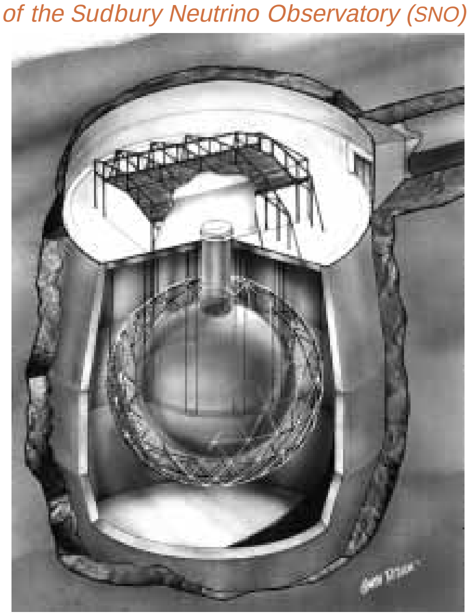
THERE'S GOT TO BE A PONY IN THERE SOMEWHERE*

The two topics on which nearly everybody agrees that astronomers and particle physicists must cooperate if answers are ever to be found are "the solar neutrino problem" and the complex of questions concerning the existence and nature of dark matter, the origin of large-scale structure in the universe (formation and distribution of galaxies and clusters of galaxies), and whatever happened before big bang nucleosynthesis, including inflation, baryogenesis, phase transitions, and miracles. Neither is at all new to regular readers of these pages.

John Bahcall summarized the solar neutrino situation here (see the Fall/Winter 1994 *Beam Line*, Vol. 24, No. 3, page 10). I will summarize still further. First, Raymond Davis Jr.'s chlorine-37 experiment has been seeing a bit less than a third of the predicted flux of high energy neutrinos since before 1970, and the first generation of possible excuses already included many of the astronomical and weak-interaction fiddles that are still with us (for examples see the Trimble and Reines review mentioned under "more reading"). Second, three additional experiments have not clarified things as much as one might have hoped. At the very highest energies that come only from boron-8 decay, the Kamiokande electron-scattering detector has reported about half the number of expected events from the direction of the sun (none of the other devices provides any directional information). And the SAGE and GALLEX gallium detectors also see about half the expected flux, mostly in the form of lower energy neutrinos from the proton-proton reaction ($p + p \rightarrow d + e^+ + \nu_e$).

Third, it is rather difficult to make this combination come out from any fiddle you can think of, mostly because it is the middle energy range that seems to be most deficient. New weak interaction physics, along the lines of neutrino oscillations catalyzed by the presence of nuclei (MSW effect), seems to work better than non-standard models of the solar interior. Fourth, even MSW-type oscillations are squeezed into a very narrow corner of the space of neutrino masses and coupling constants when you also insist on accounting for the anomalous ratio of neutrino flavors among cosmic-ray secondaries made in the atmosphere. Fifth, new detectors under construction or planned (SNO, SuperKamiokande, Borexino) could sort things out (but need not), and I suspect that the last word has not been said on this topic, not even my last word.

**Readers who remember the joke of which this is the punch line are invited to share it with those who don't, preferably keeping in mind that roughly half the preprint pile comes from my side of the interdisciplinary fence and half from yours—unless we are on the same side.*



Artist's conception of the Sudbury Neutrino Observatory (SNO) detector. When fully operational, it will detect all three flavors of neutrinos and give some indication of the direction from which they come. Although sensitive only to the very highest energy (boron-8) solar neutrinos, it should be able to decide if some of the missing electron neutrinos have rotated into mu- or tau-neutrinos. (Courtesy Lawrence Berkeley National Laboratory)

Finally, we come to the constellation of issues associated with dark matter and the very early universe. The observational situation is quickly summarized: 90 percent or more of the stuff in the universe that contributes to gravitational potentials does not emit (or absorb) its fair share of electromagnetic radiation. Dark matter unquestionably exists and outweighs the luminous matter in stars, galaxies, and the gas between them. But we haven't a clue what it is.

Colleagues often object to this second statement. What they mean, however, is not that we have any very definite information about what the dark matter is, but only that we know quite a lot of things it is not. This is progress only if the number of ideas generated by theorists is finite (not by any means a safe bet). For starters, the requirement of not messing up big bang nucleosynthesis almost certainly means that the dark matter cannot all be ordinary stuff made of protons, neutrons, and electrons. Thus we are forced to hypothesize other stuff that is capable of, at most, gravitational and weak interactions, and not of electromagnetic or nuclear ones (again a few colleagues would disagree at some level).

Dark matter, structure formation, inflation, phase transitions, etc. get mixed up together in several ways. First, most obviously, galaxies and clusters live in potential wells made mostly of dark matter, and the nature of the stuff is bound to make a big difference to how galaxies form (and whether we can model them at all successfully, to which the present answer is no, not entirely). Second, galaxy formation might be aided (or impeded) by various topological singularities (cosmic strings, textures, . . .) left from the phase transitions associated with the four forces gradually separating themselves. The supersymmetry arguments that go with the forces having once been the same more or less automatically imply the existence of several kinds of nonbaryonic particles associated with assorted unfamiliar but conserved quantum numbers.

Third, the "inflaton field" responsible for early, exponential expansion of the universe (inflation) could possibly leave behind a small ghost of itself to act as a cosmological constant (Einstein's unloved Λ). Fourth, inflation, at least some kinds, is supposed to leave behind both the exact critical density required to stop universal expansion in infinite time and a spectrum of perturbations of that density with a definite form, well shaped to grow into galaxies and clusters. No obvious astronomical observation would seem capable of proving that inflation happened, but one could imagine definitive dynamical evidence for a total density less than the critical one or for a spectrum of not-yet-evolved density perturbations different from the inflationary prediction. But there are already variants of inflation in the literature that can live with one or both anomalies.

In some ways, this mess looks slightly simpler from the astronomical side. As far as we can tell, for the purposes of galaxy formation and creation of large-scale structure, everything nonbaryonic can be divided among four categories, and it doesn't much matter which example nature has chosen to favor. The four categories are non-zero cosmological constant, seeds (like the topological singularities), hot dark matter (consisting of particles light enough that they are relativistic at $T \approx 3000$K when baryonic matter and light stop talking to each other; ordinary neutrinos of 5–25 eV are the most obvious candidate), and cold dark matter (consisting of particles massive enough to be non-relativistic at the same temperature, like the lowest-mass supersymmetric particle and its cousins; or axions which are low mass but form at rest; and no, I don't know why).

You can, if you wish, have two of these or even three. I am not aware of any scenarios that involve all four simultaneously, but this may well come. The variety is welcomed because no current simulation of galaxy (etc.) formation simultaneously does a very good job of accounting for structures on relatively small linear scales (a megaparsec or less, promoted by CDM), the largest scales (up to 100 Mpc, promoted by HDM), the largest deviations from smooth cosmic expansion that we see, and the observed sizes of those deviations (for example, the dispersion of pair-wise velocity differences between nearby galaxies) as a function of scale length. Choosing a spectrum of initial density fluctuations different from the standard inflationary one allows yet another degree

of freedom. It is not, I think, clear whether what is needed is just further exploration within the territory described above or whether there may still be some important piece of physics missing from the simulations.

There is, however, one thing you can be sure of. I am not going to be the person to holler that the astronomical observations require new physics (or new imperial clothes, or whatever) or to suggest the form that physics should take.

MORE READING

For the multitude of limits on particle properties that arise from considerations of stellar structure, see G. G. Raffelt, **Stars as Laboratories for Fundamental Physics,** 1996, University of Chicago Press.

Strange Quark matter is discussed in G. Vassiliadis et al. (eds) **Proc. Int. Symp. Strangeness and Quark Matter**, World Scientific Press, Singapore and in *Nuclear Physics B* (Proc. Supplement) 24B on Strange Quark Matter in Physics and Astrophysics, 1992.

Atmospheric neutrinos are featured in T. K. Gaiser et al. (1995) *Phys. Reports* 258, 173 and in M. Fukugita and A. Suzuki (Eds.) 1994, **Physics and Astrophysics of Neutrinos** (Springer-Verlag).

Various snapshots of the solar neutrino problem appear in V. Trimble and F. Reines, 1973, *Rev. Mod. Phys.* 45, 1; J. N. Bahcall, **Neutrino Astrophysics** (1989), Cambridge University Press; and Y. Susuki and K. Nakamura (Eds.) 1993, **Frontiers of Neutrino Astrophysics** (Universal Academy Press, Tokyo).

For the various kinds of WIMPs, inos, and other dark matter candidates implied by supersymmetry, see G. Jungman, M. Kamionkowski, and K. Griest 1995, *Phys. Reports*.

And, finally, inflation and other highlights of the early universe appear in A. Linde 1991, **Particle Physics and Inflationary Cosmology**, Harvard Univ. Press, E. W. Kolb and M. S. Turner 1990, **The Early Universe**, Addison-Wesley, and G. Boerner, **The Early Universe, Fact and Fiction**, 2nd ed. 1992, Springer-Verlag.