THE WEAK INTERACTION IN THE UNIVERSE

The mighty mite of particle physics may be what makes supernovas explode.
It may also have pushed the big bang around.

Everybody's favorite supernova remnant, the Crab nebula is a relic of an explosion recorded by Chinese astronomers in 1054 A.D.

BY DIETRICK E. THOMSEN

Supernova explosions are a fairly frequent astrophysical phenomenon. Although a visible one in our own galaxy hasn't happened in more than 300 years, they are often seen in other galaxies and form a staple subject of Astronomical Telegrams, the astronomers' express information network run by the Smithsonian Astrophysical Observatory. Yet astrophysicists have not been able to come up with a good explanation of how they happen.

Steven Weinberg of Harvard University and others now propose one. Their explanation relies on the existence of neutral weak currents, one of the most important features of the new theories of the forces and fields of particle physics, the so-called gauge theories, that Weinberg and others have worked out in recent years. It is, in Weinberg's view, the most telling of the effects of the new theory of the weak interaction in astrophysical phenomena that Weinberg reviewed at the recent meeting of the American Physical Society in Washington.

The weak interaction produces only short-range forces. Unlike gravity, which acts between the galaxies, the weak interaction forces do not extend beyond the dimensions of an atomic nucleus. Of the four interactions known to physics, its role also seems the most marginal. Gravity is responsible for the architecture of the universe; electromagnetism determines chemistry, and the strong interaction governs nuclear physics. The domain of the weak interaction is mainly the spontaneous decays of certain unstable elementary particles, one of which, the neutron, is responsible for nuclear beta decay.

In spite of its short range and comparatively marginal position, the weak interaction does have a role in astrophysics and cosmology. The transmutations of matter that happen under its aegis play a part in the internal dynamics of astronomical bodies, and at certain epochs in the history of the universe they may have had an important influence. The existence of neutral weak currents, which the new theories demand and which experiments are starting to find, alters the astrophysical and cosmological effects in ways that range from significant to minor, and gives an opening for the new supernova theory as well as some more speculative suggestions that are worth mentioning because there could be something to them.

"Current" is a term that represents one way of looking at interactions between moving particles. Electrically charged particles in motion constitute an electric current. On that analogy has grown up a whole theoretical mindset that treats moving particles of all kinds as currents, not necessarily electric, and regards the interaction of two particles, as in a scattering experiment, as an interaction between currents. If one of the effects of the interaction is to exchange a unit of electric charge between the participants, it is said to be a charged-current interaction. If no charge is exchanged, it is a neutral-current procedure. The older theories of the weak interaction involved only charged currents; the new theories require neutral currents as well.

The supernova problem is how to make

it explode. A star reaches the supernova stage late in life. At this point its core has condensed to a neutron star or protoneutron star with a mass about equal to that of the sun. The core is surrounded by an envelope 20 times as massive. Gravitationally one would expect the heavy envelope to collapse onto the core and turn the whole thing into a black hole. Sometimes this may happen, but in a star that becomes a supernova it manifestly does not. The question, says Weinberg, is "how a heavy star can manage to blow off its outer envelope and leave a neutron star at its center."

The pressure of the large number of neutrinos that would appear in such a situation had been suggested as a mechanism, but the calculation did not seem to work, and when James Wilson of the Lawrence Livermore Laboratory put it through his computer code that models explosions, "It seemed to fizzle," as Weinberg puts it, "unlike other explosive simulations they do at Livermore." Then Daniel Freedman of the State University of New York at Stony Brook pointed out that the existence of neutral weak currents permitted a coherent interaction between a neutrino and a whole heavy nucleus that was 200 times as strong as anything permitted by charged currents. Oddly, this new coherent neutrino scattering does not transfer more energy into the stellar envelope than charged-current interactions, but it does transfer a lot of momentum, and momentum is what you need to make an explosion go.

Wilson put this new idea into his computer, and Weinberg and a graduate student, Ira Wasserman, did analytic calculations. In both cases the result is barely enough push to make the explosion. Whether it happens or not depends on details not yet in the computer and possibly extraneous triggering factors. This may explain why supernovas are a sometime thing. They do not happen to every star. Although several dozen a year are observed, that is a minuscule sample compared with the billions of stars in the galaxies under observation.

A less dramatic astrophysical effect is on the cooling rates of condensed bodies such as white dwarfs or neutron stars. These objects cool by neutrino emission, and the addition of weak currents to the theory changes their expected cooling rates. However, the difference is not very striking and has not yet been confirmed or refuted by observation.

Neutrinos are very important in the early history of the universe according to the big-bang theory, and the introduction of neutral weak currents also affects expectations about their behavior then. In the beginning there were a lot of neutrinos, and they were in thermal equilibrium with the rest of the matter, which consisted of various other particles. Since the neutrinos interact much less with the world around them than other particles do, there comes a time when they go out of thermal equilibrium with the rest. After that, if the neutrinos cool (and therefore expand) at a different rate from the rest of the matter, the story of nucleosynthesis in the early universe will be affected because neutrinos are necessary for that. Although the neutral weak currents make a big difference in the moment when thermal equilibrium is broken, there comes to be no observable difference (in abundances of elements, for example) in the end because the subsequent cooling rate for neutrinos turns out to be the same as that for the rest of the universe.

A more striking, and more speculative, cosmological point has to do with the unification of forces and a basic principle of the new theories—spontaneous symmetry breaking. Although he has participated in the speculating, Weinberg does not wish to be presented as an advocate of the significance of these ideas, not wishing to earn, as he puts it, "the reputation of a wild man."

In the new theories the underlying equations, from which all else is derived, possess certain symmetries or invariances, cosmic indifferences to particularity. But the existence of specific things, say, a particular kind of elementary particle, comes about as a result of breaking symmetry. The breaking is said to be spontaneous because it comes about naturally in solving equations and not as a result of intervention by some outside agency. Some examples would seem to be in order.

The equations possess translational symmetry or invariance. Translation here means moving from place to place, and translational invariance means the equations don't care where something is. The equations governing the behavior of free atoms don't care whether an atom is in Boston or Johannesburg. But if a crystal forms, location becomes very important. The behavior of atoms within the crystal and the relation of other atoms to it depends strongly on location. Similarly, the equations describing conduction electrons in a metal are invariant with respect to the orientation of the electrons' spins; the spins can point any which way. But the onset of superconductivity requires the electrons to form pairs with oppositely oriented spins—the spin orientation is now crucial. The third example (all these are given by Weinberg) is ferromagnetism. The underlying equations here are indifferent to the orientation of the magnetic moments of the individual atoms; in an unmagnetized sample the moments lie in random directions. But as ferromagnetic domains begin to form and coalesce to the total magnetization of a sample of metal, the individual magnetic moments must all come to lie in the same direction, spoiling the invariance.

All these are accounted examples of spontaneous symmetry breaking because the equations representing the asymmetric states are natural solutions of the invariant underlying equations. Physically—an important point for what follows— all these breakings of invariance come about as a result of a fall in temperature.

The gauge theories began as attempts to unify the weak interaction and electromagnetism. As the energy goes up (and hence the temperature, which amounts to the same thing), the strength of the weak interaction increases. Experiment has seen some evidence of this, and theory says that at energies above 300 billion electron-volts, the weak interaction becomes as strong as the electromagnetic and the two fuse, so to speak. One of the consequences of the juncture is that the weak interaction can now generate long-range forces, and this ability can have cosmological significance.

Electromagnetism is a long-range interaction at low energies, but it does not play much of a role in the architecture of the universe because the cosmos as a whole and the larger bodies in it apparently are electrically neutral. There is no imbalance of charge for electromagnetic forces to take hold of. No one knows whether this is the case for weak charge, the quality that the weak interaction couples to. It may be that weak charge is not balanced in the cosmos or was not at the epoch when the temperature of the universe was above 300 billion electron-volts. If so, then the weak interaction affected the expansion of the universe, and, since it is so much stronger than gravity, its effect would have totally dominated that of gravity.

Moreover, there is some evidence that the strong interaction weakens as energy goes up, and it may approach a convergence with the weak-electromagnetic union. Gauge theorists are already on this trail.

A short time ago Weinberg, Howard Georgi and Helen Quinn observed that field theories that unite weak, electromagnetic and strong forces require the appearance of a force with a fantastically short range. This happens at a point where gravitational effects become comparable to those of other interactions.

Perhaps, therefore, gravity is a kind of relict of the original great symmetry breaking, and its properties are related to the way that symmetry is broken. An energy level could be reached at which gravity disappears and all interactions become one—one force, one coupling constant. The energy where this would happen is about 10^{19} billion electron-volts, which translates to 10^{29} degrees K. In the history of the cosmos this would have occurred at 10^{-40} of a second after the creation.

There is much in these ideas for the philosophically-minded to toy with. Weinberg warns us, however, not to make too much of them. They are mostly beyond experimental or observational verification. ☐