Competition Between Neutrino and Gravitational Radiation

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Summary

This essay discusses the competition between neutrino radiation and gravitational radiation for the dominant method by which forming neutron stars radiate away their gravitational collapse energy. It is shown that neutrinos may, in fact, be the dominant mode, thus a failure to detect gravitation radiation from a supernova does not imply an error in general relativity but rather the existence of a more efficient radiation mechanism.

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It has long ago been proposed that neutron stars and black holes, should be, at least in some cases, the collapsed central remnants of a supernova explosion. Although the above hypothesis has gained strong support with the discovery of the Crab pulsar, the detailed mechanism by which the stellar mantle and envelope is ejected and the collapsing core left behind is still unknown. However, recent developments have shown that a large amount of energy, originating from the collapse of the stellar core may be carried away via neutrino radiation. It has also been noted that if the collapsing core is in any way not radially symetric then large amounts of gravitational radiation may be emitted. Much effort in recent years has been spent in developing detectors which detect this gravitational radiation. However, if the neutrino radiation is dominant it would hinder any other competing mechanism of radiating energy, including gravitational radiation. It is this competition between gravitational neutrino radiation, in the collapse of a stellar core, that this essay is addressed.

Gravitational radiation, a purely general relativistic effect, is emitted from systems with a non-vanishing, time changing, quadropole (or higher) moment. Since the effect is purely relativistic it is expected to be particularly prominent when relativistic systems are associated with its emission, i.e., systems whose dimensions are comparable to their Schwarchild radii. Such systems are encountered only in astrophysical situations and are observationally known to exist due to the identification of the pulsars with neutron stars. Since it is believed that, at least in some cases, the neutron stars have been created in a supernova explosion, it is expected that substantial amounts of gravitational radiation are emitted in such events, due to the non-radial pulsations of the newly formed collapsed central object. In addition, since black holes do not require significantly smaller radii than neutron stars, it is sometimes assumed that in some cases black holes might also result from supernovae.

Detailed analysis[2] of such non-radial pulsations has shown that large amounts of gravitational radiation are indeed produced, which damp out the non-radial oscillations and carry away energy in the form of gravitational waves. A measure of how fast the different modes of oscillation are radiated away is called the damping time. (Mathematically defined as the time it takes the amplitude of oscillation of a particular mode to decrease its amplitude to 37% of its initial value because of radiation losses.) The damping time is essentially the energy lost in a period of oscillation over the total pulsational energy. Calculation[2] of the damping times for such non-radially pulsating neutron stars shows that they depend on the density of the neutron star, varying between 12 sec for a density 10^{14} g cm^{-3}, and 0.4 sec for a density 10^{15} g cm^{-3}. The power of gravitational radiation is thought to be sufficiently intense to be detected by existing or future gravitational wave detecting devices, thus testing General Relativity. Before, however, superhuman efforts for testing General Relativity are put into the detection of gravitational waves from supernova outbursts, perhaps one should also closely examine the detailed microphysics of a supernova explosion.

As mentioned before no well established current theory exists explaining in detail the way a supernova goes off, there exists a general scenario[1] for the final stages of stellar evolution and supernovae explosions. It is thought that sufficiently massive stars (greater than seven times the mass of the sun) will eventually evolve to a star with a core of iron and nickel approximately 1.4 times the mass of the sun. Further gravitational contraction raises the temperature about 10^{10} ^{o}K and the density above 10^{10} g cm^{-3} and breaks up the iron-nickel nuclei to alpha particles and free nucleons. With the increased density the electrons are absorbed by the protons thus decreasing their contribution to the pressure, which causes further contraction and further heating of the core. This electron capture, changing protons into neutrons, releases huge amounts of neutrinos. Neutrinos are also produced copiously from various thermal processes (pair annihilation, plasmon decay, bremstrahlung). These neutrinos may transfer sufficient momentum to the overlying high density mantle of the star to reverse its implosion, the neutronized core continuing its collapse to form a neutron star or black hole remnant.

The conclusion one can draw from the above scenario is that the main way energy is taken away from the collapsing core during the collapse is neutrino rather than gravitational radiation, the latter coming into play only at the very late stages of the collapse. This suggests the possibility that neutrino radiation can also contribute to the decay of non-radial oscillations of the collapsing core and the newly formed neutron star. It is clear that if neutrino radiation is proven to be more effective in damping out such oscillations not much gravitational radiation would be expected to be detected, since the non-radial modes may be damped out before they could gravitationally radiate.

Calculations,[3] motivated by the above considerations, were made to study the effects of neutrino radiation on the non-radial pulsations of a collapsing core. The quantity of greatest interest in such a situation is how fast these non-radial oscillations are damped out due to neutrino radiation. Even with an underestimation of the neutrino luminosity (consideration of only one neutrino producing reaction, i.e., pair annihilation) the damping times appear to be very short, 10^{-3} sec for density 10^{14} g cm^{-3} and 2 10^{-5} sec for density 10^{15} g cm^{-3}, if one assumes that neutrinos stream out of the collapsing core without interacting with the core matter. However such an assumption is not really accurate for the very dense hot matter that comprises the collapsing core. The neutrino mean free path in such situations will be smaller than the core dimensions, and this tends to decrease the neutrino luminosity, since neutrinos now spend more time in the core before they escape. Using diffusion theory to estimate such finite mean free path effects, the damping times appear to be more like 1 sec for 10^{14} g cm^{-3} and 0.1 sec for 10^{15} g cm^{-3}. It must be noted that the above figures represent only lower limits to the damping times (underestimation of the luminosity and use of extremely short mean free path); the actual values will be between these diffusion times and the streaming limit ones.

It appears from the above discussion that the neutrino damping times are shorter, maybe by more than an order of magnitude in some cases, than the gravitational damping times corresponding to the same core density. The significance of the fact has already been mentioned. It implies that neutrino radiation damps out non-radial oscillations of newly born neutron stars much faster than gravitational radiation does, and thus not much pulsational energy is left to be radiated gravitationally and trigger the gravitational wave detectors. Furthermore the same kind of analysis indicates that there is substantial neutrino damping at even lower densities, 10^{12} and 10^{13} g cm^{-3}, from neutrinos emitted during the neutronization of the collapsing core, (corresponding damping times about 10^{-3} sec), at which gravitational radiation is essentially absent. This seems to imply that most of the non-radial deformations have already been neutrino radiated away before the core reaches the neutron star regime.

In conclusion it should be stressed that the absence of gravitational radiation detected in the situation which was previously considered the most likely place for it to appear, namely a supernova explosion, does not necessarily imply the non-existence of gravitational radiation but rather the existence of another mechanism more efficient in carying away the neutron star pulsation energy.

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Biographical Sketch

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Demosthenes Kazanas was born in Kavala, Greece, in 1950. He obtained his S.B. in physics from the University of Thessaloniki, Greece, in 1973 and his M.S. from the University of Chicago in 1974. He is currently a graduate student in physics at the University of Chicago.

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David N. Schramm was born in St. Louis, Mo., in 1945. He obtained his S.B. in physics from M.I.T. in 1967 and his Ph.D. in physics from Caltech 3½ years later. He stayed at Caltech as a postdoctoral fellow for another 1½ years and then went to the University of Texas at Austin as an Assistant Professor. Since 1976 he has been an Associate Professor of Theoretical Astrophysics at The University of Chicago, working on problems in Nuclear, Relativistic and High Energy Astrophysics and Cosmology. He has won several awards including the first annual Trumpler award from the Astronomical Society of the Pacific in 1974 for outstanding astronomical research by a recent Ph.D. recipient. He has over 90 scientific publications. He is married and has 2 children.