Brief Reports

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Tests of relativity from SN1987A

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The observation of neutrinos and light from the recent supernova in the Large Magellanic Cloud has provided us with a wealth of new information, both about stellar collapse and about neutrinos. I point out that, in addition, the nearly simultaneous arrival of the photons and neutrinos after a journey of some 160 000 yr shows that the limiting velocity of electron antineutrinos is equal to that of light to an accuracy $\sim 2\times10^{-9}$, which is a more stringent test of special relativity than previous Earth-based measurements. It also provides an important new test of relativity and probes the structure of spacetime on intergalactic scales.

The nearly simultaneous detection of light[1] and neutrinos[2] from the supernova SN1987A has provided us with an important verification of theories of stellar collapse.[3] The arrival of neutrinos with a wide range of energies in a period of a few seconds, after having traveled some 50 kpc, also leads to a useful upper limit on the electron-neutrino mass.[4]

In addition to these important results, SN1987A also provides us with a unique probe of spacetime on intergalactic scales. The fact that the transit time of photons and neutrinos from SN1987A to Earth is the same within several hours in $\sim 1.6\times10^5$ yr yields a high-precision test of special relativity. It also provides a new test of the weak equivalence principle, or the principle of the uniqueness of free-fall,[5] which states that the path through spacetime of a freely falling (neutral) test body is independent of its composition or structure. Experiments of the Eötvös-Dicke-type test this principle near Earth.[5]

Stated more explicitly, in this case the equivalence principle requires that photons and neutrinos follow the same geodesic path from SN1987A to Earth. This in turn requires that the transit time be the same for both. The arrival time of the neutrinos is known to be within a few seconds of 7:35:40 UT on 23 February 1987.[2] The arrival time of the first light from the supernova is less well known. The last confirmed evidence of no optical brightening[6] was by Shelton[1(c)] at approximately 2:20 UT. The earliest observations of optical brightening were by Garradd[1(b)] and by McNaught[1(b)] at 10:38 UT. It is also expected that the neutrinos are emitted in the first few seconds of the collapse while the outburst of visible light begins ~ 1 h later when the cooler envelope is blown away. Altogether this leads to an uncertainty of approximately ± 3 h in the relative transit times for neutrinos and photons reaching us from the Large Magellanic Cloud (LMC). The fractional transit time difference between neutrinos and photons can thus be at most ~ 3 h$/(1.6\times10^5\times365\times24)\approx 2\times10^{-9}$.

Thus we can conclude that to high accuracy the metric in the intervening space is identical for photons and neutrinos. The simplest parametrization of the test is in terms of an effective limiting velocity of neutrinos c_ν compared to that for photons c. Thus in the space between LMC and Earth

$$|(c_\nu - c)/c| \lesssim 2\times10^{-9} . \quad (1)$$

This test of the equivalence of geodesics for photons and neutrinos is especially interesting in view of the neutrino's paradoxical role in quantum geometrodynamics. As pointed out by Wheeler[7] many years ago, "The most evident shortcoming of the geometrodynamical theory as it stands is . . . that *it fails to supply any completely natural place* for spin $\frac{1}{2}$ in general and *for the neutrino* in particular." It is hard to imagine test particles more suitable than the photon and the neutrino for testing relativity. The photon has a leading role in the theory of relativity while, as Wheeler describes in some detail,[7] incorporating the neutrino has proven to be difficult. Thus if a violation is to occur we might expect this to be a likely place.

In a sense this serendipitous "experiment" is the extragalactic equivalent of the Eötvös-Dicke experiment.

If the ratios of the gravitational mass to the inertial mass were different for neutrinos and photons, they would follow different spacetime trajectories from SN1987A to Earth and arrive there at different times. Furthermore this experiment probes the space near a collapsed star as well as the space between galaxies.

The most precise comparison of neutrino velocities with that of light made previously was that of Kalbfleisch *et al.*[8] who found $|\beta_\nu - 1| < 4\times 10^{-5}$. Guiragossián *et al.*[9] found $|\beta_e - 1| < 2\times 10^{-7}$ for 20-GeV electrons. Brown *et al.*[10] compare the velocity of 7-GeV photons with that for visible photons and find a difference $< 6\times 10^{-6}$. Thus the limit presented here for the limiting velocity for electron antineutrinos from SN1987A, $|\beta_\nu - 1| < 2\times 10^{-9}$ is the most precise test of special relativity of this type.[11]

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[1](a) I. Shelton, International Astronomical Union (IAU) Circular No. 4316, 1987. (b) R. H. McNaught, IAU Circular No. 4316, 1987; G. Garradd, IAU Circular No. 4316, 1987. (c) I. Shelton, IAU Circular No. 4330, 1987.

[2]K. Hirata *et al.*, Phys. Rev. Lett. **58**, 1490 (1987); R. M. Bionta *et al.*, *ibid.* **58**, 1494 (1987).

[3]See, for example, J. N. Bahcall, A. Dar, and T. Piran, Nature (London) **326**, 135 (1987); D. N. Schramm, R. Mayle, and J. R. Wilson, Nuovo Cimento **9C**, 493 (1986).

[4]See, for example, W. D. Arnett and J. L. Rosner, Phys. Rev. Lett. **58**, 1906 (1987).

[5]C. W. Misner, K. S. Thorne, and J. A. Wheeler, *Gravitation* (Freeman, San Francisco, 1973).

[6]There is a possible observation of no optical brightening of SN1987A at 09:22 UT by A. Jones (IAU Circular No. 4340, 1987). This would restrict the arrival time of the first light to a much narrower window: 09:22 to 10:38. This in turn would give a significant improvement on the limit (1). However, to be conservative we use the less restrictive limit based on Ref. 1(c).

[7]J. A. Wheeler, *Geometrodynamics* (Academic, New York, 1962).

[8]G. R. Kalbfleisch *et al.*, Phys. Rev. Lett. **43**, 1361 (1979).

[9]Z. Guiragossián *et al.*, Phys. Rev. Lett. **34**, 335 (1975).

[10]B. C. Brown *et al.*, Phys. Rev. Lett. **30**, 763 (1973).

[11]A summary of precision tests of special relativity is given in D. Newman *et al.*, Phys. Rev. Lett. **40**, 1355 (1978).