100 years ago

ON THE METEORIC IRON WHICH FELL NEAR CABIN CREEK, JOHNSON COUNTY, ARKANSAS, MARCH 27, 1885

The Johnson County meteoric iron, the tenth whose fall has been observed, is of more than ordinary interest, because its fall is so well substantiated, because it is the second largest mass ever seen to fall, and, again, because it fell within five months of the date of the ninth recorded fall, that of the Mazapil. It is almost an exact counterpart of the Hraschina (Agram, Croatia) iron, the first of the recorded falls. On the upper side of the meteorite ten nodules of troilite are exposed, measuring from 33mm in diameter, to 55mm long, and 25mm wide. On the lower side there are twelve such nodules exposed, 13mm in diameter, while the largest measures 19mm by 39mm. On the upper side these nodules are coated in spots with a black crust, similar to that found on the mass, but on the lower side the crust extends completely around the side of the nodules, showing the fusion very plainly. The troilite is very bright and fresh, and on the upper side one of the nodules shows deep striation, suggesting that the entire nodule is one crystal, and the exposed part is only one side of it.

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with its binding pions π^0, with a strength that is inversely proportional to their decay constant f_A. SN1987A constrains this to be greater than about 10^{10}–10^{12} GeV (G. Raffelt and D. Seckel, M. Turner, and K. Olive, personal communications).

The observation of neutrinos from SN 1987A also shows that the neutrinos that were emitted did not decay or oscillate on their way to the Earth, nor were they dispersed in time by more than about 1 s. Neglecting the effects of 'flavour mixing' with large mixing angles[8], the time of flight from SN1987A to the Earth means that the life time of electron-neutrinos (of mass m) is greater than about 5×10^5 (m/eV) s. The absence of detectable γ-rays from SN1987A means that no neutrinos with masses in the range 1–100 MeV were emitted that decay radiatively with lifetimes of a few thousand seconds[9]. If neutrinos had an electric charge bigger than about 10^{-16} times that of the electron, dispersion caused by intergalactic or galactic magnetic fields would have spread their arrival times to more than a few seconds[10].

The neutrinos emitted from SN1987A could not have interacted appreciably with any cosmic background of particles left over from the big bang. In particular it has been shown[11] that the dimensionless couplings (g) of neutrinos to massless vector (spin-one) particles must be less than 10^{-3}, to massive bosons (mass M) must be weaker than $g/M = 12\,\mathrm{MeV}^{-1}$, and for Majoron–electron coupling must be smaller than 10^{-3}. (For comparison, g is 1/45 for the strong force, and 1/137 for the electromagnetic force.) On their way out of SN 1987A, left-handed neutrinos would have been flipped to unobservable right-handed neutrinos if their Dirac masses were larger than 20 keV (G. Raffelt and D. Seckel, personal communication). It might also be possible to constrain the magnetic moment of the neutrino by demanding that helicity flipping to right-handed neutrinos near SN1987A did not occur. The effect of the interplay between this precession and matter interactions is still being debated (D. Seckel and S. Nussinov, personal communications).

With such remarkable agreement between simple theory and experiment, it is not surprising that astrophysicists and physicists alike have been seduced into trying to make the most of the sparse neutrino data from SN1987A. Their goal has been to pull out detailed features of both supernova and neutrino physics from the 19 neutrino events. Such attempts are to be viewed with caution for two reasons.

First, the observation of neutrinos from SN1987A, few though they may be, implies that type II supernovae are dominated by neutrino emission (the light emitted and kinetic energy of the shock represent only a few per cent of the total energy released and gravitational radiation even less). Thus, the neutrino flux from SN1987A should be rather insensitive to small changes in the parameters that characterize collapse and shock dynamics. Even a supernova that generates a few hundred times more events than SN1987A could be poor for diagnosing the variations in tens-of-millisecond structure expected in various detailed models of gravitational collapse.

Second, there are dangers associated with the statistics of so few events. This is exemplified by the various calculations of the neutrino mass. To do this, many authors (over 40 papers have been written) have used the relationship between a neutrino's mass m, the time at which it was emitted, t_{em}, and observed, t_{obs}, its energy E, and D the distance travelled:

$$t_{\mathrm{em}} = t_{\mathrm{obs}} - \frac{D}{2c}\left(\frac{m}{E}\right)^2$$

For SN1987A, D is 55 ± 15 kpc (ref. 18), c is the speed of light and I have omitted an irrelevant constant. The results of such calculations can be divided into two categories. First, exact masses for one, two or three neutrino types can be obtained by comparing t_{obs} and E of all events. Values range from a few to a few tens of electronvolts. Second, upper limits to the neutrino mass are given by examining the calculated spread of emission times and requiring it not to exceed that expected from a supernova.

Which of these values are we to believe? The first type of analysis suffers from the sparsity of data. Apparently harmless approximations, neglecting the spread of energies for example, lead to erroneous values. The second approach is, by definition, more reliable, except that none of the calculations, I would argue, uses the correct method for sparse data, and thus cannot assess the model dependence of their mass limits. The correct method of statistical analysis for such circumstances is the method of maximum likelihood.

The likelihood function is the product of the probabilities, calculated from some model and allowing for instrumental effects, of each detected event. The emission times are calculated from the observed arrival times using the equation above, and the probabilities are calculated for each possible mass. In general, the mass limits obtained are somewhat model-dependent, but as the sparse data cannot distinguish the detailed models, any model that describes the generic behaviour of supernovae should do. Such analyses have given upper limits for the neutrino mass (at the 95 per cent confidence level) of 10–15 eV (refs 15, 16). A similar value is obtained using the Kamiokande data alone.

Are there any drawbacks to the method? Certain events could be given undue weight. The equation above shows that the lowest energy events give the best constraints. They also carry the most weight in the sample, because of their relatively low detection cross section. Because this also means that they are most likely to be background they can be removed from the Kamiokande sample, raising the mass limit to 28 eV. Until their exact status is known (the probability that they are real is 0.75), this difficulty will be unresolved.

Thus it can be seen that physics derived from the energy budget of SN1987A is reliable. Physics derived from the statistics of the 19 events is less certain but definitely useful. It is certain that both types of limits will influence the neutrino-physics community as it prepares for the next supernova. □

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