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COSMOLOGICAL IMPLICATIONS OF SUPERNOVA 1987a(*)

INTRODUCTION

The detection of neutrinos from supernova 1987a in the Large Magellanic Cloud [1] has been an epoch-making event for both astrophysics and particle physics. It has also turned out that the information obtained about the properties of neutrinos is of profound importance for cosmology. These cosmological implications are the subject of the present article.

A remarkable feature of the neutrino observations is how well they fit in with the simplest theoretical model of a stellar collapse followed by an explosion which leaves behind a cooling neutron star. In fact one can claim to understand the neutrinos from a supernova better than those from the sun (where only about one third of the expected neutrinos have been detected). This concordance is found for all three of the main observed features of the supernova neutrinos, namely, the duration of the burst, the energy of the individual neutrinos, and their total number. We shall begin by describing this agreement, which will also serve to introduce the main relevant features of the supernova model, and then examine the implications for cosmology.

THE DURATION OF THE NEUTRINO BURST

Two quite different factors may come into play in determining the duration of the neutrino burst. The first, obviously, is the time-scale associated with astrophysical processes occurring in the supernova. The second is the propagation time of each neutrino to the detector, which would depend on the energy of the neutrino if the particle has a non-zero rest-mass. This question of a possible mass for the neutrino leads to one of the cosmological aspects of our discussion, into which we shall enter later.

The astrophysical timescale is governed by the production rate and transport of

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neutrinos in the supernova. A full discussion would be rather complicated, involving several different processes and extensive numerical computations. It is not our intention to enter into these matters here, and the interested reader is referred to two excellent articles which attempt to give a clear physical picture of these complex processes, namely Bethe [2] and Cooperstein [3].

For our purpose it is sufficient to note that the neutrinos are produced on a timescale of order milliseconds, but take several seconds to diffuse through the dense nuclear medium produced in the collapse. The observed neutrinos are almost certainly pair-produced in the high temperature heat bath created by the outgoing shock wave which results from the bounce of the stellar core after the collapse. These neutrinos are scattered by the ambient nucleons, whose density is so great that the neutrinos are strongly trapped and slowly leak out on a diffusion time scale of a few seconds.

A full treatment of the neutrino transport is complicated, but a convenient picture can be constructed by introducing the concept of the neutrinosphere. This is analogous to the photosphere of the sun, and denotes the location of the region from which the outgoing neutrinos are within one mean free path of free streaming. If the temperature of the neutrinosphere is T_ν and its radius R_ν, then the effective neutrino radiation rate $\sim T_\nu^4 R_\nu^2$. The duration of the observed neutrino burst can then be regarded as the cooling-time associated with this radiation rate and with the total energy available for radiation. This latter quantity is the binding energy of the neutron star which is believed to have been formed in the collapse (although one must also keep in mind the possibility that a black hole may have been formed).

Detailed numerical calculations of the supernova phenomenon have been carried out by a number of groups, and in general the agreement between them is good. An outstanding problem is whether the outgoing shock wave is strong enough to expel the envelope and so produce the observed optical supernova, or whether it stalls and has to be "refreshed" by the deposition of energy from the outflowing neutrinos. This intriguing problem is not yet fully resolved, but this uncertainty does not affect the calculation of the timescale with which we are concerned here. All the calculations find that this timescale is of the order of a few seconds, and this is just what is observed.

The Individual Neutrino Energies

A complete discussion of the expected distribution of individual neutrino energies is again complicated, particularly because the mean free path of a neutrino depends sensitively on its energy, the relevant scattering cross-sections being typically proportional to the square of the energy. One has to take this into account in defining the neutrinosphere which is usually related to the mean neutrino energy. One then finds a temperature T_ν for the neutrinosphere of about 4 Mev and a radius R_ν of about 40 km. One would not expect the observed distribution of energies to agree closely with a thermal distribution and since, as we shall see, we are dealing with a few events (of order 10 in each detector) we are involved with the statistics of small numbers. For our present purpose it is sufficient to note that for a Fermi-Dirac distribution we would expect the mean energy to be about $3kT_\nu$, and thus about 12Mev. When allowance is made for the thresholds of the detectors, this agrees well with the observations.

THE TOTAL NUMBER OF NEUTRINO EVENTS

To calculate the total expected number of neutrino events we need to know the total energy emitted by the supernova in neutrinos, the distribution of neutrino energies, the distance of the supernova, the volume and energy threshold of the detector and the cross-section. As we have already stated, the total energy radiated is the binding energy of the neutron star formed in the collapse. This quantity depends on the mass of the neutron star and on the equation of state of the nuclear material forming the star. The mass is related to the mass of the iron core of the pre-supernova star and is expected to be about 1.4 M_0. The equation of state is still not well known, but for the expected range of possibilities one arrives at a binding energy of about 3×10^{53} ergs, with an uncertainty of about 50 per cent.

Various methods exist for estimating the distance to the Large Magellanic Cloud which works out to be about 50kpc. Interestingly enough, one can obtain a distance just from observations of the supernova itself (the so-called Baade-Wesselink method). One does this by comparing the linear dimensions of the supernova envelope, derived from its age and expansion velocity, with its observed angular dimension. The method requires an understanding of the physical conditions in the neighbourhood of the supernova photosphere. Assuming blackbody emission Branch [4] obtained a distance of 55 ± 5kpc. More recently Chilukuri and Wagoner [5], from a detailed calculation of the emergent spectrum, obtained a distance of 43.3 ± 4kpc. The advantages of this method are that it is direct, involving no intermediate distance ladder calibrations or selection effects, that the treatment of the photosphere is subject to observational check and that the derived distance should remain constant as the envelope expands. As an aside, we may mention that there is a cosmological aspect to this method of distance determination, since if it can be shown to work well, it can be used on supernovae in external galaxies, so providing us with a reliable extragalactic distance scale and perhaps an eventual solution of the notorious problem of the correct value of the Hubble constant which measures the rate of expansion of the Universe. In any case we see that for our estimate of the expected number of neutrino events, we have to use a distance to supernova 1987a which is uncertain to 20 per cent (and, of course, the distance comes into the calculation squared).

The volumes and energy thresholds of the detectors are known, so there remains the question of the cross section of the interaction process or processes leading to a successful detection. Here one must first take note of the fact that three different types of neutrino are known, namely those associated with the electron (ν_e) the μ meson (ν_μ) and the τ particle (ν_τ) together with their anti-particles. The calculations described earier indicate that the supernova emits comparable amounts of energy in each neutrino type. However, while all types can scatter electrons in the detector (via the so-called charged-current interaction) only the $\bar{\nu}_e$ can be absorbed by a proton in the detector, emitting a positron (via a neutral current interaction):

$$\bar{\nu}_e + p \rightarrow n + e^+$$

At the neutrino energies involved this latter process is by far the most probable and it is believed that all (or nearly all) the observed events are induced in this way by $\bar{\nu}_e$. The emitted positron is detected by Cerenkov counters, and the energy and direction of motion of the positron can be derived. The neutrino energy would then be close to the derived positron energy, and this fact has already been used in our earlier discussion of neutrino energies. The expected directions of motion of the positrons would be isotropic in the laboratory frame for the $\bar{\nu}_e$ absorption process, whereas electron scattering would lead to a preponderance of forward motions. The observed directions strongly favour the absorption process, although there remain some puzzles about the observed angular distribution. These may arise from the statistics of small numbers, as is indicated by Monte Carlo calculations. It therefore is appropriate to use the cross-sections for the $\bar{\nu}_e$ absorption process to determine the expected number of events.

We now have estimates for all the quantities needed to carry out this calculation. The result, somewhat fortuitously, is that a measurable number, namely about 10 events are expected for each detector, with an uncertainty of a factor 2-3 arising from uncertainties in the binding energy of the neutron star, the distribution of neutrino energies and the distance to the supernova. This estimate is gratifyingly close to the observed number, namely 11 in the Kamiokande detector and 8 in the IMB detector.

With this background of successful analysis we are now ready to consider the cosmological implications of supernova 1987a.

The Rest-Mass of the Neutrino

It is not yet known whether neutrinos have a non-zero rest mass, and so propagate more slowly than do photons. This question is of obvious importance for particle physics and, as we shall see, it is also of importance for cosmology. If they do have a finite rest-mass their arrival time from the supernova would depend on their energy. The resulting speard of arrival times leads to the possibility of either measuring the mass of the detected type of neutrino (the $\bar{\nu}_e$), or of placing an upper limit on its mass.

What mass might we expect the $\bar{\nu}_e$ (and the ν_e which should have the same mass) to possess? There is an old laboratory upper limit of 60ev. In recent years great excitement has been created by a Russian experiment, which claimed to measure an actual mass of about 40ev. Part of the excitement stemmed from the realisation that with such a mass neutrinos surviving from the hot big bang origin of the universe would today have a greater mean density than ordinary matter in the form of baryons (neutrons and protons). Indeed the universe would have close to the so-called critical density, which just divides models expanding forever from those which eventually recollapse under their self-gravitation. Moreover, the universe could not be much denser than this since otherwise, according to general relativity, its age since the big bang would be less than the known ages of objects like the sun which lie within the universe.

More recently the Russian experiment has come under criticism, and Kundig and his group in Zurich have claimed a new upper limit of 18ev. This is the most stringent laboratory limit at the present time, and it seems unlikely that a stronger limit than about 10ev could be achieved by these methods. It is a remarkable coincidence that with a mass of this order, and with the energy distribution observed for the supernova neutrinos, the spread of arrival times of these neutrinos, if emitted simultaneously, would be just of the order of a few seconds, that is precisely what is observed. This led some over-excited astrophysicists to claim that one could extract a definite mass for the neutrino from the supernova data. However, as we have already seen, astrophysical processes occurring in the supernova would be expected also to produce a timespread of this order, and these processes are virtually certain to occur. Detailed analysis, carried out by a number of independent groups, has shown that only an upper limit for the neutrino mass can be safely extracted from the data. The precise value of this limit depends somewhat on the detailed model of the supernova phenomenon which is adopted, but a favoured value is 10ev. This would be a slightly stronger limit than is currently available from the laboratory.

What are the cosmological implications of this result? If the actual ν_e mass were close to 10ev, such neutrinos would still contribute a greater density to the universe than do baryons, but significantly less than the critical density. Some modern theories of the early universe (especially the so-called inflation theory) would lead one to expect the universe today to possess a density very close to the critical value. One thus arrives at the famous "missing mass" problem, namely, to identify the nature of the material which may provide most of the density of the universe.

One's first thought is to turn to the other neutrino types, the ν_μ and the ν_τ. If either of their masses were of the order of 40ev, they would provide close to the critical density. Laboratory limits on these masses are much too weak to be relevant. The only argument that can be used at the moment to limit their masses in a useful way involves the famous solar neutrino problem. The nuclear reactions occurring at the centre of the sun, which provides its main energy source, lead to a calculable flux of neutrinos at the Earth. These neutrinos have been detected by Ray Davies, but he observes a flux which is only about one third of the calculated flux. There are many proposals for explaining this discrepancy. The most attractive is one of the most recent, according to which the ν_e's emitted in the nuclear reactions oscillate into ν_μ's and/or ν_τ's as they propagate through the sun. Since Davies detects only ν_e's, a discrepancy with the correct sign would be produced by such a process. To obtain the correct size of the discrepancy one must appeal to a resonant effect occurring along the neutrino flight path through the sun at the place where the density of the solar material takes on a particular value. For this to work, the mass of the neutrino type into which the ν_e oscillates must lie within as little as 10^{-2}ev of the ν_e mass. Thus if this explanation is correct, one at least of the ν_μ and ν_τ must have a mass essentially less than 10ev, and so could also not provide the missing matter needed to achieve the critical density in the universe.

There still exists the possibility that the remaining neutrino type could have the necessary 40ev or so of mass. What I want to emphasise, however, is that the general trend of these considerations is making it more difficult for neutrinos to provide the missing mass. Therefore we should at least now take more seriously the possibility that an exotic type of particle, such as the photino required by the (hypothetical) supersymmetry theories, may be responsible. I will return to this question after discussing the number of neutrino types implied by the supernova data, but I stress here that the most important cosmological implication of supernova 1987a is the strenghtening of the odds in favour of exotic explanations for the missing matter.

The Number of Neutrino Types

We have already seen how well the energetics of the supernova phenomenon fits in with the observed neutrino data. We can use this to place a limit on the number of neutrino types in the following way. We are supposing that most of the observed neutrinos are $\bar{\nu}'_e$s. The inferred total energy emitted by the supernova in this form is about 5×10^{52} ergs. The model calculations show that neutrinos of all types capable of being radiated by the heat bath in the supernova (that is, whose rest-mass is less than about 4 Mev) are radiated in equal amounts. Hence if there are N_υ such neutrino types, the total energy radiated in neutrinos is $10^{53} N_\upsilon$ ergs (remembering that each type comes in a particle-antiparticle pair). Now the total energy available is about 3×10^{53} ergs. Hence N_υ is about 3, which is just the presently known number of neutrino types.

This represents remarkable agreement, but how precise is the comparison? We have already mentioned the uncertainties involved, and detailed analysis suggests that they lead to an uncertainty of about a factor 2 in the comparison. Thus $N_\upsilon \leq 6$. This result is of cosmological importance because each neutrino type contributes to the energy density in the heat bath of the early universe when light elements like He^4 were formed by thermonuclear reactions. This energy density in turn controls the timescale of expansion and so influences the outcome of the nuclear reactions. A combination of general relativity and nuclear physics is needed to work out the dependence of the abundance of He^4 on the number of neutrino types. One finds that in the neighbourhood of $N_\upsilon = 3$, each additional neutrino type would add 0.01 to the mass fraction Y of He^4.

We now turn to astronomy for the measurement of Y and for the calculation of the contribution to Y of nuclear reactions occurring in stars. The most recent measurements of Pagel and his colleagues [6], combined with estimates of the effects of stellar evolution lead to a primordial value Y_p of Y given by

$$Y_p = 0.235 \pm 0.004$$

To turn this into an estimate of N_υ, we need to know the half-life of the neutron (which determines the coupling strength of weak interactions and so the relative abundances of neutrons and protons at the commencement of the nuclear reactions). This quantity is surprisingly poorly known from laboratory measurements. The latest value is 10.1 ± 0.2 minutes, compared with the value 10.4 ± 0.2 minutes of a year or two ago. One also needs to know the abundance of nucleons relative to the photons of the heat bath, another quantity which is not very well known. Despite all these uncertainties there is still a tight constraint on N_υ, namely

$$2 < N_\upsilon \leq 4$$

It is interesting to compare this limit with the laboratory limit. Before the discovery at CERN of the W and Z particles, the best laboratory limit on N_υ which was model-independent was about 100,000. By comparison the cosmological limit was very much more stringent and represented a real prediction by which the standard model of the hot big bang could be tested. Now the current Z data lead to a strong limit on N_υ namely

$$N_\upsilon \leq 5$$

The agreement of this limit with the cosmological one gives strong support to the standard model of the hot big bang. The further agreement with the supernova limit adds to our confidence in this discussion.

It is generally expected that data from the next generation of particle accelerators will be sufficiently accurate to lead to a definite measurement of N_ν rather than an upper limit. In this connexion it is important to remember that the laboratory method does not measure quite the same quantity as the cosmological and supernova ones. There could be a neutrino with rest-mass of order 1 Gev which would be counted by the Z data, but not by the other methods. In addition some hypothetical particles, such as the photino invoked by supersymmetry theories, are not coupled directly to the Z, but might contribute like a neutrino type (or perhaps a substantial fraction of a type) to the cosmological and supernova tests. One can thus turn these tests around to place useful limits on the possible number and properties of hypothetical particles.

The so-called axion has nearly been excluded in this way [7]. However, at the moment my own favourite particle, a photino with a mass of about 40ev, is still just permitted. Such a particle could give the critical density in the universe (and also dominate the halos of galaxies like our own Milky Way). My liking for it stems from the possibility, first suggested in Rome by Cabibbo, Farrar and Maiani [8], that such photinos could decay into another lighter supersymmetry particle, emitting a photon in the process. If the photino has a mass of 40ev, the photon would be an ultra-violet one and might show up in astronomy. Whether it does so depends on the decay lifetime which is not known theoretically, as it involves an undetermined parameter of the supersymmetry theory. For reasonable values of this parameter the lifetime could be about 10^{24} seconds. Despite the length of this lifetime (it is over a million times longer than the age of the univers) so many photinos would be expected to exist in the universe that the resulting ultra-violet flux at large red shifts might dominate more conventional sources and account for recent puzzling features of the distribution of Lyman α clouds (Sciama [9]).

Be that as it may, it is clear that the neutrino data from Supernova 1987a has had a major impact on cosmology. May we not have to wait several centuries for the next opportunity!

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