NEUTRINOS, A DIFFERENT WAY TO LOOK AT THE SKY*

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Neutrinos from astrophysical sources carry unique information, complementary to the photons, that is of extraordinarily value to develop our understanding of these objects. Two sources: the Sun and Supernova 1987A have already been observed in neutrinos, and future experiments are expected to detect ν in different energy ranges from several other sources. This includes $E_\nu \sim 10\,\mathrm{MeV}$ ν from gravitational collapse Supernovae and very high energy ν ($E_\nu \gtrsim 1\,\mathrm{TeV}$) from sources like young supernova Remnants, Gamma Ray Bursts or Active Galactic Nuclei that are likely acceleration sites for cosmic rays. Other more exotic sources are also possible, of particular interest is the search of ν from Dark Matter annihilation in the center of the Earth and the Sun. The ν observations have the potential to deeply enrich our vision and understanding of the Universe around us.

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1. Introduction

Neutrinos are in many ways special particles, they are several orders of magnitude lighter than all other fermions (a fact that could be related to their being Majorana particles, that is the antiparticles of themselves), their mass differences and mixing, that have been recently measured in experiments involving solar [1, 2], atmospheric [3], reactor [4] and accelerator [5] experiments, show remarkable features, that are still without a commonly accepted theoretical interpretation, but are likely to contain important lessons about physics beyond the Standard Model. An intense program of experimental studies is currently attempting to determine unambiguously and with good precision the entire set of relevant parameters, including the CP-violating phase δ.

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Neutrinos are also emitted by many astrophysical sources (see Fig. 1), and since they travel along geodetic lines, it is in principle possible to "image" these sources, "looking" at the sky with neutrinos. The Sun and the closest Supernova in the last three centuries (SN1987A in the Large Magellanic Cloud) have been the first two astrophysical objects to be "seen" in neutrinos, and in the (hopefully) not too far future, new detectors should be able to detect ν from other astrophysical sources, and neutrinos will become a new precious "messenger" from distant objects. The smallness of the ν interaction cross-section is at the same time the biggest problem for the newly born science of ν astronomy, since very massive detectors are required to have appreciable event rates, and also an extraordinary opportunity,

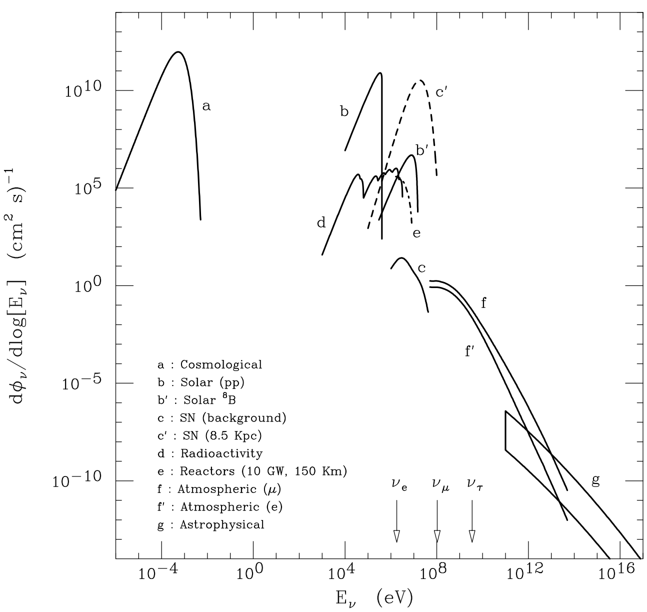

Fig. 1. Flux of neutrinos at the surface of the Earth. The three arrows show the energy thresholds for charged current interactions on a free proton target. The line that refers to cosmological neutrinos assumes that the neutrino mass is vanishing. For massive neutrinos the flux is modified since gravitational clustering enhances the density, the ν velocity is decreased and the energy spectrum is modified. The line that refers to Supernova neutrinos describes $\overline{\nu}_e$. Different neutrino species have similar spectra, with differences difficult to appreciate in the figure. The line that describes geophysical neutrinos includes the ^{238}U and ^{232}Th decay chains, the flux weakly depend on geographical location. The atmospheric neutrino fluxes are calculated for the Kamioka location. Only the lowest energy part depends on the location. A range of prediction for the flux of astrophysical neutrinos is shown.

because ν can emerge from deep inside the core of astrophysical objects, revealing directly the physical processes that operate there. For example solar neutrinos come directly from the Sun inner core, and directly tell us about the nuclear fusion reactions that are the source of the solar luminosity, while the visible photons are emitted from the surface with a black body spectrum.

2. Cosmological neutrinos

Cosmological neutrinos [6] were produced in the early hot Universe, and are intimately related to the photons of the cosmic microwave background radiation (that have a black body spectrum with temperature $T_\gamma^{\rm now} \simeq 2.728\,{\rm K}$). When the Universe was sufficiently hot, ν and γ where kept in equilibrium by reactions such as $\gamma\gamma \leftrightarrow \nu_\alpha\overline{\nu}_\alpha$. The ratio T_ν/T_γ is now $(4/11)^{1/3}$, because the photon field was heated by the annihilation of $e^\mp$ when the temperature dropped below $T \sim m_e$. This corresponds to a ν flavor independent number density[1] $n_{\nu_\alpha} + n_{\overline{\nu}_\alpha} \simeq 112\,{\rm cm}^{-3}$. In our galaxy the ν density could be enhanced by gravitational clustering. In the estimate of the ν density we have considered a single spin state. If ν are Dirac particles, one additional ν ($\overline{\nu}$) spin state exists, however, these "wrong helicity" states are singlets with respect to the Standard Model, interact extremely weakly, and are, therefore, expected to be present only in negligible number.

The cosmological ν energy density depends critically on the ν masses. For $m_\nu \gg T_\nu^{\rm now} \simeq 1.6 \times 10^{-4}\,{\rm eV}$, the kinetic energy of the neutrinos is negligible and the ν energy density is simply $\rho_\nu = m_\nu\, n_\nu$. In units of the critical density $\rho_{\rm c} = 3H^2/(8\pi G)$ one has:

$$\Omega_\nu = \frac{\rho_\nu}{\rho_{\rm c}} = \frac{1}{h^2}\,\frac{\sum_j m_j}{93\ {\rm eV}}\,, \qquad (1)$$

where $h \simeq 0.7$ is the Hubble constant in units of 100 km/s/Mpc. Neutrinos are disfavored as the main source of the dark matter in the Universe, because of the properties of observed cosmic structures, but could account for a subdominant "hot dark matter", component which suppresses the power spectrum of density fluctuations in the early Universe at "small" scales, of the order of 1–10 Mpc. This suppression depends on the sum of neutrino masses $\sum_k m_k$. Recent high precision measurements of density fluctuations in the Cosmic Microwave Background (WMAP) and in the Large Scale Structure distribution of galaxies (2dFGRS, SDSS), combined with other cosmological data, have allowed to put stringent upper limits on $\sum_k m_k$, of the order of 1 eV [9, 10]. The future sensitivity of cosmological measurements of the

[1] It is also possible that the Universe has a large net lepton number, with $(n_\nu - n_{\overline{\nu}})/(n_\nu + n_{\overline{\nu}})$ large. In this cases the ν number density is modified.

Large Scale Structure of the Universe using SDSS+Planck, and the weak gravitational lensing of background galaxies and of the CMB is expected to reach a value of $\sum_k m_k \gtrsim 0.1\,\mathrm{eV}$.

Cosmological neutrinos have not yet been directly observed, and a realistic detection method has not yet been proposed.

3. Supernova neutrinos

Neutrinos with an energy $E_\nu \sim 10\,\mathrm{MeV}$ are emitted in very large number ($\sim 10^{58}$) in brief ($\Delta t \simeq 10\,\mathrm{seconds}$) but very bright bursts during Supernova explosions of the core collapse type. These events [11] mark the end of the life of massive stars (with $M \gtrsim M_\odot$) that have developed an iron core surrounded by several onion-like burning shells and an outer envelope of hydrogen and helium. When the mass of the star iron core reaches the Chandrasekhar limit ($M \simeq 1.4\,M_\odot$) it becomes unstable, and collapses. The collapse is very rapid, with a time scale similar to the free fall of a small fraction of a second. The compressed core heats, "boiling" the iron nuclei into separate nucleons, then it becomes energetically favorable to capture the electrons on free protons in the neutronization process $e^- + p \to n \to \overline{\nu}_e$ that converts nearly all protons in the collapsing core into neutrons. The ν_e produced in these reaction rapidly escape from the core generating a "neutronization burst" of ν_e's. When the collapsing core reaches nuclear density (at a radius $R \sim 10\,\mathrm{km}$) the implosion is halted because of the stiffness of nuclear density matter. At this point a shock wave is formed that propagates outward ejecting the outer layers of the star and producing the spectacular visible explosion. The newly formed proto-neutron star has a radius $R_{\mathrm{n.s.}} \simeq 10\,\mathrm{km}$ (and therefore, the density is of the same order of nuclear matter), and contains a kinetic energy of order $E_{\mathrm{kin}} = -E_{\mathrm{grav}} = GM^2/R_{\mathrm{n.s.}} \simeq 3\times 10^{53}$ erg. Nearly all (99%) of the energy is radiated away in the form of neutrinos, with only $\sim 1\%$ going into producing the spectacular explosion as kinetic energy of the ejected layers and electromagnetic radiation. It is likely that the neutrinos emitted by the proto-neutron star play a crucial role in the explosion, depositing enough energy near the outward propagating shock to "push" it out of the star, generating the explosion.

All six ν species contribute approximately equally to the energy outflow, since they are produced in the hot core by "flavor blind" processes like $\gamma\gamma \to \nu_\alpha \overline{\nu}_\alpha$. The energy spectra are thermal, with average energies $\langle E_{\nu_e} \rangle \simeq 11\,\mathrm{MeV}$, $\langle E_{\overline{\nu}_e} \rangle \simeq 15\,\mathrm{MeV}$, and $\langle E_{\nu_{\mu,\tau}} \rangle \simeq \langle E_{\overline{\nu}_{\mu,\tau}} \rangle \simeq 25\,\mathrm{MeV}$. The ν emission lasts a time of order $\Delta t \simeq 10\,\mathrm{seconds}$ that corresponds to the time needed for ν to "random walk" out of the core undergoing many scatterings in the dense material. Most of the ν interactions are elastic scatterings with the neutrons in the star, where the ν direction changes but little energy is transfered because of the neutron mass is much larger than the neutrino energy. The different average energies of the different components are the consequence of the different cross-sections for elastic scattering with the remaining electrons in the star. Electron neutrinos (with the largest cross-section) are emitted from a more external "neutrino-sphere", while $\nu_{\mu,\tau}$'s and $\overline{\nu}_{\mu,\tau}$ (with smaller cross-section) are emitted from deeper inside the stars and are slightly "hotter".

The theory of neutrino emission in Supernova explosions has had a dramatic confirmation the 23rd February 1987, when the neutrinos and the radiation of Supernova SN1987A that had exploded 170,000 years before in the Large Magellanic Cloud (a small satellite galaxy of our Milky Way) reached the Earth. Two detectors: Kamiokande in Japan and IMB in the US detected [12] a few events (11 Kamiokande, 7 IMB) in coincidence with each other and in a time interval of 13 seconds. These events can be interpreted as the detections of positrons from the reaction $\overline{\nu}_e + p = e^+ + n$. From the number and energy spectrum of the observed events, it is possible to extract (with large statistical errors) a fluence and a temperature for $\overline{\nu}_e$ emitted by the Supernova with results in reasonable agreement with the theoretical predictions. The handful of events detected from SN1987A have allowed to determine (or put limits) several neutrino properties, such as the ν mass and electric charge [13].

The ν produced by all Supernovae explosions in the past history of the Universe form a diffuse flux that is in principle detectable [14], giving very valuable information on cosmic history of the stellar formation rate,

4. High energy astrophysical neutrinos

Fluxes of high energy neutrinos ($E_\nu \gtrsim 10^{12}$ eV) are expected [15, 16] from the astrophysical objects that generate cosmic rays. Fluxes of cosmic rays exist up to energy $E \simeq 10^{20}$ eV, however, the sources of these particles have not yet been clearly identified. Possible sources for the highest energy particles, that are believed to be of extra-galactic origin are Active Galactic Nuclei or Gamma Ray Bursts. Our poor understanding of the origin of the cosmic rays is mostly related to the fact, that electrically charged particles are bent by magnetic fields and do not point back to their sources. It is natural, in fact essentially unavoidable that the cosmic rays sources are also ν sources, since a cosmic ray accelerator will in general contain a non negligible amount of "target material" in the form of gas, radiation fields, and at least some of the accelerated hadrons will interact producing secondary particles that decay into neutrinos (with chains such as $\pi^+ \to \mu^+\nu_\mu$ followed by $\mu^+ \to e^+\nu_e\overline{\nu}_\mu$).

In order to detect these astrophysical neutrinos one needs very massive detectors. The most promising method is based on the detection of Cherenkov light in water or ice. Water (or ice) is a dense, abundant cheap medium, where relativistic charged particles emit efficiently Cherenkov photons, and is transparent in the relevant wavelength range (blue light) for these Cherenkov photons. To construct a high energy ν telescope it is, therefore, sufficient to distribute in a large volume of the medium a number of photo-sensible devices (Photo Multipliers Tubes or PMT's) capable to detect the Cherenkov photons of particles produced in ν interactions. The telescope must be screened from the background of the charged cosmic ray radiation, placing it deep under the Earth surface. The original concept of a very large water telescope for high energy neutrinos was developed by the DUMAND group, that originally planned to build a detector in the deep ocean (at a depth of $\sim$ 4500 meters in the Hawaii archipelago) made of "strings" of photomultipliers. Each string should be anchored to ocean floor, and supported by buoyancy. Similar concepts are now pursued by three groups in the Mediterranean (the NESTOR (Greece), ANTARES (France), and NEMO (Italy) projects) [17, 18]. The most advanced project (AMANDA, now evolving into IceCube) [19] is located in Antarctica, at the South Pole and is based on the same Cherenkov method but uses ice instead of liquid water. Ice at sufficiently low temperature and high pressure, becomes transparent and is a good Cherenkov medium, and can be used also as the mechanical structure that supports the photomultipliers, that are placed in deep holes melted in the ice before its permanent refreezing.

5. Other neutrino sources

Neutrinos are copiously produced in thermonuclear reactions which occur in the stellar interior and in particular in our Sun. In main sequence stars, the effective fusion reaction that liberates nuclear binding energy is the process: $4p + 2e^- \rightarrow {}^4\mathrm{He} + 2\nu_e$ that generates 26.73 MeV of kinetic energy. Each fusion cycle produces two ν_e. The inner core of our Sun generates at the Earth a flux of approximately 6×10^{10} cm^{-2} s^{-1}. The precise value and detailed spectrum of the solar ν_e flux depends on the "path" taken by the nuclear reactions to burn hydrogen into helium. Most of the solar neutrinos have energy below 0.41 MeV, but a smaller component (of the order of 5×10^6 (cm^2 s)$^{-1}$) due to the beta decay of boron–8 extends up to 14 MeV, and plays a very important role in the detection of solar neutrinos. Measurements of the solar neutrinos fluxes have dramatically confirmed the theoretical predictions for the mechanism of energy productions in the stars, and at the same time have given evidence for the existence of ν flavor transitions of type $\nu_e \rightarrow \nu_\mu$ and/or $\nu_e \rightarrow \nu_\tau$.

Atmospheric neutrinos are produced by cosmic rays interacting in the upper atmosphere. These interactions generate secondary mesons that decay into neutrinos in channels like $\pi^+ \to \mu^+ + \nu_\mu$ followed by $\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$. In the absence of oscillations the atmospheric ν fluxes are up–down symmetric, reflecting the isotropy of the primary cosmic rays and the spherical shape of the Earth, however, the pathlength-dependent oscillations introduce an asymmetry, that has being detected, giving robust evidence for the existence of $\nu_\mu \to \nu_\tau$ oscillations [20].

Geophysical neutrinos [21] are produced in the β decays of radioactive nuclei in the Earth material. These decays generate approximately 40% of the observed 40 TeraWatt of energy outflow from the Earth, most of it due to the decay chains of uranium and thorium. The β decays in these chains produce neutrinos of $\overline{\nu}_e$ type with a maximum energy of 3.27 MeV, and a flux (at the surface) of order $\sim$ few $\times\, 10^6\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$. The flux depends on the detector location, because chemical processes during the Earth's formation have concentrated uranium and thorium in the Earth's crust that has a variable thickness. The high energy tail (above the threshold energy of 1.8 MeV) of the geophysical $\overline{\nu}_e$ flux can be observed studying the $\overline{\nu}_e$ capture on free p followed by the detection of the n capture: ($\overline{\nu}_e + p \to e^+ + n$, $n + p \to \gamma + d$). The KamLand detector [22] has recently obtained first evidence for geophysical neutrinos. These measurements can give information on the structure, dynamics and evolution of the present Earth [23].

One of the most interesting goals for the high energy neutrino telescopes is the observations of ν from dark matter annihilation in the center of the Earth and the Sun [15,24]. If weakly interacting massive particles (WIMP's) constitute the dark matter of the Universe, they accumulate in the center of astrophysical bodies, because of gravitational accretion. The annihilation $\chi + \overline{\chi} \to$ final state will produce neutrinos that can be observed as emerging from the center of the Sun and Earth with an energy $E_\nu \lesssim m_\chi/2$.

6. Outlook

Nearly all the information that we have about the Universe has been obtained with photons, and each developments in instrumentation that has allowed to perform observations in a new range of wavelength, has resulted in important discoveries. The neutrino is a new "messenger", that because of its deeply different properties, allows in principle a very significant expansion of our observation possibilities. We can, therefore, be confident that the opening of the neutrino "window" will lead to a deeper understanding of known astrophysical objects, and to the discovery of new unexpected classes of sources. Neutrino observations are extraordinary challenging, because the smallness of the cross-section requires the development of very massive detectors. Neutrino astronomy has already obtained the first successes, and large efforts are invested in the construction of new detectors.

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