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On the goals of neutrino astronomy

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Summary. — What do we mean by neutrino astronomy? Which information is able to provide us and which is its potential? To address these questions, we discuss three among the most relevant sources of neutrinos: the Sun; the core collapse supernovae; the supernova remnants. For each of these astronomical objects, we describe the state of the art, we present the expectations and we outline the most actual problems from the point of view of neutrino astronomy.

PACS `26.65.+t` – Solar neutrinos.
PACS `97.60.Bw` – Supernovae.
PACS `26.50.+x` – Nuclear physics aspects of novae, supernovae, and other explosive environments.
PACS `95.85.Ry` – Neutrino, muon, pion, and other elementary particles; cosmic rays.

The discovery of the world of elementary particles (including cosmic rays, gravitons, neutrinos) and the growing interest in astrophysical processes has opened the way to new astronomies, collectively named particle astronomies. In the case of neutrino astronomy, awarded with the Nobel Prize in Physics in 2002, the progress was unavoidably related to the solution of the neutrino puzzles, *i.e.* the solar neutrino problem and the atmospheric neutrino anomaly, which pointed out non-standard neutrino properties. Today, half a century after the deep theoretical insights of B. Pontecorvo and the pioneristic detection of neutrinos from natural sources by the Homestake, KGF and CWI experiments, we know a lot about these particles. We can, thus, go back to the original program and use neutrinos to probe the inner parts of the stars, the processes of cosmic ray acceleration, the primordial Universe, etc. In this contribution, based on our review paper [1], we describe the perspectives of neutrino astronomy by discussing expectations and pending problems regarding some of the best-known sources of neutrinos.

1. – Solar neutrinos

Solar neutrino observations have been planned in the sixties to probe the nuclear reactions in the solar core. But this research program has been hostage, till very recently, of our ignorance of neutrino properties. Nowadays, the situation has changed. The "solar" squared mass difference, δm^2, is determined at the level of about $\sim 2\%$, mainly by the KamLAND reactor neutrino experiment. The leptonic mixing angle θ_{12} is fixed at the $\sim 6\%$ level essentially by the SNO solar neutrino experiment and a robust upper limit on the leptonic mixing angle θ_{13} is obtained from the CHOOZ experiment. All this implies that the solar neutrino oscillation probability is reliably known. Furthermore, there is a weak evidence for $\theta_{13} \neq 0$ which is crucial for next steps in neutrino physics (see the contribution of E. Lisi for a complete discussion of our present knowledge of neutrino masses and mixing).

When we consider the Sun as an astrophysical system, the discussion acquires more facets and becomes even more interesting. The solar neutrino experiments have demonstrated that nuclear reactions transforming hydrogen into helium,

$$4p + 2e^- \rightarrow {}^4\mathrm{He} + 2\nu_e \quad (Q = 26.7\,\mathrm{MeV}), \tag{1}$$

occur inside the Sun. Assuming that the energy radiated by the Sun on the Earth, $K_\odot$, is due to nuclear processes and that the Sun is in equilibrium, the total flux of neutrinos can be easily estimated as $\Phi_\nu \sim 2K_\odot/Q \simeq 6.5 \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. However solar neutrinos have a complicated spectrum resulting from different nuclear reactions chains (*i.e.* the PP chains and the CNO cycle) cooperating for helium production in the Sun. The neutrino spectrum has to be calculated by constructing a Standard Solar Model (SSM), which represents the state-of-the-art theoretical model of the Sun and provides an important benchmark for all stellar evolutionary calculations.

Solar neutrino experiments can check the predictions of the SSMs which are obtained under a number of hypotheses and are affected by theoretical uncertainties. At present, the only part of the solar neutrino spectrum which has been *directly* probed by experiments concerns some secondary branches of the main chain, namely the Boron neutrinos (SNO, Super-Kamiokande) and the Beryllium neutrinos (Borexino). The Boron neutrino flux is strongly dependent on the central temperature of the Sun, $\delta\varphi_\mathrm{B} \sim 20 \times \delta T_c$, so that it allows us to constrain T_c better than 1%.

The 90% of the solar neutrino flux is not directly measured. This concerns the most abundant component, *i.e.* PP neutrinos; we know it *only if we assume* that the Sun is in a state of equilibrium. We would like to measure the less abundant but more energetics PEP neutrinos, since the efficiency of PP and PEP neutrino producing reactions are strictly related. Also, we did not probe yet the amount of CNO neutrinos. These are subdominant in the Sun, but extremely important for stars in more advanced evolutionary stages. CNO neutrinos will also provide us with a handle to address the problem of the observed photospheric abundances of elements, that disagree with the predictions and suggest that certain theoretical hypotheses of the solar model need revision. Borexino should be soon able to provide these important measurements, as discussed in the contribution of D. Franco; the main issue is not the signal (there are several events per day) but rather a sufficient understanding of the background in the signal region.

All this witnesses that the study of solar neutrinos is a very lively topic, both on the experimental and on the theoretical point of view. Also, solar neutrino detectors will permit us to study the geoneutrinos. Borexino is in a leading position also in this respect; KamLAND and SNO+ will be soon in the position to contribute.

2. – Neutrinos from core collapse supernovae

Stars with sufficiently large masses, at the end of their life, are characterized by an iron core inert to nuclear reactions, surrounded by outer shells in which lighter elements are burned. The mass of the iron core grows as the stellar evolution proceeds. When it exceeds the mass of $\sim 1.4\ M_\odot$, the core collapses. This eventually originates a compact stellar object, most commonly a neutron star and, through mechanisms which still have to be clarified, produces the explosion of the stellar mantle, leading to an optical supernova (SN). The order of magnitude of the potential energy of the neutron star can be estimated through its mass, its radius and the Newton constant G_N:

$$\mathcal{E} \sim G_N \frac{M_{\rm NS}^2}{R_{\rm NS}} = 3.5 \times 10^{53} \left(\frac{M_{\rm NS}}{1.4\, M_\odot}\right)^2 \left(\frac{15\,\rm km}{R_{\rm NS}}\right) \text{erg}. \tag{2}$$

This is remarkably large, the rest mass being 2.5×10^{54} erg if $M_{\rm NS} = 1.4\, M_\odot$. Most of this energy is released in neutrinos of all types.

However, the frequency of core collapse SN in the Milky Way is very low. In fact the expected number of SN, the number of the progenitors (*i.e.* the stars with masses $> 8M_\odot$) and of their descendants of a certain age, such as pulsars and supernova remnants (SNR), are linked among them from the relation

$$\frac{4\ 10^5\ \text{stars}}{2\ 10^7\ \text{years}} \sim \frac{1\,\text{SN}}{50\,\text{years}} \sim \frac{4\ 10^4\ \text{pulsars}}{2\ 10^6\ \text{years}} \sim \frac{20\,\text{SNR}}{10^3\ \text{years}} \tag{3}$$

that assumes that all these populations, that are short-lived on galactic time-scale, are in equilibrium among them (more discussion in the proceedings of IFAE 2005, held in Catania). We close this introduction by recalling that due to galactic dust, only 1 SN out of 7-8 of them has been seen; the last one in 1604 by Keplero.

In 1987, a supernova was seen in the Large Magellanic Cloud and four neutrino detectors announced evidences of signals, possibly attributable to electron antineutrinos emitted by the supernova. It should be kept in mind that, in conventional detectors, the inverse beta decay of electron antineutrinos on free protons, $\bar{\nu}_e p \to e^+ n$, is the most important nuclear reaction to reveal events of 10–20 MeV of energies. Despite many puzzling aspects of these observations, the common view is that the 20–30 events seen by Kamiokande-II, IMB and Baksan agree with the expectations. In particular, under the assumption that the electron antineutrinos are 1 sixth of the emitted neutrino signal, the data seem to confirm the total emitted energy corresponding to the formation of a neutron star. The 5 events seen by the fourth detector, LSD, occurred several hours before the others cannot be accommodated in the simplest scenario for neutrino emission. They require more complicated models with several emission phases, that are being developed and that we will not consider in the following.

In the standard scenario (known as neutrino assisted-or delayed-explosion or Bethe and Wilson scenario) the main phases that give observable neutrino fluxes are:
1) *The rapid accretion around the nascent neutron star.* The positrons yield observable antineutrinos by interacting with the nucleons via $e^+ n \to p \bar{\nu}_e$:

$$L_{\rm accr} \sim N_n \sigma_{e^+ n} T_a^4 \sim 5 \times 10^{52}\ \frac{\rm erg}{\rm s} \left(\frac{M_a}{0.1\ M_\odot}\right) \left(\frac{Y_n}{0.6}\right) \left(\frac{T_a}{2\,\rm MeV}\right)^6 . \tag{4}$$

Here, T_a and M_a are the temperature of the plasma (of the positrons) and the mass of neutrons exposed to the flux of positrons; Y_n is the neutron fraction. This phase of emission lasts a fraction of a second, precedes the shock revival and it is crucial for the explosion to occur.

2) *The thermal cooling of the protoneutron star.* This happens on a time scale of about 10 seconds. The luminosity is proportional to the radiating area:

$$L_{\mathrm{cool}} \sim R_c^2\, T_c^4 \sim 5 \times 10^{51}\ \frac{\mathrm{erg}}{\mathrm{s}} \left(\frac{R_c}{10\,\mathrm{km}}\right)^2 \left(\frac{T_c}{5\,\mathrm{MeV}}\right)^4 . \tag{5}$$

Here, T_c is the initial temperature of the emitted antineutrinos and R_c is the radius of the sphere that characterizes the emission, that is expected to have the size of the neutron star. On comparing with the luminosity in eq. (4), it is evident that the thermal phase is much less luminous than the first one.

Recent analyses of the data performed using a two-phase emission model showed an evidence for the first luminous phase of about 2.5 sigma. This result is particularly interesting in view of the difficulty to simulate the explosion with computers. It is curious that this result was obtained so late; but this can be understood considering that a large part of the recent discussion was guided by particle physics considerations (mostly, on neutrino oscillations) rather than astrophysical considerations.

It is pretty evident that we will learn a lot from a future galactic supernova. Consider, *e.g.*, that Super-Kamiokande would detect about 10^5 events from a supernova exploding in the location of the Crab Nebula (2 kpc), allowing us to probe the details of the neutrino emission. Moreover, it will become possible to do astronomy with neutrinos *only*: in fact, the elastic scattering events as seen in a Čerenkov-type detector will permit us to reconstruct the direction of an event in the Galactic center with a precision of a few degrees. Also, the analysis of $\bar{\nu}_e$ permits us to predict with 10 ms precision the moment of maximum crunch (when the matter bounces on the core of the neutron star) which is plausibly associated to a strong emission of gravitational waves.

In summary, the importance of collecting neutrinos from a galactic supernova should not be underestimated. The fact that core collapses are rare in the Milky Way in human standards should not let us forget that neutrinos will offer us a unique chance to progress on the understanding of these extraordinary events. More discussion in the appendix.

3. – Neutrinos from supernova remnants

The Ginzburg and Syrovatskii conjecture, formulated in 1964, expresses the fact that the energy stored in galactic cosmic rays is one order of magnitude smaller than the kinetic energy of the supernova remnants (SNR) of the Milky Way:

$$\frac{\rho_{\mathrm{CR}} V_{\mathrm{CR}}}{\tau_{\mathrm{CR}}} \approx 0.1 \times \frac{\mathcal{L}_{\mathrm{SN}}}{\tau_{\mathrm{SN}}}. \tag{6}$$

This suggests the idea that SNR act as cosmic ray accelerators. The most plausible mechanism to realize this possibility was proposed by Fermi in 1949 and is known as "diffusive shock wave acceleration". We do not have yet a complete understanding of this phenomenon, but the above conjecture is widely considered of great appeal.

A few SNR were recently observed to radiate gamma well above the TeV. This could be explained if the cosmic rays, accelerated in the SNR, collide with the surrounding medium and produce copious fluxes of mesons, that eventually decay and lead to gammas, *e.g.*, $\pi^0 \to \gamma\gamma$. It is not yet possible to exclude that (part of) the observed radiation is produced by electromagnetic processes. In order to reach a definitive proof of the hadronic origin of the observed gammas more detailed studies are needed.

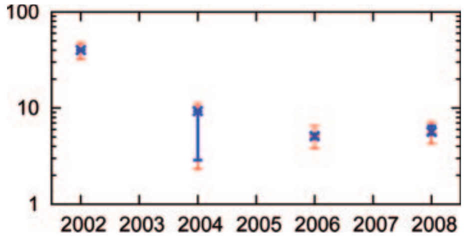

Fig. 1. – (Colour on-line) Predictions for the SNR RX J1713.7-3946. In the abscissa, year of prediction; in the ordinate, number of muon events per km^2 per year above a threshold of 50 GeV. In blue, the expected number of events and their error due to the uncertainties on the VHE gamma-rays spectrum; in red, a conservative estimation of the theoretical error, set to 20%.

In the assumption that the observed radiation is produced from hadronic processes, one expects that a flux of high energy neutrinos is also emitted by SNR. In hadronic processes, in fact, charged mesons are abundantly produced and their decay yields charged leptons and neutrinos. Since the background due to atmospheric neutrinos drops rapidly with energy, there is some hope that these neutrinos can be observed by the modern neutrino telescopes. It is not difficult to calculate the neutrino fluxes expected from SNR with known gamma-ray spectra. Since the relative amount of charged and neutral mesons produced in hadronic interactions is almost fixed, and since the fluxes of gamma and neutrinos are not attenuated by the diffuse medium in which they propagate, the gamma and neutrino fluxes are linked by a simple linear relation:

$$F_{\nu_\mu}(E_\nu) + F_{\bar{\nu}_\mu}(E_\nu) = 0.66 F_\gamma\left(\frac{E_\nu}{1-r_\pi}\right) + 0.02 F_\gamma\left(\frac{E_\nu}{1-r_K}\right) + \int_0^1 \kappa(x) F_\gamma\left(\frac{E_\nu}{x}\right)\mathrm{d}x, \tag{7}$$

where $r_{\pi,K} = (m_\mu/m_{\pi,K})^2$ and where

$$\kappa(x) = \begin{cases} x^2(33.8 - 54.3x) & \text{if } x < r_K, \\ (1-x)^2(-0.63 + 12.45x) & \text{if } x > r_\pi, \\ 0.04 + 0.20x + 7.44x^2 - 7.53x^3 & \text{otherwise.} \end{cases} \tag{8}$$

The above formula includes the contribution of charged pions and charged kaons to neutrino production and the effects of neutrino oscillations. It is essentially model independent and does not require any parameterization of the gamma-ray flux F_γ. We can thus apply it directly to the gamma-ray observational data to calculate the neutrino fluxes (and their uncertainties) and the corresponding signal in neutrino telescopes.

In fig. 1, we summarize the expected signal for the best studied SNR: RX J1713.7-3946; the last three points are consistent among them and their difference reflects the improved knowledge of the gamma-ray flux. For this SNR, one expects about 2.5 signal events on top of 1 background event per year and above a threshold of 1 TeV in an ideal detector of 1 km^2 of area located in the Mediterranean. There is the hope that the number of events from another nearby SNR, Vela Jr, is a few times larger. We are waiting to know whether the γ-ray observations from H.E.S.S. will support these hopes.

4. – Conclusions

We close remarking the following three major points:

1) There is a lively research program on solar neutrinos. Borexino is providing the main results; interesting spinoff measurements such as reactor and geo-$\bar{\nu}_e$ are also possible.

2) At present, the processes happening in a gravitational collapse are only partly understood. The main possibility to study them is given just by future neutrino observations; the paucity of galactic supernovae does not diminish the importance of these studies.

3) The neutrinos from supernova remnants could be the turning point to test the origin of the galactic cosmic rays; they could be observable with an exposure of several $\mathrm{km}^2 \times \mathrm{y}$.

These discussions are in different stages of maturity, but it is important to emphasize that they concern the same discipline, neutrino astronomy, that involves astrophysicists, particle physicists and nuclear physicists and that sees Italy in a leading role.

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Appendix A.

A limit on the occurrence of galactic supernovae

As mentioned above, it is not possible to use the astronomical records to know the absolute rate of core collapse SN f in the Milky Way, due to dust extinction of the emitted light. The only firm information comes from the fact that in about 25 years of observations, no neutrino telescopes happened to record an event; applying Poisson statistics, this amounts to the 90% CL upper limit $f < 1\,\mathrm{SN}/11\,\mathrm{y}$.

The problem of dust extinction is less severe for other galaxies, that we see head-on. If, additionally, we are able to reliably know (or to put a limit on) the *relative* rate of occurrence of supernovae in another galaxy that we observe, we could use the astronomical records to get information on the absolute frequency in the Milky Way.

E.g., suppose that the rate of core collapse SN is 3 times lower in Andromeda, due to different galaxy mass and stellar population, which seems a conservative statement and that can be refined. Since the last supernova has been observed in 1885, we can apply again Poisson statistic to get the 90% limit on the absolute frequency in Andromeda $f_A < 1\,\mathrm{SN}/54\,\mathrm{y}$. This implies the following limit on the occurrence of galactic supernovae:

$$f < 1\,\mathrm{SN}/18\,\mathrm{y}, \tag{A.1}$$

that is significantly more stringent than the existing direct limit. This limit becomes more (respectively, less) tight presuming that the supernova in 1885 was not due to a core collapse event (respectively, that some light extintion could be present for Andromeda).

The above discussion shows an interesting direct link between the ordinary astronomy and neutrino astronomy. Our argument is close in spirit to the one invoked to infer the value $f = 1\,\mathrm{SN}/(30\text{–}70)\,\mathrm{y}$ in the Milky Way, based on the observation of supernovae in other galaxies and on the correlation of this frequency and the observed (blue) luminosity of the galaxies. As for the previous argument, one needs to correlate the properties of the observed galaxies to those of the Milky Way to make the point.

REFERENCES

[1] Pagliaroli G., Villante F. L. and Vissani F., *Nuovo Saggiatore*, **25**, no. 3-4 (2009) 5-19 (freely available online on the SIF web site).