Author: Visser, Erwin Lourens
Title: Neutrinos from the Milky Way
Issue Date: 2015-05-12

SUMMARY

When you find yourself away from light pollution of cities and look up at the night sky, a dim "milky" band of light can be seen: the Milky Way. The best view is from the Southern Hemisphere, since the central part of the Milky Way is then visible at a higher position above the horizon. The milky band corresponds to the plane of our Galaxy and appears bright since it contains most of the stars.

Since ancient times the universe has been studied using light in the range of wavelengths that is visible to the human eye. Today, observations of the universe are also made using light at different wavelengths, ranging from low-energy radio waves to high-energy γ-rays. The Milky Way clearly stands out at these wavelengths as well. When observing high-energy γ-rays or infrared light, the Milky Way actually stands out even more, because the dust in our Galaxy does not absorb those photons as much as the photons in the visible range of wavelengths.

Following the discovery of cosmic rays by Victor Hess in 1912, a new way of observing the universe became possible, usually referred to as astroparticle physics. Cosmic rays are fully ionised atomic nuclei (like hydrogen and iron) which constantly bombard the Earth's atmosphere from all directions. The origin of cosmic rays is still unclear. Because cosmic rays are charged, they are deflected in the (extra-)Galactic magnetic fields. As a result, they no longer point back to their source by the time they arrive on Earth. One of the prime candidate sources for cosmic rays originating in our Galaxy are supernova remnants, which are the left-overs after a massive star goes supernova. Identifying the sources of cosmic rays is one of the main goals in astroparticle physics.

During their travel through our Galaxy, the cosmic rays interact with the interstellar matter. In these interactions, unstable particles are created which decay to other stable particles such as photons (i. e. γ-rays), electrons and neutrinos. These neutrinos are the main subject of this dissertation. Even though the corresponding flux of neutrinos is guaranteed, it has not yet been observed. The only published result so far is an upper limit of this flux of neutrinos set by the AMANDA-II collaboration which operated a neutrino telescope at the South Pole.

Neutrinos can be detected by looking at the products of an interaction of a neutrino with matter in the vicinity of the detector. The list of interaction products generally includes various charged particles. When the velocity of a charged particle exceeds that of the light in a medium, a kind of electro-magnetic shock wave is produced which is referred to as Čerenkov light (the effect is similar to the acoustic shock wave that is created when an airplane goes faster than the speed of sound). Neutrino telescopes are therefore built in transparent media like water or ice. The Čerenkov light can then be observed using a sparse array of light sensors. Because neutrinos only interact weakly with matter, a big instrumented volume of water or ice is required. A big advantage of neutrinos is the fact that they do not carry any charge, so that they are not deflected in the (extra-)Galactic magnetic fields. When cosmic rays interact in the vicinity of their source and thus produce neutrinos, the direction of the neutrinos will point to the source of the cosmic rays.

There exist three flavours of neutrinos: the electron-neutrino, the muon-neutrino and the tau-neutrino. Depending on the flavour of the neutrino, a different particle is produced in their interaction. Due to oscillations of neutrinos (a phenomenon in which a neutrino spontaneously changes flavour during its journey), neutrinos with all three flavours are expected to arrive on Earth. Traditionally, neutrino astronomy focuses on the muon-neutrino, since in its interaction a muon (a heavier version of the electron) is created. The advantage of detecting a muon is that the muon can travel a large distance through the medium before it stops. This provides for a long lever arm which in turn allows to determine the direction of the neutrino with good accuracy.

The main background for neutrino telescopes consists of muons which are created by the interactions of cosmic rays with the atmosphere of the Earth. To reduce this background, neutrino telescopes are located under a thick layer of sea or ice to provide for a natural shielding. Because neutrinos interact weakly with matter, neutrinos are the only particles that can pass through the entire Earth. So the field of view of a neutrino telescope is generally pointing downwards instead of upwards. By doing so, the atmospheric muon background can effectively be reduced to an acceptable level. Neutrinos, which are also created by the interactions of cosmic ray with the Earth's atmosphere, constitute an *a priori* irreducible background since they cannot be rejected in the same way.

As with γ-rays, the Milky Way is expected to stand out when neutrinos are observed. Since neutrino telescopes primarily look through the Earth, a detector on the Northern Hemisphere is best suited to observe the signal (as opposed to looking for light). The ANTARES neutrino telescope, located about 40 km offshore from Toulon, France is at a prime location. The ANTARES detector is located at a depth of 2475 m and consists of a total of 885 light sensors, distributed along 12 vertical lines. All signals that are recorded by the light sensors are sent to shore, where the interesting signals are selected in a process called *triggering*. The triggered events are processed offline to determine the direction and energy of the neutrino that caused the interaction. Several different algorithms exist for the reconstruction of the direction of the neutrino. For this work a new algorithm (GRIDFIT) has been developed. Compared to previous algorithms, it provides for a 20% higher efficiency to reconstruct low-energy neutrinos.

To distinguish the signal neutrinos from the background of atmospheric neutrinos, two aspects can be used. First, the signal is expected to be strongest in the inner region of the Galactic plane, since the matter density is highest there. By using a simulation of the detector response to neutrinos, it is found that a region which extends 39° in longitude and 4.5° in latitude on either side of the Galactic Centre is optimal. Second, the energy of the neutrinos can be considered. The typical energy of the signal neutrinos is expected to be higher than that of atmospheric neutrinos. This difference is due to the lower matter density in the Galaxy compared to that in the Earth's atmosphere. Unstable particles produced in the Earth's atmosphere may interact before they decay whereas those produced in the Galaxy will all decay. Because the effective lifetime of the unstable particles increases with energy due to relativistic effects, the energy spectrum of the background neutrinos will be steeper than that of the signal neutrinos.

To detect an excess of neutrinos above the background, the measured number of neutrinos is compared to what is expected assuming only background. Usually, the background expectation is obtained from a model. To avoid a bias due to the uncertainties associated with the assumed model of the background, a measurement of the background is performed. For this purpose, eight additional regions are defined in which no signal is expected. These regions are chosen to have the same size and detector coverage as the signal region. Using the ANTARES data from the beginning of 2007 until the end of 2012, an average background of 166 events is found, whereas 177 events are measured in the signal region. The statistical significance of this excess is 0.8σ which is compatible with a fluctuation of the background (a discovery of a new signal can only be claimed when an excess of 5σ or more has been observed).

Since no significant excess of events has been observed, upper limits can be placed on the neutrino flux. The obtained upper limits can be found in table 5.14. They are worse than those obtained by the AMANDA-II experiment. However, the present limits are focused on the inner region of the Galactic plane and are thus the most stringent.

The current flux upper limits are more than a factor of ten above the expected fluxes. Hence, a more powerful neutrino telescope is needed to detect the signal. The planned successor of ANTARES, the KM3NeT detector, is ideally suited for this. It will also be located in the Mediterrenean Sea, but it will be a factor of about 100 larger than the ANTARES detector. It is found that within one year of operation of KM3NeT, flux limits can be set which are almost a factor of seven better than those obtained with ANTARES. By using all three neutrino flavours and after about three years of operation of the KM3NeT detector, one can constrain the various neutrino flux models and possibly obtain the first evidence of the expected signal.