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Multimessenger Astrophysics : Session Summary

Markus Ahlers
Niels Bohr International Academy & Discovery Centre, Niels Bohr Institute,
University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen, Denmark
E-mail: markus.ahlers@nbi.ku.dk

Manuela Vecchi
KVI-Center for Advanced Radiation Technology,
University of Groningen, NL-9700 AB Groningen, Netherlands
Instituto de Física de Sao Carlos,
Universidade de Sao Paulo, CP 369, 13560-970, Sao Carlos, Sao Paulo, SP, Brazil
E-mail: m.vecchi@rug.nl

We summarize in the following the *Multimessenger Astrophysics* parallel session of the *Neutrino Oscillation Workshop* (NOW) 2018. This session covered recent observations of cosmic rays, gamma rays and neutrinos, open issues concerning the interpretation and modeling of these results, and an outlook on future observatories and analysis strategies. A special focus in this session was on the multimessenger aspect of sources.

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1. Introduction

Neutrinos are ideal messengers for astronomy and unique probes for astrophysics. They can escape dense environments, that are otherwise opaque to photons, and travel cosmic distances without being affected by background radiation or magnetic fields. The astrophysical conditions that lead to the emission of neutrinos are often preceded by cataclysmic cosmic events, like core-collapse supernovae or binary neutron star mergers, which can be visible by gravitational waves prior to the neutrino signal. Neutrinos at very-high energies ($\gtrsim$ 1 GeV) require the interaction of cosmic rays with background gas or radiation, which inevitably lead to the associated production of gamma rays. These arguments highlight that astrophysical neutrinos are deeply rooted in the framework of multimessenger astrophysics.

The *Multimessenger Astrophysics* parallel session at NOW 2018 complemented five overview talks in the plenary session that covered recent results of TeV-PeV astrophysical neutrinos (**Claudio Kopper**), recent results of gravitational wave astronomy (**Ian Harry**), neutrino searches from γ-ray blazars (**Matthias Kadler**), charged Galactic cosmic rays (**Giovanni Ambrosi**), and the prospects of detecting the next core-collapse supernovae via MeV-GeV neutrinos (**Shunsaku Horiuchi**). Details can be found in the corresponding proceedings contributions. In the following, we summarize the twelve presentations given in the parallel session, covering astrophysical neutrinos, supernova neutrinos, γ-rays, and cosmic rays. For references of the individual topics we refer to the presenter's proceedings contribution [1].

2. Observation of High-Energy Astrophysical Neutrinos

Maurizio Spurio provided an overview of the ANTARES neutrino detector in the Mediterranean with a focus on recent multimessenger results. The experiment is located off the shore of Toulon (France) and has been operating since 2007. Its detection volume of $\mathcal{O}(0.01)\mathrm{km}^3$ is only a fraction of the cubic-kilometer IceCube observatory located at the South Pole, but its location in the Northern Hemisphere allows for a compatible sensitivity for sources in the Southern Hemisphere, in particular sources towards the Galactic Center. Maurizio presented limits on point-like sources using ANTARES data collected from 2007 to 2015. ANTARES has been looking for sources in an all-sky search as well as emission from a catalogue of 106 known γ-ray sources. No significant neutrino emission has been detected, resulting in upper limits for sources in the catalogue.

The search of diffuse neutrino emission with ANTARES is an important check of recent IceCube observations. The data collected between 2007 and 2015 shows 33 candidate events for an isotropic astrophysical neutrino flux in comparison to 24 ± 6 events expected from backgrounds. This corresponds to a mild excess of 1.6σ above background. The corresponding limit at 90% confidence level (CL) of the diffuse flux is $E_\nu^2 \phi_{\nu_\mu + \bar{\nu}_\mu} \simeq 4 \times 10^{-8}\mathrm{GeVs}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}$ and consistent with IceCube's observation.

The diffusive propagation of Galactic cosmic rays and their interaction with gas in the vicinity of the Galactic Plane should also be visible as diffuse high-energy neutrino emission. A recent joint analysis of ANTARES and IceCube places upper limits on the emission. The result is starting to probe optimistic Galactic diffuse models, that assume a strong dependence of cosmic ray densities with Galactic radius and a high cosmic ray cutoff at 50 PeV.

An important aspect of transient neutrino astronomy is the low-latency communication with multimessenger partners. ANTARES communicates alerts via the Astrophysical Multimessenger Observatory Network (AMON) and the Gamma-ray Coordinate Network (GCN). Well-reconstructed neutrino candidates with an angular resolution of 0.5° can trigger alerts in the case of doublet events (0.04 events/yr), events from the direction of local galaxies (10 events/yr), as well as single high-energy events (20 events/yr above 5 TeV and 3-4 events/yr above 30 TeV).

In return, ANTARES performs offline follow-up studies on transient electro-magnetic sources, ultra-high energy cosmic rays, high-energy neutrinos, and gravitational waves. Recent highlights are the search of neutrinos from fast radio bursts, neutrino emission from *TXS 0506+056*, and the binary neutron star merger *GW170817*. Again, no significant neutrino emission above backgrounds were detected for all these candidate sources leading to upper limits on the time-integrated neutrino emission. The telescope will continue observation until the end of 2019 coinciding with the end of the third observation period of gravitational waves with LIGO and Virgo.

The next-generation neutrino telescope in the Mediterranean will be KM3NeT. The present status of the observatory and the expected science potential were summarized by **Rosa Coniglione**. The detector will have two components – the low-energy detector ORCA, off the shore of Toulon (France), and the high-energy detector ARCA, off the shore of Capo Passero (Sicily, Italy). Both detectors use the same detection units (DUs), consisting of vertical slender strings equipped with 18 Digital Optical Modules (DOMs), but with different inter-spring spacing. The individual DOMs use a novel design with an arrangement of 31 small 3-inch photo-multiplier tubes, that reduce the cost per photocathode area while improving the angular acceptance. For a discussion of the physics with KM3NeT ORCA we refer to the contribution by **Dorothea Samtleben** in these proceedings.

In its final configuration, KM3NeT ARCA will consist of two building blocks with 115 DUs, each, with an inter-string spacing of 80 meters. The first construction phase (*Phase-1*) is fully funded and consist of 24 DUs for ARCA, corresponding to an effective volume of $\mathcal{O}(0.1)$ km^3. The first three DUs at the ARCA site were deployed in December 2015 and March 2016. Two of these DUs operated successfully until a junction box failed in March 2017. The recovery of DUs and the restoration of the sea bed infrastructure are ongoing.

The fully instrumented ARCA detector will have excellent sensitivity in point-source and diffuse neutrino searches. The field of view will be complementary to IceCube in the Southern Hemisphere. KM3NeT expects to reconstruct cascade events with an angular resolution better than 2° and an energy resolution of better than 5%. The combined event samples of muon tracks and cascades allow for a discovery of the diffuse neutrino flux observed by IceCube within six months. Optimistic predictions of the Galactic diffuse neutrino emission can be discovered within four years. Bright Galactic supernova remnants, like *RXJ1713.7-3946*, can show evidence (3σ) for neutrino emission within five years, if the γ-ray emission is of hadronic nature.

Future upgrades and extensions of the IceCube detector at the South Pole were summarized by **Marek Kowalski**. The IceCube collaboration is presently preparing an upgrade with seven strings, that will be deployed in the existing IceCube DeepCore array. These strings will carry new DOM designs with upgraded electronics, smaller diameter for efficient deployment, larger acceptance and/or effective area. Together with integrated calibration devices (LED flashers, acoustic sensors, and optical cameras), the new strings will also carry stand-alone light sources, that allow for a better calibration of the existing and new strings.

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The improved knowledge of the glacial ice can be used to reduce systematic uncertainties and the improvement of IceCube's archival data with respect to angular, energy, and flavor reconstructions. The IceCube-Upgrade will also allow for the study of fundamental neutrino properties, similar to the existing physics program of DeepCore, but with a significantly improved sensitivities. Further details can be found in the proceedings contribution by **Andrii Terliuk**. The deployment of the IceCube-Upgrade strings is foreseen in 2022/23.

The long-term vision for multimessenger astronomy at the South Pole is IceCube-Gen2 – a multi-component facility covering low- and high-energy neutrinos. This facility will include an in-ice optical Cherenkov detector with an instrumented volume of up to 10 km^3, depending on inter-string spacing. In combination with the improved systematics from the calibration methods introduced for the IceCube-Upgrade, the IceCube-Gen2 detector is expected to have an improved angular resolution reaching 0.2° for horizontal muons. The increased event statistics beyond 100 TeV will allow to probe the spectrum and flavor composition of the diffuse neutrino flux with unprecedented precision.

3. Modeling and Observation of Supernova Neutrinos

Francesco Capozzi discussed the possibility of identifying self-induced neutrino flavor conversions during the accretion phase of core-collapse supernovae (SNe). This nonlinear effect is expected to occur in the dense neutrino flux in the vicinity of the neutrino sphere ($\simeq$ 10 km), but its effect on neutrino spectra and flavor compositions is difficult to characterize. It has been considered that self-induced flavor conversions can lead to an equalization of neutrino fluxes and spectra. At larger distances of $10^4 - 10^5$ kilometers, neutrino flavors are expected to experience coherent matter effects with the dense background of electrons. This has no further effect on the neutrino fluxes if flavor equalization has previously occurred. Otherwise, matter effects will dominate flavor composition of the emitted neutrino spectra.

Francesco and collaborators have considered a model-independent way to decipher the two extreme cases of pure flavor equalization vs. matter effect for the next Galactic core-collapse supernova. They suggest to look for the neutrino flux inferred from proton elastic scattering (pES) in scintillators ($\nu_x + \bar{\nu}_x$), inverse β-decay (IBD) in water Cherenkov detectors ($\bar{\nu}_e$) and charged-current interactions in Argon (ArCC) detectors (ν_e). Francesco suggests to consider the relative contributions $F_{\rm pES}/F_{\rm ArCC}$ and $F_{\rm pES}/F_{\rm IBD}$ that is only mildly dependent on neutrino flux predictions of SN simulations. If these ratios take on critical values and the neutrino mass hierarchy is known, a separation from pure matter effects and complete flavor equalizations is possible.

The effect of collective neutrino oscillations and strong flavor transformations in core-collapse SNe were also discussed in the presentation by **Rasmus Hansen**. He considers neutrino-neutrino refraction above the neutrino sphere via external potentials that allow to describe the evolution of a probe neutrino as a linear problem. This effective approach allows to formulate conditions on the Hamiltonian for strong flavor conversions: resonant conversion (vanishing diagonal elements), adiabatic conversion (weak gradient), or parametric enhancements (periodic time/distance modulations).

A particular focus in Rasmus' presentation was on the extended neutrino sphere, *i.e.* the width of the neutrino emission region. Averaging neutrino fluxes over the emission region affects the neutrino state. In particular, the small effective neutrino oscillation length in matter compared to the width of the neutrino sphere (~ 1 km) leads to a strong suppression of oscillatory terms. In this setup, the presence of strong neutrino conversion can be studied via a linear stability analysis. This allows to decide, if strong flavor conversions have the potential to occur.

Giulia Pagliaroli presented her work on identifying neutrino bursts from core-collapse SNe. Typically, the selection of short ($\Delta t_i \lesssim 20$s) event clusters with high multiplicity m_i is optimized by observatories with respect to the false alarm rate, estimated from background fluctuations. Giulia and collaborators suggest to introduce an additional cut on the parameter $\zeta_i \equiv m_i/\Delta T_i$, *i.e.*, the ratio of cluster multiplicity and cluster duration. The threshold $\overline{\zeta}_i$ is determined by comparing the TS distribution of simulated background and background+signal distributions, where the injected signal corresponds to a the emission of a core-collapse SN at a distance of $\lesssim 400$ kpc.

The optimal threshold parameters were discussed for Borexino, SuperK, KamLAND and LVD, depending on the observatories' different energy thresholds and background rates. Giulia claims that this method allows to decrease the misidentification of SN bursts in individual detectors by a factor of 10-20 without loosing detection efficiency. This method can be extended to the search of SN bursts in multiple neutrino detectors as well as the combined search in neutrino and gravitational wave detectors. Other astrophysical scenario that could be visible by this time-dependent search are failed supernovae (with direct black hole formation) and hypothetical quark novae (from the collapse of a neutron star to a strange quark star).

4. Multimessenger Studies with Gamma Rays

Elisabetta Bissaldi reported on multimessenger studies with the *Fermi* gamma-ray satellite, operating in space since 2008. The *Fermi* satellite is a key instrument for multimessenger astrophysics, given the high pointing accuracy as well as the high quality data for, both, temporal and spectral analyses.

A recent milestone in multimessenger astronomy was the first gravitational-wave detection of the binary neutron star merger, labelled *GW170817*. Details of this observation can be found in the proceedings contribution of **Ian Harry**. The source was observed by Virgo and LIGO on August 17th 2017 and took place in the galaxy NGC 4993, located at a distance of about 44 Mpc. For the first time it was also possible to unambiguously identify the electromagnetic (EM) counterpart of a gravitational wave event. The detected EM emission includes three main components: *(i)* the prompt gamma-ray emission of a short GRB observed with *Fermi* GMB, demonstrating the association between GW and GRBs, *(ii)* the first observation in the ultraviolet, optical and infrared of a kilonova from the radioactive decay of heavy elements formed by neutron capture, followed by *(iii)* the delayed X-rays and radio counterparts.

Andrew Taylor presented the results of the search for a TeV gamma-ray counterpart of the *GW170817* event: upper limits to the TeV gamma-ray emission from the High-Energy Stereoscopic System (H.E.S.S.) and other Imaging Atmospheric Cherenkov Telescopes (IACTs) were set. **Gerd Kunde** reported that the source region was visible to the High Altitude Water Cherenkov detector (HAWC) only 9 hours after the trigger and it was observed for 2 hours, allowing to set 95% CL upper limits for energies above 1 TeV. Moreover, an extended search for neutrinos in the direction

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of the source was carried out for two weeks following the merger, finding no significant neutrino emission.

Another milestone was achieved a few weeks later, on September 22nd 2017, when a neutrino event of about 290 TeV detected by IceCube was found to be coincident in direction and time with a gamma-ray flare from the blazar *TXS 0506+056*. Details of the neutrino emission can be found in the proceedings contribution of **Claudio Kopper**. The arrival time of the event, labelled *IC-170922A*, falls within a period of flaring activity, first observed in GeV gamma rays detected by *Fermi*-LAT and above 100 GeV by the Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescope. The probability of a high-energy neutrino being detected by chance coincidence with a flaring blazar from *Fermi*-LAT catalogs was found to be disfavored at a 3σ CL. These first observations triggered an extensive multiwavelength campaign, from radio frequencies up to VHE gamma-rays. No signal was found in H.E.S.S., and upper limits at 95% CL on the gamma-ray flux were derived. IceCube also performed an archival search for neutrino outbursts in the direction of *TXS 0506+056*, that found 3.5σ evidence of a a three-month flare in 2014-2015. However no gamma-ray flare was found in archival data from *Fermi*-LAT or HAWC.

Concerning the study of galactic CR sources with gamma-rays, the recent detection of extended TeV gamma-ray emission coincident with the locations of two nearby middle-aged pulsars (Geminga and *PSR B0656+14*) triggered a lot of interest. The HAWC observations of the spectral and spatial properties of these sources are used to constrain their contribution to the positron flux at Earth. Assuming that all the observed gamma-ray emission at TeV energies is produced by relativistic electron/positron pairs, the positron flux produced by these sources at Earth was computed. The measured TeV emission profile is used to constrain the diffusion of particles away from these sources, and it is found to be much faster than previously assumed. The HAWC collaboration thus concluded that, under the assumption of isotropic and homogeneous diffusion, the two pulsars are ruled out as sources of the CR positron flux.

The combined electron/positron spectrum was also measured by the High-Energy Stereoscopic System (H.E.S.S.), located in Namibia, from 250 GeV to 20 TeV. This measurement can be described by a smooth broken power law, with no sharp features. This result allow us to exclude models that describe prominent features from nearby sources such as Vela.

5. Cosmic Rays from Galactic and Extragalactic Sources

Fiorenza Donato provided a summary of recent improvements in the field of galactic cosmic rays (CRs). Following the hints provided by previous experiments, the AMS-02 collaboration showed that the proton and helium spectra cannot be described as a single power law (between 1 GV to 1.8 TV), and that a transition in the spectral index takes place above 200 GV. Moreover, not only the helium flux cannot be described by a single power law, but the ratio between the proton and the helium flux is rigidity-dependent. This unexpected behavior was also observed in the flux ratio of other species, like C/p, O/p.

The secondary-to-primary flux ratios are very sensitive to the propagation of CRs in the Milky Way. In particular, the boron-to-carbon flux ratio (hereafter B/C) can be considered as a *standard candle* for the study of galactic CR propagation. The observed transition in the spectral index above

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200 GV can be generated either at the source (injection or acceleration) or during the propagation in the Milky Way.

The comparison between the expected antiproton flux from conventional astrophysical processes (whose *baseline* is derived from the B/C analysis) and the precise AMS-02 data is still an open issue, especially because the antiproton production cross sections should be known with high accuracy in order to avoid introducing high theoretical uncertainties. Antiprotons constitute a powerful channel for dark matter (DM) searches, allowing setting strong upper bounds on the annihilation cross section and in some cases even to improve the fit by adding a DM contribution.

Martin Lemoine summarized the present status of the observation and interpretation of ultra-high energy CRs (UHECRs). Presently, the main challenge in this field is the modeling of the observed UHECR spectra and mass composition and relating them to potential sources, most likely extra-galactic. The Pierre Auger Observatory (PAO) energy spectrum, presented by **Rogerio de Almeida**, shows a clear suppression at $E_s = (3.9 \pm 0.2(\text{stat.}) \pm 0.8(\text{syst.})) \times 10^{19}$ eV, compatible with the expected location of the Greisen-Zatsepin-Kuzmin cutoff from interactions of UHECRs with photons of the cosmic microwave background. However, this spectral feature could also be indicating the maximal energy that can be achieved at acceleration sites. The UHECR composition and arrival directions constitute two additional observables to shed light on the problem. The PAO collaboration reported evidence for a mixed composition at high energies, resulting in an increasingly heavier composition above 10^{18} eV. The results from the Telescope Array (TA), initially in tension with those from PAO, have been shown to be compatible with mixed composition, which best describes the PAO data.

The PAO and TA have access to different regions of the sky: the TA collaboration reported the existence of a hot spot in the Northern sky with a significance of 3.4 σ, while a recent analysis by the PAO provided evidence for an intermediate-scale clustering in the arrival direction of UHECRs, indicative of the presence of strong nearby sources. The arrival directions of PAO events with energies above 39 EeV are in good agreement with starburst galaxies: the model fits the data better than isotropic arrival directions, with 4σ significance. However, caution is required when identifying these objects as the preferred sources prior to understanding the impact of magnetic deflections. Rogerio also reported on the discovery (5.2σ) of a dipolar anisotropy in the arrival directions of CRs with energies above 8 EeV was also reported, while no significant second harmonic amplitude was observed. No significant dipole anisotropy was observed in the $4-8$ EeV data. These results can be interpreted as a strong evidence against the galactic origin of UHECRs.

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References

[1] Marrone, A., Mirizzi, A. and Montanino, D., ed., *Proceedings of the Neutrino Oscillation Workshop (NOW) 2018*, Proceedings of Science, 2018.