The Soviet DUMAND program (1980-1991) and development of alternative large-scale neutrino telescopes

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In 1958-1962 it was proposed by M. Markov et al. [1,2,3,4,5] that a number of fundamental problems of Particle Physics and Astrophysics (Astronomy) could be studied using deep underground and deep underwater installations for detection of high- energy neutrinos produced in the Earth's atmosphere and in space. Specific features of the Soviet DUMAND program led by M.A. Markov in 1980-1991 to develop alternative (in particular radio) neutrino telescopes using new natural neutrino targets of multi-gigaton masses (Antarctica, the Moon) are highlighted. First discussions (since 1983) on how to use Antarctic ice as a natural target for optical and radio neutrino telescopes are described. R&D of the Radio Antarctic Muon and Neutrino Detector (RAMAND), capable to search for astrophysical sources of ultrahigh-energy (UHE $> 10^{14}$ eV) neutrinos, which had been performed in 1985-1990 at the Soviet Antarctic station Vostok, is described. The Radio Astronomical Method of Hadron and Neutrino Detection (RAMHAND) had been suggested in 1988-1989 to study extremely high-energy cosmic rays (EHE $>10^{19}$ eV) bombarding the Moon. First deep underwater measurements and experiments aimed at development of large-scale optical and hydro-acoustical neutrino detectors were conducted in 1989-1991 in the Mediterranean Sea.

1 Early years of high-energy neutrino physics in cosmic rays and neutrino astronomy (1957-1962).

In 1956 Frederick Reines and Clyde Cowan had done a great job: they first registered the interaction of antineutrinos with matter using the flux of low energy (a few MeV) antineutrinos from the world's most powerful nuclear reactor.

1957: M.A. Markov initiates development of High-Energy Neutrino Physics in Cosmic Rays.

In 1957 I made my student work at Moscow University under leadership of Moisei A. Markov who suggested me to consider the possibility of detecting atmospheric high-energy neutrinos and antineutrinos placing the installation deep underground to reduce the background from atmospheric muons. In fact in 1957 Markov initiated development of a new branch of the High-Energy Physics: the High-Energy Neutrino Physics – with aim to investigate fundamental problems of the weak interaction theory. I defended my diploma "On interactions of high-energy neutrinos in cosmic rays with substance" in 1958 [1]. Results presented (flux of atmospheric neutrinos, suggestion to investigate a possible linear growth of the total neutrino-nucleon cross-section with energy, test the hypothesis of existence of two neutrino types in underground experiments) were published later in [2,4].

1958: Why not to develop High-Energy Neutrino / High-Energy Gamma Astronomy?

It was also suggested in my diploma to search for fluxes of high-energy neutrinos from astrophysical objects in underground experiments to find powerful sources of HE Cosmic Rays (see references [2,4]). Reviewing my diploma M. Markov wrote: "The initiative belongs to Zheleznykh to consider a possible role of space neutrinos, i.e. a neutrino flux, arising not in an atmosphere of the Earth, … but in specific processes in depths of the Universe. Here Zheleznykh has made a number of interesting estimations and proposals of experiments with high-energy gamma quanta, coming to an atmosphere of the Earth from Space, which could check the existing hypothesis of origin of cosmic rays…" Ideas of the HE Neutrino Astronomy and HE Gamma Astronomy were approved as well by Ya. Zeldovich (September 1958) and V. Ginzburg (1959) (see reference [6]).

1960: M. Markov suggests an idea of deep underwater neutrino detection.

An idea of deep underwater neutrino detection was reported by Markov at the Rochester conference in 1960: "we propose setting up apparatus in an underwater lake or deep in the Ocean to separate charge particle direction by Cherenkov radiation" [3]. 15 years later in 1973–1976 this idea was revived by F. Reines, J. Learned et al. to construct the large underwater optical neutrino telescope DUMAND of cubic kilometer size. After completion of the creation of the Baksan Neutrino Observatory in 1977, Markov pays more attention to the development of the deep-sea method of detecting muons and neutrinos. In 1978 L. Bezrukov and I. Zheleznykh took part at the DUMAND-78 Workshop at La Jolla. Next DUMAND Workshop took place in August 1979 at Khabarovsk and Lake Baikal. From American side 9 physicists and sea scientists (John Learned, Hugo Bradner, Arthur Roberts, George Wilkins and others) had participated and we had a very friendly and constructive meeting! Following this Workshop Fred Reines and Moisey Markov agreed in October 1979 that USSR would join the International DUMAND–Hawaii Project. But such collaboration was not approved by US authorities.

2 Antarctic ice as a natural target for optical and radio neutrino telescopes.

In 1980 Markov headed the "Soviet DUMAND" program in which more than 10 Institutes from Kaliningrad up to Vladivostok collaborated to develop deep underwater optical and acoustical methods of UHE and EHE neutrino detection in the World Ocean (e.g. Mediterranean Sea) and in Lake Baikal. But alternative radio methods of UHE and EHE neutrino detection and new large-scale natural targets for cosmic neutrino detection were also discussed.

Askaryan's idea of the 1960s [7] to detect coherent Cherenkov radio emission of cascades produced by cosmic rays in dense dielectric media was revived in 1983 by G.Gusev and I.Zheleznykh to be used for development of radio-wave methods of UHE and EHE neutrino detection [8]. However, to register successfully radio pulses-from cascades induced by neutrinos in a natural dielectric target, the right neutrino target with weak radio-wave absorption had to be chosen. Optimal antenna systems (with proper detection thresholds) placed outside or inside the target had to be developed.

In 1983 in order to check whether Antarctic ice is transparent enough in optical and radio diapasons to be used as a natural target for neutrino telescopes, INR requested information from the leading institute of the USSR on polar issues – Arctic and Antarctic Research Institute (AARI), which had a deep drill hole (1400 m in 1980) at the Antarctic station Vostok . AARI (N. Barkov) responded that the optical transparency of a deep Antarctic ice was poor. As it became known later, such information was fair, but only for ice at depths of no more than 1000–1300 m. But the information from AARI (V.Bogorodsky) that: "the transparency of cold ice for decimeter and meter radio waves is very good" was very optimistic. Thus in 1983, it was suggested to build a large-scale Radio Antarctic Muon And Neutrino Detector (RAMAND) using the ice in Antarctica as a neutrino target, taking advantage of very weak radio-wave absorption of ice at low temperatures at frequencies less than a few GHz [8]. But in September 1984 N.Barkov and V.Lipenkov had published the results of studying the structure of ice from the core of a 1400 m depth which was performed by Lipenkov at Vostok station in 1980 [9]. It had been noted that "air dissolution in ice basically ends at a depth of 1300 m, below which the ice density corresponds to the density of "pure" polycrystalline ice" and "in the interval of 1300-1400 m in completely transparent ice only sporadic inclusions of air are noted". It was a pity that this paper with very important information on transparent ice below 1300 m for several reasons was not known for INR and other physicists up to 1988 (in particular, it was not mentioned about ice transparency in the Abstract of the article). But since 1988 this information became known due to glaciologists and greatly contributed to the development of the optical neutrino detection in deep Antarctic ice (F. Halzen, J. Learned).

3 R&D of Radio Antarctic Muon And Neutrino Detector: RAMAND experiments in Antarctica at Vostok station (1985-1990).

Proposed design of RAMAND involved deploying a surface grid of antennas listening to radio pulses in the frequency band from a few hundred MHz up to 1 GHz, produced by cascades from UHE neutrinos in the ice volume of 10^9- 10^{10} m^3. Thus RAMAND collaboration (INR, AARI and Moscow Energetic Institute) started in 1985.

After experiments performed at Vostok in the summer seasons of 1986 and 1987 with three channel installation "Gidra", the R&D stage of the RAMAND [10,11], an ice radio-wave detector with effective volume up to 10 km^3, was approved in 1988 by the Soviet authorities. The hexagonal form of the array with 1280 local stations placed at the 10 km^2 detector area was chosen [12]. During expeditions in 1988 and 1990, a seven channel pilot installation "Gidra-7" was deployed and tested at Vostok [12]. Unfortunately, RAMAND work at Vostok was abruptly discontinued in 1991. Later TEM horn antennas made Russian collaborators became part of the RICE experiment. More about R&D of RAMAND at Vostok is given in the overview of reference [13].

4 June 1988: J. Learned proposes to discuss possible collaboration upon particle astrophysics experiments in Antarctica.

J. Learned wrote in a telex of 14 June 1988 to M.A. Markov: "Dear Prof. M.A. Markov: I would like to propose that we initiate discussions about possible collaboration upon particle astrophysics experiments in Antarctica. After initial discussions with Dr. I.M. Zheleznykh of your Institute I am encouraged that area of common interest exists and that collaboration may be mutually beneficial. We have in mind the exploration of the use of the deep ice at the South Pole, or Vostok station, or elsewhere, as a medium for detection of high energy extraterrestrial neutrinos and gamma ray showers. We want to explore the use of optical Cherenkov radiation in the ice for the TeV energy range, radio and acoustic emission for UHE interactors. . . ." M.Markov writes to the President of the USSR Academy of Sciences G.I. Marchuk: "It seems highly appropriate to consider the creation of a complex detector in Antarctica in collaboration with American physicists which could register not only radio, but also optical Cherenkov radiation of particles in ice. . . ". Marchuk approved such a proposal. Unfortunately, the approaching collapse of the USSR did not contribute to the development of such a collaboration.

5 The Moon is proposed to be used as a giant target for the radio detector of EHE neutrinos and hadrons.

In 1988-1989 the Radio Astronomical Method of Hadron and Neutrino Detection (RAMHAND) was proposed to use the Moon and even other celestial objects as giant targets for radio detectors of EHE hadrons and neutrinos [14]. The Moon had been considered as a perspective large-scale target and it was suggested to use large ground-based radio telescopes to search for Cherenkov-Askaryan radio pulses from cascades produced in the regolith by EHE ($> 10^{20}$ eV) neutrinos and other cosmic particles. The possibility to detect radio emission of cascades of lower energies ($> 10^{16}$ eV) using a lunar satellite was also discussed. During more than a quarter of century a number of lunar experiments were carried out mainly in the 1-3 GHz frequency range using the large radio telescopes of Australia, USA, Russia and other countries but these experiments only put upper limits to the EHE cosmic rays fluxes.

6 First deep-water experiments for the neutrino astrophysics (astronomy) in the Mediterranean.

In October 1989, a cruise of the Soviet R/V "Dmitry Mendeleyev" took place in the Mediterranean Sea. The main goals of the cruise were deep-water experiments in a framework of the program "Soviet DUMAND" and selection of a place for the future neutrino telescope (the Hellenic trench was considered as the favorite). A prototype of the optical module for the neutrino telescope (a titanium frame with four Hamamatsu PMTs and a box of electronics) was tested and atmospheric muon fluxes at depths up to 3500 m were measured [15]. In Summer 1991 during a cruise of the R/V "Vityaz" with the participation of the Greek colleagues a prototype of the NESTOR module of ten Hamamatsu PMTs (an effective area of 400 m^2 for underwater muon detection) was tested and a variety of hydrographic, hydro-acoustical and hydro-physical measurements in the Hellenic trench were performed [16].

7 Conclusion.

First studies of the use of Antarctica (Antarctic ice), the Moon (lunar regolith) and Mediterranean Sea (Hellenic Trench) as large-scale targets for alternative neutrino telescopes were carried out as part of the "Soviet DUMAND" Program in 1980-1991. Development of multi gigaton Radio Antarctic Muon And Neutrino Detector (RAMAND, 1983-1990) for UHE ($> 10^{14}$ eV) Neutrino Astronomy at Antarctic Vostok station was very successful in 80th, but ended with the collapse of the Soviet Union. The new generation of huge radio neutrino telescopes under construction in Antarctica (ARA and ARIANNA) have great prospects as discovery instruments for astrophysical neutrinos of $E > 10^{15-17}$ eV. Radio Astronomical Method of Hadron And Neutrino Detection (RAMHAND) had started in the framework of the Soviet DUMAND program since 1988. Using the new larger-scale radio astronomical telescopes (SKA and others) for lunar experiments would give great opportunities for studying fundamental problems of Cosmic Ray (Astroparticle) Physics and Neutrino Astronomy in the interval of energies more than 10^{19} eV. In the coming years, new deep-sea neutrino telescopes in the Mediterranean and in Baikal may also become, like IceCube, the most important instruments of UHE neutrino astronomy.

Acknowledgements

I am deeply grateful to the participants of the DUMAND Hawaii and Soviet DUMAND programs for the fruitful cooperation and support, in particular, J. Learned, Ch. Spiering, V. Matveev, R.Dagkesamanskii, O.Ryazhskaya, L.Dedenko, A.Butkevich, G.Gusev, A.Provorov, V.Boyarsky, V.Lukin, N.Surin, V.Paka, L.Bezrukov, A.Petrukhin, V.Beresnev, S.Karaevsky, N.Litvinova, Z.Sadygov, A.Gassanov. I am also deeply grateful to Daniel Vignaud, Michel Cribier and the

other members of the Organizing Committee for their great contribution to the History of the Neutrino Conference dedicated in particular to the unique history of research on the fundamental problems of the micro-world and macrocosm with the help of large-scale neutrino detectors and neutrino telescopes.

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