CRD main achievements in 2019-2020

Cosmic Ray Division physicists perform research in many areas of Astroparticle physics and high-energy Atmospheric physics:

- CR Origin and acceleration mechanisms.
- Solar-terrestrial connections; solar modulation of galactic CRs.
- Solar proton accelerators.
- High Energy phenomena in Atmosphere, Thunderstorm Ground Enhancements (TGEs).
- Lightning physics.
- Monitoring of geophysical parameters.
- Scientific instrumentation.
- Multivariate data analysis and Machine Learning.

Among the main achievements of recent years are:

- Estimation of the maximum energy of solar proton accelerators (protons with energies greater than 20 GeV) accelerated in the vicinity of the Sun during Ground Level Enhancement (GLE) event N 69.
- Discovery of simultaneous fluxes of electrons, gamma rays, and neutrons, as well as, prolonged radiation of 222Rn progeny, comprising a new phenomenon in the geoscience, called thunderstorm ground enhancement (TGEs).
- Direct observation of the “Cloud Extensive Showers - CESs”, the relativistic runaway avalanches (RREA) developed in thunderclouds.
- Discovery of a new source of enhanced natural gamma radiation – Modification of the electron energy spectra (MOS) in the strong electric field inside the thundercloud.
- Estimation of the maximum achievable value of the atmospheric electric field.
- Discovery of the Radon and its progeny circulation during thunderstorms.
- Discovery of the violet line spots at altitudes 200-300 m above earth’s surface during TGEs.
- Development of the Aragats Space Environmental Center (ASEC) and Armenian Geophysics Network.
- Founding of the worldwide network of the particle detectors measuring 3 species of cosmic rays, called SEVAN (Space Environment Viewing and Analysis Network). Nodes of the SEVAN network are now operating in Armenia, India, Bulgaria, Croatia, Slovakia, Germany, and Czech Republic.

- Installing on Aragats facilities with precise detection of atmospheric discharges and introducing of a new model of lightning initiation and lightning type determination.
- Founding of Armenian Geophysics Network in Armenia and Arcakh (Shushi University).

In 2020 following tasks were accomplished:

1. 7/24 monitoring of particle fluxes incident on the earth's surface by all facilities located on slopes of Aragats Mountain on heights 3200 and 2000 m.
2. Provide uninterruptable access to CRD databases containing unique information on multi-year monitoring of major geophysical parameters and cosmic ray data. Improve operation of ADEI knowledge platform.
3. Develop model of Thunderstorm Ground enhancement (TGE) initiation, including Relativistic Runaway Electron Avalanches (RREA) and 222Rn chain progenies isotropy radiation in the thunderous atmosphere.
4. Install new fast cameras providing streaming video of skies above Aragats for direct observations of RREA.
5. Measure with 4sq. m. area and 60- cm thick plastic scintillators flux of TGE electrons. Perform GEANT4 simulation of the ASNT detector response function. Recover energy spectra of TGE electrons.
6. Perform measurements of atmospheric discharges with particle detectors, fast and slow antennas, interferometer, and a variety of particle detectors synchronized on a time scale of a microsecond.
7. Develop the methods of determining the types of lightning discharges.
8. Incorporate in the TGE model data on estimation of the vertical profile of thundercloud obtained by the Weather research and forecasting model (WRF).
9. Update constriction of the one-channel compact NaI spectrometers for improving energy resolution.
10. Operate SEVAN particle detector network, prepare documentation, continue Monte Carlo studies of SEVAN detector response function.

Brief description of activities:

A continuous data stream from various particle detectors and field meters located on Aragats (3200 m a.s.l.) is entering a MySQL database in Yerevan's CRD headquarters; data is available on-line via the ADEI interactive WEB platform. In 2019 it will be 10 years since CRD physicists started research in the new direction of High-Energy Atmospheric Physics (HEAP). Important results were obtained in proving a runaway mechanism of particle acceleration and multiplication in thunderclouds [1,6,14].

We also determined the types of lightning flashes that abruptly terminated TGEs [9]. Another finding was connected with the enigmatic problem of lightning initiation. CRD physicists discovered a direct relation between particle fluxes and subsequent atmospheric discharges. New findings were made relating to estimations of the intracloud electric field strength by measurements of the energy spectra of the "thundercloud" particles. This very important and very difficult to assess topic has been examined by CRD since 2014 and was continued by our former researcher Bagrat Mailyan, now working in NASA [6].

The atmospheric electric field influences measurements made by large Astroparticle experiments using the terrestrial atmosphere as a target for the multiplication of ultra-high energy particles accelerated in the most violent star explosions in the Universe. We investigated these effects with models of particle propagation in the strong atmospheric electric fields [2,3].

In the low energy domain (0.3 – 3MeV) the natural gamma radiation coming from long living isotopes in Earth's crust and surrounding rocks makes major contributions to the background radiation measured by gamma spectrometers on Aragats. To distinguish the fluctuations of natural radiation from the enhancements due to electron-photon avalanches initiated in the atmospheric electric fields, in 2019-2020 we monitor 222Rn progeny concentration in the atmosphere and in the rainwater that results in the discovery of the radon circulation effect [7,8,12,18]. A.Chilingarian discuss the 222Rn progeny radiation during his visits to Ariel and Tel-Aviv universities where he delivered seminars.

We install new facilities on Aragats for lightning research [16] and a new seismological station in Nor Amberd in collaboration with the Institute of Geophysics and Engineering Seismology of the National Academy of Sciences of Armenia. This is a unique facility measuring electric and geomagnetic fields, neutron fluxes, and seismic waves.

The scientists and engineers of CRD, AANL (YerPHI) visited Germany from October 28 to November 10, 2019 to install two SEVAN (Space Environmental Viewing and Analysis Network) detectors at DESY, Hamburg and Zeuthen. This visit was organized within the framework of SEVAN network, started as a United Nations Basic Space Science Initiative (UNBSSI) project to assist scientists and engineers from all over the world in participating in the International Heliophysics Year 2007 (IHY-2007).

The SEVAN is a unique radiation detection device which used for the continuous monitoring of different species of secondary cosmic rays. Simultaneous measurements with SEVAN device, placed in Armenia, Germany, Slovakia, Czech Rep., Bulgaria, and Croatia to a better understanding of Solar activity, Space Weather, and atmospheric physics, including particle fluxes from thunderclouds and lightning initiation. Based on the SEVAN network databases, it is planned to produce and disseminate outreach materials, suitable for laypersons, pupils, school teachers, and students, in Armenian, German and English language, to organize summer schools for the training of students and young postdocs on topics relevant to modern physics research in astroparticle, particle, and atmospheric physics.

Gamma-ray bursts (GRBs) are the most violent explosions in the Universe, suddenly appearing in the sky, about once per day. They are thought to result from the collapse of massive stars or the merging of neutron stars in distant galaxies. The first GRB detected by the MAGIC telescopes, known as GRB 190114C, reveals for the first time the highest-energy photons measured from these objects. This ground-breaking achievement by MAGIC provides critical

new insight for understanding the physical processes at work in GRBs, which are still mysterious. Two papers in the Nature issue of 21 November describe the detection of the gamma rays up to TeV energies with MAGIC and the indication that inverse Compton scattering is the responsible process at work [10,11].

Based on measurements of the intensity and energy spectra of NGR on Mt. Aragats, we present a comprehensive model explaining NGR enhancement during thunderstorms. We describe the TGE phenomenon as a mixture of two separate processes, both having roots in the electric fields (intracloud and near-surface) emerging during thunderstorms. For the first time, we observe the airglows initiated by electron-gamma ray avalanches developing in the lower atmosphere [12].

In a comment published in PRL [13], we point to the erroneous inference from muon detection in OOTY, India on an enormously large potential drop in the troposphere (1.2 GV). The correct methodology was developed and the maximum achievable electric field estimate was calculated based on the muon stopping effect measured on Aragats [17]. The estimate of the maximum electric field based on the largest ever-measured TGE at Lomnitskcy Stit in Slovakia equals 500 MV, the paper is submitted to PRD.

CRD research also includes projects with institutions from many countries where CRD installed new particle detectors or shares data from the world's largest cosmic ray center on Mt. Aragats. Recently several US universities have proposed research projects, which include Aragats as a site where they would like to install modern detectors. CRD international collaborations are shown at the end of this report.

CRD physicists actively participate in the American Geophysics Union Fall meeting in 2019, presenting 6 reports. CRD continues to collaborate with Neutron Monitor Database consortium, presenting 4 reports on the virtual symposium on cosmic ray studies with neutron detectors,13-17 July 2020 [20].

	All	Since 2016
Citations	13074	3836
h-index	55	34
i10-index	133	69

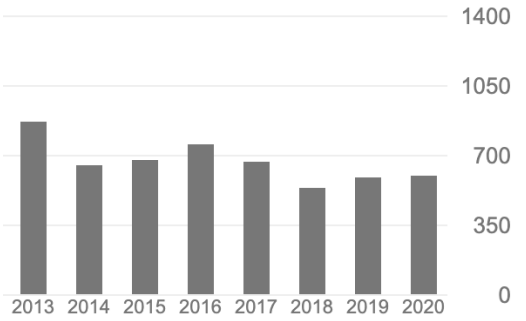

Figure 1. CRD papers citation by GOOGLE scholar

10 of CRD papaers has citation number above 50 reaching 700.

Journal publications in 2019-2020:

1. A.Chilingarian , S. Soghomonyan , Y. Khanikyanc , D. Pokhsraryan , On the origin of particle fluxes from thunderclouds, *Astroparticle Physics* 105 , 54(2019).
2. A.Chilingarian, Energetic radiation from thunderclouds: extended particle fluxes directed to Earth's surface, Rendiconti Lincei. Scienze Fisiche e Naturali, doi.org/10.1007/s12210-018-0755-y, 2019.
3. A.Chilingarian, J.Knapp and M.Zazyan, Monitoring of the atmospheric electric field and cosmic-ray flux for the interpretation of results in high-energy astroparticle physics experiments, EPJ Web Conf., Volume 197, 2019, Atmospheric Monitoring for High-Energy Astroparticle Detectors (AtmoHEAD-2018), Article 03001.
4. K.Apresyan, A.Chilingaryan, A.Ghalumyan, V. Ghazaryan, Upgrade of YerPhI polarization LIDAR System for Investigation of the Influence of Static Electric Fields on the Elastic and Raman Backscattered Beams Polarization, The European Physical Journal Conferences 197(6):03005, DOI: 10.1051/epjconf/201919703005
5. K.A.Nicoll, R.G.Harriso,V.Barta et al.,A global atmospheric electricity monitoring network for climate and geophysical research, JASTP, 184, 18 (2019).
6. A.Chilingarian, H. Mkrtchyan, G. Karapetyan, et al., Catalog of 2017 Thunderstorm Ground Enhancement (TGE) events observed on Aragats, (2019) Nature Scientific Reports 9(1):6253, DOI: 10.1038/s41598-019-42786-7
7. A.Chilingarian, Reply to "Comment on 'Long lasting low energy thunderstorm ground enhancements and possible Rn-222 daughter isotopes contamination, Phys. Rev. D 99, 108102 (2019)
8. A.Chilingarian, A. Avetisyan, G. Hovsepyan, T. Karapetyan, L. Kozliner, et al., Origin of

the low-energy gamma ray flux of the long-lasting thunderstorm ground enhancements, Phys. Rev. D 99, 102002 (2019).

9. A.Chilingarian, Y. Khanikyants, V. A. Rakov, and S. Soghomonyan, Termination of thunderstorm-related bursts of energetic radiation and particles by inverted-polarity intracloud and hybrid lightning discharge, Atmospheric Research 233 104713, (2020).
10. Magic collaboration, Avery-high-energy component deep in the γ-ray burst afterglow, Nature 575 , 464–467, 20 November, 2019.
11. Magic collaboration, Observation of inverse Compton emission from a long γ-ray burst, Nature 575 , 459–463, 20 November, 2019.
12. A.Chilingarian, G. Hovsepyan, A. Elbekian, T. Karapetyan, L. Kozliner, H. Martoian, and B. Sargsyan, Origin of enhanced gamma radiation in thunderclouds, Physical review research, **1**, 033167 (2019)
13. A.Chilingarian, G. Hovsepyan, E. Svechnikova, E. Mareev, Comment on "Measurement of the electrical properties of a thundercloud through muon imaging by the GRAPES-3 experiment'', PRL 124, 019501 (2020)
14. Chilingarian, A. A. (2020), Understanding high-energy physics in Earth's atmosphere, Eos, 101, https://doi.org/10.1029/2020EO138276. Published on 08 January 2020.
15. A.Chilingarian, G. Hovsepyan, T. Karapetyan, et al., Structure of thunderstorm ground enhancements, PRD 101, 122004 (2020).
16. A.Chilingarian, M. Dolgonosov, A. Kiselyov,Y. Khanikyants and S. Soghomonyan, Lightning observations using broadband VHF interferometer and electric field measurements, 2020 *JINST* 15 P07002
17. A.Chilingarian, G. Hovsepyan, G.Karapetyan, and M.Zazyan, Stopping muon effect and estimation of intracloud electric field, Astroparticle Physics 124 (2021) 102505.
18. Chilingarian, A., Hovsepyan, G.,& Sargsyan, B. (2020). Circulation of Radon progeny in the terrestrial atmosphere during thunderstorms. *Geophysical Research Letters*, *47*, e2020GL091155. https://doi. org/10.1029/2020GL091155.
19. Hunting, E. R., Matthews, J., de Arróyabe Hernáez, P. F., England, S. J., Kourtidis, K., Koh, K., et al. (2020). Challenges in coupling atmos- pheric electricity with biological systems. *International Journal of Biometeorology*. https://doi.org/10.1007/s00484-020-01960-7.
20. Ashot Chilingarian[1], Tigran Karapetyan[1], Mary Zazyan[1], Gagik Hovsepyan[1], Balabek Sargsyan[1], Nina Nikolova[2], Hristo Angelov[2], Jaroslav Chum[3], Rony Langer[4], Analyzing atmospheric electric field by the European SEVAN network of particle detectors, NMBD symposium, July, 2020, Kiel University, Proceedings in press.

CRD International collaborations

1. SEVAN Collaboration (Solar Physics, Atmospheric physics and Geophysics) includes Yerevan Physics Institute, Armenia, Institute of Nuclear Research and Nuclear Energy, Bulgaria, Ustav Jaderne Fyziky AV, Czech Rep., Ustav Experimentalnej Fyziky, Slovakia, Zagreb Observatory, Croatia.

2. NMDB Collaboration: Real-Time Database for high-resolution Neutron Monitor measurements; more than 40 European, Asian and American groups including CRD join efforts for research in solar physics and space weather.
3. GloCAEM project (global network for atmospheric electric field monitoring) – International project headed by the group of Redding Univ. UK, for atmospheric electricity research funded by NERC International Opportunities Fund grant NE/N013689/1.
4. Horizon 2020 COST Action: CA15211: "Atmospheric Electricity Network: coupling with the Earth System, climate and biological systems"
5. International Space Science Institute (ISSI) research group for "High-Energy Particles Sources and Powerful VHF Radiations in Electrically Active Atmosphere: Theoretical Models and Space Borne Instruments"
6. DESY – research and measurements of intracloud electric field for Cherenkov Telescope Array project.
7. Russian Scientific Foundation project 17-12-01439/2017, "Comprehensive research of high-energy particles sources and powerful VHF radiation in electrically active atmosphere based on ground-based measurements and satellite observations", joint project of CRD with Institute of space Research of RAS, Moscow and Institute of Applied Physics of RAS, Nizhny Novgorod, headed by A.Chilingarian.
8. Work according to bilateral agreements with National Research Nuclear University MEPhI, and Scobeltcin Nuclear Physics institute, MSU, Moscow, Russia successfully continued.
9. MAGIC is European collaboration, operating is a system of two 17 meter Imaging Air Cherenkov Telescopes, located at the Observatorio Roque de los Muchachos at an altitude of 2200 meters on the Canary island of La Palma. MAGIC detects gamma rays in the very high energy regime between a few tens of GeV and tens of TeV.
10. Network of Solar Neutron Telescopes coordinated by Solar-terrestrial Environmental Laboratory, Nagoya University, Japan.
11. European Horizon 2020 CRREAT (**Center of *C*osmic *R*ays and *R*adiation *E*vents in the *At*mosphere)** project, Nuclear Physics Institute of the CAS.
12. European Radiation Dosimetry Group (EURADOS).
13. World-Wide Lightning Location Network (WWLLN), University of Washington in Seatle.