Understanding High-Energy Physics in Earth's Atmosphere - Eos

Thunderstorms present a variety of hazards, including emissions of ionizing radiation. An international group of scientists met at an Armenian observatory to share their findings.

Armenia's Lake Kari sits near the top of Mount Aragats. In this summertime view, the south summit is visible in the background. Attendees at a conference in 2019 visited a nearby research station that collects data on atmospheric radiation associated with thunderstorms. Credit: Ashot A. Chilingarian

All living organisms are continuously exposed to natural radioactivity from Earth's minerals and atmosphere, as well as from sources beyond the atmosphere. Protecting against the harmful effects of radiation requires us to understand all sources of radiation and the possible ways in which radiation levels are enhanced. Recently, scientists discovered that a given individual's cumulative radiation exposure can reach significant levels during thunderstorms [*Chilingarian et al.*, 2018]. Thus, models used for forecasting thunderstorms and other severe atmospheric phenomena need an accurate accounting of radiation in the atmosphere.

Long-lasting streams of gamma rays, electrons, and neutrons called thunderstorm ground enhancements (TGEs) have been observed in association with thunderstorms. These observations demonstrate that levels of natural gamma radiation in the 10– to 50–megaelectron volt range can jump to 10 times their normal level over the course of several minutes, and levels of gamma rays with energies of hundreds of kiloelectron volts can be doubled for several hours.

Until recently, the origin of these elevated TGE fluxes was debated. The most popular hypothesis, that the particle bursts were initiated by runaway electrons, had not been confirmed by direct observation. The emerging research field of high-energy atmospheric physics (HEAP) is now shedding light on what causes these particle showers.

HEAP comprises studies of various physical processes that extend to altitudes of many kilometers in thunderclouds and many hundreds of kilometers in space. Research into TGEs has been active since 2010. Since this time, the Cosmic Ray Division (CRD) of Armenia's Yerevan Physics Institute has organized international conferences at which HEAP researchers discuss the most intriguing problems of high-energy physics in the atmosphere and explore possible directions for the advancement of collaborative studies. The ninth annual meeting, held in Byurakan, Armenia, in October 2019, provided an environment for discussing important observations of particle fluxes correlated with thunderstorms occurring on Earth's surface, in the troposphere, and in space.

Understanding Thunderstorm Phenomena

The concept of runaway electrons in thunderclouds extends back almost a century. One of the first particle physicists and atmospheric electricity researchers, Nobel laureate Sir C. T. R. Wilson, was the first to recognize that "the occurrence of exceptional electron encounters has no important effect in preventing the acquisition of large kinetic energy by particles in a strong accelerating field" [*Wilson*, 1925]. The astronomer Arthur Eddington, referring to this electron acceleration by the strong electric fields in thunderclouds, coined the term "runaway electrons" [*Gurevich*, 1961]. However, until now, this and many other electromagnetic processes in our atmosphere have been only partially understood, and key questions about thundercloud electrification and lightning initiation have remained unanswered.

HEAP research currently includes three types of measurements. Orbiting gamma ray observatories in space observe terrestrial gamma ray flashes, which are brief bursts of gamma radiation (sometimes with electrons and positrons). Instruments on balloons and aircraft observe gamma ray glows. Detectors on Earth's surface register TGEs, which consist of prolonged electron and gamma ray fluxes (also neutrons; Figure 1). The durations of these different enhanced particle fluxes range from milliseconds to several hours.

Research groups from many nations—Argentina, Bulgaria, China, the Czech Republic, Japan, Mexico, Russia, Slovakia, the United States, and others—are joining the field of HEAP research. Meanwhile, physicists from Armenia have been working on the detection of cosmic rays for many decades and focusing on intensive studies of TGEs for the past 10 years.

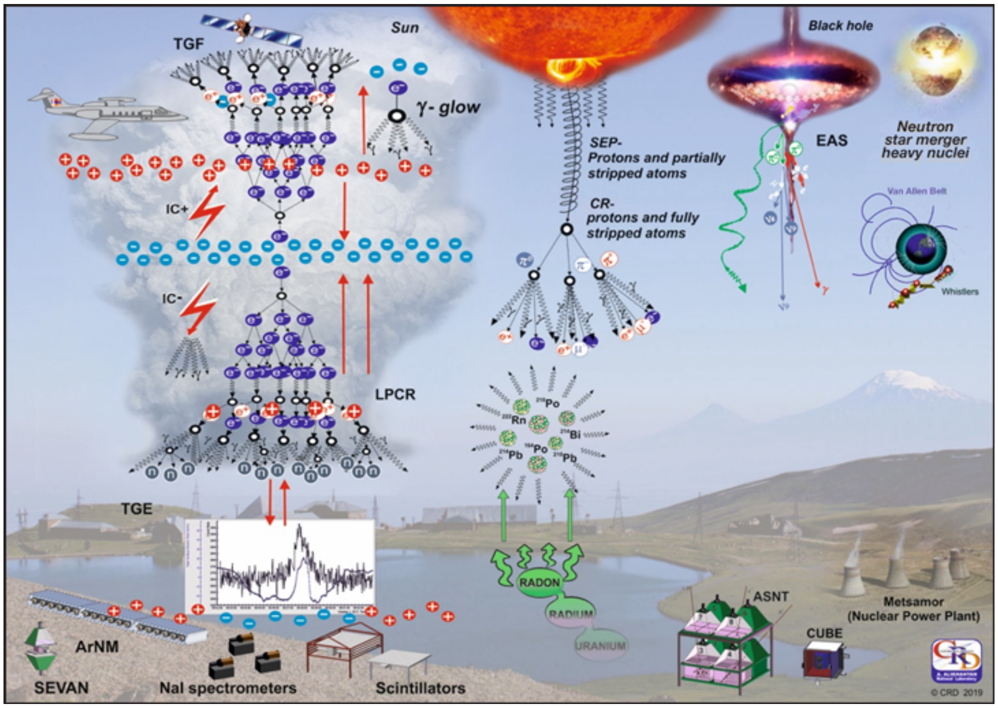

Fig. 1. The origins of natural gamma radiation include the newly discovered long-lasting thunderstorm ground enhancements (TGEs). These enhancements consist of short emissions of high-energy electrons and gamma rays and hours-long emissions of radon-222 progenies lifted into the atmosphere by the thunderstorm's electric field. Abbreviations are ArNM, Aragats Neutron Monitor; ASNT, Aragats Solar Neutron Telescope; CR, cosmic ray; EAS, extensive air shower; IC+, positive intracloud discharge; IC–, negative intracloud discharge; LPCR, lower positively charged region; NaI spectrometers, sodium iodide spectrometers; CUBE, Cube particle detector assembly; SEP, solar energetic particle; SEVAN, Space Environment Viewing and Analysis Network; and TGF, terrestrial gamma ray flash. Credit: Cosmic Ray Division, Yerevan Physics Institute

Observations from Aragats

At the Nor-Amberd and Aragats research stations on the slopes of Mount Aragats, an isolated volcano massif in Armenia, numerous particle detectors have been continuously registering fluxes of charged and neutral particles for the past 75 years. At the main facility, the Aragats research station of the Yerevan Physics Institute's CRD, the main topic of research is the physics of the high-energy cosmic rays accelerated in our galaxy and beyond. Surface arrays consisting of hundreds of plastic scintillators measure extensive air showers, the cascades of billions of particles born when primary high-energy protons or fully stripped nuclei originating outside our solar system interact with atoms in Earth's atmosphere.

The Aragats station is located on a flat volcanic highland 3,200 meters above sea level near Lake Kari, a large ice lake, and is especially well situated to record thunderstorm phenomena because the bases of thunderclouds are often very close to Earth's surface. Electrons and gamma rays travel only a short distance through the atmosphere between the clouds and the particle detectors on the ground with very little, if any, attenuation.
In 2008, during a quiet period of solar cycle 24, the CRD turned to investigations of high-energy phenomena in the atmosphere over the Aragats station. Since then, existing and newly designed particle detectors at the Aragats station have observed more than 500 TGE particle bursts—about 95% of the strongest TGEs recorded to date. (There have been only a few other reports of TGEs elsewhere [e.g., *Enoto et al.*, 2017].) Aragats researchers recently published the first catalog of TGE events [*Chilingarian et al.*, 2019a].

TGEs observed from Aragats consist not only of gamma rays but also of sizable enhancements of electrons and also, rarely, neutrons [*Chilingarian et al.*, 2010]. The relativistic runaway electron avalanches (RREAs) that produce these TGEs are believed to be a central engine initiating high-energy processes in thunderstorms. During the strongest thunderstorms on Mount Aragats, RREAs directly observed using scintillator arrays and simultaneous measurements of TGE electron and gamma ray energy spectra proved that RREAs are a robust and realistic mechanism for electron acceleration.

Models and Discoveries

Our research group at Aragats was a major contributor at the 2019 symposium. We gave five talks about our newly developed model of natural gamma radiation (NGR) and the enhanced radiation fluxes incident on Earth's surface during thunderstorms [*Chilingarian et al.*, 2019b], which was a central topic of discussion at the meeting. This comprehensive model, along with observations of minutes-long fluxes of high-energy electrons and gamma rays from RREAs, helps clarify the mechanism of hours-long isotropic fluxes of low-energy gamma rays (<3 megaelectron volts) emitted by radon-222 progeny species.

It has been known for many years that radon-222 progenies are the main source of low-energy gamma rays [see, e.g., *Reuveni et al.*, 2017]; however, the mechanism of abrupt enhancement of this radiation during thunderstorms was unknown. Experiments on Aragats, performed in 2019, proved that emanated radon progenies become airborne, immediately attach to dust and aerosol particles in the atmosphere, and are lifted by the near-surface electric field upward, providing isotropic radiation of low-energy gamma rays.

NGR is one of the major geophysical parameters directly connected to cloud electrification and lightning initiation. Low-energy NGR (<3 megaelectron volts) is due to natural isotopic decay. Middle-energy NGR during thunderstorms comes from the newly discovered electron accelerators in the thunderclouds (<50 megaelectron volts), and always existent high-energy NGR (>50 megaelectron volts) is caused by solar accelerators and ionizing radiation coming from our galaxy and the universe (Figure 1, top right).

The Aragats group also observed direct evidence of an RREA for the first time in the form of fluorescent light emitted during the development of electron–gamma ray cascades in the atmosphere, work we reported on at the symposium. This observation correlated well with the high-energy electron flux registered by surface particle detectors.

Next, we proved that in the lower dipole (a transient positively charged region at the base of thunderclouds), electrons are accelerated to high energies, forming avalanches that reach Earth's surface and initiate TGEs [*Chilingarian et al.*, 2020]. We also performed simulations of electron propagation in strong atmospheric electric fields, proving the origin of the runaway electron phenomenon.

Shedding Light on Lightning

Other attendees at the 2019 symposium presented reports on lightning initiation and its relation to particle fluxes originating in thunderclouds. They spoke of classifying lightning types according to which sensors detected the atmospheric discharges and according to parameters of particle fluxes (intensity, maximum energy, and percentage of flux decline) abruptly terminated by the lightning flash. Attendees also presented on remote sensing methods for studying thundercloud structure and atmospheric electric fields, as well as on the influence of atmospheric electric fields on extensive air showers and Cherenkov light emitted by rapidly moving subatomic particles.

During an excursion to the Aragats research station, conference attendees visited new facilities for the detection of atmospheric discharges. These new facilities use interferometry to study the causes of lightning initiation, which remain enigmatic. The interferometer operating at this station registered more than 400 lightning flashes in 2019 synchronously with the detection of cosmic rays and a near-surface electric field—a powerful demonstration of this very new application. The conference visitors were convinced that the interferometer data on atmospheric discharges and the associated particle flux characteristic measurements will lead to a comprehensive model of lightning initiation coupled with particle flux propagation in thunderstorm atmospheres.

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