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FLASHES IN THE SKY LIGHT – ELECTROMAGNETIC RECORDS IN THE EARTH'S ATMOSPHERE

Abstract. The Earth is a large magnet and has a magnetosphere that largely protects it from the influence of the interplanetary magnetic field and the charged particles of the solar wind. Charged particles from active regions and coronal holes that are in a geoeffective position on the Sun move along the lines of the interplanetary magnetic field and reach the Earth's magnetosphere and cause geomagnetic disturbances and storms. The variability of the Earth's magnetic field is an indicator of the influence of Solar activity on the terrestrial system. The development and application of space technology has provided a lot of valuable instrumental data on the activity of the Sun and its influence on the Earth's magnetic and electric fields. This has contributed to the expansion of knowledge and their connection with the mechanism of meteorological processes in the Earth's atmosphere. The entry of charged particles of the solar wind into the Earth's atmosphere causes the appearance of various light-electromagnetic phenomena, starting from auroras, through ordinary lightning, to a multitude of other phenomena that are not easily accessible to the human eye and have been discovered with the development of space and computer technology. Over the last few decades, other forms of auroras and phenomena called blue jets, elves and sprite have been discovered. These light phenomena occur in the higher layers of the atmosphere (stratosphere and ionosphere) as a short-lived flash. The mechanism of lightning in the troposphere is similar to the formation of lightning and auroras in the stratosphere. The charged particles of the solar wind throw out electrons from the atoms of chemical elements in the air, and then the electrons, when returning to their original energy level in the atom, quickly release energy in the form of light. Flashes (lightning) in the higher layers are an indicator of the entry of charged particles from the Sun, and those in the troposphere are also associated with meteorological phenomena, primarily with thunderclouds.

Keywords: Solar activity, charged particles, lightning in the atmosphere

1. Introduction

The main source of energy in the Earth's atmosphere is the Sun. The immaterial part (electromagnetic radiation) makes up 99 %, and 1 % is material (corpuscular) radiation in the form of charged elementary particles (solar wind). Cosmic rays originating from the depths of space also penetrate the Earth's atmosphere.

The Earth has its magnetic field. It is assumed that the magnetic field is created according to the laws of electromagnetism. The flow of electric current (telluric current) through the interior of the planet, primarily through the iron core, creates its magnetic field. The Earth's magnetic field has its own north and south magnetic poles whose locations differ from the geographic poles. The magnetosphere is the region of space surrounding the Earth where its magnetic field is stronger than the magnetic field of interplanetary space. The magnetosphere largely protects the Earth from the effects of the interplanetary magnetic field and the charged particles that originate from the Sun [1].

Due to the presence of charged particles, and positive and negative ions in the atmosphere, the Earth has an electric field. Atmospheric ionization occurs under the influence of:

- galactic cosmic rays, which are high-energy nuclei of hydrogen and helium that are formed outside our solar system in supernova explosions; generate a cascade of ions as they penetrate downward through the atmosphere and are the main source of ionization,

- solar energetic particles that are formed by coronal mass ejections during explosions and eruptions on the Sun (solar wind),

- natural radioactivity from soil and rocks above the land (not above the ocean) that penetrate upwards from the surface to a height of about 1 km [2].

In the higher layers of the ionosphere, the gases that make up the atmosphere are partly atomic structures or plasma.

In addition to the global drivers of atmospheric electricity, there are local influences:

- weather conditions; almost any type of weather can affect atmospheric electricity, for example, fog causes a large increase in the potential gradient, rain causes it to become negative and very variable, and snow causes it to be positive,

- air pollution; for example, smoke particles from exhaust gases and fires and droplets create additional resistance and a correspondingly large potential gradient.

- changes in the physical environment; for example, pointed metal structures such as poles and fences distort the electric field near the Earth's surface [2].

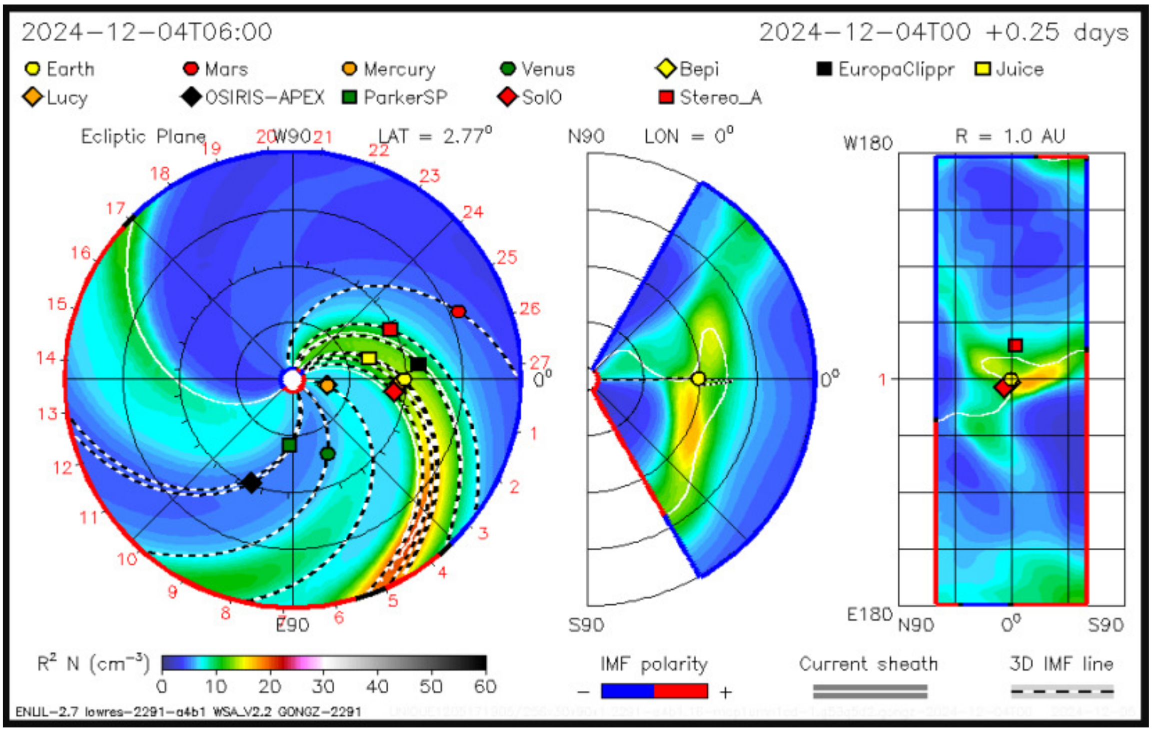

Figure 1. ENLIL Spiral | Magnetic Sector Boundaries and CME Events [5]

Based on the laws of electromagnetism, charged particles in the atmosphere move in the direction of magnetic fields. The atmospheric electric field is directed vertically in such a way that it drives positive charges downward, towards the ground [3]. The solar wind continuously flows outward from the Sun and consists mainly of protons and electrons in a state known as plasma. The magnetic field that is embedded in the plasma moves along with the solar wind. Different regions of the Sun produce solar wind of different speeds, densities, and temperatures. The Sun rotates on its axis, one rotation taking approximately 27 Earth days, and the solar wind becomes a complex spiral of high and low speeds and densities (Figure 1), [4], [5].

WSA-Enlil is a large-scale, physics-based prediction model of the heliosphere, used by the Space Weather Forecast Office to provide 1- 4 day advance warning of solar wind structures and Earth-directed coronal mass ejections (CMEs) that cause geomagnetic storms. Solar disturbances have long been known to disrupt communications, wreak havoc with geomagnetic systems, and pose dangers for satellite operations [5].

When active regions and coronal holes on the Sun are in a geoeffective position, charged particles move along the lines of the interplanetary magnetic field after the eruption and reach the Earth's magnetosphere, causing geomagnetic disturbances. The variability of the Earth's magnetic field is an indicator of the impact of the Sun's activity on the terrestrial system. Most of the Sun's charged particles enter the atmosphere in the polar regions, around the northern and southern polar regions (from 60^{o} to 70^{o} latitude), on the night side of the magnetosphere. The solar wind has great variability in space and time [6].

2. The influence of solar activity on meteorological processes in the Earth's atmosphere

The development of space technology (satellites, optics, computers) has made it possible to obtain a multitude of valuable instrumental data on the activity of the Sun and its influence on the Earth's magnetic and electric fields. This has contributed to the expansion of knowledge and its connection with processes in the Earth's atmosphere. Over the past few decades, many papers have been published on the connection between solar activity and meteorological processes in the Earth's atmosphere. For example, there is a connection between solar activity and the strengthening of tropical cyclones [7], [8] and cyclones in the North Atlantic [9], a connection between the repeatability of some meteorological phenomena and the periodicity of the Sun's rotation [10], a connection between geomagnetic activity and the dynamics of cold fronts [11].

3. Light-electromagnetic phenomena in the stratosphere and ionosphere

The entry of solar wind charged particles from the solar wind into the Earth's atmosphere causes a variety of light phenomena, from the aurora borealis, through common lightning, to a multitude of other phenomena that are not easily visible to the human eye and have been discovered with the development of space and computer technology. A century ago, there were over 80 theories to explain the aurora borealis [12].

3.1. Northern Lights. The northern lights (aurora polaris, borealis, australis) are well explained. They represent the illumination of the night sky, mainly in the polar regions. During high solar activity and strong eruptions of charged particles, the northern lights are also visible at lower latitudes, sometimes, very rarely, for example in the Mediterranean region.

The northern lights (Figure 2) are caused by charged particles, primarily fast electrons, which are part of the solar wind and have an energy of 1 keV to 15 keV, that is, they are accelerated by a voltage of up to 1000 V to 15,000 V. The electrons collide with atoms and molecules in the air and transfer a certain amount of energy to them. Therefore, electrons from the electron shell of an atom briefly move to a higher energy level. When they return to their ground state, the electrons (and the atom as a whole) release energy in the form of light. When an excited oxygen atom, elektrons returns to its ground state in less than a second, it emits green light. The remaining electrons, which return within two minutes, emit reddish light. When the density of gases is higher, the energy emitted by electrons from the shell is lost through mutual collisions between atoms. At altitudes of about 80 km, the concentration of oxygen atoms is low, and there are few collisions, but there is enough time for excited atoms to emit green light (557.7 nm), and those at higher altitudes to emit brownish-red light (630 nm). Ionized nitrogen atoms emit light blue, and unionized ones emit red light [13].

Auroras polaris can also be observed in the ultraviolet part of the spectrum, especially when observed from space. The space probe "Polar" recorded the aurora even in the X-ray range. Auroras appear as "diffuse light", like a "curtain" or "arcs", which move in the direction from east to west. The light changes often ("active aurora"). Each curtain consists of numerous parallel strips (rays) that are directed toward the magnetic field lines. Otherwise, it is known that charged particles move along the magnetic field lines, which indicates that the interplanetary and Earth's magnetic fields influence the appearance of the aurora.

Auroras also exist on Jupiter and Saturn, whose magnetic fields are much stronger than Earth's, and are a consequence of the action of the solar wind, as on Earth. Also, Jupiter's moon Io has pronounced auroras. Recently, auroras have also been discovered on Mars [14].

3.2. Proton aurora. Around the planet Earth, there are rings of electric current that are invisible to the naked eye, unlike the visible icy rings of Saturn. During strong solar flares and strong magnetic storms, charged particles from the rings fall and cause a secondary shower of electrons that strike the atmosphere and cause auroras. Satellites in Earth's orbit have recorded the downward motion of protons in the rings. Proton auroras usually occur at dusk, are pulsating, and are accompanied by red arcs of light emanating from the rings of electric current (Figure 3). [15].

3.3. Blue Jets, Elves and Sprite. Over the past few decades, space technology has enabled new knowledge and the discovery of previously unknown light phenomena in the stratosphere and ionosphere (Figure 4). he common feature of all forms of these light phenomena (Blue Jet, Elves, Red Sprite) is that they are created by the strike of the solar wind-charged particles on the upper layers (tops) of a thundercloud (Cumulonimbus). The mechanism is similar to that of the formation of auroras. The arriving particles break out electrons from atoms, which is manifested by white flashes Then the positively ionized atoms in the electric field move upwards from the top of the cloud. Due to the increase in the concentration of electrons at higher altitudes, the resulting light (flash, lightning) becomes stronger due to the increasing number of proton and electron collisions. Flashes of light of this type can be of various colors depending on which chemical element is ionized. Oxygen creates blue lightning, nitrogen creates red.

Blue jets (Blue Jet) have a high speed (100 km/s) and are formed at altitudes of 40 km to 50 km. They last about ¼ s and can be seen with the human eye. They have bluish shades of color (Figure 5).

Figure 2. Aurora polaris. https://nationalgeographic.rs/. Source: Foto: Shutterstock

Figure 3. Aurora borealis, isolated proton aurora. Image from the International Space Station. (Image credit: NASA/ Scott Kelly)

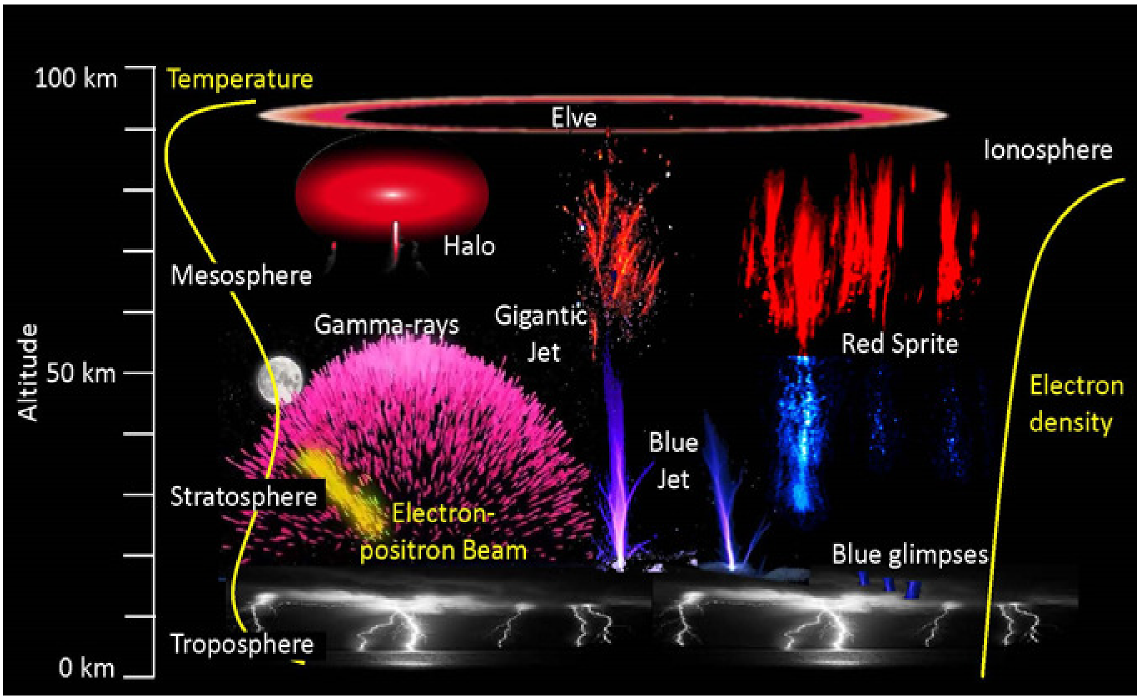

Figure 4. Blue Jets, Elves and Sprite [16]. (pictorial representation)

Elves (ELVE - Emissions of Light and Very Low-Frequency Perturbations due to Electromagnetic Pulse Sources) are large halos at altitudes of about 100 km above thunderclouds (Cumulonimbus - Cb). Their horizontal dimensions are about 400 km. It takes a few milliseconds. They represent the emission of light due to disturbances after the impact of a low-frequency electromagnetic pulse (Figure 6).

Sprite or Red Sprites have the shape of an atomic mushroom. They last very short and are recorded only by high-speed cameras. They are usually reddish-orange in color. They have various shapes (ghosts, stripes, fish). Sprites are observed at altitudes from 50 km to 90 km. Their typical horizontal dimension is about 50 km. They have a halo at the upper boundary. It takes a few microseconds, barely visible to the human eye (Figure 7).

3.4. STEVE - Strong Thermal Emission Velocity Enhancement. STEVE is an aurora-like glow that often accompanies the northern lights [24], yet is a distinct phenomenon, according to the American Geophysical Union (AGU) [25].

STEVE, an unusual aurora-like structure characterized by a glowing purple arc, was first observed by amateur skywatchers, the study reported. Unlike usual auroras, which are caused by charged particles from the sun colliding with Earth's magnetic field, STEVE is believed to be a stream of hot gas [20], (Figure 8).

Figure 5. Blue Jet emerging from a thundercloud into the stratosphere, captured from the International Space Station 2019. DTU SPACE, DANIEL SCHMELLING/MOUNT VISUAL, [17]

Figure 6. An Elves above a severe thunderstorm near Ancona, Italy. The red ring marks the spot where an electromagnetic disturbance (EPM) hit Earth's ionosphere. (photo:Valter Binotto, 27.03.2023. [18]

Figure 7. Red sprite in the ionosphere captured in August 2015 from the International Space Station. A white flash and a cluster of red shapes are seen above the top of a thunderstorm over Mexico. https://earthsky.org/space/ [19]

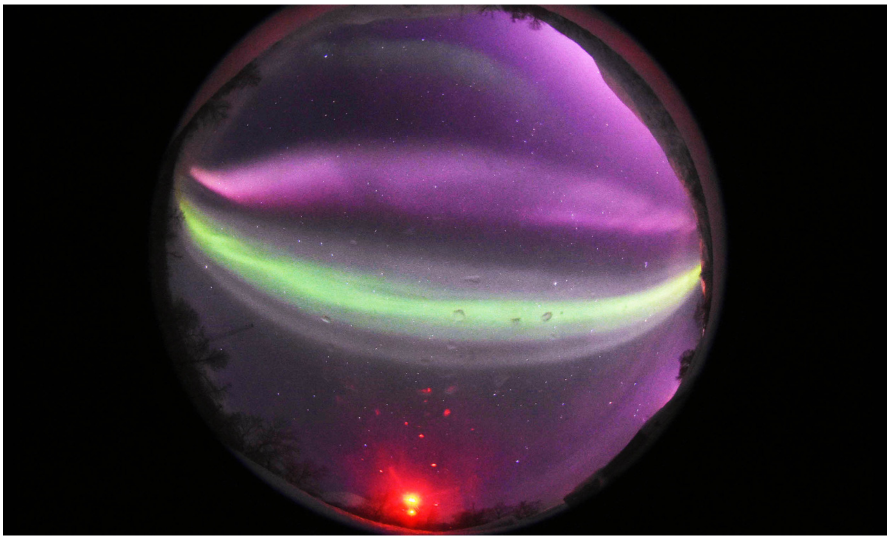

Figure 8. STEVE - Strong Thermal Emission Velocity Enhancement https://www.earth.com/news/steve-phenomenon-not-aurora-has-dawn-side-twin-swarm-satellites-discovery/ [21]

Figure 9. Lightning from a thundercloud (Cumulonimbus)

4. Light-electromagnetic phenomena in the troposphere

Ionized chemical elements in the atmosphere are constantly being created and destroyed. Ionization is caused by ultraviolet and X-ray radiation as part of the spectrum of the Sun's non-material radiation and by charged elementary particles, protons, and electrons, which enter the Earth's atmosphere from the Sun in the form of the solar wind and from the depths of space as cosmic radiation. Each ion has its electric field around it, and the electric field of the atmosphere is the result of all such elementary fields.

The electric potential of the atmosphere is the electric voltage relative to the Earth's surface and it increases with height. It increases especially rapidly in the layer up to 1 km. This change in potential with height shows the strength of the electric field, which is 130 V/m at the surface, and only 4 V/m at an altitude of 12 km [22].

There are two types of electric currents in the atmosphere [23].

Conduction currents are caused by the movement of existing ions in the air and they are usually weak. When a critical potential difference is established between two areas of the atmosphere, a discharge in the form of lightning and thunder occurs.

Convective currents represent the movement of charged particle jets (protons and electrons) with high kinetic energy that enter the atmosphere in the form of the solar wind. They move along the lines of the resulting interplanetary and geomagnetic field. They are not a consequence of the difference in electric potential between clouds and the ground. Proton lightning is characterized by a strong electric current and relatively low voltage, and electron lightning by a weak electric current and high voltage.

The mechanism of lightning in the troposphere (flashes) is similar to the formation of auroras and other light-electromagnetic phenomena in the ionosphere. The charged particles of the solar wind break out electrons from the atoms of chemical elements in the air. Therefore, electrons from the electron shell of an atom briefly move to a higher energy level. When they return to their ground state, the electrons (and the atom as a whole) release energy in the form of light (Figure 9).

5. Conclusion

The entry of charged particles of the solar wind into the Earth's atmosphere causes the appearance of various light-electromagnetic phenomena, starting from auroras, through ordinary lightning, to a multitude of other phenomena that are not easily accessible to the human eye and have been discovered with the development of space and computer technology. Other forms of auroras have also been discovered and phenomena are called blue jets, elves, and ghosts. These light-electromagnetic phenomena (lightning) occur in the higher layers of the atmosphere (stratosphere and ionosphere) as a short-lived flash in the sky. The mechanism of lightning in the troposphere is similar to the formation of lightning and auroras in the stratosphere. The charged particles of the solar wind break out electrons from the atoms of chemical elements in the air. When electrons return to their original energy level in the atom, quickly release energy in the form of light. Flashes in the upper layers are an indicator of the entry of charged particles from the Sun. Flashes in the troposphere are also associated with meteorological phenomena, primarily with thunderclouds.

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