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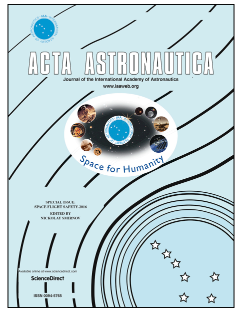

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Radiation and Space Flights Safety: An Insight

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Abstract
Cosmic radiation hazard is cornerstone of space flights safety. Different properties of solar electromagnetic and corpuscular radiation with emphasis on its dangerous influence on astronauts and spacecraft equipment and systems are discussed. Solar and galactic cosmic rays (SCR and GCR) pose a serious obstacle in terms of safety and security of space flights, especially beyond the Earth's magnetosphere. Solar flares and GCR are of special concern. Solar flares are distinguished as extremely complex phenomena observing across the whole electromagnetic spectrum from radio wavelength to extreme ultraviolet, X-ray and gamma ray. Powerful fluxes of energetic particles in very wide energetic spectrum are generated which interact with the home planet and disturbing tremendously our space environment. Altogether, it is referred to as space weather. Geomagnetic storms induced by solar flares affect the ground facilities, social-economic infrastructure and global system operations involving electric power supply, aviation and ground transportation, oil-gas pipelines, geographic information system/data management (GIS), etc. As systems become more complex over time, the impacts of space weather on space flights and humanity in general are likely to increase. We analyze flares complexity and classification depending on their size, duration, morphology or magnetic topology and characteristic corpuscular radiation based on different classification systems as well protective measures to mitigate their consequences. Humans will encounter extremely serious problems of space flights safety at the beginning of new phase of the Moon exploration. Of the risks evaluation of habitation in the lunar hostile environment, specifically in the potential sites of Lunar Base deployment, monitoring of radiation doses absorbed by astronauts on the lunar surface is the first one. Underground shelters could be used to provide safe habitation and maintain the long-term humans' activity. Nowadays we face numerous problems involving many unknowns and dangers of the natural origin in the outer space, which runs in parallel with the needs of great technological advancements and breakthroughs. It is incremental in the course of growing complexity of space flights and progressive development of the human missions with an ultimate goal of undertaking manned flights to the Moon, Mars and beyond.

Key words: Radiation, Sun, Hazards, Danger, Safety, Radiation dose, Solar flares, Electromagnetic emission, Corpuscular radiation, Magnetosphere, Space weather, Geomagnetic disturbance, Classification, Space flights, Lunar base.

Introduction

Safety of space flights is cornerstone of the multifold integral problem of space exploration. Since the beginning of space age, humanity has gradually realized the dangers that pose the outer space surrounding our planet. These problems became especially acute with the onset of manned space flights and incremented with operation of orbital stations and planetary explorations running in parallel with growing concern about reliability of functioning space vehicles. Everything exposed to space experience various factors of its inimical environment such as weightlessness, deep vacuum, electromagnetic and corpuscular radiation, and meteor danger. Needless to say, that space is very hostile to humans, but also seriously affects operation of technical equipment. In this content, radiation hazards occupy the first position, which is not easy to withstand.

Space age manifested many innovated features in the development of our civilization. Human society benefits and becomes increasingly dependent on the global space systems involving communication, navigation, meteorology, geodesy, and monitoring of natural environment closely related to reconnaissance. At the same time, humankind is highly vulnerable to adverse space factors. We are becoming more aware of potential threats coming from space, such as cosmic radiation, asteroid-comet threat. Security and protection from potential natural threats domain or at least are comparable with international tensions caused by the continuously increasing life dependence on the socio-economic situation and confrontation in the world where the progressive role could play military space networks. Paradoxically, amazing technological progress open perspectives of space involvement as a new sphere of confrontation and thus promote the new risks and vulnerabilities to the very existence of our civilization.

Historically, Earth has repeatedly experienced catastrophic events caused by the consequences of strong solar flares, such as power lines failure, transformers decay, short-wave radio communication blackouts, telecommunication/radar systems failures, etc. Disturbances occurring periodically on the Sun affect governmental, military, civil and commercial structures. It concerns such vital areas as transport (aviation, railways, maritime navigation), missile control systems, power lines, oil and gas pipelines, underwater cable networks, geographical information systems and data exchange (GIS), etc. One may expect that over time, the socio-economic consequences of space threats will increase, accompanying the scientific and technological progress of the humanity.

Unfortunately, despite the immeasurably increased ability to withstand natural and fabricated disasters, our dependence on them remains extremely high. Natural factors are the key in the safety problems when planning/undertaking very ambitious plans of manned flights to the Moon and Mars. The relevant risks must be mitigated to ensure the flights safety and success. In this paper, we will not touch upon numerous technical issues related to space facilities, spacecraft design, and operations, which can be found elsewhere (see, e.g., Huntress, Marov, 2011) but mostly focus on some natural factors, among which we highlight cosmic radiation.

The Sun and Solar Activity

Life on Earth depends entirely on the Sun, which provides the energy necessary for life and sustainable development. However, the Sun is also a source of extremely harmful electromagnetic and corpuscular radiation permanently affecting the home planet. While the Sun observations has a long history and the first solar probes were sent decades ago, we are still far from understanding the key mechanisms responsible for the solar activity and its forecast, to disclose long-standing, foundational mysteries of our star. Launch of the new spacecraft, first of all NASA Parker Solar Probe and ESA-NASA Solar Orbiter superior to ESA Ulysses and RSA Koronas-F, are called to answer many challenging questions about how the Sun works in detail. This includes mechanism of magnetic field and constant stream of solar matter - supersonic solar wind - generation, what originates and drives powerful solar flares, what underlies ten million degrees temperature of solar corona, to mention a few.

Solar plasma inflowing on the Earth and other planets strongly influences their environment, first of all on theolar activity state of geomagnetic field and magnetosphere – either intrinsic or induced depending on whether a planet possesses magnetic field. Such an interaction refers to as solar-planetary coupling and is substantially dependent on the phase of 11-year cycle of solar activity. Changes in the solar activity results in magnetosphere’s shape, radiation level, magnetic storms set up and the various upper atmosphere properties.

Fig. 1 shows schematically solar wind – magnetosphere interaction when inflows the Earth. Magnetosphere formed due to its intrinsic magnetic field has a rather complicated configuration and experiences strong incoming solar plasma influence. Its main regions and the processes involved caused by interrelations of intrinsic and induced magnetic fields with electric currents are shown in Figs 2 and 3. The Earth’s rather thick atmosphere and magnetosphere nicely protect us from this radiation. Magnetosphere with radiation belts (plasmasphere) located inside forms a radiation barrier from the direct energetic solar particles impact shielding the Earth's surface. Solar wind particles flow around our planet forming a shell (magnetosheat0, its inner part calling plasma sheat and neutral sheat (magnetic tail) at the night side. Dramatic effects of solar plasma interactions with the planet occurs at the dayside where bow shock and intermediate magnetopause layer forms. Here solar plasma can partially penetrate into magnetosphere through the polar cusp regions. Magnetic shielding is much weaker and solar radiation poses especially serious danger to people (see, e.g., Marov, 2014; Panasyuk, 2019).

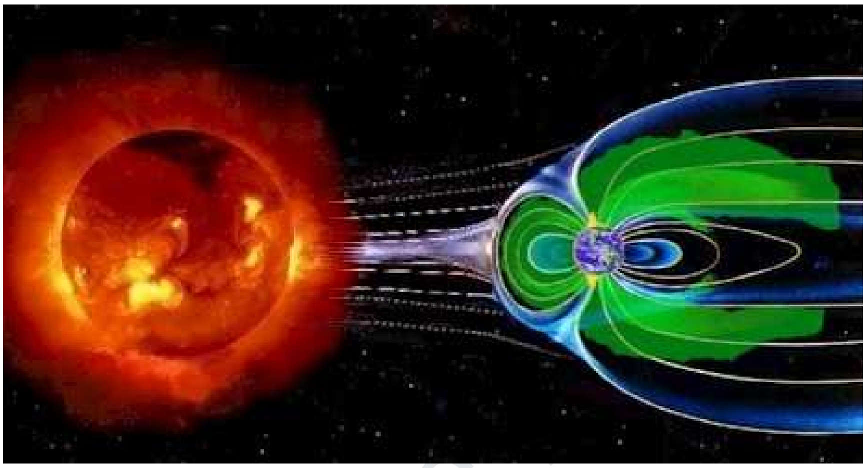


Fig. 1. Schematic view of the Sun-Earth interaction. Credit: NASA

We commonly define the complex phenomena in the near-Earth space involving very rarefied upper atmosphere and ionosphere as *space weather*, which much more profound and variable as compared to routine meteorological weather at the Earth's surface. The term was introduced soon after space era began and bulk information about our space environment became available. Solar activity disturbances exert strong influence on space weather state that is subject to severe changes affecting the overall geophysical processes on Earth. Its perturbations strongly influence the position of satellites in orbit and their lifetime, onboard satellites equipment, primarily electronic devices, and create serious risks for human activity, especially during spacewalks. Understanding of space weather phenomena allows us to understand and forecast the processes induced by solar plasma on the Earth's surface.

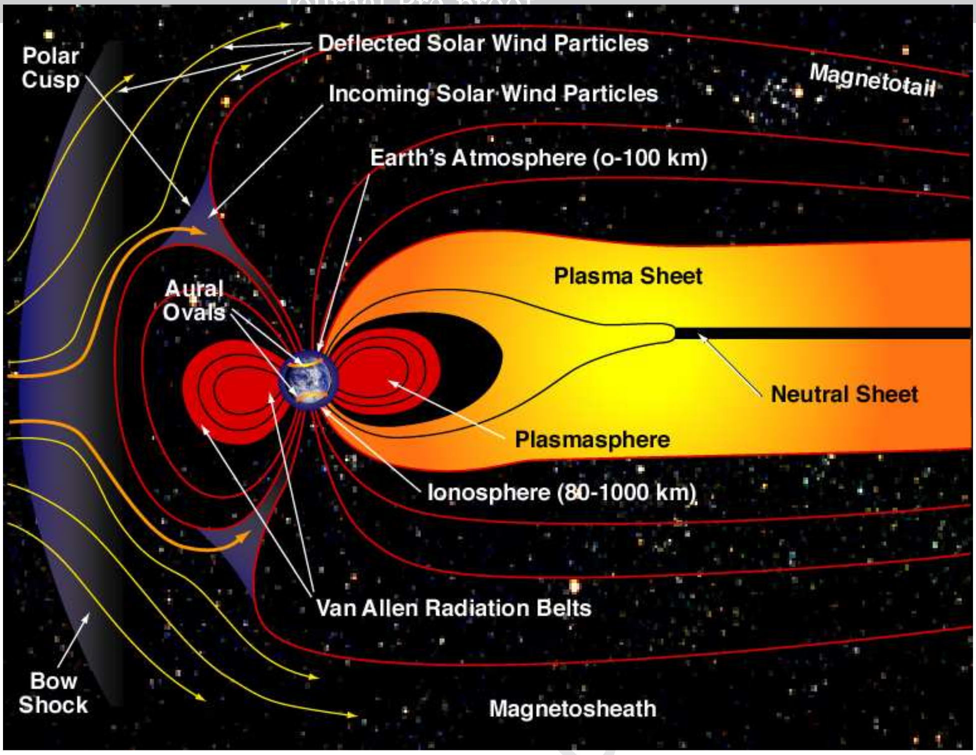


Fig. 2. Schematic image of the Earth's magnetosphere. Credit: NASA

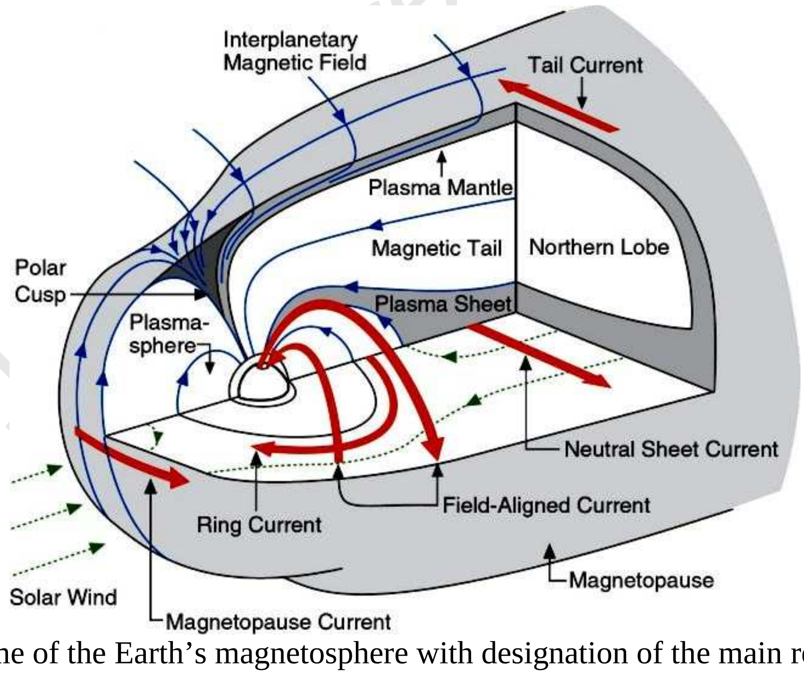
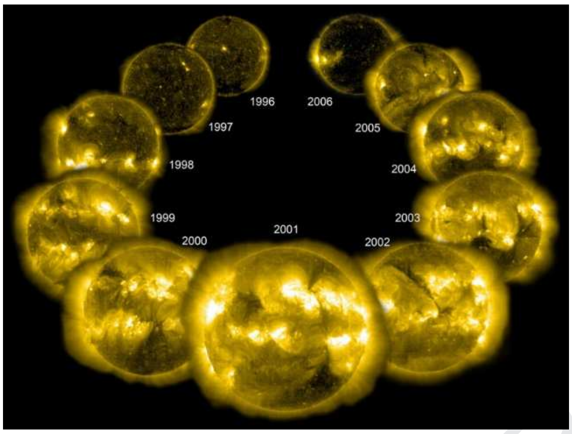


Fig. 3. Scheme of the Earth's magnetosphere with designation of the main regions and the processes of solar wind interaction with magnetic field involved.

Solar periodic activity.

Because space infrastructure involving both humans and technology is susceptible to the solar activity, its negative effect should be mitigated in terms of direct and indirect risks and losses and thus to provide the long-term stable development of space endeavors. The Sun exhibits different kinds of activity revealed by numerous ground and space observations. The most known is 11-years solar activity cycle roughly following number of sunspots and/or groups of sunspots on the Sun surface (also known as the International Wolf sunspot number, relative sunspot number or Zürich number). They can be tens of thousands of kilometers across, usually exist as pairs with opposite magnetic polarity alternating every solar cycle and are peaking at the solar maximum closer to the Sun's equator (Fig. 4). Sunspots are darker and cooler than their surroundings because these are regions of the reducing energy convective transport from the hot interiors inhibited by the strong magnetic fields. The Sun's magnetic dipole polarity changes every 11 years, such that North magnetic pole becomes the South one, and vice versa. Because solar activity changes from one 11-years cycle to another, the doubled cycles (22-years and longer) are also distinguished. Irregularity is specifically manifested by minimum of sunspots and solar activity during several cycles, as it happened in the 17th century and is known as Maunder minimum which strongly impacted on the Earth' climate. It is worth to recall that an unusual 11-year cycle solar minimum occurred in 2008 and lasted much longer with the lower amount of sunspots than normal. Therefore, solar activity recurrence is not stable. Moreover, theory claims that magnetic instabilities in the Sun core could cause fluctuations with period of tens of thousands years.



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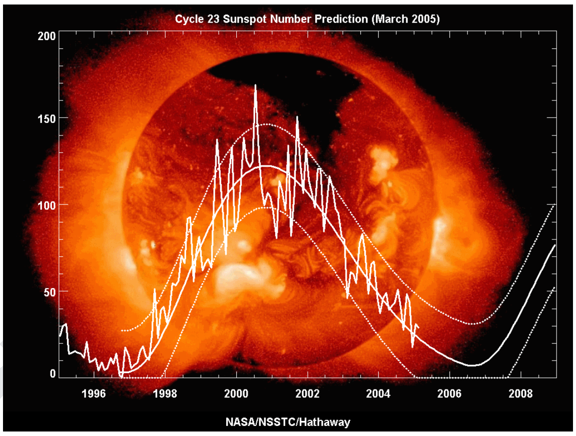

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Fig. 4. a – Change of image of the Sun from minimum to maximum activity during 11-year cycle. b – Variation of solar activity during 23-th 11-year solar cycle. Small variations are superimposed on the regular periodic mode. Credit: NASA/NSSTS/Hathway.

The Earth's upper atmosphere and ionosphere in the height range from 200 to 1000 km strongly responds to the solar 11-year cycle. Temperature changes by several times, from ~400 K to ~1500 K and mass density by one to two orders of magnitude (see, e.g., Marov, 1966). This dramatically affects artificial satellites lifetime. The solar extreme ultraviolet (EUV) and soft X-ray tightly correlated with radio emission of the Sun in decimetric wavelength are responsible for these variations (McLean, 1985). The widely recognized is the 10.7 cm solar activity index ($F_{10.7}$) continuously recorded by simple radio antennas over the globe. This index changes from about 70 to about 180 W/m^{2}Hz between solar activity minimum and maximum, respectively, and perfectly reflects the real physical space weather processes depending on the solar energy supply.

Solar sporadic activity.

The main irregular factor in solar activity is solar flares (Fig. 5). Solar flare is explosive process of energy release in the Sun's atmosphere. One regards flares as an explosive extremely complex phenomenon in an active region on the Sun's surface observing across the whole electromagnetic spectrum including harsh extreme-ultraviolet and gamma-ray emissions and radio wavelength, as well as wide energetic spectrum of emitted energetic particles. They manifest themselves as an instantaneous and intense sporadic change in brightness observed over the Sun's surface or the solar limb (Svestka et al., 1992; Jonas, 2014) . Corpuscular emissions from the solar atmosphere into the interplanetary environment represent outbursts of huge masses of solar plasma containing high-energy charged particles. Plasma flows when they hit the Earth lead to a strong change in the space weather, perturbations of the geomagnetic field, and complex various phenomena induced by the solar flare on Earth and in the near-earth space.

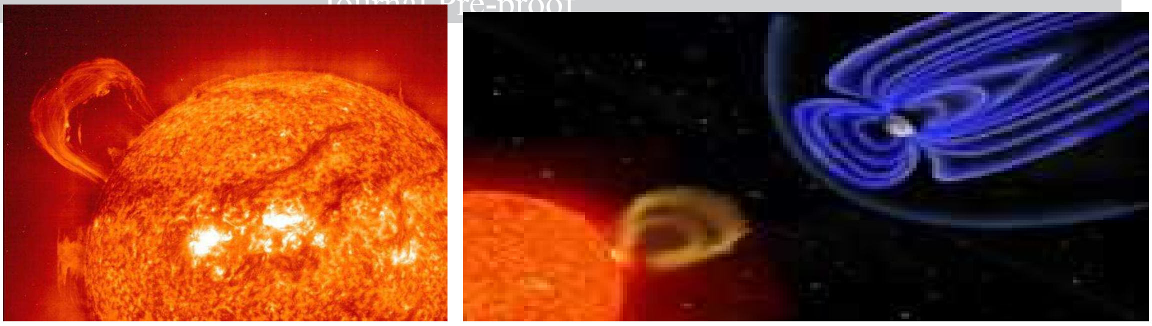


Fig. 5. Solar flare and schematic view of flare affecting the Earth’s magnetosphere

Solar flares are caused by the mechanism of tearing instability and reconnection of the magnetic field lines (B-field) in the Sun’s chromosphere (see, e.g., Shibata, 1996) accompanied by rapid releasing of release of magnetic energy stored in the corona Fig. 6). Flare is a burst exhibited as instantaneous and intense change of the brightness in an active area on the Sun surface though the majority of the flares are not visible with no special instruments. Temperature inside a flare reaches 10^8 K and energy release amounts to nearly 10^{26} joules - about a sixth of the total energy output of the Sun each second or 160 billion megatons of TNT equivalent (hundred billions of megaton bombs). Flare duration may be as long as 200 minutes, it is accompanied by strong intensity variation in the X-ray and powerful acceleration of clouds of electrons, protons and heavier particles ejected into space, whose velocity approaches tenths of the speed of light. Unlike solar wind, particles generated at the flares reach Earth very fast and strongly disturb its environment, radiation being extremely harmful for astronauts.

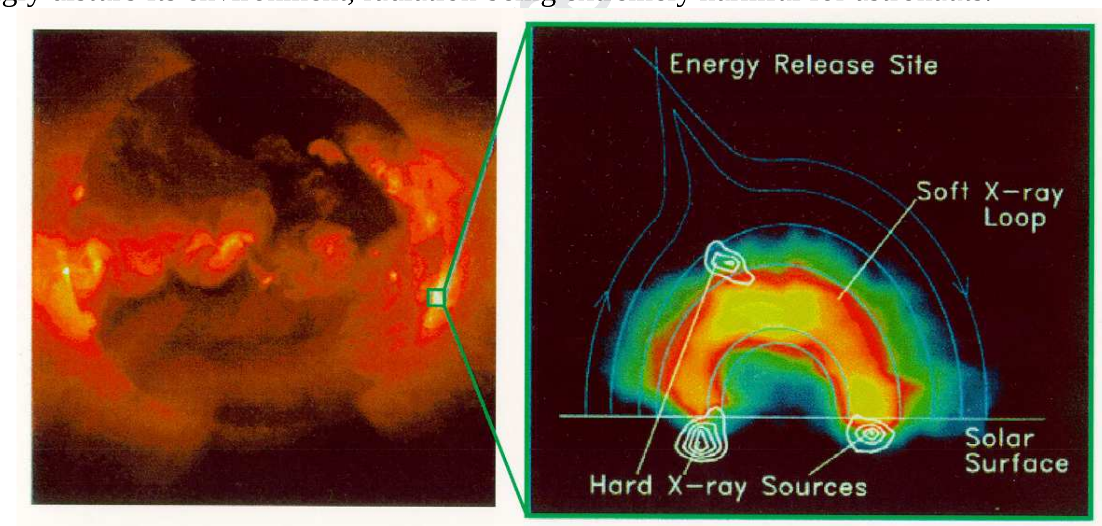
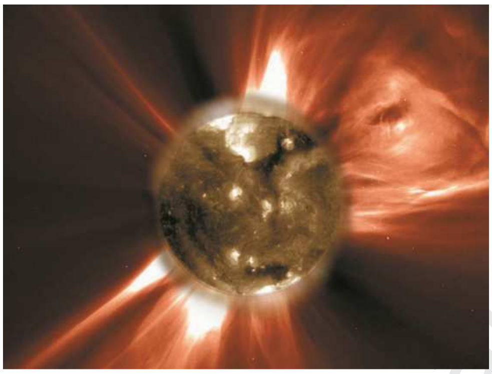


Fig.6. Mechanism of high-energy particles generation at the solar flares. Credit: ESA.

Solar flares: The main types.

Solar flares, Coronal Mass Ejection (CME) and Solar Proton Events (SPE) are the most characteristic phenomena of the solar activity manifestation. The activity rate closely relates with the 11-year solar cycle. The huge ejected amounts of high-energy protons and electrons well exceeding energy of quite solar wind particles accompany these events. They determine the state of geomagnetic field, solar plasma interaction with the solar system bodies, and in particular, with the home planet, involving processes in the Earth’s upper, middle and lower atmosphere and on the surface. Unfortunately, solar flares is difficult to forecast and to assess quantitatively the power.

The most dangerous among solar flares are powerful Coronal Mass Ejections (CME), which are giant plasma clots that propagate in space at a speed of more than 1000 km/s, which cause global magnetic storms on Earth and pose a serious threat to the Earth's infrastructure (Fig. 7). We regard CME as a strongest flare (Crooker et al, 1997; Marov & Kuznetsov, 2014), which represents the most powerful phenomenon in the solar system. Solar flare is explosive process of energy release in the Sun’s atmosphere encompassing all its layers – photosphere, chromospheres, and corona. It manifests itself as sudden brightening observed over the Sun’s surface or the solar limb. They are originated in the corona and represent outbursts of the enormous volumes of the solar plasma also caused by the magnetic field lines reconnection. Some of them are associated with the solar flares or are related with the solar eruptive protuberances maintained above the solar surface by the magnetic fields. However, while a routine solar flare is localized within an active region on the Sun (Fig. 2) CMEs have much larger angular spans encompassing several active regions and enormous power of explosive nature. CME appears periodically and are composed of very energetic particles. Giant clots of plasma form giant plasma bubbles expanding outward into space. Billions tons of matter are ejected and travel in the interplanetary medium with the velocity > 1000 km/s forming detached bow shock at the front. CME are responsible for powerful magnetic storms on Earth, magnetosphere size owing to plasma inflow decreasing from ~12 R_E to ~6 R_E at the dayside. CME carry very harmful radiation. The high-energy protons and electrons generated by these events represent the greatest radiation hazard for astronauts, although they are less intense than the most energetic galactic cosmic rays coming from the deep space, especially at interplanetary flights.



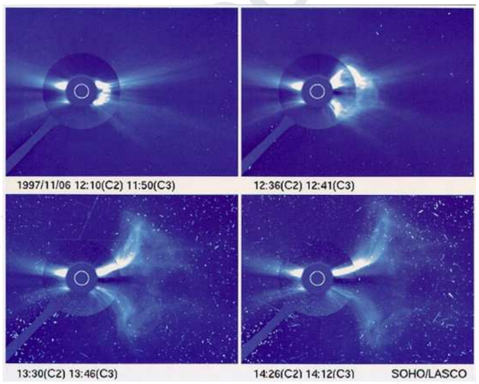


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Fig. 7 a – Powerful solar flare of CME type. b – Typical C ME set up and evolution by the results of SOHO solar probe observations. Credit: ESA.

Another phenomenon is Solar Proton Events (SPE). They occur more often than typical solar flares and CME and energies of generated protons are lower (energy $\boldsymbol{E}$ ~ 30 MeV, particle flux density ~10^{10} cm^{-3}) but their duration is longer, from a few hours to a few days. Whereas solar flares and CME are more characteristic for the maximum phase of the 11-years solar activity cycle, SPE occurs throughout the whole cycle but their influence on space environment is much lower than CME.

Solar flares: Classification.

Solar flares are classified depending on their size, duration, morphology or magnetic topology and characteristic corpuscular radiation (Cliver, 1995; Marov & Kuznetsov, 2014) There are two basic - impulsive and gradual - kinds of flares with time scales from a few minutes to tens of minutes and even several hours, respectively, fully developing flare being sometimes a combination of these two. Flare’s duration is indicative of magnetic topology: while long-duration flares link to coronal CME, impulsive flares are generally completely confined within the Sun’s lower atmosphere though some short-duration flares may also have ejects of various scales.

There is widely used optical (H_{α}) classification system that is based on H_{α} emission line spectral observations and addresses flare size (importance). This classification starts from a character S (means sub-flare) following by figures 1, 2, 3, or 4 for successively larger flares and accompanying by a letter (f = faint, n = normal, b = bright or brilliant). Basically, it denotes the flare size - area *A* (measured in millionths of a solar hemisphere) and importance class (1- 4) i.e.

power. Therefore, the most outstanding flares are classified as 4b and the smallest and faintest as Sf (Marov & Kuznetsov, 2014).

Another classification system of flare size/power is based on observations of the Sun in the soft X-ray ((1–8) 8Å wavelength) that became possible when Earth' satellites became instrumental. The system appeared and came into usage since 1970s. The power of flare is given by the peak intensity of the emission on logarithmic scale. Flares are classified with a letter (A, B, C, M or X) corresponding to the power of 10 (−8, −7, −6, −5, −4, respectively) of the peak (1–8) Å flux in W m^{-2} units and a number (1–9) that acts as a multiplier. For example, a B3 flare has a peak flux of 3×10^{-7} W m^{-2} and an M8 flare has a peak flux of 8×10^{-5} Wm^{-2}. During minimum of the solar cycle, X-ray background is low and flares only smaller than C1 can be recorded. Generally, X-class flares are confined whereas intense flares are mostly eruptive (Svestka, 1992). Flares occasionally exceed class X9 in intensity; they are simply referred to as X10, X11 etc. events (Marov & Kuznetsov, 2014). In turn, B-class flares may be associated with CME events with explosive and prolonged energy release. Moreover, some eruptive flares are regarded as a consequence of CMEs. The relationship of CMEs to long-duration flares generally interprets in terms of magnetic lines reconnection. The large fully developed flares in which an impulsive phase is followed by a gradual main phase (called "hybrid" flares) exert the most profound influence on the Earth's environments and thus they are most important from the geophysical viewpoint.

Let us note that based only on soft x-ray classification it is hardly possible to indicate as to whether the flare is eruptive or compact (confined). The decisive argument to distinguish between them is magnetic topology: whether magnetic field lines opened or closed. Unlike for the confined flares of closed configuration, in eruptive events such as CMEs newly opened field lines followed by the closing down or reconnection occurs on a time scale of hours and provides the prolonged energy release.

Because solar flares exhibit themselves in the radio wavelength ranging from millimeters to kilometers, we also classify them in association with radio events, or bursts. This classification is particularly useful in terms of the dividing flares in the above mentioned confined and eruptive categories. The five (I-V) categories are distinguished, types II and IV bursts identifying most commonly with eruptive flares while types III and V bursts attributing to flare-accelerated electrons moving along open field lines into the corona. Finally, it is worth mentioning about solar flares classification based on the energetic particle ($E > 1$ MeV/nucleon) events observed in space following flares (Marov & Kuznetsov, 2014). Likewise, soft X-ray solar radiation, it can be recorded with satellites/space probes instruments only. Monitoring include a wide range of variation in electron to proton ratios, Fe/O ratios, and $^3He/^4He$ ratios, the latter being also a good solar flares precursor. Distinctions between impulsive and gradual events may be blurred in hybrid particle events for which both flare and shock components are observed.

Influence on Earth: Geomagnetic disturbances.

Solar increasing activity and especially flares cause disturbances of the Earth's magnetic field exhibited in the forms of magnetic storms and sub storms. Similar to indexes of solar activity (Wolf numbers, $F_{10.7}$), indexes of geomagnetic activity (A_p, K_p, D_{st} and some others were introduced. They are recorded on geophysical observatories and are widely used to characterize the Earth's magnetic field disturbances.

The global reconstruction of the Earth's magnetic field in the main phase of geomagnetic storm favors the penetration of high-energy particles into the magnetosphere and modification of the topology of radiation belts. Geomagnetic storms are intimately related with the numerous perturbations in our space environment, such as temperature and density variations of the upper atmosphere, set up of ionospheric irregularities, expanding polar ovals, beautiful auroras at high to moderate latitudes, see Fig. 8. Space weather experiences dramatic changes caused by direct absorption of solar short-wave radiation responsible for the photochemistry and accompanying numerous chemical reactions. Altogether the set of kinetic processes is described by the branch of space physics - aeronomy (see Marov & Kolesnichenko, 1987; Marov et al.,1997). Powerful geomagnetic storms also disturb global and local natural parameters on the ground and strongly influence human infrastructure through satellites' orbit decay, disruption of radio network and satellite communication, GPS accuracy/positioning errors of satellite navigation, radar operations blocking, breaks in electric power supply and dramatic power grids collapse resulting in power blackouts. They induce currents resulting in gas-oil tube systems erosion.

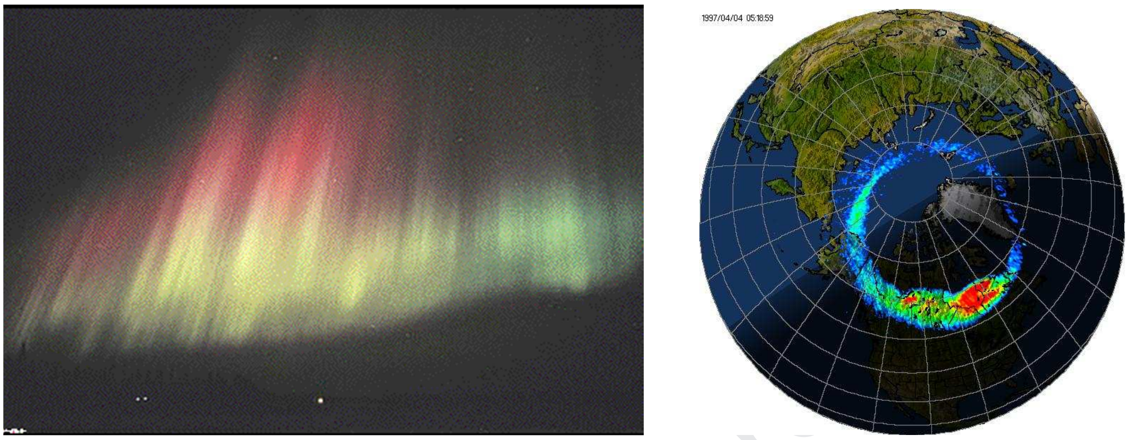

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Fig. 8. a – an example of the polar aurora: arcs with active elements. Observation at the Kola Peninsula. b – polar oval - zone of maximum aurora activity. Colors correspond to different energy of precipitated particles around geomagnetic pole.

There are also many other effects implied by geomagnetic storms. Just to mention a few, they distort geomagnetic maps using for guidance and control; affect deviation of the regular magnetic field owing to mineral deposits when using air-borne or satellite survey; badly impact on internal biological compass used by birds and some animals (pigeons, dolphins, whales) for migration, etc. The most severe magnetic storms ever recorded and described occurred in 1859, 1921, 1989, and 2003.

Cosmic Radiation

The Sun is a source of very harmful radiation. We distinguish solar electromagnetic and corpuscular radiation. Standard spacecraft shell is generally sufficient to protect astronauts from solar electromagnetic radiation while energetic particles may penetrate inside mostly as radiation of secondary origin and pose a problem during solar flares. To measure ionized radiation one commonly uses different units, such as Ber, Sievert, Rad, Grays. 1 Gray corresponds to the absorbed dose when every 1 kg mass of human body receive ionized radiation 1 joule. 1 Gray is equivalent to 100 Rad, or 114 X-ray. Ber is usually used to measure integral dose. For example, 100 Ber/year is equivalent to effective dose 1 Sievert or 1 Gray. On average, a person living on Earth surface receives a dose of 1 milliSievert (mSv) every year. An astronaut on the International Space Station (ISS) under magnetosphere protection earns daily 0.5-0.7 mSv. Note that lethal level of the absorbed dose of ionizing radiation was determined to be more than 10 Grays (10^3 rad or 10 Sieverts). Average safe daily doses are within 5-25 mRad. Doses taken by astronauts' onboard MIR/ISS orbital stations were a few times more under quiet solar conditions while significant "spikes" against the background appear reaching 500 - 700 mRad during powerful flares. It can also be noted that the lowest radiation effect of 0.010-0.020 rad/day was observed for the ISS orbital station in a low reference Earth's orbit having effective protection of 15 g / cm^2. Higher radiation doses of 0.099-0.153 rad / day were observed for the flying in a high reference orbit Skylab orbital station with protection of 7.5 g / cm^2 (see, e.g., Bubnov & Kamanin, 1964 for more detail).

Energy of both photons and electrons generated by active Sun dramatically increases compared to the quite conditions. Space missions that involve spacewalk and extra-vehicular activity at the ISS, and the future manned missions to the Moon and Mars are especially susceptible to the risk of corpuscular energetic radiation exposure by astronauts. Planning such missions requires the knowledge of radiation conditions at the Earth orbit and in interplanetary space that crucially depend on solar activity. Besides, solar cosmic rays can switch off the robotic arm and other facilities on board the ISS and, thus, suspend the planned work.

Born in the solar outbursts, powerful energetic particles propagate through the interplanetary space and interact with the Earth and other solar system bodies. As we already mentioned, interaction of solar plasmas with a planet strongly depends on whether it possesses an intrinsic magnetic field and atmosphere. In the case of Earth, unique configurations of inflowing plasma with its magnetic shell - magnetosphere set up accompanied by numerous physical phenomena, particularly magnetic storms and ionospheric irregularities.

The most hazardous are high-energy protons with their direct impacts on astronauts and space vehicle systems. Astronauts experience also enhancement energy comprised in the radiation belts, which protect them from the direct radiation influence in the quite conditions. Even stronger radiation affects astronauts outside radiation belts where solar cosmic rays (SCR) complement the most energetic galactic cosmic rays (GCR) carrying the most harmful radiation. An exposure of spacecraft to energetic particles also damage critical electronic elements, degrade solar arrays, blind some optical systems and causes temporary operational anomalies, there is also great influence of geomagnetic storms on the ground segment. Energetic protons and electrons effect space weather including ionospheric irregularities that interfere with high frequency (HF) radio communication broadcasting, Internet, and navigation systems and disturb their operation, especially at high latitudes. Polar cap absorption (PCA) events associated with sporadically occurring solar proton events may fully blackout HF communications. Geomagnetic storms induce strong aurora currents that can damage electrical systems, corrode oil and gas pipelines.

Solar electromagnetic emission.

Active Sun generates hard electromagnetic emissions from ultraviolet to X-ray and gamma ray. The fluxes may exceed the quiet Sun emission in some spectral ranges by hundred - thousand times resulting in strong enhancement of ionization in the Earth ionosphere and the associated degradation of radio communications.

At the maximum of solar activity, electromagnetic emission heats and expands the Earth atmosphere resulting in increased atmospheric drag, which affects low-orbital spacecraft and ISS, decreases the satellite lifetime, and entails additional expenditures on orbit correction. Estimating the orbital lifetime of satellites requires an accurate prognosis of the solar electromagnetic flux throughout the supposed operational period, what is yet difficult to accomplish. Atmospheric expansion by enhanced solar radiation may result in uncontrolled de-orbit and fall of huge orbital station, as it was the case for US Skylab and USSR Salyut 7.

Intense radio emission from solar flares (solar radio bursts) interferes with satellite radio signals and GPS navigation signals disabling services and data transmission. Disturbing ionosphere strongly affects the navigation signals and thus an accuracy of the object position.

Solar corpuscular radiation.

Solar energetic particles contain much more energy compared to the electromagnetic radiation. Dramatic events set up at the magnetosphere boundary - the magnetopause where it meets high-speed solar wind plasma stream, inflowing the day-side planet. Solar corpuscular radiation can penetrate deep into the atmosphere and augment the role of UV and X-ray radiation mostly responsible for the processes of photolysis and numerous chemical reactions in the upper atmosphere. Altogether, these effects defines planetary aeronomy. Fluxes of energetic particles generated in the solar flares are additionally accelerated in the Earth’s magnetosphere by complicated system of magnetic lines re-connection, ring currents, and penetrate in the upper atmosphere causing polar aurora.

Energy and topology of solar energetic particles exerting magnetosphere is different. The most dangerous are particles generated in the major solar flares and known as solar proton events that occur sporadically. Their intensity may exceed the background radiation by many orders of magnitude reaching a few GeV. They strongly disturb the operation of satellites equipment and disrupt radio communication, and even deplete the ozone layer. More than a dozen powerful SCR events may occur in the course of 11-years solar activity cycle and such events are difficult to forecast. Obviously, they may badly affect astronauts' health. It is worth also to mention anomalous ionization of the ionosphere from the high-energy protons in the Earth's polar regions resulting in the above mentioned polar cap absorption events (PCA) responsible for strong absorption of radio waves and blackout of HF radio communications lasting ten days or longer strongly affecting the navigation.

Inner magnetosphere radiation

This is a kind of corpuscular radiation exerted on humans by the Earth's radiation belts depending on the state of solar activity, specifically responding to solar flares (see Fig. 9). Though inner radiation belts particles have, on average, essentially lower energy and, hence, a weaker ionizing effect than solar energetic particles, their large fluxes contribute significantly to the radiation doses experienced by astronauts and may have a damaging effect on spacecraft electronics. Indeed, energetic protons of the inner radiation belt, like GCR and SCR, hit the satellite electronics producing single event upsets and damaging critical elements, such as onboard memory, etc.

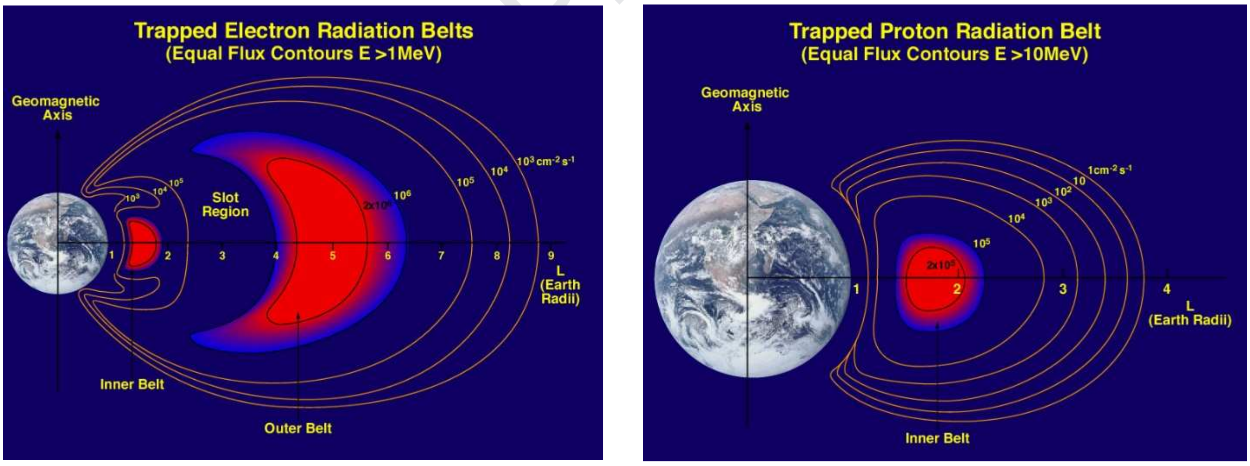

Fig. 9. Trapped electrons and protons of the inner and outer radiation belts at the different radial radii (L-shells) from the Earth's center. Red regions mark zones of the maximum energetic particles' fluxes. Credit: International Space University (ISU).

In the South Atlantic Anomaly (SAA) region and at the poles, the background radiation may be tens to hundreds of times higher than elsewhere over the globe making these regions particularly dangerous to satellites. The lower boundary of the inner radiation belt in the SAA region is as low as 250 km. Radiation hazard at the ISS orbit is shown in Fig. 10.

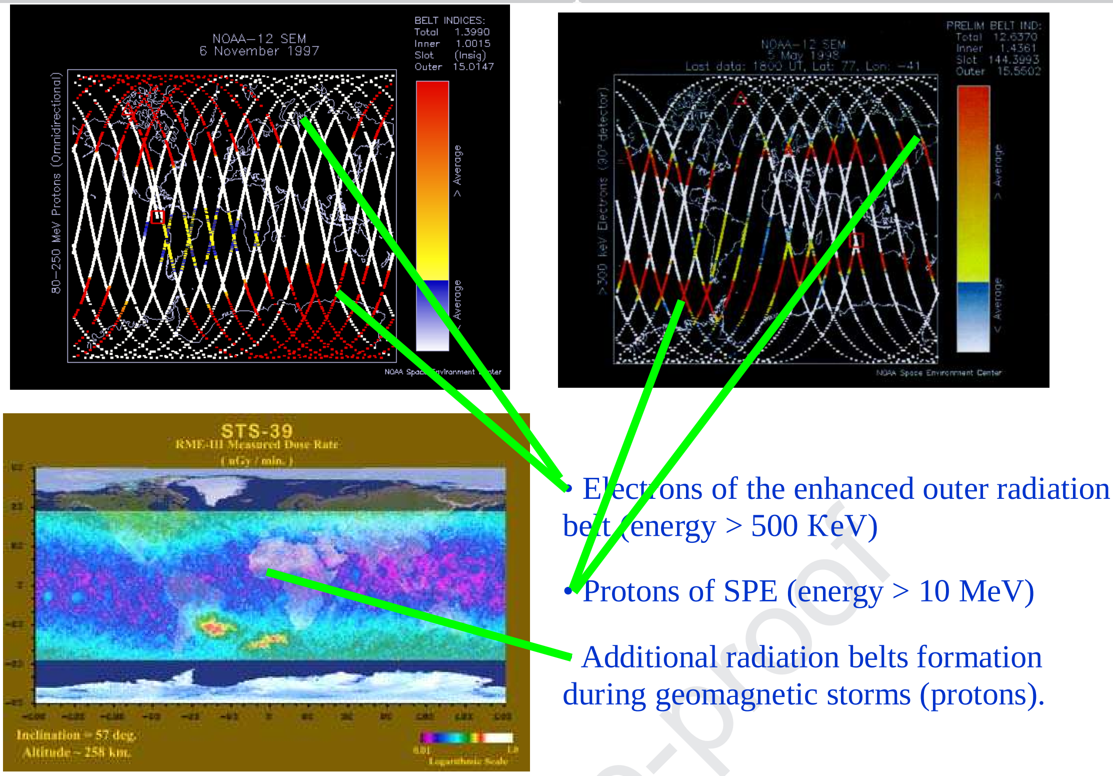

Fig. 10. Radiation hazard at the ISS orbit. Credit: NASA.

The low- and medium-energy electrons (keV to tens of keV) knock out electrons from the satellite body and create a large surface charge. This generates electric fields and discharges between different parts of the craft skin resulting in electromagnetic noise, signal distortions, and operational anomalies. High-energy electrons (from over 100 keV up to MeV and higher) penetrating inside a satellite generate the volume charge, cause dielectric breakdowns, and upset the normal operation of onboard electronics.

These effects are the main cause of outage of satellites in geostationary orbit (GEO). Periodic enhancements of energetic electron fluxes in the magnetosphere are due to the high-speed solar wind streams emanating from coronal holes at the decline of the solar cycle, as well as to acceleration of magnetospheres' electrons during magnetic substorms and their injection into the inner magnetosphere that can occur both under relatively quiet conditions and in the disturbed periods. Some spacecraft have had the reduced efficiency of their solar cells by tens percent and hence, the active lifetime by several years. Hazardous effects exerted by electromagnetic and corpuscular radiations are summarized in Fig. 11.

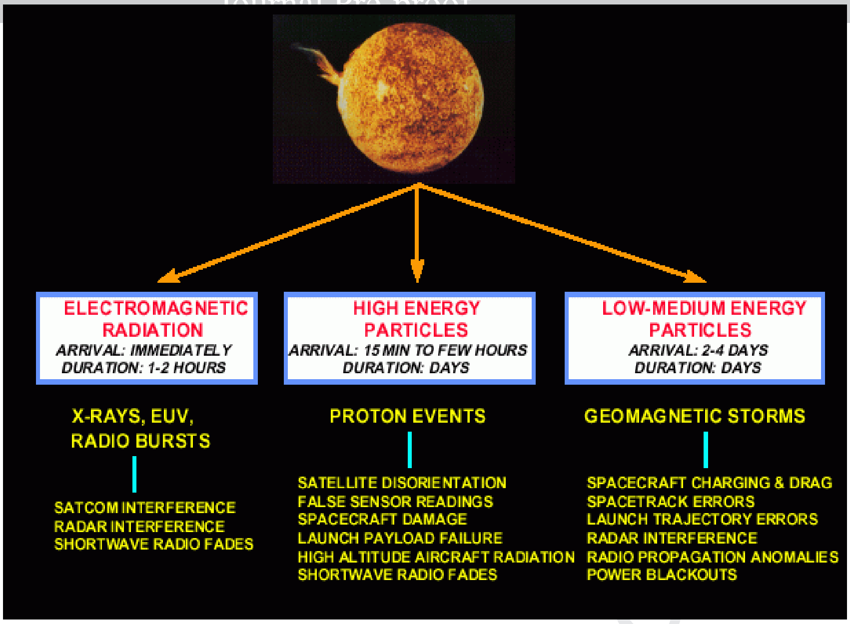

Fig. 11. Effects of electromagnetic and corpuscular solar radiation. Credit: NASA

Galactic cosmic rays (GCR)

Of special interest and importance are the galactic cosmic rays. Because of their very high energy much exceeding that of solar energetic particles they are addressed as the most hazardous space radiation yielding only neutrino. Their mean energy is 10^{10} eV while single particles amounts 10^{20} eV. Unrealistic shield of ~15 m thick lead would require protecting from such radiation. GCR may be especially dangerous during interplanetary flights giving integral dose 150-300 mBer/day or 50-100 Ber/year. In the near-Earth space, GCR intensity is modulated throughout the 11-years solar activity cycle being highest at the minimum and lowest at the maximum. This effect is referred to as the Forbush decline.

Space Safety at the Moon Exploration

The Moon is currently addressed as an important milestone in space exploration for the coming decades by space agencies of the United States, Russia, China and Europe. The most ambitious is the US NASA Artemis Lunar program aiming to put American astronauts — first a woman and next a man - near the lunar South pole by 2024 and establish sustainable missions by 2028. The proposed includes the intermediate Gateway deployed in the lunar orbit to transfer astronauts in descent module with human landing system from low-lunar orbit to the surface, and an ascent element to return them back to the Gateway. The Russian Moon strategy for the period up to 2050 involves first detailed study of the Moon with robotic missions followed by the manned flights beginning of early 2030-th with an ultimate goal of the deployment of infrastructure elements to create a habitable Lunar base with local resources utilization. The program rationale underlies the great experience and competitive advantages in launch and inter-orbital transportation systems and the manned vehicles development. It also accounts for the real resources availability involving economic and technological constraints, as well as the necessity to accommodate the requirements of high reliability and safety. In this regard, any proclaims favoring Mars human mission as the main goal seem at the present stage unjustified, and the project itself looks hardly realistic. In our mind, based on current scientific challenges, technical capabilities, and financial constraints, there is simply no alternative to the Moon exploration leaving aside Mars for the future generations.

Fundamental scientific problems.

From the scientific viewpoint, the Moon is of primary interest for planetary sciences, geophysics, geology, and geochemistry. It is a key to answer many questions about the origin and evolution of the Solar system as a whole, which remain enigmatic despite the great progress in our knowledge about nature of the planets, their moons, comets, and asteroids. We are not yet clear enough about some peculiar properties of the Moon including its interior, origin and early evolution of the Earth-Moon system. Further detailed study of this closest to us celestial body promises to advance significantly reconstruction of the main evolutionary processes of the entire family of Solar system bodies. Most important, this may promote understanding the early history of the home planet and potential path of its evolution (Marov et al., 2019).

The discovery of water in polar regions of the Moon has revealed to us a new wet rather than a dry as it was believed for centuries before (Feldman et al., 2001; Sanin et al., 2017). This, in turn, created new prospects for its exploration. The new Russian research programs suggests delivery to Earth of rock samples from polar regions and their detailed laboratory study to determine the content of volatile, rock-forming elements and organic compounds. Follow on monitoring from lunar orbit is important for the future Lunar Base site selection and local resources assessment in the near-surface regolith layer. The primary goal for the future development is to estimate local water and volatiles reserves, their distribution and possibility of extracting components from the regolith for life support systems. The next stages are related to the prospects of industrial use of minerals containing Fe, Al, Mg, Ca, Si, Ti as sources of building materials, air, water and rocket fuel from H_2 and O_2 contained in rocks (Marov et al., 2019).. In the longer term as well a possible use for energy needs of an effective source of thermonuclear fuel - the ^{3}He isotope is discussed. Fundamental scientific problems also include conducting a set of laboratory studies at the Earth's labs in order to develop methods and means for extracting water, air, and a number of necessary materials from analogues of lunar regolith and surface rock minerals. The results should serve as the basis for safe technologies utilization in the future production cycles on the Moon.

Lunar Base Deployment.

The strategy for deploying the future Moon infrastructure should include several stages. The first stage provides for geological mapping of the lunar surface in order to identify areas containing the largest reserves of water and minerals in the regolith and minerals of the composing rocks, promising for their extraction and processing. At the next stage, a detailed topographic survey and geological exploration of the selected areas on the Moon's surface should be carried out using logging stationary and mobile installations, the deployment of robotic systems for safe experimental mining and processing of minerals, and the development of methods for water utilization. Monitoring of the level and variations of the radiation and micrometeorite situation in selected areas on the Moon's surface is to be provided beginning of this stage on as the key element of security, with careful doses analysis. This activity will accompany testing of life support systems and shelters with partial replenishment of expendable materials, methods of adaptation to lunar conditions during a long stay on the surface and testing of effectiveness of local resources utilization for underground habitats. One may address this stage also for creation of an interactive complex integrating robotic systems and systems for orbital and ground control-navigation as a necessary element of the lunar infrastructure prior to the beginning of manned flights.

Security considerations.

Obviously, the strategy of Moon exploration involves organization, science-technology development and management of the very complex integrated program. Large-scale research and innovative technologies used for technical equipment of lunar infrastructure should be running in parallel with the development of means and measures providing utilization of save materials, technical equipment, robotic and control systems since the very beginning. Starting operations of the first crew on the Moon surface strongly augment the safety requirements with incorporation of many security problems. Security issues should play a primary role at all planned stages of the human Moon exploration strategy implementation, including adaptation to the hostile environment, numerous operations with the equipment, traveling on the lunar surface by walk and/or in lunar vehicles, etc.

The following natural factors prerequisite peculiarities of living/operations on the Moon:

- Very rarefied atmosphere (~ 10^{-16} of the Earth's)
- Reduced gravity (1/6 of the Earth's)
- Sharp changes of radiative temperature (by about 300
- Lunar dusty atmosphere.
- Harmful direct (unprotected) radiation (SCR and GCR)
- Meteoritic particles impact

These factors complement lacking of expended funds, the need to replenish stocks and water, as well as isolation from the outside world involving the problems of psychological compatibility in a small society. Of technical security/safety issues, we just mention reliable autonomous life support systems, well-protected homes, reliable communications, power supplies, mechanical devices, and automatic and information systems.

Of the listed natural factors, the most important are radiation hazard, meteor danger from falling particles of different mass/energy, and lunar dusty atmosphere. The latter permanently hang near the lunar surface owing to electrostatic charge bearing by small particles lifting from the surface at meteoritic impacts. They form the lunar dusty plasma and may represent some danger if penetrate somehow through a spacesuit. Meteorites permanently bombard the lunar surface being in particular, responsible for regolith formation. Frequency of their impacts are in inverse proportion to size-energy particles and thus probability of dangerous or catastrophic events of meeting astronaut is very low.

The most hazardous for astronauts on the lunar surface is direct exposure to harsh cosmic radiation (SCR) and especially energetic particles generated at the solar flares. As we mentioned above, monitoring of the level and variations of the radiation with careful doses analysis in selected areas on the Moon's surface potential for the Lunar Base deployment is the key element of security. Currently, estimated doses are based on the results of Apollo missions and dosimeters measurements onboard of automatic spacecraft. NASA declared the radiation doses of 0.022-0.136 rad/day during Apollo flight to the Moon in the lunar module with protection thickness of 1 g/cm^2 (Etzglisb et al., 1973). This do not differ from the radiation doses of 0.010-0.153 rad/day for orbital flights, influence of the Earth's radiation belt being zero. However, calculation shows that the radiation doses during the Moon missions could be 100-1000 times higher and reach 3-7 rad. For the crew protection from the direct radiation on the Moon surface the most efficient appears to be lunar soil and underground shelters of at least 5 m deep. Schematic view of such a shelter shown in Fig. 12.

Fig. 12. Lunar Base conception with underground habitant. Credit: ESA.

Let us emphasize that in the future missions to the Moon (and especially Mars) astronauts unprotected by the Earth magnetosphere will be exposed to larger radiation dozes during longer times than they were in the first flights to the Moon. It is worth to recall that if the «Apollo-16» and «Apollo-17» Moon missions had occurred in April and December 1972, but in August when one of the most intensive solar flares on record emitted large fluxes of high-energy protons, the radiation doses experienced by the astronauts would have been lethal. The radiation protection of astronauts in transit to Mars and on the Mars surface will be one of the main problems of the planned mission to this planet.

Conclusions

Safety is a cornerstone of space exploration. It is incremental in the course of growing complexity of space flights and progressive development of the human missions with an ultimate goal of undertaking manned flights to the Moon, Mars and beyond. We face numerous problems along this challenging track involving many unknowns and dangers of the natural origin in the outer space, which runs in parallel with the needs of great technological advancements and breakthroughs.

Among the natural problems, we distinguish cosmic radiation as the most hazardous factor in space exploration. In this review, we attempted to summarize various features of solar electromagnetic and corpuscular radiation with emphasis on its dangerous influence on astronauts and spacecraft equipment and systems. Solar and galactic cosmic rays (SCR and GCR) pose a serious obstacle in terms of safety and security of space flights, especially beyond the Earth's magnetosphere. Of special concerns are solar flares.

Solar flares are extremely complex phenomena observing across the whole electromagnetic spectrum from radio wavelength to extreme ultraviolet, X-ray and gamma-ray and very wide energetic spectrum of emitted energetic particles. Flares are classified depending on their size, duration, morphology or magnetic topology and characteristic corpuscular radiation based on different classification systems. Sun's activity exhibited at flares generate powerful fluxes of energetic particles interacting with the home planet and disturbing tremendously our space environment, altogether referred to as space weather. Energetic particles may break down operating spacecraft and damage onboard electronics. They pose a great danger to astronauts, specifically during spacewalks and extravehicular activity. Geomagnetic storms induced by solar flares affect the ground facilities and social-economic infrastructure involving electric power supply, aviation-railways-marine transportation, oil-gas pipelines, geographic information system/data management (GIS, Internet), just to mention a few. Nowadays, all components are intimately coupled with and dependent on space global system including space communication, navigation, geodesy, oceanography, natural resources management, ecology, etc. Therefore, any breaks/disturbances in these global system operations badly influence on the modern human society making it progressively vulnerable on the solar activity. As systems become more complex over time, the social and economic impacts of space weather are likely to increase. Different protective measures are to be developed to mitigate solar flares painful consequences.

Humans pose even more complicated problems, which are closely connected with space safety starting the Moon exploration. Based on the data available and geological-geochemical reconnaissance with robotic spacecraft including lunar resources and their distribution, the most suitable regions for the Lunar Base deployment should be selected. Provinces near by the lunar South Pole are regarded as the most perspective.

Thorough monitoring of the natural conditions in these areas aims careful evaluation of risks of habitation in the lunar hostile environment. Long-term observations in the site should answer first the question on radiation doses absorption due solar/galactic cosmic rays, danger of meteoritic particles impact, propertied of lunar dusty plasma, regolith properties and composition including water/volatiles content, etc. At the next step a more detailed assessments of mineral resources in the selected sites will be undertaken. In parallel, one may expect lab study of the various physical and chemical methods of regolith/lunar minerals processing in order to extract consumable materials including those for life support. This procedure is also targeted to assess appropriate techniques and simultaneously requirements to the safety/security. Results of the study of local resources utilization will allow us to assess the required cargo flow on the Earth-Moon route at all stages of the Moon exploration to maintain the humans' activity.

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Radiation and Space Flights Safety: An Insight

Mikhail Ya. Marov

Highlights

Danger of cosmic solar and galactic radiation as a cornerstone of space flights safety

Impact of solar radiation on astronauts, spacecraft and ground-based infrastructure

Solar flares types, classification, energy and hazard

Space safety and security problems at the Moon exploration

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: