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# Investigation of exceptional solar activity in September 2017: GLE 72 and unusual Forbush decrease in GCR

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**Abstract.** The exceptional solar activity in early September 2017 at minimum of solar cycle 24 is analyzed. Intensive solar-terrestrial disturbances was caused by Active Region AR2673, which produced four powerful eruptions class X, including the strongest flare X9.3 of Solar Cycle 24 on September 6, 2017, after which began G4 – Severe geomagnetic storm on 07-08.09.2017 with  $A_p = 96$ , and also the second strongest flare X8.2 of Solar Cycle 24 on September 10, 2017, which generated Ground Level Enhancement (GLE) of cosmic rays. This was GLE72 with increase of solar cosmic ray flux 6% in Oulu Station (Finland) (effective vertical geomagnetic cutoff rigidity: 0.8 GV), and increase 9% in DOMC Antarctica and 14% in DOMB Antarctica (in the latter case - lead free neutron monitors with effective vertical cutoff rigidity  $<0.01$  GV). The GLE72 develops under the conditions of a deep Forbush decrease (around 15%) in South Pole cusp caused by September 7th Coronal Mass Ejection. The Forbush effect ends on September 11th (<http://cosmicrays.oulu.fi>). But cosmic ray measurements by flying balloons to the stratosphere over California show that after solar eruptions in September 2017 the radiation levels in stratosphere took more than two months to fully rebound to the conditions of minimal solar activity. This is interesting fact which deserves to be explored in detail. It is precisely the study and interpretation of this process that is concerned with this work.

## 1. Coronal mass ejections on September 4 – 6 and 10, 2017 in solar minimum

The cause of the intensive solar-terrestrial disturbances in early September 2017 at minimum of solar cycle 24 was the Active Region AR2673, which produced four powerful eruptions class X, including the strongest flare X9.3 of Solar Cycle 24 on September 6, 2017, after which began G4 - Severe geomagnetic storm on 07-08.09.2017 with  $A_p = 106$ , and also - the second strongest flare X8.2 of Solar Cycle 24 on September 10, 2017, which generated instantly the ground level enhancement of cosmic rays or Ground Level Event № 72 (GLE72) [1,2]. This GLE72 is the second GLE in the current solar cycle (Solar Cycle 24) after GLE71 on 17 May 2012 at solar maximum conditions [3, 4]. Therefore, the new GLE72 in solar minimum represents special interest.

## 2. The rapid development of the AR2673 active region for 24 hours

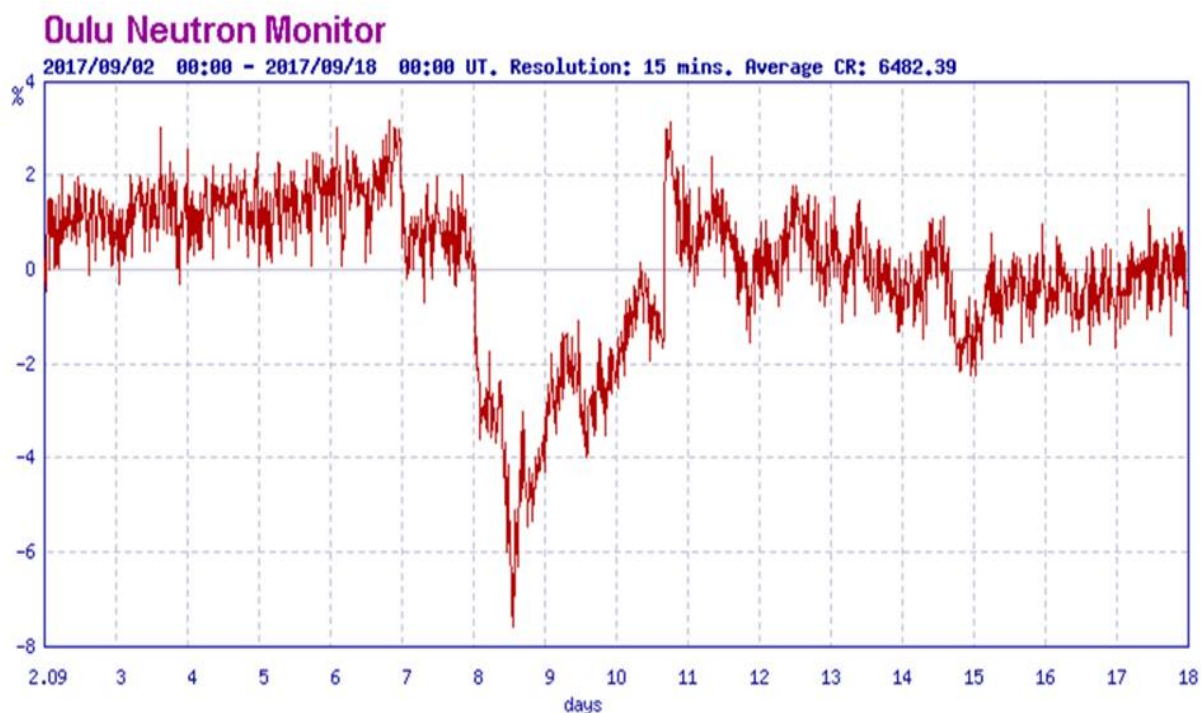
In the investigated period (02-08.09.2017), two CMEs were observed in sequence over two days. The first event was observed on September 2, 2017. There are four active regions in the solar photosphere.



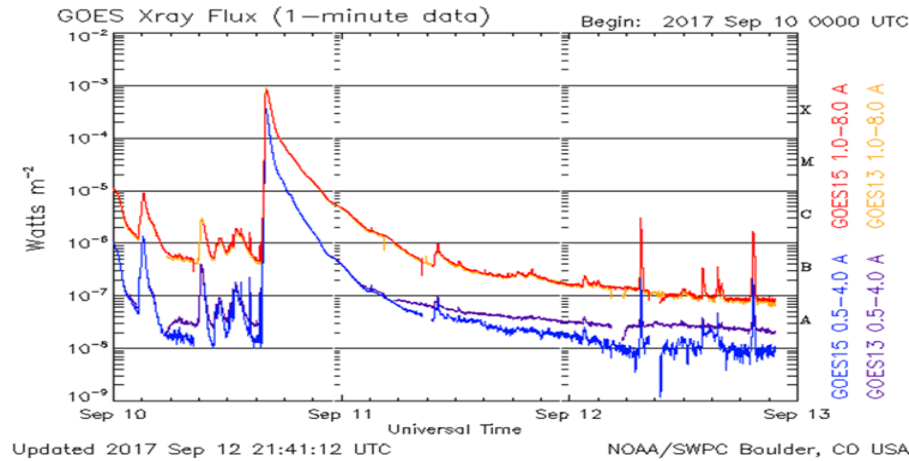
Two of the active regions are in the eastern part of the Sun. The Active Regions AR2673 and AR2674 pass through the central meridian and occupy a frontal position with respect to the Earth. The double solar spot AR 2674 grows relatively rapidly, expanding both in terms of area and number of sunspots. As the number of sunspots increases, the magnetic field becomes more unstable. There is evidence of the development of a combined "beta-gamma" magnetic field, which is a prerequisite for outbreaks in the X-ray bursts of the solar spectrum, at least of class M [1, 2]. On September 3, it was found that while the AR2674 sunspot group grew for days, the AR2673 group increased its area fourfold, and the sunspots in just 24 hours. The fast-growing solar AR2673 has a "beta-gamma-delta" magnetic field that charges energy for M-class solar flares. On September 4, two eruptions have already been detected in the M1 class of X-ray area. On 4.09 at 19:00 UT there is a coronal mass ejection directed to the Earth.

CMEs on 4 and 6 September 2017 cause a geomagnetic storm, with the Dst geomagnetic index reaching  $-150$  nT. As a result of the two events, there is a deep Forbush decrease in the galactic cosmic ray flux, which in the maximum phase reaches around 15% in South Pole cusp [1]. The decrease measured with the neutron monitor in OULU is -8% (figure 1). On September 6 was observed new CME. Going behind the apparent horizon of the solar disk, almost on the edge, the AR2673 solar plexus caused another CME accompanied by a powerful X9 X-ray burst at 16:06 UT, at 10.09, (figure 2). At the same time, this event reveals high energy proton emission (figure 3).

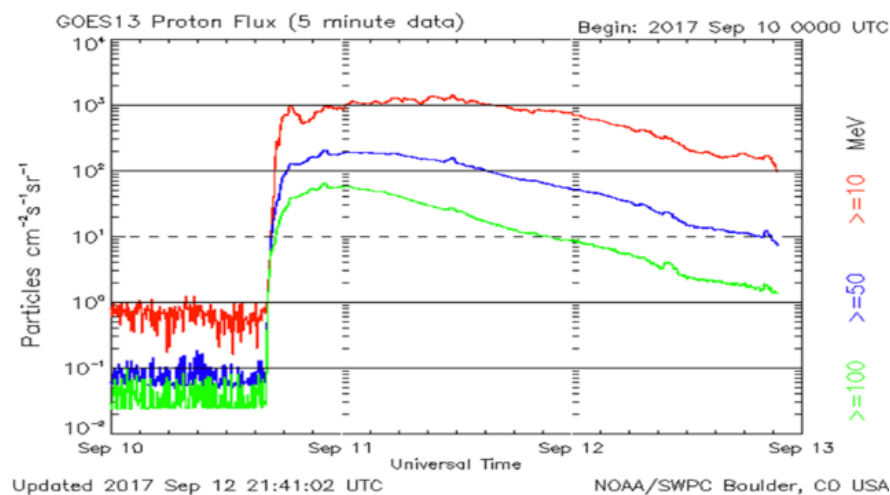
In the period September 4-9, 2017, the second largest geomagnetic storm was observed. It begins on Sept. 7 in the evening with a sudden increase of  $K_p = 8$ . On September 8 it continues with  $K_p = 8$ , passes through a brief decrease and again  $K_p = 8$ , after which the geomagnetic storm ceases until the end of the day (figure 4).



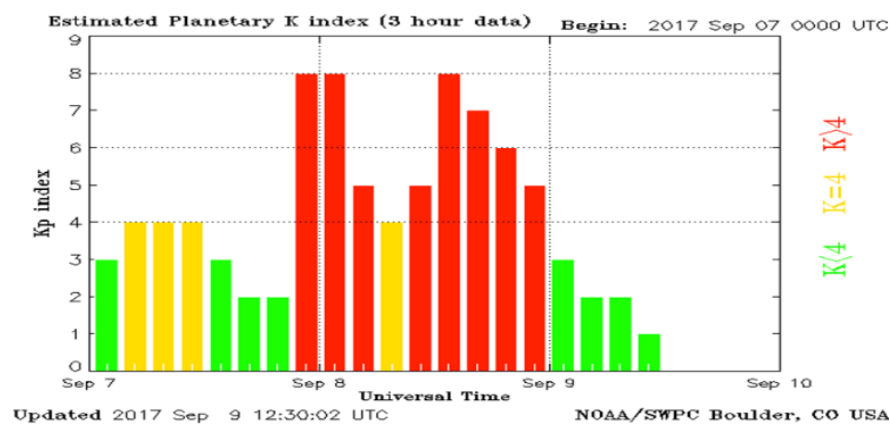
**Figure 1.** Oulu Neutron Monitor (NM) count rate variations in September 2017. It is clearly visible the Forbush decrease ( $-8\%$ ) of galactic cosmic rays on September 08, 2017 caused by CME on September 7<sup>th</sup>, and also the Solar Cosmic Ray increase – i.e. the Ground Level Event No 72 (GLE72) on September 10, 2017 caused by the flare X8.2 slightly earlier that day.



**Figure 2.** GOES observations of X-ray flux during 10 – 12 Sept., 2017. The X9 flare from 10 Sept. triggered the radiation storm in the Earth environment.



**Figure 3.** GOES observation: proton flux during GLE 72 from 10 September 2017.



**Figure 4.** The 3-hour planetary Kp - index of the geomagnetic activity during storm on 07 and 08 Sept. 2017.

**3. Energetic parameters of solar wind for the period September 2 – 15, 2017**

Measurements of the basic parameters of the solar wind are taken for the period March 10 – 24, 2015 and September 2 – 15, 2017. These parameters are: the velocity  $V$ , density or concentration  $N$  and

temperature  $T_p$  of solar wind and the intensity of Interplanetary Magnetic Field (IMF)  $B$ . In this study, measured solar wind parameters from the SOHO, ACE and WIND probes were considered. SOHO data for 2017 reveals growth of radial velocity, a more significant on 08.09.2017. At that time, the vector of IMF is in the south direction. There are all preconditions for the presence of geo-efficiency of those parameters [5]. For quantification of the different energies from the investigated CME events were calculated the following energetic parameters of solar wind [5]:

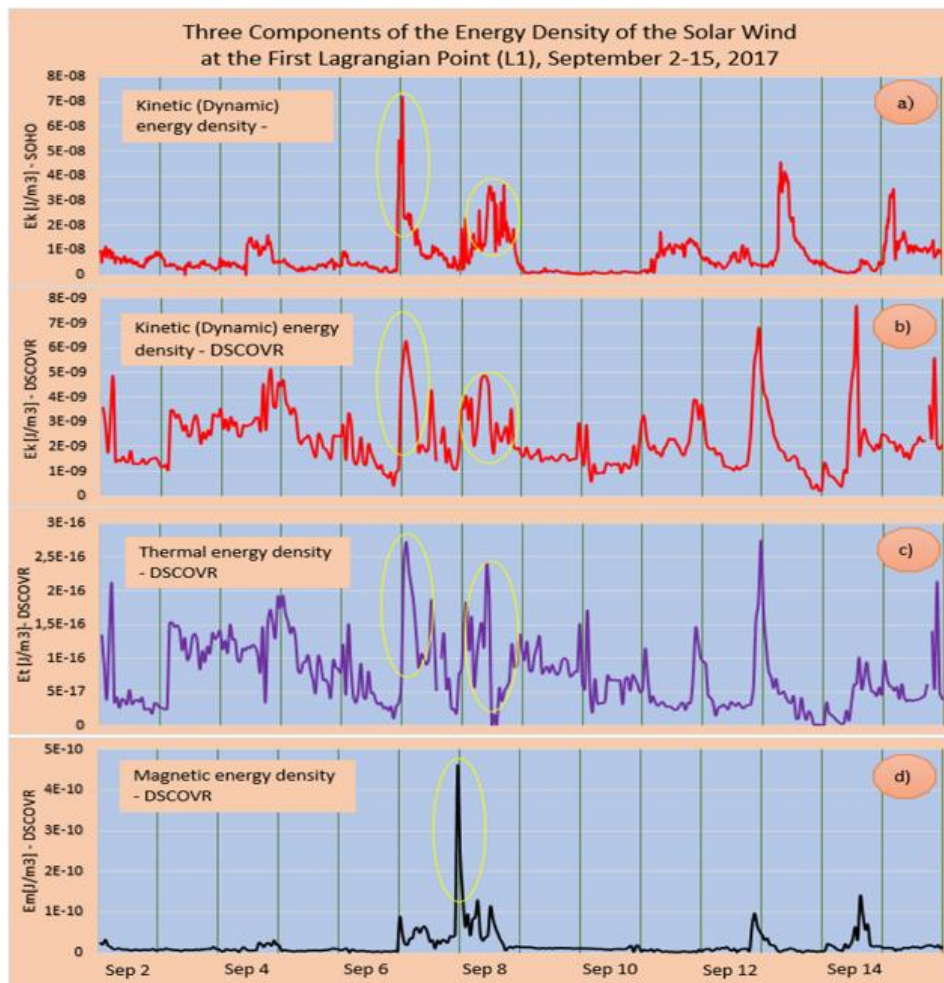
$$\text{thermal energy } E_t = 3/2 N k T_p$$

$$\text{magnetic energy } E_m = B^2 / 2\mu_0$$

$$\text{dynamic energy } E_k = 1/2 N V^2$$

where  $k$  is the constant of Boltzmann,  $T_p$  is the temperature of the protons,  $\mu_0$  is the magnetic permeability of vacuum (figure 5).

There are some unexplained experimental results related to stratosphere ionization. Since spring of 2015, Dr. Tony Phillips from Spaceweather.com and the students of Earth to Sky Calculus performed measurements of cosmic rays have by stratospheric balloons over California [6]. Soon after their monitoring program began, they quickly realized that radiation levels are increasing. The main reason for this behavior of stratosphere ionization is descending phase (2015-2018) of solar cycle 24 and the corresponding inverse course of cosmic rays, i.e. the increase of their intensity. In recent years, sunspot counts have plummeted as the Sun's magnetic field weakens, which allowed more galactic cosmic rays to penetrate in the Solar system. The latest measurements in 2017 show the radiation increase continuing apace—with an interesting exception in September – October after the G4 – Severe geomagnetic storm on September 08, 2017, and GLE72 on September 10, 2017. During the storm, the pace of the launch of the balloons was accelerated, and it was found that the radiation fell to levels that were not seen by 2015. The series of solar flares and CMEs actually pushed some cosmic rays away from Earth causing their strong modulation [7].

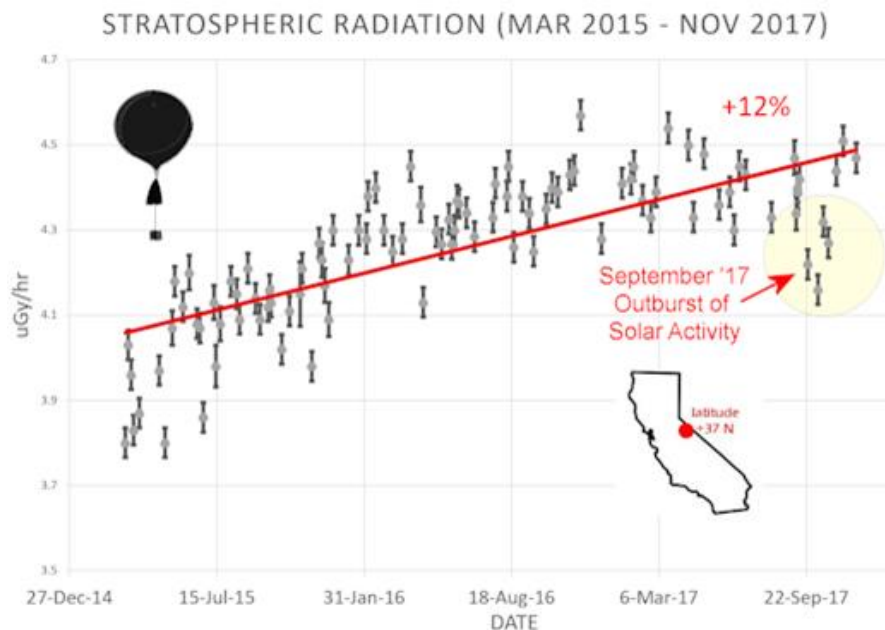


**Figure 5.** Calculations of the solar wind parameters from measurement by SOHO and DSCOVR space probes in the point of Lagrange: a, b) the kinetic energy density  $E_k$  - SOHO, DSCOVR. c) thermal energy density  $E_t$  and, d) magnetic energy density  $E_m$  during the investigated period September 02-15, 2017.

#### 4. Explanation of decreased stratosphere radiation

The most reasonable and predictable explanation for the observed reduction in stratospheric radiation is the registered decrease in the intensity of the primary cosmic rays, the so-called Forbush effect [8-12] (figure 6).

The Forbush effect is usually observable by particle detectors on Earth within a few days after the a CME and the corresponding geomagnetic storm; the cosmic ray decrease takes place over the course of a few hours. A recovery is observed in the following several days. In this study the observed Forbush decrease of about 7% within the recovery can't explain the observed experimental results in stratosphere ionization [6]. That is why we are attracting a new additional physical mechanism that we call *cumulative Forbush effect*. However, the calculations and numerical evaluations performed by the methods presented in the works [8-12] show that the cumulative Forbush effect can't explain the observed long term decrease of stratospheric ionization in September-October 2017 [6].



**Figure 6.** Stratosphere radiation measurement form March 2015 to November 2017. Toni Philips and his team show that radiation levels were increasing [6]. The main reason is the decreasing solar activity during the 24th cycle.

## 5. Variations of cosmic rays and Radiation Belts

First discovered before 60 years - at the dawn of the space age, the RBs are two collections of charged particles that circle Earth, held in place by the planet's magnetic field.

The pair of radiation belts surrounding Earth stop high-energy particles in their tracks. Data gathered by NASA's twin Van Allen Probes, which launched in August 2012, show that the donut-shaped RBs present a nearly impenetrable barrier to high-energy electrons, keeping them from hitting Earth. The barrier for the ultrafast electrons is a remarkable feature of the belts [13].

The variations of cosmic rays of galactic origin near the Earth is mainly influenced by heliosphere and geomagnetic factors. The nature of Galactic Cosmic Ray (GCR) variability has been explored in short and long-term scales and they reveal significant information on important processes related to the transport of GCRs from the source to the neutron monitor stations [7]. A significant factor is solar activity - the occurrence of CMEs on September 8-10, 2017, leads to significant variations of GCRs. On the one hand, this is reflected in a significant Forbush effect in the high energy region of GCRs, on the other it is associated with a general reduction in the intensity of the low energy region of GCRs. The latter is a fact, as mentioned above in stratospheric balloon measurements [6]. The first effect associated with the Forbush decreases of GCRs in the period of September 2017 can be relatively accurately interpreted as a process of shielding the GCR particles from the shock wave of the solar plasma stream of CME with a frozen magnet fields. This process is global for the Earth and has a classic first phase of GCR intensity decrease and a second subsequent recovery phase. The whole process lasts for three to five days [9-12]. More interesting is the fact of a reduction of the intensity of the low energy part of GCRs. This process is considerably longer in time, about two months, according to the measurements [6]. As we are talking about a low energy spectrum of GCRs, their effect will be observed with a decreased ionization in the stratosphere. Interpretation of such processes may be related to the passage of the GCRs through the heliosphere and their modulation. There are a few modulation mechanisms: 1) dispersion of the particles from the heterogeneity of interplanetary magnetic fields; 2) diffusion processes in interplanetary plasma; 3) adiabatic delay, etc. [13]. In addition, the geomagnetic factors generated by the radiation belts must also be taken into account. Radiation belts discovered in the dawn of the cosmic era still hide many of their secrets. In addition to the fact that they are special reservoirs of charged particles in the magnetosphere, they are also a shield against high energy electrons for the Earth. The data collected by NASA's Van Allen twins, launched in August 2012, show that Van Allen's radiation belts represent an almost impenetrable barrier for high energy electrons, preventing them from striking the Earth [14].

The cloud of the colder plasma, known as the Plasmosphere, sits in the middle of the conical belts and acts as a barrier to keeping fast-moving electrons away from Earth. But moreover, the information collected by the Van Allen probe shows that the inner edge of the outer belt is very abruptly defined. In solar events such as CME, this inner edge significantly shrinks to the Earth as a result of the shock wave. This leads to a particular reduction in the content of charged particles in the external radiation belt. This can also be interpreted as a fact of a decrease in ionization in the stratosphere after September 22, 2017, a few days after the coronal mass ejection of 8 and 10 September. Thus, the decrease in ionization in the stratosphere is not related to the Forbush reduction of the GCR and most likely to the modulation of the GCR stream from Van Allen's external radiation belts.

### Acknowledgments

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