S E S 2 0 1 0
Sixth Scientific Conference with International Participation
SPACE, ECOLOGY, SAFETY
2–4 November 2010, Sofia, Bulgaria

EFFECTS OF TERRESTRIAL MAGNETOSPHERE ON RADIATION HAZARD DURING MOON MISSIONS

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Keywords: *radiation, Moon, magnetosphere*

Abstract: *One potential method of radiation mitigation during extra-terrestrial missions is in the form of magnetic fields. For Moon missions, the Earth magnetosphere is a source of magnetic field, as the Moon spends about 25% of its orbit inside it. Recent modelling results have conflicted in their conclusions as to whether the Earth's magnetotail at lunar distances is sufficiently strong to provide shielding from GCR with energies greater than 10 MeV. Using RADOM data from the Chandrayaan-1 satellite we try to reveal a possible shielding. The first results show that during the solar cycle minimum, the magnetotail does not mitigate doses on Moon orbiter. However, there is certain evidence that acceleration processes inside the magnetosphere could enhance the flux of energetic electrons at Moon orbit. More detailed analysis is needed to check the magnetospheric effect on doses for different Moon locations.*

ВЛИЯНИЕ НА ЗЕМНАТА МАГНИТОСФЕРА ВЪРХУ РАДИАЦИОННИЯ РИСК ПРИ ПОЛЕТИ ДО ЛУНАТА

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Ключови думи: *радиация, Луна, магнитосфера*

Резюме: *Приложението на подходящо магнитно поле е един от възможните методи за облекчаване на радиационната обстановка при полети извън земната магнитосфера. При полети до и около Луната земната магнитосфера е естествен източник на магнитно поле, тъй като около 25% от Лунната орбита попада в нейната област. Численото моделиране на влиянието на геомагнитната опашка върху потока на галактични космични лъчи в местоположението на Луната дават противоречиви резултати. В настоящата работа ние се опитваме да разкрием възможна екранировка от магнитосферата като използваме данни от експеримента РАДОМ на спътника Чандраяаан-1. Първите резултати показват, че в условията на слънчев минимум геомагнитната опашка не намалява радиационните дози, получавани в орбита около Луната. Нещо повече, съществуват известни свидетелства, че процесите на ускорение, ставащи в земната магнитосфера, могат да увеличат потока на енергетични електрони, регистрирани в орбита около Луната. За окончателно заключение относно въздействието на магнитосферата върху радиационните дози при различно местоположение на Луната са необходими по-задълбочени изследвания.*

Introduction

Outside the protective atmosphere and magnetosphere of the Earth galactic cosmic rays (GCRs) and solar energetic particle events (SEPs) constitute a substantial radiation hazard to astronauts and technological systems. GCRs have the harder spectrum with a maximum flux near 1 GeV/nucleon. The flux at this level varies by a factor of about 10 between solar minimum and solar maximum. SEPs have a softer spectrum, but their flux can vary by more than four orders of magnitude on a time scale of less than an hour for periods of several days and yield an energetic particle flux higher than GCRs. A possible shielding of these energetic particles is by material walls, which however have to be very thick to avoid the effect of secondaries. Though such shielding is possible for planet bases, astronauts in transit or involved in surface exploration would not have the benefit of it.

Another potential method of radiation mitigation on extra-terrestrial missions is in the form of magnetic fields. Since there are no material interactions, the production of harmful secondaries is not a problem**.**

For Moon missions the Earth magnetosphere is a source of magnetic field, as the Moon spends about 25% of its orbit inside it. Recent modelling efforts have conflicted in their conclusions as to whether the Earth's magnetotail at lunar distances is sufficiently strong to provide shielding from GCR with energies greater than 10 MeV. On one hand, a recent numerical study by Winglee and Harnett [1] concluded that the quiet-time magnetosphere could offer some magnetic shielding from GCR and SEP at the Moon's orbit. They argued that GCR would be shielded by the magnetosphere since a GCR's gyroradius is comparable to the length scale of the magnetotail. By integrating the magnetic intensity from distant points to the Moon in a global MHD code, they reported that Earth's magnetosphere could shield particles up to 5 GeV/nucleon at the Moon's orbit, especially at an equatorial lunar base facing the Earth. On the other hand, Huang et al. [2] came to the opposite result. To determine any variation of GCR flux due to possible magnetotail shielding at the Moon's orbit, they performed particle simulations using realistic magnetic fields to model the lunar radiation environment. Their simulation results showed that Earth's magnetosphere does not substantially modify GCR (with proton energies greater than 1 MeV) at the lunar environment during typical solar wind conditions.

The aim of this work is to check for effects of Earth magnetosphere on the flux of energetic particle in low Moon orbit.

Instrumentation and data

In our analysis we use data from RADOM instrument [3] aboard Chandrayaan-1 satellite [4]. The RADOM spectrometer is designed to measure the spectrum (in 256 channels) of the deposited energy from primary and secondary particles. It is a miniature spectrometer-dosimeter containing a single 0.3 mm thick semiconductor detector with area of 2 cm^2. Pulse analysis technique is used for obtaining the spectrum of the energy deposited in the silicon detector, which is then analysed and further converted to deposited dose and flux. The solid-state detector of the instrument is shielded by several layers with equivalent shielding of about 0.45 g/cm^2. Thus, direct hits on the detector are possible for electrons with energies ≥ 0.85 MeV and for protons with energies ≥ 17.5 MeV. We use data for the interval January – March 2009 when Chandrayaan-1 (CH-1) was at a 100 km circular lunar orbit. Solar activity during this period is extremely low; the period falls in the unusually deep and prolonged minimum between 23rd and 24th solar cycles. There were no SPEs, coronal mass ejections or other geomagnetically effective solar phenomena. We should remind that as interplanetary magnetic field is week during solar cycle minimum, the flux of GCR is enhanced in comparison to solar cycle maximum conditions,

Can the terrestrial magnetosphere mitigate radiation hazard on Moon missions?

In this work we present only one of the 6 Chandrayaan-1 crossings of Earth magnetotail, that in January 2009 – Fig.1. The Moon crossed the bow shock and entered the magnetosheath on 07.01. Between 9th and 13th of January it was inside the magnetotail. On January 15th Ch-1 together with the Moon finally crossed the bow shock and exited the magnetosheath. Interplanetary and geomagnetic conditions, displayed in Fig. 2a, were very quiet. Interplanetary magnetic field (IMF) – top panel, was small, with typical values ~ 2 – 6 nT; Bz – second panel - was fluctuating around zero, but for several hours during magnetotail crossing obtained values around +5 nT, favourable for shielding of the flux of energetic particle, according to [1]. Flow pressure – third panel - did not exceed 2.5 – 3 nPa. AL index was also less than 300 nT and SYM/H index, which is proportional to Dst index also did not indicated a development of a storm. RADOM flux data shown in Fig. 2b did not exhibit any effect of magnetotail or magnetosheath encounter, neither in the total flux, nor in the counts in the lowest energy (and most sensitive) channels. The total flux stayed at 2.5 particles/cm^2.s,

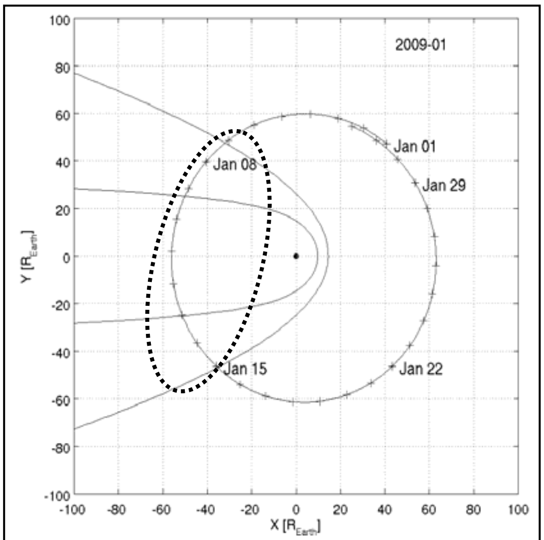

Fig. 1. Moon orbit in January 2009 in GSE system of reference. The oval marks the part of orbit inside the magnetosphere and the magnetosheath.

This example shows that in solar cycle minimum conditions, when there are no SPE and GCR flux is enhanced, we could not find any indication that Earth magnetosphere can provide additional shielding on Moon orbiter.

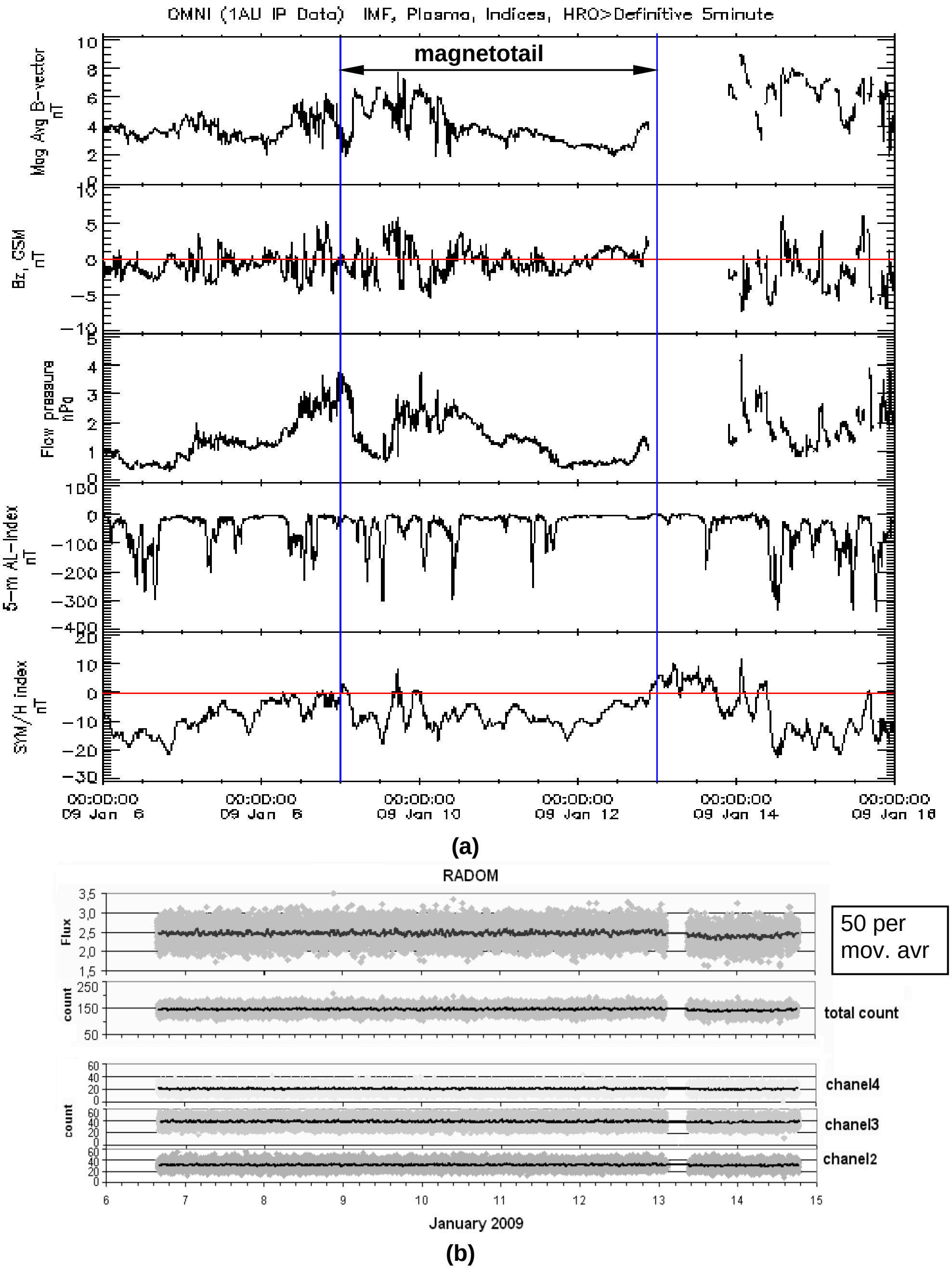

Fig. 2. (a) Interplanetary and geomagnetic conditions at 1 AU on 6 – 15 January 2009. From top to bottom: magnitude of IMF, IMF Bz, flow pressure, AL index, SYM/H index. (b) RADOM flux data for the same period, in the low energy channels, total count and total flux in particles/cm^2.s.

Effect of magnetospheric disturbances on energetic particle flux at Moon orbit

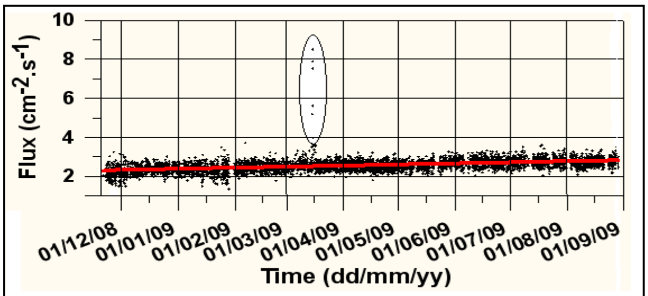

Fig.3. Particle flux registered by RADOM on Moon orbit.

Figure 3 displays the one-hour average of the particle flux registered by RADOM in Moon orbit for the whole interval of observations. The increasing trend in the flux follows the trend of Oulu Neutron monitor data and could be attributed to the increase in GCR intensity due to decreasing solar activity and consequent decrease of interplanetary magnetic field [5].

On the background of the well-grouped data, the local increase up to 4 times around 15th March in flux is distinguished. Figure 4 presents RADOM measurements and characteristic features of the interplanetary and geomagnetic conditions. As reported in [6], during 9 – 17 March 2009 no flares and no SPE were observed. However starting in the second half of 14th RADOM particle flux exhibits enhancement, modulated by the rotation of the Chandrayaan-1 satellite around the Moon and by the rotation of the Moon around the Earth.

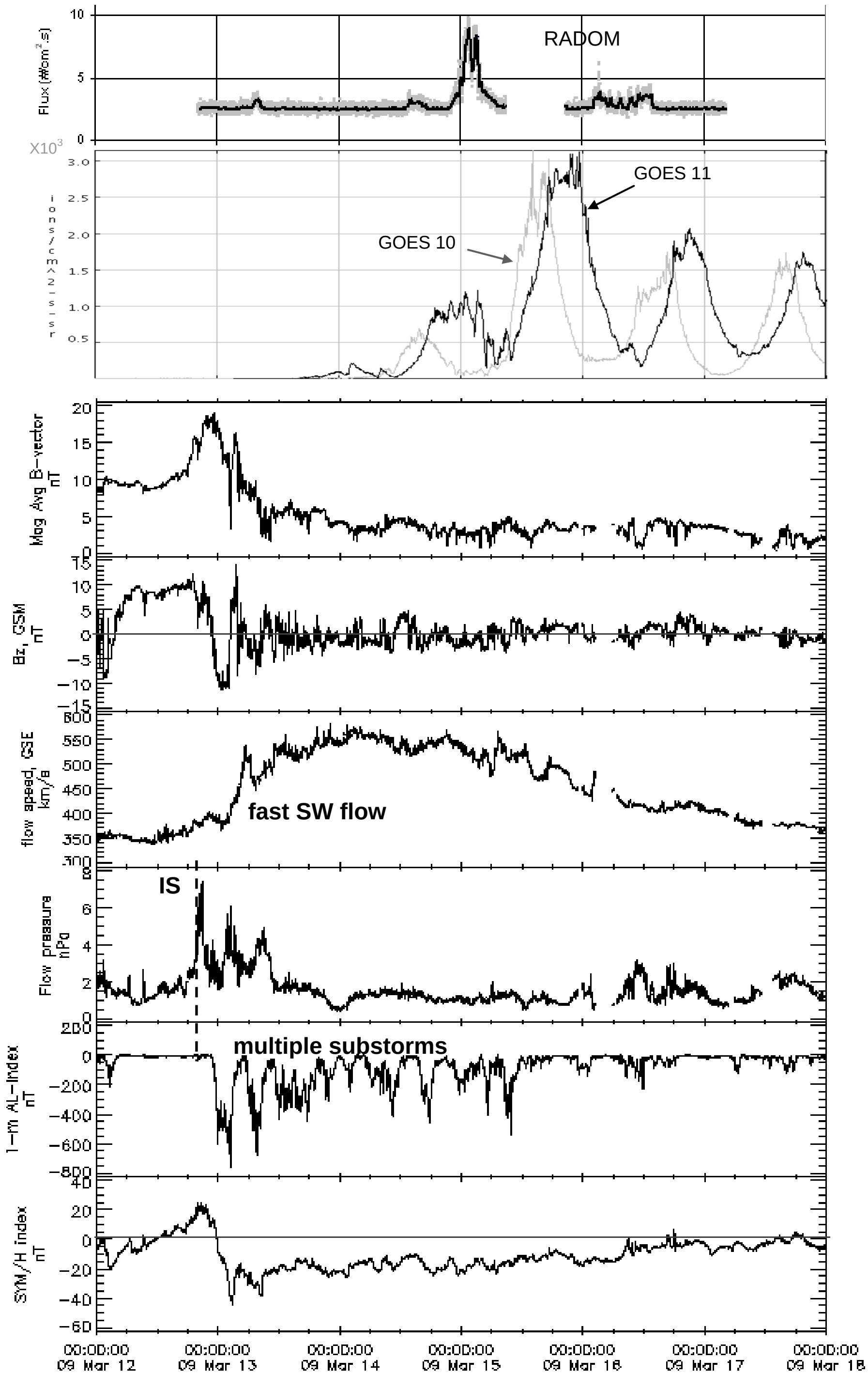

Fig.4. The event on 12 – 17 March 2009. From top to bottom: RADOM full flux; GOES 10 and GOES11 flux of electrons with energies ≥ 2 MeV; intensity of IMF; IMF Bz; flow speed, flow pressure (quantities at 1 AU); AL index, SYM/H index.

At ~ UT 19:53 on 12 March an interplanetary shock hit the Earth, causing a sudden commencement of a small geomagnetic storm. About three hours later, in the course of the growth phase, IMF Bz changed to southern. A great number of substorms followed with AL reaching ~ -800 nT. The interplanetary shock was caused by a high-stream solar wind produced by a coronal hole.

The combination of high-speed solar wind and negative IMF Bz is favorable for the processes of accelerating electrons in the magnetosphere resulting in the production of the so called 'killer electrons' – electrons with energies greater than 1 MeV in the inner magnetosphere [7]. Indeed in the second half of 14 March GOES 10 and GOES 11 satellites begin to register enhanced flux of electrons with energies greater than 2 MeV. The flux reaches its maximum of ~ 3.10^3 particles/sm^2.s.sr on 15 March. The modulation in GOES fluxes is due to satellite rotation around Earth [7] as at night side they are positioned at $L \geq 7$ and go out of the outer radiation belt.

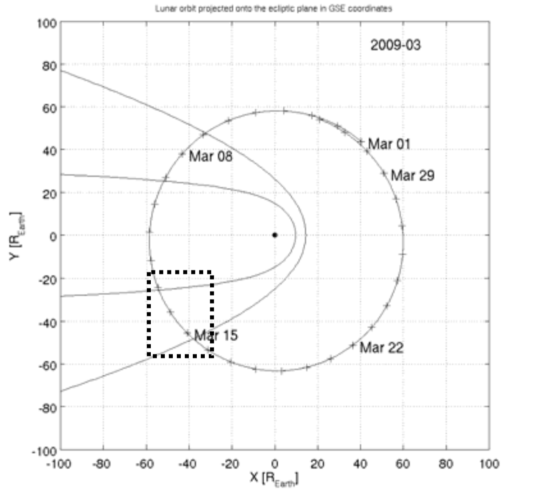

Fig. 5. Moon orbit in March 2009 in GSE system of reference. The square marks the position of Moon when RADOM measures enhanced particle flux

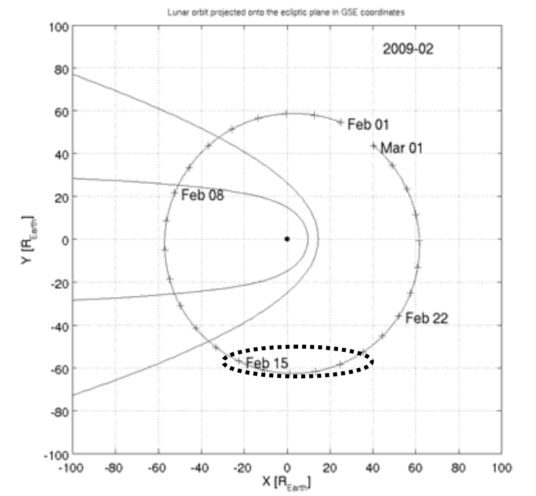

Fig. 6. Moon orbit in February 2009 in GSE system of reference. The oval marks the position of Moon during the geomagnetic event 15 – 18 February

The enhancement in RADOM data is registered only in the first energy channel, which makes us believe that these are electrons with energies slightly above the instrument threshold of 0.85 MeV. Nevertheless their relatively low energies and effectiveness, they rise the dose rate from ~ 10μGy/h to 14 μGy/h. As seen from Moon orbit in Fig. 5, on 13 – 15 March CH-1 is situated in the magnetosheath, and on 16 March – out of the magnetosheath but still in the vicinity of the bow shock. This gives us ground to suggest that on 14 – 16 March RADOM being at Moon orbit registered enhanced dose rates due to electrons, accelerated in the Earth magnetosphere, which have escaped through the dayside magnetopause and populated the turbulent magnetosheath, and penetrated upstream the solar wind in the vicinity of the bow shock.

Additional support to our hypothesis is a similar geomagnetic event that took place on 15 – 18 March 2009. As reported in [8,9], "Solar activity was very low. Old-cycle polarity Region 1012 (S06, L=278, class/area Axx/010 on 11 February) produced isolated B-class flares during 10 - 13 February. Region 1012 decayed to spotless plage on 14 February. No proton events were observed at geosynchronous orbit". Characteristic features of interplanetary and geomagnetic conditions are shown in Fig. 7. An interplanetary shock hit the Earth at ~ UT 00:00 on 14 February. The shock was caused of a co-rotating interaction region in advance of a recurrent high-speed stream and was associated with increased velocities, increased IMF Bt and intermittent periods of enhanced southward IMF Bz. These conditions are favourable for acceleration of electrons in the inner magnetosphere. The greater than 2 MeV electron flux at geosynchronous orbit increased to high levels on 15 February and stayed at high levels till 18 February.

Although these features are similar to the event of 14 - 16 MARCH, RADOM spectrometer at Moon orbiter did not register any flux enhancement (see Fig. 3). According to our hypothesis, RADOM does not see the electrons accelerated in the inner magnetosphere as the Moon is the solar wind, far upstream the bow shock (Fig.6).

Conclusions

We discussed data about the flux of energetic particles gathered by the RADOM experiment while in circular Moon orbit. The cases investigated showed that the Earth magnetosphere does not mitigate radiation hazard at a Moon orbiter. On the opposite, magnetospheric disturbances can increase the flux of energetic particles and the dose rates when the spacecraft is in or near the Earth magnetosphere.

Acknowledgements. Plots of Moon orbits were retrieved from http://neptun.umea.irf.se/~peje/moon/moon-orbits/. GOES data were retrieved from http://spidr.ngdc.noaa.gov/spidr/. We are thankful to J.H. King, N. Papatashvilli at

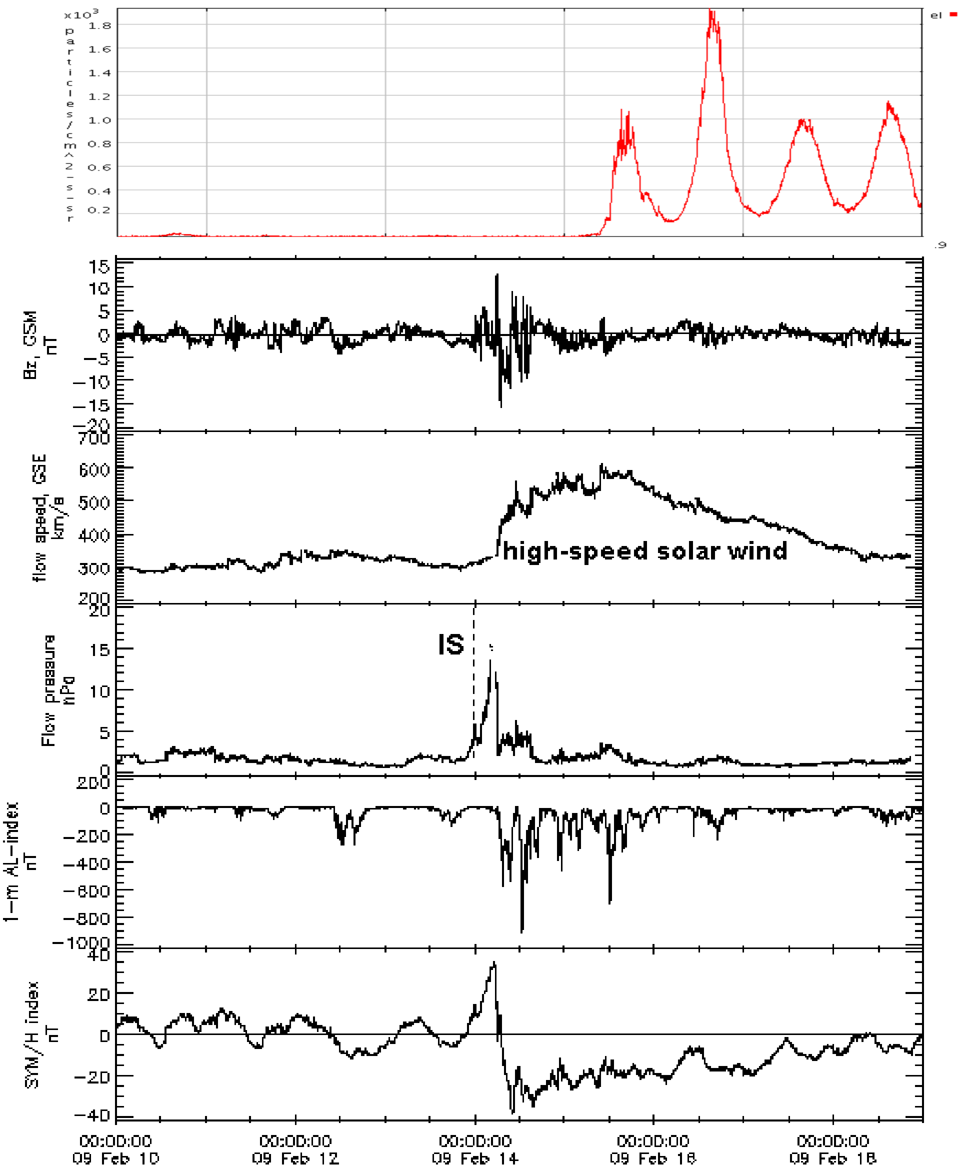

Fig.7. The event on 15 – 18 February 2009. From top to bottom: GOES 10 flux of electrons with energies ≥ 2 MeV; IMF Bz; flow speed, flow pressure (quantities at 1 AU); AL index, SYM/H index.

ADNET, NASA GSFC and CDAWeb for providing geomagnetic data. This work was partially supported by a grant DID-02/8 from the Bulgarian National Science Fund.

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