THE NEAR EARTH RADIATION ENVIRONMENT BY THE RADOM INSTRUMENT ON THE INDIAN CHANDRAYYAN-1 SATELLITE

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Abstract: *The Radiation Monitor (RADOM) is a miniature dosimeter-spectrometer onboard the Chandrayaan-1 mission for monitoring the local radiation environment. The primary objective of the RADOM experiment is to measure the total absorbed dose and spectrum of the deposited energy from high energy particles both en-route and in lunar orbit. RADOM was the first experiment to be switched on after the launch of Chandrayaan-1 and was operational till the end of the mission in August 2009. The RADOM experiment was selected from the number of the AO (Announcement of Opportunity) proposals for India's first mission to the Moon – Chandrayaan-1. RADOM proved that it could successfully characterize different radiation fields in the Earth and Moon radiation environment. All components like proton and electron radiation belts, as well as galactic cosmic rays were well recognized and measured. The modulation of the galactic cosmic rays due to the solar activity was also clearly observed. The electron radiation belt doses reached ~40000 μGy h^{-1}, while the maximum recorded flux was ~15000 particle cm^{-2} s^{-1}. The proton radiation belt doses reached the highest values of ~130000 μGy/h, while the maximum flux was ~9600 particle cm^{-2} s^{-1}. The comparison of these results with other similar instrument on board the ISS shows that RADOM performance is as expected. Outside the radiation belts, en-route to the Moon, the particle flux (~3 particle cm^{-2} s^{-1}) and the corresponding dose were very small (~12 μGy h^{-1}) which further decreased slightly in the lunar orbit because of the shielding effect of the Moon. Average flux and dose in lunar orbit were ~2.5 particle cm^{-2} s^{-1} and ~10 μGy h-1 respectively at 100 km orbit. These increased to ~2.8 particle cm^{-2} s^{-1} and ~11 μGy h^{-1} respectively, at 200 km orbit. The total accumulated dose during the transfer from Earth to Moon was found to ~1.3 Gy. Due to the lack of significant solar activity, only minor variations in the particle flux and dose were observed in the lunar orbit. Comparison of RADOM observations with theoretical models of the radiation environment for both the Moon and the Earth is underway which shows good preliminary results.*

НАБЛЮДЕНИЯ НА РАДИАЦИОННАТА СРЕДА В ОКОЛОЗЕМНОТО ПРОСТРАНСТВО С ПРИБОРА RADOM НА ИНДИЙСКИЯ СПЪТНИК НА ЛУНАТА CHANDRAYYAN-1

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Ключови думи: *Радиационна среда на Земята, Радиационна среда на Луната, Дозиметрия, Спектрометрия.*

Резюме: *Радиационния монитор (RADOM) е миниатюрен дозиметър-спектрометър на спътника Chandrayaan-1 за измерване на локалните параметри на радиационното поле като тоталната абсорбирана доза и спектърът на депозираната енергия от високо енергийни частици по трасето и в около лунна орбита. RADOM е първият научен експеримент, който е активиран след изстрелването на спътника Chandrayaan-1. Той работи практически без прекъсвания до края на мисията на спътника през август 2009 г. Експериментът с прибора RADOM е селектиран в резултат на конкурс, организиран от ISRO за спътника Chandrayaan-1. Приборът RADOM доказа, че може успешно да характеризира различните радиационни полета в около лунна и околоземна орбита. Всички компоненти на радиационното поле като протонен и електронен радиационен пояс и галактически космически лъчи са добре отделени и измерени. Дозите в електронния радиационен пояс достигат стойности от ~40000 μGy h^{-1}, докато максималният измерен поток е ~15000 частици cm^{-2} s^{-1}. Най-високите измерени дози в протонния радиационен пояс са ~130000 μGy/h, докато максималният поток е ~9600 частици cm^{-2} s^{-1}. Сравнението на резултатите от RADOM с подобен експеримент на Международната космическа станция показва, че те са съгласно очакванията. Извън радиационните пояси и по пътя към Луната потокът частици и дози намаляват до стойностите от ~3 частици cm^{-2} s^{-1} и ~12 μGy h^{-1}. Поради екранирането от масата на Луната, потокът частици на 100 км височина е ~2.5 particle cm^{-2} s^{-1}, а дозата е ~8.6 μGy h^{-1}. Те леко се увеличават на 200 км височина до ~2.8 частици cm^{-2} s^{-1} и ~11 μGy h^{-1}. Тоталната акумулирана доза при трансфера от Земята до Луната е ~1.3 Gy. Вариациите на дозите и потоците в окололунна орбита са малки, поради отсъствието на значителна слънчева активност. Сравнението на получените резултати от прибора RADOM с теоретични модели на околоземното и окололунното радиационно поле показва предварителни добри резултати.*

Introduction

This paper describes scientific results from the measurements of the Earth and Moon radiation environment by RADOM instrument since 22nd October 2008. The instrument is a miniature (98 grams, 100 mW) 256 channels spectrometer of the deposited energy (dose) in a single 2 cm^2 0.3 mm thick silicon detector.

Instrument description

The RADOM spectrometer (see Figure 1.) main tasks are to measure the spectrum of the deposited energy from primary and secondary particles onboard the Indian Chandrayaan-1 mission (Goswami and Annadurai, 2009) and to transmit these data to the Earth. RADOM (Dachev et al., 2009) a miniature spectrometer-dosimeter containing a semiconductor detector. Pulse analysis technique is used for obtaining the deposited energy spectrum, which is further converted to absorbed dose and flux in the silicon detector. The unit is managed by microcontrollers through specially developed firmware. RS232 interface provide the transmission of the data stored in the buffer memory to the Chandrayaan-1 telemetry. The instrument is very similar to: 1) The Liulin-E094 4 Mobile dosimetry units flown in 2001 on American Destiny module of International Space Station (ISS) (Dachev et al., 2002); 2) R3D-B2/B3 instruments flown on the Foton M2/M3 spacecraft in 2005/2007; 3) R3DE/R3DR instruments launched February/October 2008 toward the EuTEF platform of the European Columbus module of ISS and the Zvezda module of ISS Russian Segment respectively (Dachev 2009; Dachev et al., 2009a).

Fig. 1. RADOM instrument.

Scientific results

Earth radiation environment

The solid state detector of RADOM instrument is behind ~ 0.45 g cm^{-2} shielding from angle of 2π, which allows direct hits on the detector by electrons with energies in the range 0.85-10 MeV. The protons range is 17.5-200 MeV. On other 2π angle where the satellite is the shielding is larger but not known exactly.

RADOM instrument was switched on about 2 hours after the launch of the Chandrayaan-1 satellite on 22nd October 2008. The preliminary results are shown on Figure 2, obtained by overlapping the 2- and 3- dimensional graphics of the "RADOM-FM.exe" software. On the X axis is plotted the Universal Time between 18:25 and 20:55 UT on 22nd October 2008. On the Y axis on the right side are the 256 channels of each spectrum obtained by the RADOM spectrometer. Totally there are 1800 spectra obtained for 1.5 hours with a 10-second resolution. The count rate for 10 sec in each channel is logarithmically color coded by the color bar shown in the right-down part of the figure.

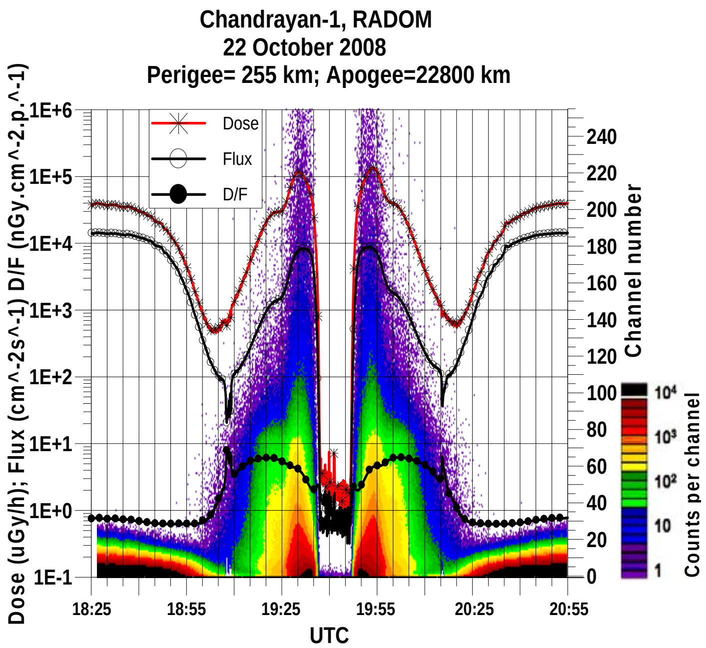

Fig. 2. Overlap of 2 and 3 dimensional presentation of RADOM data for 22800 km altitude.

The vertical axis on the left side of the figure shows the variations of 3 parameters: the measured dose in μGy h^{-1}, the flux in particles per square cm per second (cm^{-2}.s^{-1}) and the ratio of the dose to flux in (nGy cm^{-2} particle^{-1}). The last parameter is known also as specific dose per particle. A proton in the energy range 17.5-200 MeV can deposit in the matter between 6.5 and 1.08 nGy, while one electron because of much smaller mass in the range 1-10 MeV can deposit between 0.3 and 0.35 nGy (Heffner, 1971).

On the left part of Figure 2 are relative short spectra (up to 30th channel) and high doses and fluxes. We interpret these spectra as generated by electrons in the outer radiation belt, because the specific doses are less than 1 nGy per particle. The specific doses here are higher than expected by Heffner 0.3-0.35 nGy.cm^{-2}.particle^{-1} because the population is not purely by electrons - counts from GCR counts exists in the range above 30th channel. These single counts are not seen because of logarithmic coding of the count rate in the spectra. The doses here reach 4.10^{4} μGy.h^{-1}, while the fluxes are 1.5.10^{4} cm^{-2}.s^{-1}.

Gradually from left to right in Figure 2 the spectra first shortened when the satellite moves toward the slot region and next reached highest channels in the region of the inner radiation belt where high energy protons exists. In same time the doses reached about the 3 times higher values of 1.2.10^{5} μGy h^{-1} nevertheless the fluxes here are smaller than in the outer belt. Here in the middle of the inner belt the highest values of the specific doses are seen of about 5.8 nGy cm^{-2} particle^{-1}. This means that protons with energies about 13 MeV are detected. Further motion of the satellite toward the perigee brings a drastic decrease of doses and fluxes to the minimal observed values in the center of the figure. This happen when satellite moves below the proton radiation belt. The spectra here are composed mainly by GCR particles and the doses are very similar to the observed (by us) doses of 12 μGy h^{-1} on ISS in 2008 (Dachev 2009; Dachev et al., 2009) and on Foton M3 satellite in 2007 (Damasso et al., 2009).

After the crossing of the perigee region at about 250 km altitude the satellite starts to move back to the proton belt and to the region between the two belts at about 12000 km altitude. The slot region radiation is mixed between protons, electrons and GCR particles and the dose rates are only few tens of μGy h^{-1}. Later the doses rise up again in the electron belt and are similar to the observed at the left part of the figure.

Similar features to those on Figure 2 were observed at any time when Chandrayaan-1 was on Earth orbits till 7th November 2008. The doses out of radiation belts are dominated by the GCR particles. Because of the very low solar activity no solar proton events were registered during the whole period till 29th August 2009.

Comparison of the spectra at ISS with these obtained on Chandrayaan-1 satellite

Figure 3 shows a comparison between the spectra obtained by RADOM instrument in October 2008 with data from R3DE instrument on ISS in February-March 2008 (Dachev, 2009).

Three pairs of curves are plotted on Figure 3. At the bottom, two GCR spectra overlap one over the other, because the measured GCR dose rates are very similar. 11.4 μGy h^{-1} is the measured dose rate obtained by averaging 9951 spectra of R3DE instrument, while the average from 46591 spectra from RADOM dose rate is 11.8 μGy h^{-1}. The second pair of averaged spectra is obtained inside of the inner (proton) radiation belt (IRB). Because of the great difference of the altitudes of both satellites the measured dose rates at ISS are 2 orders of magnitude below the line from RADOM. ISS and respectively the R3DE instrument are at an average altitude of 354 km, whereas the Chandrayaan-1 satellite with RADOM is at a 4800 km altitude. The fact that RADOM is crossing the maximum of the inner radiation belt registers more events in the spectrum, which gives better statistics. This allows a more precise determination of the location of the knee at 6.2 MeV deposited energy. Similar is the situation with the outer (electron) radiation belt (ERB) spectra. RADOM dose rate is 37615 μGy h^{-1} at 22000 km altitude, while the R3DE dose rate is 8994 μGy h^{-1} at 360 km altitude.

The main conclusion from Figure 3 is that the spectra obtained by RADOM at the altitudes of the maxima of both radiation belts, with no doubt about the predominant population of particles, are with the same shape as the spectra obtained in LEO on ISS.

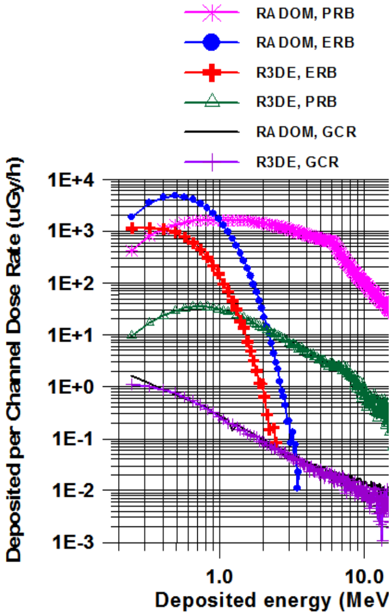

Fig. 3. Comparison of spectra obtained by the R3DE on ISS and RADOM instrument on Chandrayaan-1 satellites. (PRB) means Proton (inner) Radiation Belt. ERB means Electron (outer) Radiation Belt. The obtained spectra shape for both satellites are very similar due to similar radiation sources.

Entry into deep space and lunar orbit capture

Chandrayaan-1 was placed into the lunar transfer trajectory on 3rd November 2008 (13th day after launch) and a lunar orbit capture manoeuvre was carried out on 8th November (18th day after the launch). Figure 4 shows RADOM observations for about 3 days before the lunar orbit capture and about one day after it. More than 40000 measurements with 10 s resolution are used for the figure. The middle 2 graphics of Figure 4 show the moving average over 200 points of measured particle flux and the absorbed dose rate. The bottom graphic shows the distance from the Moon, while the top graphic shows the Oulu Neutron Monitor running average of measured count rate per minute averaged over 10 minutes. The average dose rate from more than 33000 measurements in the altitudinal range between 308000-20000 km from the Moon is ~12.76 μGy h^{-1}. The range of the measured dose rates is between 3.34 and 41.34 μGy h^{-1} with a standard deviation of 4.25 μGy h^{-1}. The average flux is 3.14 particles cm^{-2} s^{-1}, while the flux range is between 1.71 and 4.82 particles cm^{-2} s^{-1} with a standard deviation of 0.41 cm^{-2} s^{-1}. For the above mentioned altitudinal range the flux correlates with the Oulu NM count rate and respectively with the solar activity. Later on during the two closer approaches to the Moon at an altitude about 508 km the flux and the dose rate decrease because the enhanced shielding of the cosmic rays by the Moon itself. A closer look at the top panel reveals that the second periselene crossing is deeper than the first one. This mostly related with a local increase of the solar activity as evident from the simultaneous decrease of the Oulu NM count rate.

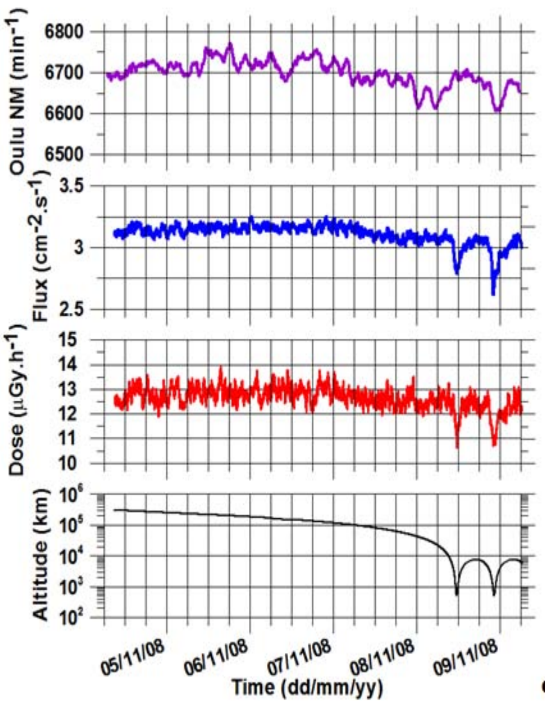

Fig. 4. RADOM observations during lunar transfer trajectory and lunar orbit capture. The distance is from the Moon. The trends in particle flux coincide with the Oulu neutron monitor data trends.

Variations of the dose rate and flux in lunar orbit

When on 14th November 2008 the satellite entered a 100 km circular orbit around the Moon the GCR doses fall down because of the Moon shielding to about 8.8 µGy h^{-1} and stayed stable around this value. The average flux is 2.29 cm^{-2} s^{-1}.

Table 1. Comparison of RADOM instrument and model data

Altitude	Flux ($cm^{-2}s^{-1}$)	Absorbed dose rate (µGy h^{-1})	Apparent dose equivalent rate (µSv^{-1})
10000 km data	2.79	10.78	25.80
10000 km model	3.05	11.16	26.76
100 km data	2.45	9.46	23.21
100 km model	2.55	9.76	23.90

The results from the comparison of the obtained by RADOM instrument fluxes, absorbed dose rates and apparent dose equivalent rates (Spurny and Dachev, 2009) at 100 and 10000 km altitude and the Moon radiation model [9] are presented in Table 1.

It is well seen from the table that the preliminary model (Angelis et al., 2007, 2009) and measured data well coincide. Further work on the model improvement is in progress.

Long term variation of GCR flux and dose rate during declining phase of solar activity

Figure 5 shows the RADOM observations in the lunar orbit until the end of the mission. The RADOM 10 and 30 sec resolution data were added and averaged to obtain hourly flux and dose rates. Overall particle flux in the 100 km orbit (20/11/2008-18/05/2009) was found to be 2.45 particles cm^{-2} s^{-1}, and the corresponding absorbed dose rate was 9.46 µGy h^{-1} over 3545 hours of measurements. The averaged Oulu NM count rate was 6762 counts min^{-1}. During the last three months of the mission (20/05/2009-28/08/2009), Chandrayaan-1 was in 200 km orbit, where the flux and dose rate increased slightly to 2.73 cm^{-2} s^{-1} and 10.7 Gy h^{-1} respectively. Oulu NM count rate also increase to 6809 counts min^{-1}. The solid angle of acceptance for open space at 200 km altitude increases by about 10 % then that at 100 km altitude. The observed increase of particle flux and dose rate at 200 km can thus be explained as due to reduced self-shielding of GCR by the Moon.

From Figure 5 it can also be seen that over the whole measurement period between 22/11/2008 and 28/08/2009 the particle flux and dose rate (bottom 2 graphics) show increasing trends, which coincide with the Oulu Neutron monitor data trends in the top graphic. This could be attributed to the increase in GCR intensity due to decreasing solar activity and consequential decrease of interplanetary solar magnetic field. A local increase in the flux rate data around 15th March 2009 is observed and highlighted with an ellipse.

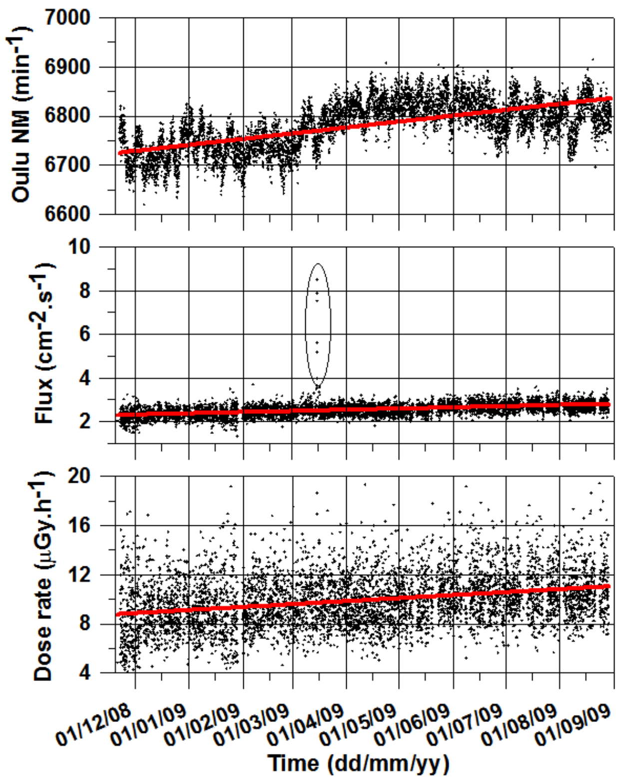

Fig. 5. Long term monitoring of the lunar radiation environment. The particle flux (middle graphic) and dose rate (bottom graphic) show increasing trends. The comparison with the Oulu neutron monitor data (top graphic) shows that this is an actual increase in the GCR. A minor increase in the flux rate connected with increase of the Earth magnetic activity around 15th of March 2009 is observed.

Summary

RADOM observations which began within two hours after launch of the Chandrayaan-1 and continued until the end of the mission demonstrated that it could successfully characterize different radiation fields in the Earth and Moon environments. Signature and intensity of proton and electron radiation belts, relativistic electrons in the Earth magnetosphere as well as galactic cosmic rays were well recognized and measured. Effect of solar modulation of galactic cosmic rays could also be discerned in the data. The electron radiation belt doses reached ~40000 μGy h^{-1}, while the maximum flux recorded was ~15000 cm^{-2} s^{-1}. The proton radiation belt doses reached the highest values of ~130000 μGy h^{-1}, while the maximum flux was ~9600 particle cm^{-2} s^{-1}. Comparison of these results with other similar instruments on board ISS shows good consistency, indicating nominal performance RADOM. Outside the radiation belts, en-route to the Moon, the particle flux (~3 particle cm^{-2} s^{-1}) and corresponding dose were very small (~12 μGy h^{-1}) which further decreased slightly in the lunar orbit because of the shielding effect of the Moon. Average flux and dose in lunar orbit were ~2.45 cm^{-2} s^{-1}, and the corresponding absorbed dose rate was 9.46 μGy h^{-1} respectively at 100 km orbit. These increased to 2.73 particles cm^{-2} s^{-1} and 10.7 μGy h^{-1} respectively, at 200 km orbit. The total accumulated dose during the transfer from Earth to Moon was found to ~1.3 Gy. Due to the lack of significant solar activity only minor variations in the particle flux and dose were observed in the lunar orbit.

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