BULGARIAN PARTICIPATION IN FUTURE INTERPLANETARY MISSIONS

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Abstract: *The paper is divided in 2 parts. The first part describes the past interplanetary experiments, which were developed in Bulgaria for the Mars-96/98, Chandrayaan-1 and Phobos-Grunt missions. The second part of the paper describes the following future interplanetary experiments: 1) The Liulin-L experiment, which will measure the radiation environment in the 3 axes of the Luna-Glob-Orbiter at 100 km distance from the Moon surface; 2) The particle telescope Liulin-MO, which will measure the radiation environment on the ExoMars-Orbiter around Mars in 2 perpendicular directions. The beginning of the missions is expected in 2016.*

БЪЛГАРСКО УЧАСТИЕ В БЪДЕЩИ МЕЖДУПЛАНЕТНИ МИСИИ

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Ключови думи: *Космическа радиация, Космическо време, Дозиметрия, Спектрометрия*

Резюме: *Статията е разделена на 2 части. Първата част описва междупланетните космически експерименти в миналото, в които са участвали български учени като спътниците Mars-96/98, Chandrayaan-1 и Phobos-Grunt. Втората част на статията е посветена на следните нови междупланетни космически експерименти: 1) Експериментът с прибора Liulin-L, който ще измерва радиационните условия по 3-те оси на спътника Luna-Glob-Orbiter на 100 km от лунната повърхност; 2) Телескопът за частици Liulin-MO, които ще измерва радиационните условия на спътника ExoMars-Orbiter около планетата Марс фв 2 перпендикулярни направления. Началото на двата експеримента се очаква през 2016 г.*

1. Introduction

Deep space manned missions are already a near future of astronautics. Radiation risk on such a long-duration journey, the greater part of which takes place in interplanetary space, appears to be one of the basic factors in planning and designing the mission.

The radiation field in interplanetary space is complex, composed by GCR, solar energetic particles, and secondary radiation produced in the shielding materials of the spacecraft or the space suit and in the biological objects.

1.1 Galactic cosmic rays

The dominant radiation component in the interplanetary radiation environment is the GCR, which are not rays at all but charged particles that originate from sources beyond the Solar System. They are thought be accelerated at highly energetic sources like neutron stars and supernovae within our Galaxy. GCR are the most penetrating among the major types of ionizing radiation [1]. The flux and spectra of GCR particles show modulation, which anti-correlats with the solar activity. The distribution of GCR is believed to be isotropic throughout the interstellar and interplanetary space. The energies of GCR particles range from several tens up to 10^{12} MeV/nucleon. The GCR spectrum consists of 98% protons and heavier ions (baryon component) and 2% electrons and positrons (lepton component). The baryon component is composed of 87% protons, 12% helium ions (alpha particles) and 1% heavy ions [2]. Highly energetic particles in the heavy ion component, typically referred to as high Z and energy (HZE) particles, play a particularly important role in space dosimetry [3] and affect strongly the biological objects and humans in space [4]. HZE particles, especially iron, possess high linear energy transfer (LET) and are highly penetrating, giving them a large potential for radiobiological damage [5]. The average dose rate in the interplanetary space measured by RADOM instrument on Chandrayaan-1 satellite [6] was 12.8 μGy h^{-1}.

From a radiation protection aspect the most important characteristic of CGR is that they are a continuous source of radiation and far more penetrating than other types of radiation. The doses expected on an interplanetary mission are very large in comparison with the allowed dose to the general public of 0.005 Sv $year^{-1}$ (according to USA standards). The USA suggested radiation guidelines allow for astronauts a maximum annual dose of 0.5 Sv to the blood – forming organs (BFO) [7]. The Russian standards allow on manned space missions 0.665 Sv a year, but not more than 1.625 Sv per 3 years [8].

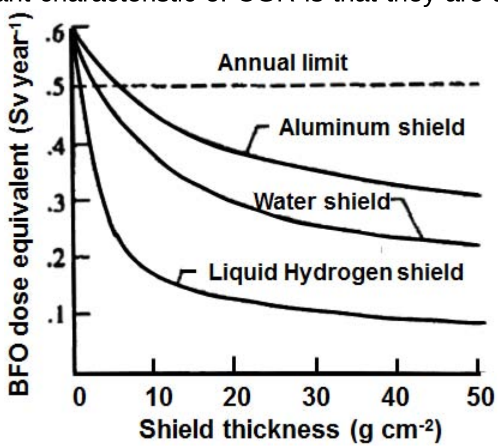

Fig. 1. Dose equivalent in BFO as function of shield type and thickness [9].

Calculation of the effects of radiation along a long-duration manned space mission requires three distinct procedures: i) Knowledge and modeling of the particle radiation environment; ii) Calculation of primary and secondary particle transport through shielding materials; and iii) Assessment of the biological effect of the dose.

Estimations of the dose equivalent from GCR in blood - forming organs (BFO) as a function of the shield type and the thickness for solar minimum conditions are presented in Figure 1. [9]. Figure 1 shows: i) That behind relatively thin shielding the annual dose equivalent is larger than the annual limit by 0.5 Sv $year^{-1}$; ii) That the dose equivalent is a slowly decreasing function of the shield thickness. As pointed out in [9] the uncertainties and the possible inaccuracies involved in the calculations could result in a potential shield mass increase by up to a factor of 2. If the exposure is underestimated by a factor of 2, then the shield mass must be increased by an order of magnitude.

1.2 Solar energetic particles

Solar energetic particles (SEP) emitted and accelerated during solar flares are randomly distributed events, but they may deliver very high doses over short periods and that is why they could be associated with lethal equivalent doses in the interplanetary space. The SEP are mainly produced by solar flares, sudden sporadic eruptions of the chromosphere of the Sun. High fluxes of charged particles (mostly protons, some helium and heavier ions) with energies up to several GeV are emitted. The time profile of a typical SPE starts with a rapid exponential increase in flux, reaching a peak in minutes to hours. The energy emitted lies usually between 15 and 500 MeV $nucleon^{-1}$ and the intensity can reach 10^4 particle cm^{-2} s^{-1} sr^{-1}. The time period of the 100 MeV enhancements varies in 1 to 3 days. The most intense solar proton fluence observed was that on August, 1972 and October 1989. The flare containing the largest peak flux of highly penetrating particles was in February, 1956. On this basis the so-called worst-case flare is composed, which is thought to occur once a century, but statistics are extremely poor. Model calculations [10] give a dose rate of about 0.42 Sv h^{-1} for a standard solar proton event and up to 0.70 Sv h^{-1} without shielding for the worst-case solar proton event. Under these estimations the necessity of effective shielding is more than evident.

Shielding against solar energetic particles is, at first glance, simpler than against GCR. However the benefit of less penetration of the flare particles because of their softer spectrum is offset to a large degree by their high intensity. In addition, solar energetic particles also produce secondaries, which build up in shielding materials. In particular the commonly used aluminum proves to be an insufficiently effective shielding material (see Figure 1).

Present calculations show that radiation doses expected on manned interplanetary missions can easily exceed the suggested allowed doses, but we must keep in mind that these estimations bear a lot of uncertainties. Present models of all three stages, involved in calculations, are far from precise. Therefore experimental measurements on unmanned missions like Luna-Glob and ExoMars are of a great importance for the future planning of manned mission in the interplanetary space and on the surface of Moon and Mars.

2. Historical overview of the past Bulgarian participations in interplanetary missions

The first participation of SRTI-BAS scientists in an interplanetary mission was in the Mars-96/98 interplanetary missions.

2.1 Mars-96/98 interplanetary missions

Scientists from SRTI-BAS participated in the Mars-96 interplanetary mission with the RADIUS-MD Liulin-1/2 solid state detectors (SSD) on the orbiter [11]. The Dose-M instrument for the ARIS spectrometer on the aerostat station's tethered guiderope was foreseen for the Mars-98 mission [11]. Because of the failed transfer to Mars orbit in 1996 the Mars-96 mission was not really performed and Mars-98 mission was cancelled. Never the less the necessary instruments were built and qualified for space. The RADIUS-MD instrument was mounted on the Mars-96 interplanetary probe. The experiments were planned to be realized at three stages of the mission:- During the spacecraft's path to Mars (instrument RADIUS-MD);- On Mars's orbit (instrument RADIUS-MD);- On Mars's balloon's guiderope on the surface and in the atmosphere of Mars (instrument Dose-M - part of ARIS spectrometer).

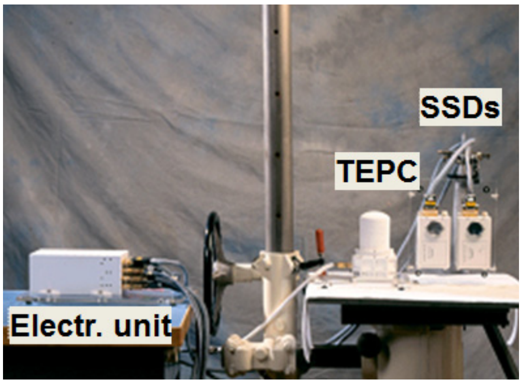

Fig. 2. RADIUS-MD instrument external view.

Figure 2 presents the external view of the RADIUS-MD system, which contained one Electronic unit and one Liulin type SSD inside the spacecraft, a tissue-equivalent proportional counter (TEPC), and a second SSD outside the spacecraft. The Liulin type SSDs were similar to the detector unit of the LIULIN instrument [12].

The scientific cooperation involved in the RADIUS-MD experiment: i) From France- Life Science Division (LSD), RE/RS Division - CNES, Toulouse (Electronic unit and TEPC), - Institute of Protection and Nuclear Safety - CEA, Fontenay-Aux-Roses (Electronic unit and TEPC); ii) From Bulgaria – the former Solar-Terrestrial Influences Laboratory at the Bulgarian Academy of Sciences (2 SSDs); and iii) From Russia - Institute of Biomedical Problems, Moscow.

2.2 Chandrayaan-1 Moon satellite

Scientists from the former Solar-Terrestrial Influences Institute (now part of SRTI-BAS) participated with the RADOM instrument [13] in the first Indian lunar satellite - Chandrayaan-1. Except the baseline payloads developed manly by Indian scientists, the Indian Space Research Organization (ISRO) also offered the international scientific community the possibility to participate in the Chandrayaan-1 mission through an announcement of opportunity (AO) in the early 2004. The response was overwhelming and on the base of peer reviews several payloads that complemented and supplemented the basic objectives of the Chandrayaan-1 mission have been selected. Three payloads, SIR-2, C1XS and SARA, developed at the Max-Planck Institute, Lindau, Germany, Rutherford Appleton Laboratory, UK, and Swedish Institute of Space Physics respectively were provided by ESA. NASA provided Mini-SAR, developed by the Applied Physics Laboratory at John Hopkins University and NAWC, and the Moon Mineralogy Mapper, developed by the Brown University and the Jet Propulsion Laboratory. The RADOM instrument was provided by the Solar-Terrestrial Influences Institute (STIL) at the Bulgarian Academy of Sciences [14].

Chandrayaan-1 was launched on 22 October 2008 and injected into a 255 km x 22,860 km orbit. By five consecutive in the plane of the perigee maneuvers the satellite achieved the required 386,000 km apogee that placed it in a lunar transfer trajectory.

Chandrayaan-1 was placed into the lunar transfer trajectory on 3 November 2008 (13th day after launch) and a lunar orbit capture manoeuvre was carried out on 8 November (18th day after the launch). Figure 3 shows RADOM observations for about 3 days before the lunar orbit capture and about one day after it. It aims to present the interplanetary radiation conditions. More than 40000 measurements with a 10 s resolution were used for the figure. Figures 3b and 3c show the moving average over 200 points of measured particle flux and the absorbed dose rate respectively. Figure 3d shows the distance from the Moon (in km), while Figure 3a [6] shows the Oulu Neutron Monitor running average of the 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 real measured dose rates is between 3.3 and 41.3 μGy h^{-1} with a standard deviation of 4.3 μGy h^{-1}. The average flux is 3.1 particles cm^{-2} cm^{-2} s^{-1}, while the real flux range is between 1.7 and 4.8 particles cm^{-2} s^{-1} with a standard deviation of 0.4 cm^{-2} s^{-1}. Figures 3b and 3c don't show this real dynamics of the values because only the moving averages are plotted there. These values of the dose rate and flux may be used as reference values for the "interplanetary space" radiation conditions during the very low level of solar activity in the late 2008.

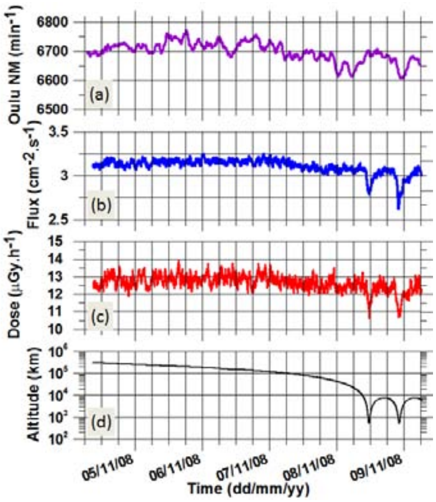

Fig. 3. RADOM observations during lunar transfer trajectory and lunar orbit capture. The altitude in panel (d) is from the Moon.

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 of the enhanced shielding of the cosmic rays by the Moon body itself. A closer look at Figure 3a reveals that the decrease in data during the second periselene crossing is deeper than the first one. This is mostly related with a local increase of the solar activity as evident from the simultaneous decrease of the Oulu NM count rate.

2.3 Phobos-Grunt mission

The Liulin-Phobos (abbreviated as Liulin-F) instrument [15] was developed during 2005-2011 for radiation research on the Russian Phobos - Soil sample return mission to the satellite of Mars – Phobos. The Liulin-F particle telescope was mounted on the Descent Module of the Phobos – Sample spacecraft. Because of the failed transfer to Mars orbit in 2011 the Phobos-Soil mission was not really performed. The main goal of the Liulin-F experiment was investigation of the radiation conditions and radiation doses in the heliosphere at distances of 1 to 1.5 AU from the Sun and in near-Mars space. That research was planned to be used for estimation of the radiation doses received by the components of a spacecraft and for assessment of the radiation risk to crewmembers of future exploratory flights.

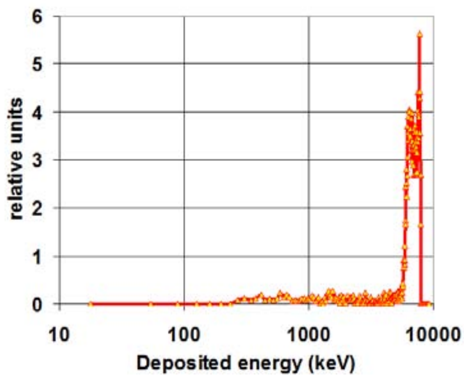

Fig. 4. LET spectrum of Carbon ions with energy 400 MeV, obtained in D2 detector at 0^0 inclination of D1&D2 telescope axis to the incident beam.

The Liulin-F instrument contained two dosimetric telescopes arranged at two perpendicular directions. Every pair of telescopes consisted of two 300 μm thick Si PIN photodiodes, operating in a coincidence mode to obtain LET. The entire Liulin-F instrument had a mass of 0.5 kg and consumed 2.4 W. The telemetry data rate was 250 kB day^{-1}.

The Liulin-F flight unit was calibrated with proton and heavy ion beams at the cyclotron and at the HIMAC accelerator at the National Institute of Radiological Sciences (NIRS), Japan in January - February 2009 [16]. The calibrations were performed in agreement with the Memorandum of Understanding on collaboration concerning development, calibration, space flight measurements and data analysis of the Liulin-F instrument onboard the Phobos-Soil mission, which was signed between STII-BAS, IBMP-RAS and the National Institute of Radiological Sciences (NIRS), Chiba, Japan.

As an example of the obtained results, Figure 4 shows the energy deposition spectrum in the D2 detector in a coincidence mode with D1 (LET spectrum) of Carbon ions with energy 400 MeV. The distribution was obtained in the low energy range of the detector, when the telescope's D1-D2 axis was inclined at 0^0 to the ion beam. The maximum of the LET distribution is in the 180 ADC channel and corresponds to 6426 keV, practically coinciding with the preliminary calculated value and confirming the correctness of the electronic calibrations.

3. Future Bulgarian participations in interplanetary missions

3.1 Luna-Glob mission

According to the recent presentation [17] and the statement of the Head of NPO "Lavochkin" – V. Khartov [18] there are 3 currently planned Russian lunar missions (see Figure 5): 2015, Luna-25 (Luna-Glob-Lander) with a minimal scientific payload which will develop the technology of polar soft landing and the study of Lunar South pole; 2016, Luna-26 (Luna-Glob-Orbiter) with a full range of scientific instruments and a long duration of the observations; 2017, Luna-27 (Luna-Resource-1), studies of the South Pole regolith and exosphere in cooperation with India.

Fig. 5. Currently planned Russian lunar investigations-Schematic view [18].

SRTI-BAS expects to participate with an experiment named Liulin-L in the Luna-Glob-Orbiter mission in 2016. The Liulin-L instrument will contain 3 blocks looking in 3 perpendicular directions along the axes of the satellite. Every single block will be very similar to the RADOM instrument flown in 2008-2009 on the Indian Moon satellite Chandrayaan -1

In Figure 6 the flight model of the RADOM instrument [6, 13] is presented as a sample of the expected external view of the Liulin-L single block. The dimensions of the Liulin-L single block will be ~10x4x2 cm and weight ~90 g. The instrument will be very similar to: 1) The Liulin-E094 4 Mobile dosimetry units flown in 2001 on the American Destiny module of the International Space Station (ISS) [19, 20] in the frame of the European DosMap Project [20]; 2) The R3D-B2/B3 instruments flown on the Foton M2/M3 spacecraft in 2005/2007 [22, 23]; 3) The R3DE instrument which worked between February 2008 and September 2009 on the EuTEF platform of European Columbus module of ISS as part of the EXPOSE-E Facility; 4) R3DR instrument, which operated outside the Russian Zvezda module of ISS till August 2010 [24-26].

Fig. 6. Expected external view of the Liulin-L unit block. (It will be identical to the flight model of the RADOM instrument.

The solid state detector of the Liulin-L single block instrument will be situated in the left part of the unit below a cover of 1 mm aluminium (see Figure 6) as is denoted by the dashed quadrangle. At the right side of the unit will be the Canon-9M connector (or other space qualified Russian RS type connector(s), through which the instrument will be connected to the satellite power supply of 12 V DC and telemetry. According to the Exchange protocol between SRTI-BAS and The Scientific and research institute "Component" («НИИ «Компонент», Russia) this will be a standard RS-485 interface. The typical power consumption of the Liulin-L single block is expected to be less than 0.3 W. The solid state detector, including the thermo-vacuum shielding, will be behind ~ 0.45 g cm^{-2} shielding from the front angle of 2π, which will allow direct hits on the detector by electrons with energies above 0.85 MeV [27]. The allowed minimal proton energy will be 17.5 MeV [27]. On the rear 2π angle where the satellite will be, the shielding will be larger but not known exactly.

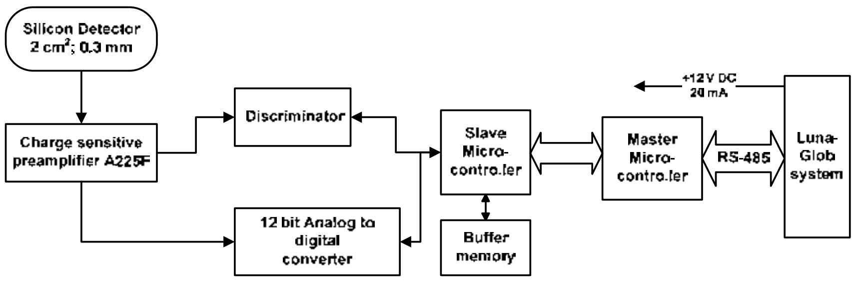

Fig. 7. Block-scheme of the Liulin-L single block spectrometer.

The Liulin-L single block instrument will contain: a Hamamatsu S2744-08 PIN diode with 2 cm^2 active area and 0.3 mm thickness; a low noise, hybrid, charge-sensitive preamplifier (A225F type of AMPTEK inc.); a fast 12 channel Analog to Digital Converter (ADC); Discriminator; Buffer memory and 2 microcontrollers (see Figure 7).

The input measurement circuit in the left part of Figure 7 will be managed by the slave microcontroller through specially developed software. Pulse height analysis technique will be used for the measurement of the amplitude of each pulse in the detector. The master microcontroller will manage the whole activity of the spectrometer and the communication with the Luna-Glob spacecraft through RS-485 interface.

The main measurement unit in the spectrometer is the amplitude of the voltage pulse generated by particles or photons hitting the detector. The amplitude of the pulse is proportional to the energy loss in the detector by a factor of 240 mV MeV^{-1} and respectively to the dose and LET. The ADC digitizes the pulse amplitude with a 12 bit resolution, however only 8 bits are used to generate the 256 channel spectrums.

The following method for absorbed dose in the silicon detector calculation is used (by definition the dose D [Gy] is one Joule deposited in 1 kg):

$$D = K \sum_{i=1}^{255} i k_i A_i MD^{-1} \qquad (1)$$

where MD is the mass of the detector in kg, k_i is the number of pulses in channel "i", A_i is the amplitude in volts of the pulses in channel "i", and K is a calibration coefficient. The term $K.i.k_i.A_i$ is the deposited energy (energy loss) in Joules in channel "i". Summing over all 255 deposited dose values, gives the total energy deposited in the detector during one unit of exposure time, which is further divided by the mass of the detector to obtain the absorbed dose in silicon.

The calibrations revealed that except for charged energetic particles, the detector has high effectiveness toward gamma rays. The ADC and the slave microcontroller will generate 256 channel energy spectrums from the measured deposited energies for each measurement interval. The spectrum will be used for the calculation of the deposited dose and flux from primary and secondary particles. Also it will be used for the estimation of the flux and dose rates from different radiation sources as protons, electrons, neutrons, He+ and heavier ions [24, 28].

Very new investigations of the performance of the Hamamatsu S2744-08 PIN diodes (Liulin-L instruments will use these type of diodes) in fast neutron radiation field yield information that these detectors do have sensitivity to detect fast neutrons by "induced nuclear counter effect". In the paper of Zhang et al., 2011 [29] the effect is described as follows: "It is believed to be realized in a two-step process in the bulk silicon of these detectors. In the first step fast neutrons lose a fraction of their kinetic energy to nuclei through elastic neutron-nucleus collisions. In the second step the charged nuclei deposit their kinetic energies in detectors through ionization, which are converted into electron signals." The secondary neutrons in the interplanetary radiation environment through the fast neutron induced nuclear counter effect may contribute for the population with counts the whole energy range of the Liulin type spectrometers but they are well seen only above the threshold of 6.2 MeV deposited energy (channel number 78), which is equal to the stopping energy of impinging normally to the 0.3 mm detector protons. Except neutrons, long pathlength low-LET particles (protons), He^+ and heavier ions may populate all channels between 78 and 255.

Our previous calibrations [28, 30-32] of Liulin type instruments by ^{252}Cf, AmBe and AmF neutron sources and in CERN-EC reference field also show their sensitivity against neutrons but the "induced nuclear counter effect" in Hamamatsu PIN diodes and the investigations performed by Zhang et al., (2011) [29] explain it in doubtless way. Based on these calibrations a method for estimation of the contribution from different sources was developed.

According to the above described features of the Liulin-L single block spectrometer the following objectives of the experiment with the Liulin-L instrument on Luna-Glob-Orbiter were specified:

- Measurements of the space radiation doses and fluxes in the Earth magnetosphere and on the route to Moon. Mapping of the space radiation distribution at 100 km from the Moon surface. Evaluation of the shielding characteristics of the near Moon environment;
- Measurements of the dose contribution of relativistic electrons, protons, He+ ions and HZE particles in the dose composition;
- Estimation of the radiation doses received by the components of the spacecraft;
- Contributions to the verification of the radiation environment models and assessment of the radiation risk to the crewmembers of future exploratory missions

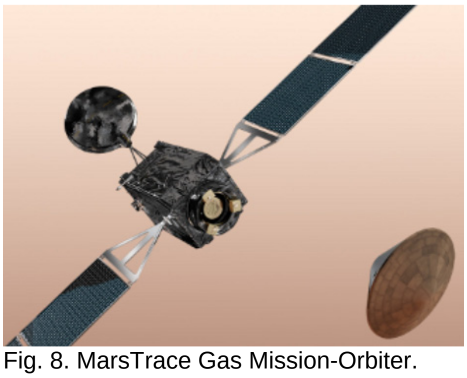

Fig. 8. MarsTrace Gas Mission-Orbiter.

to the Moon.

3.2 ExoMars mission

ExoMars is a joint investigation of Mars carried out by Roscosmos and ESA that has 2 launches foreseen, in 2016 and 2018. Planned for launch in 2016, its first element, the Trace Gas Orbiter (see Figure 8 http://exploration.esa.int/science-e-media/img/3d/ExoMars_Mission2016_410.jpg) will spend at least one Martian year orbiting the planet [33].

The Fine Resolution Neutron Detector (FREND) instrument was proposed by Roscosmos and will measure thermal, epithermal and high energy neutrons with energies ranging up to 10 MeV, whose variations are an excellent signature of H bearing elements presence in the regolith at up to 1 meter depth [32].

The FREND's dosimeter module (specified as Liulin-MO particle telescope) is another important part of the system, providing measurements of the dose and the flux of charged particles every minute and measurements of the energy deposited and the linear energy transfer spectra every hour. This will provide information for the radiation environment on the orbit around Mars [33].

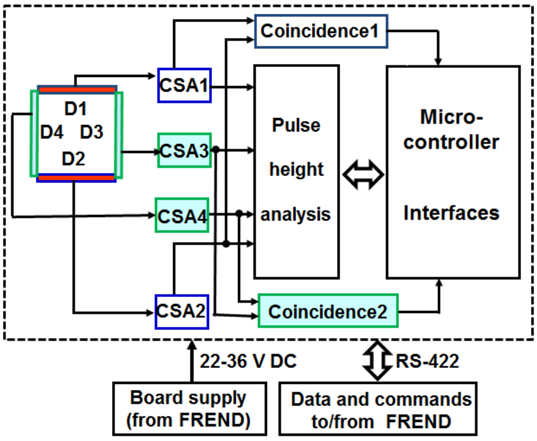

Fig. 9. Block-diagram of Liulin-MO charged particle telescope.

The Liulin-MO particle telescope is similar to the Liulin-F instrument developed for the Phobos-Grunt mission [15]. It contains two dosimetric telescopes - D1&D2, and D3&D4 arranged at two perpendicular directions. The block-diagram of the instrument is shown in Figure 9. Every pair of telescopes consists of two 300 µm thick, 20x10 mm area Si PIN photodiodes (Hamamatsu S2744-08 type), operating in a coincidence mode to obtain LET. The detectors, the charge-sensitive preamplifiers - shaping amplifiers CSA1-CSA4, and the voltage bias circuits are mounted in a separate volume inside the box of the Liulin-MO instrument and are connected to printed circuit boards that contain threshold discriminators, pulse height analysis circuits, coincidence circuits, and other circuitry, mounted in another separate volume. The last volume also contains a CPU board, including microprocessor, flash memory for data storage, timer, DC-DC converters, and an interface to the board telemetry/command system. The entire package has a mass of 0.5 kg and consumes less than 3 W (Figure 10).

Fig. 10. FREND's dosemeter (Liulin-MO) will be similar to Liulin-F

The parameters, which will be provided by Liulin-MO are: Absorbed dose rate in the range 0.04 x 10^{-6} Gy h^{-1}-1 Gy h^{-1}; Particle flux in the range 0 - $\geq 10^{4}$ particle cm^{-2} sec^{-1}; Energy deposition spectra in the range 0.1-90 MeV; LET spectrum (in H_2O) in range 0.18-160 keV μm^{-1}; Quality factor Q = f(LET) and average quality Qav; Dose equivalents H = Qav x D. All above parameters will be measured by each of two dosimetric telescopes**.** In addition the instrument will provide the angular distribution of the charged particles in 3 sectors.

4. Conclusions

Data obtained with the Bulgarian instruments in future interplanetary missions will contribute to the evaluation of the radiation environment in transit to Moon and Mars and in Moon and Mars orbits, validation of models for dose and flux assessment, estimation of the radiation doses received by the components of a spacecraft, assessment of the radiation risk to crewmembers of future exploratory flights and evaluation of the shielding requirements on future manned Moon and Mars mission.

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