ANNEX 1

TYPES OF RADIATION IN SPACE

Types of space radiation

Radiation is defined as energy in transit in the form of high-speed particles or electromagnetic waves. Radiation may be classified as:

1. **Ionizing radiation -** is the type of radiation that has sufficient energy to create charged particles (ions) from atoms by removing electrons. Ionizing radiation may remove electrons, which are not located on the outermost orbits of the atom. This creates a highly unstable atom – the resultant ion is extremely reactive. This process is different from ordinary ion formation (in usual chemical reactions) in which only the outermost electrons are removed and positively charged ions are formed. Gamma rays and protons are included in the category of ionizing radiation. The purpose of the shield is to protect the inhabitants or equipment inside the settlement against exposure to harmful doses of ionizing radiation.
2. **Non-ionizing radiation –** is the radiation with low energy that can't strip off electrons from their orbits. As examples of non-ionizing radiation, we give: visible light, microwaves and radio waves.

Sources of radiation in space

There are 3 main sources of radiation in space (characterization based on the originating point of the radiation): the solar wind (and SPEs – solar particle events), cosmic radiation and particles trapped in the Van Allen Belts. As the space settlement is not located in a geo-synchronous orbit (or in a low-Earth-orbit), we are not interested in the particles trapped in Van Allen belts.

Cosmic radiation

Cosmic rays represent a mixture of interstellar material enriched with matter from evolved stars - supernovae and Wolf-Rayet stars[1].

Cosmic radiation is composed of charged particles (ions, electrons) and a set of secondary particles (resulting from the interaction of primary radiation with matter. Primary cosmic radiation consists of nuclei – 90% are protons, 9% alpha particles (He

[1] Wolf –Rayet stars are hot, massive stars, with a high mass loss rate. They are stars in an advanced degree of evolution and they are ejecting hot gas at very high speeds (the wind of particles has a speed of over 2000 km/s). The wind is so thick that it completely obscures the light emitted by the star. They can be detected by the high quantity of ejected ions of helium, carbon, oxygen and nitrogen. The mass of a Wolf-Rayet star typically ranges between 20-25 solar masses. The temperature of the star is exceptionally high, ranging from $25000^o K$ to $50000^o K$ Wolf-Rayet stars are near the end of their lifetime and it is considered that massive stars evolve into Wolf-Rayet stars just before exploding into supernovas [3], [4].

nuclei) and 0.9% heavier nuclei (iron, nickel) and other particles – electrons (0.1%) and positrons (1‰). Galactic cosmic rays also have an antimatter component. The antimatter component has been detected using the Alpha Magnetic Spectrometer in the Space Shuttle Discovery that detected 200 antiprotons with energy above 1GeV [1]. A special phenomenon is that galactic cosmic rays also include enriched Li/Be/B isotopes – these are produced in the interstellar medium by collisions of accelerated protons with carbon, nitrogen and oxygen atoms. To produce a significant number of these enriched light nuclei (Li/Be/B), the galactic cosmic rays have to travel about 10 million years such that significant interstellar collisions are produced.

The secondary cosmic radiation consists of charged particles (protons, charged pions, electron-positron pairs), neutrons, gamma rays and X-rays [2]. Secondary cosmic radiation is particularly important when designing the shield's material, as the material influences the number and types of secondary particles that are produced. Secondary cosmic radiation can prove to be even more damaging than primary radiation, as secondary particles have a lower energy and may be stopped and remain in the bodies of people.

Primary galactic cosmic rays are thought to have originated from supernovae explosions. The rays are accelerated by the shock wave that follows the explosion and travel through interstellar gas. The formation of the cosmic rays is given by a complex mechanism of interactions: the primary cosmic rays collide with interstellar hydrogen to produce charged mesons. The majority of the produced charged mesons are pions (that have very short half-lives and decay rapidly through muons and produce electrons and neutrinos). Neutral pions decay rapidly into high-energy gamma-rays [5].

A classification of cosmic rays can be made considering the energy of the rays. The majority of galactic cosmic rays have energies between 100MeV and 10GeV. The occurrence of cosmic rays with energies above 1GeV decreases by a factor of 50 for every factor of 10 increase in energy.

Of particular interest in our radiation source analysis are the sources that produce bursts of radiation. The only source in our Solar System is the Sun – the shield must protect the settlement both against solar wind and against the strongest solar flares. The Sun also emits X ray bursts.

Outside the Solar system are produced massive gamma ray bursts. These are short-lived bursts of high-energy gamma rays that last from a few milliseconds to several minutes. Such bursts signal the collapse of massive stars. The energy released during such an event is larger than the energy of the Sun during its entire lifetime. A gamma ray burst is several hundred times brighter than a supernova. These events are of interest in our source analysis because a significant level of energy from the distant gamma bursts may hit the Solar system.

Bibliography

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ANNEX 2

CALCULUS DETAILS

The calculus for this derivative is needed in order to determine the points where the derivative is zero. These points are candidates for the extrema of the function in the interval of definition. The function $f(\lambda)$ is expressed as:

$$f(\lambda)=\frac{\lambda\cdot(1+\lambda\cdot\cos\alpha)\cdot tg\left[\alpha-arctg\left(\frac{\lambda\cdot\sin\alpha}{1+\lambda\cdot\cos\alpha}\right)\right]+\sin\alpha}{(2d\cdot\sin\alpha)\cdot(\lambda+1)\cdot tg\left[\alpha-arctg\left(\frac{\lambda\cdot\sin\alpha}{1+\lambda\cdot\cos\alpha}\right)\right]}$$

The following notations are used:

$$h(\lambda)=\left\{\lambda\cdot(1+\lambda\cdot\cos\alpha)\cdot tg\left[\alpha-arctg\left(\frac{\lambda\cdot\sin\alpha}{1+\lambda\cdot\cos\alpha}\right)\right]+\sin\alpha\right\};$$

$$g(\lambda)=(2d\cdot\sin\alpha)\cdot(\lambda+1)\cdot tg\left[\alpha-arctg\left(\frac{\lambda\cdot\sin\alpha}{1+\lambda\cdot\cos\alpha}\right)\right].$$

The expression of $f'(\lambda)$ is:

$$f'(\lambda)=\frac{df}{d\lambda}=\frac{h'(\lambda)\cdot g(\lambda)-g'(\lambda)\cdot h(\lambda)}{g^2(\lambda)} \qquad (1)$$

We present step-by-step the calculus of the first derivative of the function $f(\lambda)$. The calculus of $f''(\lambda)$ is analog to the calculus of $f'(\lambda)$. We will first determine the derivative of the function $arctg\left(\frac{\lambda\cdot\sin\alpha}{1+\lambda\cdot\cos\alpha}\right)$, then the derivative of the function $tg\left[\alpha-arctg\left(\frac{\lambda\cdot\sin\alpha}{1+\lambda\cdot\cos\alpha}\right)\right]$ and next the derivatives of the functions $h(\lambda)$ and $g(\lambda)$.

Notice that $(2\cdot d\cdot\sin\alpha)$, $\sin\alpha$ and $\cos\alpha$ are constants (α is not in dependence with λ and *d* represents the thickness of the shield and it is a specified constant here):

$$\alpha=const\Rightarrow\begin{cases}(\sin\alpha)'=0\\(\cos\alpha)'=0\end{cases}$$

We first calculate the expression of $\left[arctg\left(\frac{\lambda \cdot \sin\alpha}{1+\lambda \cdot \cos\alpha}\right)\right]'$. Denote $u = \frac{\lambda \cdot \sin\alpha}{1+\lambda \cdot \cos\alpha}$; the expression of the derivative of $arctg(u)$ is:

$$[arctg(u)]' = \frac{u'}{1+u^2} \tag{2}$$

We denote by $v(\lambda) = \lambda \cdot \sin\alpha$; $t(\lambda) = 1+\lambda \cdot \cos\alpha$. The expressions of $v'(\lambda)$ and of $t'(\lambda)$ are:

$$\begin{cases} v'(\lambda) = \sin\alpha \\ t'(\lambda) = \cos\alpha \end{cases}$$

The expression of $[u(\lambda)]'$ is:

$$u'(\lambda) = \frac{v'(\lambda)\cdot t(\lambda) - t'(\lambda)\cdot v(\lambda)}{t^2(\lambda)} = \frac{(\sin\alpha)\cdot(1+\lambda\cdot\cos\alpha) - (\cos\alpha)\cdot\lambda\cdot\sin\alpha}{(1+\lambda\cdot\cos\alpha)^2} \Rightarrow$$

$$\Rightarrow u'(\lambda) = \frac{\sin\alpha}{(1+\lambda\cdot\cos\alpha)^2} \tag{3}$$

From (2) and (3) we obtain:

$$[arctg(u)]' = \frac{\frac{\sin\alpha}{(1+\lambda\cdot\cos\alpha)^2}}{1+\left(\frac{\lambda\cdot\sin\alpha}{1+\lambda\cdot\cos\alpha}\right)^2} = \frac{\sin\alpha}{(\lambda\cdot\sin\alpha)^2 + (1+\lambda\cdot\cos\alpha)^2} \Rightarrow$$

$$\Rightarrow [arctg(u)]' = \frac{\sin\alpha}{\lambda^2\cdot(\sin^2\alpha+\cos^2\alpha)+1+2\cdot\lambda\cdot\cos\alpha} = \frac{\sin\alpha}{\lambda^2+1+2\cdot\lambda\cdot\cos\alpha} \tag{4}$$

The derivative of $tg\left[\alpha - arctg\left(\frac{\lambda\cdot\sin\alpha}{1+\lambda\cdot\cos\alpha}\right)\right]$ may be computed now. We denote $q(\lambda) = \alpha - arctg\left(\frac{\lambda\cdot\sin\alpha}{1+\lambda\cdot\cos\alpha}\right)$. It is known that $[tg(q)]'$ has the expression:

$$[tg(q)]' = \frac{q'}{\cos^2 q} \tag{5}$$

Therefore

$$q'(\lambda) = \left(\alpha - arctg\left(\frac{\lambda\cdot\sin\alpha}{1+\lambda\cdot\cos\alpha}\right)\right)' = -\frac{\sin\alpha}{\lambda^2+1+2\cdot\lambda\cdot\cos\alpha} \tag{6}$$

From (5) and (6) we obtain:

$$tg'\left[\alpha - arctg\left(\frac{\lambda \cdot \sin\alpha}{1+\lambda \cdot \cos\alpha}\right)\right] = \frac{-\dfrac{\sin\alpha}{\lambda^2+1+2\cdot\lambda\cdot\cos\alpha}}{\cos^2\left[\alpha - arctg\left(\dfrac{\lambda \cdot \sin\alpha}{1+\lambda\cdot\cos\alpha}\right)\right]} \tag{7}$$

Using (7), we compute the derivatives of the functions $h(\lambda)$ and $g(\lambda)$:

$$h'(\lambda) = \left[\left(\lambda + \lambda^2 \cdot \cos\alpha\right) \cdot tg\left[\alpha - arctg\left(\frac{\lambda \cdot \sin\alpha}{1+\lambda \cdot \cos\alpha}\right)\right]\right]' + (\sin\alpha)' = \left(\lambda + \lambda^2 \cdot \cos\alpha\right)' \cdot$$

$$\cdot\, tg\left[\alpha - arctg\left(\frac{\lambda \cdot \sin\alpha}{1+\lambda \cdot \cos\alpha}\right)\right] + tg'\left[\alpha - arctg\left(\frac{\lambda \cdot \sin\alpha}{1+\lambda \cdot \cos\alpha}\right)\right] \cdot \left(\lambda + \lambda^2 \cdot \cos\alpha\right)$$

Finally, using these functions in (1), we obtain the derivative as:

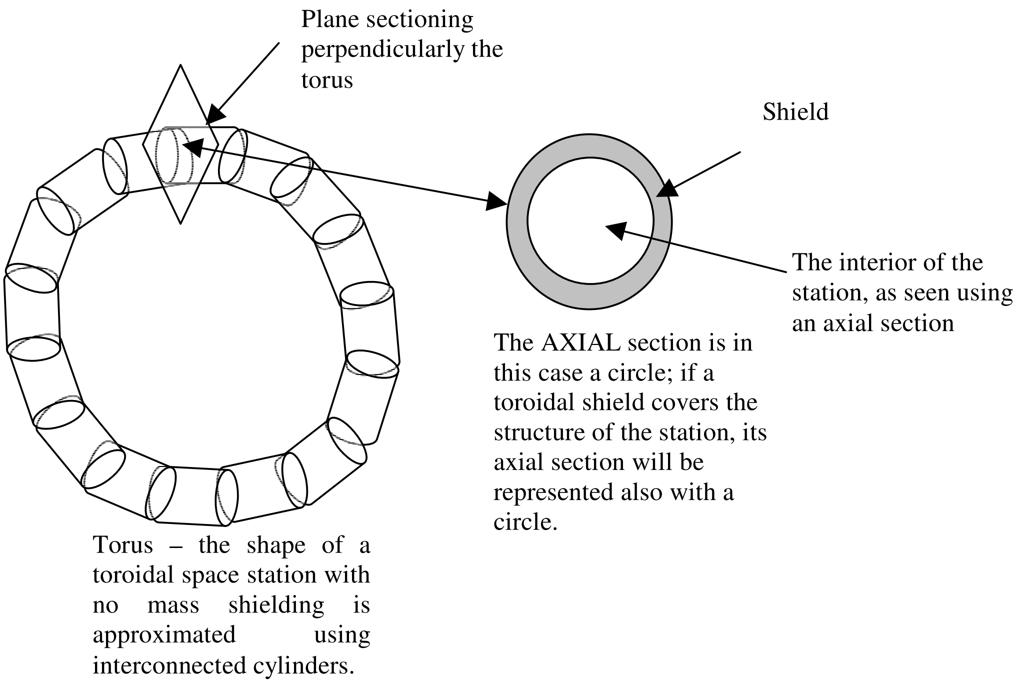
$$f'(\lambda) = \frac{df}{d\lambda} = \frac{h'(\lambda) \cdot g(\lambda) - g'(\lambda) \cdot h(\lambda)}{g^2(\lambda)}$$

ANNEX 3

AXIAL AND TRANSVERSAL SECTIONS

I recall that axial sections of a 3-Dimensional structure are obtained by “cutting” perpendicularly the structure with a plane. The axial section is a 2-D feature. Some transversal and axial sections – referred to in the paper – are presented below.

Representation of the axial section of a toroidal space station protected using a mass shield:



Representation of the transversal section of a cylindrical space station protected using a mass shield: