Invited Plenary Talk
Spring Conference of the Korean Space Science Society (KSSS)
Gangneung-si, Gangwon-do, Republic of Korea

Space Radiation Research at NASA

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Friday April 29, 2016
1. **3 SOURCES OF SPACE RADIATION**

2. **RADIATION & DOSE**

3. **NUCLEAR & PARTICLE PHYSICS & TRANSPORT**

4. **MOON, MARS, JUPITER, SATURN**

5. **CONCLUSIONS**
3 SOURCES OF SPACE RADIATION

SPE = Solar Particle Event
GCR = Galactic Cosmic Rays
Geo = Geomagnetically trapped particles

https://oltaris.larc.nasa.gov
GCR Composition, Spectrum, Origin

3 regions
- High Energy < PeV
- Very High Energy (knee) PeV - EeV
- Ultra High Energy (ankle) > EeV

keV = 10^3 eV  MeV = 10^6 eV
GeV = 10^9 eV  TeV = 10^{12} eV
PeV = 10^{15} eV  EeV = 10^{18} eV
ZeV = 10^{21} eV

Large Hadron Collider
14 TeV cm ⇒ 400 PeV lab
Space radiation problem

GCR (primary) composition

- 98% nuclei, 2% $e^+ e^-$
- Nuclear component:
  - 87% Hydrogen
  - 12% Helium
  - 1% heavy nuclei

GCR origin

- Emitted in stellar wind & flares & accelerated by supernova shock waves
  (within our Galaxy)

Solar System Abundances

GCR Abundances

Abundance (Si = 100)

Element
Relative contribution in fluence, dose and dose equivalent of different elements in the GCR spectrum. Calculation is an average over 1 year in solar minimum behind 5 g/cm² Al shielding.

SOLAR PARTICLES

e, p & some heavy nuclei < 1 GeV/N (v ~ 0.9c)

A. Galactic Cosmic Rays

The free space GCR environment is made up of heavy and light charged ions originating outside the solar system. This ever-present environment is modulated by the solar wind and, therefore, varies with distance from the sun and to a larger extent, the solar cycle. Maximum GCR intensity is at solar minimum, when the sun is least active while minimum GCR intensity occurs at solar maximum, when the sun is most active. Short duration exposure to GCR provides little health risk, but longer duration exposure may result in late term effects such as cataracts and cancers. The sample calculations described in this document utilize the 1992 Badhwar-O'Neill model which defines a solar maximum GCR environment and a solar minimum GCR environment at 1 AU as shown in Fig. 1. Here the ions are grouped by charge, Z. The GCR environment for a given day is calculated by interpolating between solar maximum and solar minimum. One method for doing this interpolation utilizes the neutron count measured by the Deep River Neutron Monitor (DRNM). The charged ions making up the free-space GCR environment interact with the atoms making up the Earth's atmosphere in two ways. When an atomic interaction occurs, the charged ion strips an electron from an atom and loses energy in the process. When a nuclear interaction occurs, the charged ion collides with or comes very close to an atom's nucleus. Nuclear collisions often result in the destruction of the original ion and the production of a number of smaller ions and neutrons. The neutron count measured on the Earth's surface, in this case at the Deep River station in Canada, is therefore a good predictor of free-space GCR intensity, because the number of neutrons produced in the Earth's atmosphere increases when the number of charged ions impinging on this atmosphere increases. Predicted DRNM numbers have been used since the monitor was turned off in 1995. Figure 2 demonstrates the inverse relationship between solar activity and GCR intensity by showing measured and predicted DRNM neutron counts on the same plot with measured and predicted sun spot numbers.

B. Large Solar Particle Events

Unlike the GCR environment, solar particle events are isolated events with durations usually measured in hours. Solar particle events occur when a large number of particles, mostly protons, move through the solar system. These events happen during periods of increased solar activity and appear to correspond to large coronal mass ejections. Large SPE have occurred only rarely, one or two per eleven year solar cycle in the past sixty years, but exposure to a large SPE could be lethal if
**Geomagnetically Trapped Particles**

**Inner belt:** 0 - 3 $R_E = 18,000$ km - mainly $p$
- Starts about 3,000 km
- But SAA dips down to 400 km

**Outer belt:** 3 - 12 $R_E = 36,000$ km ($e,p$) - mainly $e$
(LEO: 200 - 500 km    GEO: 22,000 miles = 35,000 km)

![Diagram showing geomagnetically trapped particles](image_url)
Unit of absorbed dose:
1 Gray == 1 J/kg

Radiation quality factor $Q$
Sievert = Gray $\times Q$

ICRP estimate: 5% per Gy
1 in 20,000 risk of fatal cancer per 1 mSv dose (lifetime)
### Space Radiation Problem – Dose Equivalent

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Dose Equiv. (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest x-ray</td>
<td>0.1</td>
</tr>
<tr>
<td>USA annual background</td>
<td>4</td>
</tr>
<tr>
<td><strong>Public annual limit (above background)</strong></td>
<td>1</td>
</tr>
<tr>
<td>International Airline crews</td>
<td>4</td>
</tr>
<tr>
<td><strong>Radiation worker annual limit</strong></td>
<td>50</td>
</tr>
<tr>
<td>No observed effects (Abomb, instant)</td>
<td>200</td>
</tr>
<tr>
<td>Death (instantaneous dose)</td>
<td>3,000</td>
</tr>
<tr>
<td>ISS (with shield) annual</td>
<td>150</td>
</tr>
<tr>
<td><strong>Astronaut career limit effective dose</strong></td>
<td>470</td>
</tr>
<tr>
<td>Mars (3 year, incl. surface) annual</td>
<td>1,000</td>
</tr>
<tr>
<td>Large solar flare (free space)</td>
<td>10,000</td>
</tr>
</tbody>
</table>

ICRP cancer risk estimate: 5% per Gy ~ 5% per Sv (for Q=1)
1 in 20,000 risk of fatal cancer per 1mSv dose (lifetime)
* 30 year old female, 1 year mission (50 yr m/f ~ 1,000 mSv)
An investigation into the nature of high altitude cosmic radiation in the stratosphere

Figure 7. The Pfotzer curve. Adapted from [3].

\[
0.00388579 \times 17 = 0.05760585
\]

expected number of lost counts per 17 s (package) due to dead time.

\[
227 + 0.05760585 = 227.0576059
\]

expected number of counts if lost counts are included.

\[
0.05760585 \times 227.0576059 \times 100 = 0.025370588
\]

percentage of counts lost.

As only 0.25% of the counts are lost at the maximum count rate, we can safely assume that there was no significant effect on our readings due to an influence by dead time.

Conclusion

We concluded that the peaks in the graphs are to be attributed to the maximum flux of the components of cosmic rays that are of secondary origin. In other words, at an approximate altitude of 20 km, there is a peak amount of ionizing material produced from air shower cascades that are propagating downwards to the surface. This peak can be understood by identifying two competing effects. Firstly, cosmic ray intensity will decrease as altitude decreases, because there have already been collisions higher up. Secondly, atmospheric density will increase as altitude decreases, increasing the likelihood of collisions. The product of these two competing effects produces a maximum in cosmic ray flux at \( \sim 20 \) km. As we did not use multiple coincidence arrays to isolate our cosmic radiation measurements solely to the vertical direction, we are unable to ascertain the impact that ionizing particles interacting with the Geiger–Müller tube from the side had. We can only assume, based on previous research, that the majority of the radiation detected was in the vertical plane.

Looking at previous investigations, we discovered an article produced by cosmic ray physicist Pfotzer in the 1930s [3], based on his work with Regener. Their published graph (see figure 7) has remarkable similarities with our own results. It should be noted that the count rate on the Pfotzer curve (see figure 7) was measured in counts per 4 min, and our count rates were measured per every approximate 17 s. The two graphs seem to be supporting each other. Our Geiger–Müller tube recorded omnidirectionally, whereas their apparatus consisted of threefold coincidences which isolated their recordings to the vertical plane. This does not seem to have caused a major difference between our graphed results. This suggests that the majority of cosmic radiation is propagating downwards in a vertical direction.
An investigation into the nature of high altitude cosmic radiation in the stratosphere

Figure 7. The Pfotzer curve. Adapted from [3].

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http://www.scienceinschool.org/2010/issue14/cloud/maltese
Domestic crews 1 - 2 mSv /yr

International crews < 4 mSv / yr

Pregnant woman < 5 mSv (to fetus per pregnancy)
AIRCRAFT - **WHY ALL THE CONCERN NOW?**

- NCRP & ICRP have lowered radiation worker exposure
  - 50 mSv / yr to 20 mSv / yr

- Air crews most highly exposed of any occupation group

- FAA criticized for not paying enough attention

- Many more polar flights

- Future High Speed Civil Transport (HSCT) radiation levels
  - 3 times higher than for crews of subsonic transport

- Only solution available now:
  - reduce flight hours

- **NAIRAS** - Mertens (Langley)
Computers

- Junction density increasing
- Switching energy decreasing

Need for predicting Single Event Upsets (SEU)

- satellite electronics
- aircraft electronics (civilian & military)

Shuttle - several hundred SEU / mission

http://holbert.faculty.asu.edu/eee560/see.html
Electronics on Spirit, Opportunity, Curiosity etc. are radiation hardened

Shielding very important for Jupiter, Saturn

http://mars.jpl.nasa.gov/msl/multimedia/images/?imageid=3504

Credit: NASA/JPL/Space Science Institute
http://photojournal.jpl.nasa.gov/catalog/PIA04866
These are the doses received

- How were results obtained?
- How to design spacecraft & aircraft shields so dose is minimal?

Need

- Accurate atomic, nuclear, particle physics theory
- Accurate transport theory
- Biological models
TRANSPORT

Solve Boltzmann transport eqn (HZETRN)

Deterministic, not Monte Carlo
- Want quick answers
- Real time dose as function of position & time
- Both transport & nuclear physics must run fast
- → Applied nuclear physics

Wilson et al., NASA-RP 1257, 1991
The effects on the radiation environment of localized magnetic fields on the Martian surface are not examined in this paper.

The charged ions making up the free space environment and the atoms making up the atmosphere, primarily CO2, neutrons.

The charged ions lose energy due to ionization, and nuclear collisions occur, producing secondary ions as well as neutrons. The neutron count measured on the Martian surface is, therefore, approximately half that of the free space environment due to interactions between the free space ions and the Martian atmosphere and/or surface regolith.

The neutron spectrum on the surface of the moon only includes low energy neutrons. The neutron spectrum on the surface of Mars is more complex, due to the presence of water ice, CO2 ice, or some combination of these materials. Calculated Mars surface environments for solar maximum and solar minimum depend on the free space environment at that time, on the altitude of the location (the amount of shielding provided), and on the time of year (the amount of sunlight blocking cosmic rays).

The charged ions and neutrons also interact with atoms making up the Martian regolith material, producing secondary ions as well as neutrons. In order for momentum to be conserved, most of these secondary particles are produced in the same direction or close to the same direction as the original ion and the production of a number of smaller particles is often achieved.

When a nuclear interaction occurs, the charged ion strips an electron from an atom and loses energy in the process. When an atomic interaction occurs, the charged ion collides with or comes very close to an atom's nucleus. The neutron count measured on the surface is, therefore, approximately half that of the free space environment due to interactions between the free space ions and the Martian surface material.

Predicted DRNM numbers at any given time depend on the free space environment at that time, on the altitude of the location (the amount of shielding provided), and on the time of year (the amount of sunlight blocking cosmic rays). The neutron count measured on the Martian surface is, therefore, approximately half that of the free space environment due to interactions between the free space ions and the Martian surface material.

The GCN environment for a given day is the charged ion environment on the surface is, therefore, approximately half that of the free space environment due to interactions between the free space ions and the Martian surface material.

The spectral shape of the "design basis" SPE depend on mission characteristics, such as duration and time in the solar system. These events happen during periods of increased solar activity and appear to correspond to large coronal mass ejections.

Figure 1. Free space GCR environment at 1AU

Figure 2. Sun spot number (blue) and DRNM neutron count numbers on the same plot with measured and predicted sun spot numbers. Figure 3. Proton spectra for three of the largest historical events are shown.

Figure 4. Martian surface environment due to solar maximum and solar minimum GCR. Comparison between Fig. 4 and Fig. 1 shows a neutron range. It should be noted that the September 1989 event also included a heavy ion contribution.

Figure 5. Lunar surface environment due to GCR. The neutron spectrum on the surface of the moon only includes low energy neutrons.

Clowdsley et al., AIAA, 2006
**TRANSPORT**

Left: Primary GCR spectra at Mars for 1977 solar minimum Kim et al., NASA TP 208724, 1998

Right: Martian surface environment due to GCR Clowdsey et al., AIAA, 2006
Dose Equivalent as a function of depth for various materials

From radiation point of view, safest place is inside liquid hydrogen fuel tank!

**Major result**

- Low Z materials required for weight reduction necessary for future High Speed Civil Transport (HSCT) and for future spacecraft are *also* the best radiation protection materials
- Thank goodness!
Short duration
- Solar particle events

Long duration
- Solar particle events
- Galactic cosmic rays
### Lunar regolith composition

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>52.6%</td>
</tr>
<tr>
<td>FeO</td>
<td>19.8 %</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>17.6 %</td>
</tr>
<tr>
<td>MgO</td>
<td>10.0 %</td>
</tr>
</tbody>
</table>
The Surface of the Moon is Slightly Richer in Fe, Ca, and Mg Compared to the Earth's Crust

<table>
<thead>
<tr>
<th>Element</th>
<th>Lunar Soil</th>
<th>Earth Crust</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>45</td>
<td>10</td>
</tr>
<tr>
<td>Si</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>Fe</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Ca</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>Al</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Mg</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
Figure 12. Calculated fluence of projectile fragments after traversal of 18 g/cm² thick polyetherimide shield irradiated with 33.88 GeV 56 Fe ions.

Figure 13. Attenuation of dose equivalent due to 1977 solar minimum GCR fluence behind regolith and regolith-epoxy shield as a function of areal density [27].

Simonsen et al., NASA Conference Publication 3360, 1997
## Mars

<table>
<thead>
<tr>
<th></th>
<th>Earth</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric thickness (g/cm²)</td>
<td>1000</td>
<td>20</td>
</tr>
<tr>
<td>Magnetic field (Gauss)</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

[Diagram showing Earth and Mars with comparative data]
Chemical composition of Martian atmosphere

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>95.32</td>
</tr>
<tr>
<td>N₂</td>
<td>02.70</td>
</tr>
<tr>
<td>Ar</td>
<td>01.60</td>
</tr>
<tr>
<td>O₂</td>
<td>00.13</td>
</tr>
<tr>
<td>CO</td>
<td>00.08</td>
</tr>
</tbody>
</table>

De Angelis et al., Rad. Meas. vol.41, p.1097, 2006
Chemical composition of Martian surface

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>44.2</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>16.8</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>08.8</td>
</tr>
<tr>
<td>CaO</td>
<td>06.6</td>
</tr>
<tr>
<td>MgO</td>
<td>06.2</td>
</tr>
<tr>
<td>SO₃</td>
<td>05.5</td>
</tr>
<tr>
<td>Na₂O</td>
<td>02.5</td>
</tr>
<tr>
<td>TiO₂</td>
<td>01.0</td>
</tr>
</tbody>
</table>

De Angelis et al., Rad. Meas. vol.41, p.1097, 2006
GCR Environment

Model prediction of dose equivalent from GCR. Calculations are shown at average skin depth near solar maximum. Cucinotta, Rad. Res. vol.43, p.S35, 2002
Mars transit inside vehicle: $1.84 \pm 0.33$ mSv / day

⇒ MSL (one way) 253 days gives 466 mSv

⇒ 331 mSv for 180 day cruise DRM

⇒ 662 mSv return trip

• Plus surface exposure 200 mSv ?

• Approaching and exceeding limits
Comparative Radiation Exposures

- U.S. Annual Average All Sources: 3.6 millisieverts (mSv)
- Abdominal CT Scan: 8 mSv
- DOE Radiation Worker Annual Limit: 20 mSv
- 6 Months on ISS (Average): 75 mSv
- MSL-RAD Transit to Mars: 466 mSv

MSL-RAD = Mars Science Laboratory Radiation Assessment Detector  
Intense radiation

- On Jupiter moon Io humans could not survive for more than a few hours
- Callisto
In addition to applications to Mars science, the models will allow the use of these models to assess the impact on human exposure and allow design considerations for all components in either surface operations, in lava tubes, or in Mars orbit.

3.3. Jupiter neighborhood

The solar wind generated convective currents produce less effect on the GCR near Jupiter relative to Earth. In addition, the jovian magnetic field traps particles with electron intensities to large distances from Jupiter (70 R\textsubscript{J}). The electron flux spectrum near Callisto is shown in Fig. 9. Near a jovian moon, the intensities of all components are reduced except the induced neutron fields.

We are developing an Anytime/Anywhere software package for use in mission analysis and an example of a mission from the Earth/Lunar L1 to Callisto and return is shown in Fig. 10 for a fixed mass of four shield materials. The mission starts near an assumed solar maximum (2045 AD) using the same projection model as in Fig. 1. The large exposure rates mid-mission are due to the jovian electron belts until arrival on the Callisto surface where there is shielding below the horizon. The continued increase of the environment on the return to L1 is due to decreasing solar activity. This software will soon include the Mars models presented in the previous section.

4. Conclusions

The deep space environments developed for mission analysis use physical models to extrapolate the limited environmental data in both space and time. Induced fields are evaluated using high-speed transport models. Interesting dependence of local induced fields on atmosphere and ground composition are found which may be validated using Mars orbital data. The broader software being prepared will allow radiation exposure evaluation for arbitrary spectra in the future but limited to near Earth, near Jupiter, and interplanetary space for now. The near Mars environment will be added in the near future.

References


Wilson et al., Adv. Space Res. vol.34, p.1281, 2004
Health Effects on Human Body

- Carcinogenesis
  - Earlier appearance and more aggressive tumors not seen with controls, gamma-rays or proton induced tumors
  - Persistent oxidative damage and inflammatory pathway responses
  - New genomics data showing distinct gene expression profiles in HZE versus $\gamma$-ray or x-ray irradiated cell models

- Acute Radiation Syndrome due to Solar Particle Events
  - Research addresses dose threshold, dose-rate effects with countermeasure evaluation
  - Future work to understand impact of possible high skin dose and microgravity on immune system and blood forming organs
**Health effects on Human Body**

- **Acute or Late Central Nervous System (CNS) Effects**
  - Concern for CNS risks originated with the prediction of the light flash phenomenon from single high-Z high-energy nuclei traversals of the retina; this phenomenon was confirmed by the Apollo astronauts.
  - Major uncertainty how to extrapolate results from animals to humans.

- **Degenerative Tissue or other health effects**
  - Occupational radiation exposure from the space environment may result in degenerative tissue diseases (non-cancer or non-CNS) such as cardiac, circulatory, or digestive diseases, & cataracts.
  - Mechanisms & magnitude of influence of radiation leading to these diseases are not well characterized.
- Brookhaven National Lab on Long Island
- protons: 4 GeV
- protons - Fe: 50 MeV/n - 1.5 GeV/n
- up to Au: 165 MeV/n

Pions can contribute almost 50% to dose.
Percent contribution to BFO dose equivalent by charge group

Neutrons and light ions (H, He) can dominate Dose Equivalent
Two approaches to Galactic Cosmic Ray (GCR) simulation:

External field approach

- Beams selected to represent external, free space field before shielding

Local tissue field approach

- Beams selected to directly represent shielded tissue field
**NEW DEVELOPMENTS - MINIMUM DOSE EQUIVALENT VS. DEPTH**

Benchmark Description

- **Geometry:** Slab with equal thickness of aluminum shielding in front and behind a thin (0.03 mm) water target
  - Considered a range of aluminum thicknesses from $0 \text{ g/cm}^2$ to $100 \text{ g/cm}^2$

- **Boundary conditions:** 1977 solar minimum GCR environment
  - Considered each ion individually with greater emphasis on more abundant ions
  - Connects with ions considered in measurement piece

- **Computed flux, dose, dose equivalent, and LET spectra in all codes**
  - Carefully went through Monte Carlo options to ensure output quantities are defined consistently

**External GCR boundary condition spectrum**

- Front shield
- Back shield
- Water target
- Infinite lateral dimensions

**X g/cm$^2$ Al $\equiv$ X g/cm$^2$ Al front + 0.03 mm water + X g/cm$^2$ Al back**

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**Recent High Impact Discoveries**

- **Minimum in Dose Equivalent vs. Depth**
  - [Blattnig, Slaba, Bahadori, Norman, Clowdsley, Space Radiation Investigators' Workshop, Galveston, TX, 2014]
  - New design paradigm
    - If forward/backward (FB) neutron transport and pions turned ON
      - Minimum in dose equivalent response near $40 \text{ g/cm}^2$
      - Increased shielding (mass) changes/amplifies exposure
      - Design implication: material optimization may be more important than previously thought

- **Pions make large contributions to dose rate for particle groups at different locations on the ISS**
  - [Slaba, Mertens, Blattnig, NASA TP-2013-217983]
  - [Norman, Blattnig, De Angelis, Badavi, Norbury: Advances Space Research 50, 146, 2012]
  - [Slaba, Blattnig, Reddell, Bahadori, Norman, Badavi: Advances Space Research 52, 62, 2013]

- **Contribution to dose rate for particle groups at different locations on the ISS**

  - **Dose Rate, $\mu$Gy/day**
    - Pions + Muons + EM Ions + Neutrons
      - 41\% 49\% 47\% 26\% 48\% 53\% 59\% 74\% 52\% 51\% 48\% 53\% 59\% 74\%

**MDU = Mobile Dosimetry Unit (ISS)**

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**Internal Environment**

- [Walker, Townsend, Norbury, Advances in Space Research 51, 1792, 2013]
  - Percent contribution to BFO dose equivalent by charge group.
  - **Light ions & neutrons dominate!**

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**Pion contribution to Dose Minimum in Dose Equiv. vs. Depth**

- **Light ion & Neutron contribution to Dose Equivalent**
  - 90\% effective dose > 250 MeV/n
  - GCR simulation at NASA Space Radiation Lab (NSRL)

**Other:**

- December 14-17, 2015 DDTRB - Peer Review
Korea Contributions

- Human presence throughout solar system in 21 century
  - International endeavour
  - New frontier - many economic rewards - reaped by participants

- Korea Institute of Radiological and Medical Sciences (KIRAMS)
  - Expertise in proton and heavy ion therapy and radiological sciences
  - Highly relevant to space radiation

- Space Radiation
  - Major uncertainties associated with low dose rate
  - KIRAMS contribution?
CONCLUSIONS

- Human exploration of solar system
- Radiation protection is a major issue
- Fundamental studies in physics and radiobiology still needed
- Republic of Korea could make major contributions
THE END

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