High-energy radiation fills space and poses a short-term as well as long-term danger to humans in space, but is also of concern for electronics in spacecraft. The radiation environment on planetary bodies is quite different from that on Earth. On the airless Moon, space radiation is shielded by the massive Moon, but the interaction of radiation with it also generates new, secondary radiation. On Mars, the tenuous atmosphere provides some shielding, but also radiation interaction with it also creates secondary radiation, in addition to what is created in the soil. It is discussed measurements of the space radiation environment at Earth, Moon, en route to Mars and on Mars itself.

Robert Wimmer-Schweingruber („Bob Wimmer“) received his PhD in experimental physics from the University of Bern, Switzerland, in 1994. He was asked to return to Bern after a PostDoc in the US, to lead two space projects. He obtained his venia docendi („Habilitation“) in 2001 and is now a professor at the University of Kiel, Germany, since 2002, where he heads the Division of Extraterrestrial Physics. He is the Principal Investigator (PI) of three space instruments, and Co-PI and Co-I of many other space experiments.
From Earth to Moon, Mars, and Beyond – Space Radiation and Implications for Human Exploration

Robert F. Wimmer-Schweingruber
Extraterrestrial Physics, IEAP, University of Kiel, Germany
wimmer@physik.uni-kiel.de
Structure of my talk

- Radiation: Origin & transport in heliosphere
- Implications for human exploration
- Particle radiation at and on the Moon
- Particle radiation during the cruise to Mars
- Mars surface radiation environment
- Implications for human exploration

Why Mars, why Gale?
Was Mars habitable?
Radiation Sources Close to Earth

**Galactic Cosmic Rays:**
Very high energies, H through U
Solar modulation, predictable
Highly penetrating

**Solar Energetic Particles:**
High energies
Solar activity, unpredictable
High dose rate variability (up to ~1000)
Can be shielded

**Trapped Radiation (Radiation Belts):**
Very high energies, protons, electrons
Very high dose rate
Highly penetrating
Radiation Sources Close to Earth: GCR

2009 closer to solar min

2013 closer to solar max

Burmeister et al., 2016
Radiation Sources Close to Earth: Trapped

Log scale!

2009
@ 350 km

SAA (trapped)

2013
@ 420 km

Burmeister et al., 2016
Radiation Sources Close to Earth: Solar

Solar Particle Event: April 2001

Data:
Burmeister
Heber
NMDB
Radiation Sources Close to Earth: Comparison

Nov 1997 SPE:

Comparison of the effect of the GCR, SPE, and trapped components

Measured spectrum of energy deposit in a 315 micron Si solid-state detector.

Courtesy S. Burmeister
Particle Radiation in the Heliosphere

- Galactic Cosmic Rays
- High Speed Stream
- Anomalous Cosmic Rays
- Solar Wind
- Termination Shock 70 - 100 AU?
- Corotating Ion Events
- pickup Ions
- Energetic Storm Particles
- Corotating Interaction Region
- Interstellar Neutral Gas
- Solar Energetic Particles
- Solar Wind
Particle Radiation in the Heliosphere

- Galactic Cosmic Rays
- Anomalous Cosmic Rays
- High Speed Stream
- Solar Wind
- Termination Shock
- Corotating Ion Events
- Pickup Ions
- Corotating Interaction Region
- Energetic Storm Particles
- Coronal Mass Ejection
- Solar Wind
- Interstellar Neutral Gas
- Heliopause
Particle Radiation in the Heliosphere

Contributions to the Oxygen Fluence (10/97 to 6/00)
- Suprathermal tail
- Heated solar wind ions
- Pick-up ions
- Inner Source
- Remnant SEP, ESP, CIRs
- Bow shocks
- ...other?

Energy/nucleon [MeV/nuc]

Particles /cm² sr s MeV/nuc

Mewaldt et al., 2001
Simpson, 1983
Ave et al., 2009

O directional intensity

Semi-log graph showing contributions to oxygen fluence with energy/nucleon on a logarithmic scale.

- Slow Solar Wind
- Fast Solar Wind
- Gradual SEPs
- CIR
- Impulsive SEPs
- GCRs
- ACRs

Legend for particle contributions.
Radiation Protection in Space

Radiation is the long-lasting risk for astronauts. Radiation damage can persist after the end of a long-duration space flight. Radiation must be measured!

Personal Dosimeters

Phantom experiments MATROSHKA
(Photos courtesy G. Reitz)
Radiation Protection in Space

COLUMBUS median shielding ≈100 g/cm²

Cumulative Distribution of Equivalent Thicknesses
JPM

Cumulative Distribution of Equivalent Thicknesses
Columbus

Aluminum Equivalent Thickness [g/cm²]

Port

0.1  1  10  100

Percentage of 10,000 Ray Distribution

0.00%  10.0%  20.0%  30.0%  40.0%  50.0%  60.0%  70.0%  80.0%  90.0%  100.0%

Aluminum Equivalent Thickness [g/cm²]

0.1  1  10  100  1000

Percentage of 10,000 Ray Distribution

(courtesy Daniel Matthiä)
Radiation Protection in Space

GCR radiation exposure on ISS
Dec. 2009 (max. GCR intensity)

- Dose rates in a water sphere with radius 20 cm
  - surface (depth < 1 cm)
  - whole sphere

- Spherical aluminium shielding

- Columbus Module:
  - ≈ 100 g/cm², Stoffle et al. (2012)
  - 158 μGy/d, 448 μSv/d, $Q = 2.84$, Semones et al. (2009)
  - 150 - 157 μGy/d, 496 – 517 μSv/d, $Q = 3.30$, Burmeister et al. (2012)

- Zvezda Service Module:
  - 32 – 47 g/cm², Jardrnickova et al. (2009)
  - 100 – 110 μGy/d, Lishnevskii et al. (2012)
  - 125 μGy/d, Semones et al. (2009)

(courtesy Daniel Matthiä)
Origin of GCR

Contributions to the Oxygen Fluence (10/97 to 6/00)
- Suprathermal tail
  - Heated solar wind ions
  - Pick-up ions
  - Inner Source
  - remnant SEP, ESP, CIRs
  - Bow shocks
  - ....other?

GCRs
Gradual SEPs
CIR
Impulsive SEPs
ACRs

Particles [cm^-2 s^-1 sr^-1 MeV/nuc]

Escalation [g/cm^-2] for protons

Energy/nucleon [MeV/nuc]

- GCR
- ISS
- trapped
- solar wind
- SEPs, CIRs, etc.
- Space suit
- O directional intensity
Origin of the GCR

Galactic Cosmic Rays

High Speed Stream

Origin of GCR candidates:
- Anomalous Cosmic Rays
- pickup ions
- Corotating Ion Events
- Corotating Interaction Region
- Energetic Storm Particles
- Interstellar Neutral Gas

Origin of high energy GCR candidates:
- solar wind
- SEPs, CIRs, etc.

70 - 100 AU?

Heliopause
Origin of Galactic Cosmic Rays: Supernovae

How are nuclei simultaneously created and accelerated?
Origin of Galactic Cosmic Rays: OB-Associations

$^{59}\text{Ni}$ decays into $^{59}\text{Co}$ via electron capture $T_{1/2} = 76,000$ years

Measured $^{59}\text{Ni}/^{59}\text{Co} < 0.055$ implies acceleration $> 100,000$ years after creation of $^{59}\text{Ni}$

$^{60}\text{Fe}$ $\beta^-$-decays into $^{60}\text{Co}$ with $T_{1/2} = 2.62$ Myrs. Its measurement implies acceleration within few Myrs of nuclei creation

Wiedenbeck et al., 1999

Israel et al., 2015

One supernova creates GCR nuclei, a second one accelerates them

$\Rightarrow$ OB Associations

rfws, ieap/CAU

RPSD, 2016-10-06
Radiation Transport in the Heliosphere

- Electrically charged ions and electrons
- Interplanetary magnetic field controls propagation

For a 1 MeV proton, $r_c$ is nearly 30,000 km at 1 AU
Large-scale interplanetary magnetic field organized along Parker spiral

Charged energetic particles are tied to magnetic field...

SOHO, STEREO, Messenger widely separated in Nov '11
You don't really expect all spacecraft to see the event, do you?

(Gomez-Herrero et al., 2015)
How does the Sun connect to the heliosphere?

Wide spread events seen in
- ions,
- electrons,
- and $^3$He

This is sobering...
(can we connect S-H?)

... but also at 1 AU!

(Gomez-Herrero et al., 2015)

We need to better understand the connection!

(Richardson et al., 2014)
GCR Modulation

Galactic Cosmic Rays

Anomalous Cosmic Rays

High

Solar Energetic Particles

Neural Gas

Heliopause

GCR Modulation

Daily sunspot number

Sunspot number

Kiel NM count rate

Years:

- 1968
- 1973
- 1978
- 1983
- 1988
- 1993
- 1998
- 2003
- 2008
- 2013

Energy/nucleon (MeV/nuc)

10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{3}
10^{5}
10^{7}
10^{9}

les (cm^{-2} s^{-1} MeV/nuc)

2009

2013

Mewaldt et al., 2001
Simpson, 1983
Ave et al., 2009

Solar wind

SEP, CIRs, etc.

O directional intensity
Solar Cycle Amplitude Predictions

Geomagnetic activity indicates large amplitude for sunspot cycle 24

David H. Hathaway and Robert M. Wilson

(Hathaway & Wilson, 2006)
We don't really understand the solar dynamo which underlies all solar activity.
Predictions

How is meridиональ circulation “closed” at the poles?
We don't even know how many polar convective cells there are!
The Consequence:

- Lowest solar wind dynamic pressure
- Smallest total heliospheric flux
- Smallest CME rate

... were all not predicted.

We need to better understand the Sun!
### Human Spaceflight Risks Assessments (Jan 2015)

#### In Mission Risk - Operations

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#### Post Mission Risk - Long Term Health

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- **A** – Accepted
- **RM** – Requires
- **Green** – Mitigated
- **Yellow** – Partially controlled
- **Red** – Uncontrolled

**Radiation!**

---

**rfws, iep/CAU**

**RPSD, 2016-10-06**
GCR models show substantial differences in their predictions
Dose Rate Measurements at the Moon?

-Only results from two missions in Lunar orbit available (CRATER and RADOM) with dose values of around 200 – 300 µGy/d (depending on altitude).


J.E. Mazur et al. New Measurements of total ionizing dose in the lunar environment, Space Weather, 9, S07002, doi:10.1029/2010SW000641

-Calculations show an Effective Dose of 600 µSv/day taking into account Solar Minimum conditions.


-“Safe haven” to prevent exposures due to SPE needs approx. 80 cm of lunar regolith


NO MEASUREMENTS on the LUNAR surface available --> needed as input

a) benchmarking of radiation transport codes

b) prerequisite for future human presence on the Moon
Dose Rate Measurements at the Moon?

Radiation is modulated by changing shielding by the Moon

Dose Rate Measurements at the Moon?

Dose rates:

- ~ 100 km: 227 µGy/d
- ~ 200 km: 257 µGy/d

Particle Radiation Measurements at the Moon

Prettyman et al., 2006
Particle Radiation Measurements at the Moon

Prettyman et al., 2006
Particle Radiation Measurements at the Moon

Schwadron et al., 2016

RPSD, 2016-10-06
Particle Radiation Measurements at the Moon

Schwadron et al., 2016

RPSD, 2016-10-06
Dose Rate Measurements on the Moon?
Large solar particle event took place between Apollo 16 and Apollo 17

Jiggens et al., 2014

IMP5 measurement of August 1972 events

- > 1 MeV H flux
- > 10 MeV H flux
- > 30 MeV H flux
- > 60 MeV H flux
Effects of solar particle events

Jiggens et al., 2014

Townsend et al., 2003
Dose Rate Measurements on the Moon?
Dose Rate Measurements on the Moon?

None!
Dose Rate Measurements on the Moon?

Lunar Neutron and Dosimetry (LND) Experiment on Chang‘E-4 will provide such measurements (launch 2018)
Implications for Human Exploration

- Reliable predictions
- Interaction with environment
- Measurements

Implications for Astrobiology:
- preservation of bio-signatures
- limits for life?
Maximum production of secondaries lies approximately at the surface of Mars.
Radiation Measurements on Mars

Requirements:

- Charged particles (1 < Z < 27) up to 100 MeV/nuc
- Neutral particles (n, γ) up to 100 MeV
- LET
- Composition
- Time series
- Autonomous operations
The Radiation Assessment Detector (RAD)

Requirements:

- Charged particles (1 < Z < 27) up to 100 MeV/nuc
- Neutral particles (n, γ) up to 100 MeV
- LET
- Composition
- Time series
- Autonomous operations

Solution:

The Radiation Assessment Detector (RAD) is designed to measure charged particles (1 < Z < 27) up to 100 MeV/nuc, neutral particles (n, γ) up to 100 MeV, LET, composition, time series, and autonomous operations. The detector consists of components labeled A, B, C, D, E, and F, and is equipped to handle charged particles and neutral particles effectively.
RAD:

- Mass: 1,56 kg
- Power: 4,2 W
- Data rate: ~130 bps
- RSH: FM & FS
Summary of solar particle events seen by MSL

GCR dominated radiation exposure during RAD's cruise

eq. Dose from SEPs: 24.7 mSv for all cruise

eq. Dose from GCR: 1.84 ± 0.33 mSv per day

SEPs only ~ 5% of GCR
During cruise, RAD was heavily shielded by inhomogeneous and anisotropic structures.  
1 g/cm$^2$ < shielding < 80 g/cm$^2$  
This complicates interpretation of data.
During cruise, RAD was heavily shielded by inhomogeneous and anisotropic structures.

$1 \text{ g/cm}^2 < \text{shielding} < 80 \text{ g/cm}^2$

This complicates interpretation of data.
Inversion towards MSL long-term average spectrum

Inversion (highly problematic)

„true spectrum?“

measurements
## Summary of cruise radiation environment of MSL
(This can be measured accurately!)

<table>
<thead>
<tr>
<th></th>
<th>Estimated variability</th>
<th>Two 180-day legs return trip</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RAD cruise measurement SEPs</strong></td>
<td>24.7 mSv (5% of all)</td>
<td>Orders of magnitude</td>
</tr>
<tr>
<td><strong>RAD cruise measurement GCR</strong></td>
<td>1.84 mSv/d</td>
<td>0.33 mSv/d ± 20%</td>
</tr>
<tr>
<td><strong>6-month stay of astronaut on ISS</strong></td>
<td>75-90 mSv/(a/2)</td>
<td>20,00%</td>
</tr>
<tr>
<td><strong>Radiation worker limit (ICRP)</strong></td>
<td>20 mSv/a</td>
<td>n/a</td>
</tr>
<tr>
<td><strong>Average exposure of normal population</strong></td>
<td>4 mSv/a</td>
<td>Wide range, radon!</td>
</tr>
<tr>
<td><strong>Allowable additional exposure norm. pop.</strong></td>
<td>1 mSv/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>
How variable are solar particle events?

Jiggens et al., 2014
after Townsend et al., 2003

Likely spectrum of MSL events
Secondary radiation (neutrals!) plays an important role! (Ehresmann, 2011)
RAD Surface Measurements

diurnal variation

solar particle events

heliospheric modulation

Dose rate [micro Gy/day]

sol
RAD Surface Measurements

Graph showing dose rate [uGy/day], count rate [1/min], and REMS pressure [Pa] over time. The graph includes data for silicon and plastic, as well as neutral particles, and is labeled with dates from 104/2014 to 109/2014.
RAD Surface Measurements

- RAD measurements consistent with isotropic Martian surface radiation
- Very thin Martian atmosphere provides only a small amount of shielding
- Shielding effect partially compensated by generation of secondary particles

(Wimmer-Schweingruber et al., 2015)

(Rafkin et al., 2013)
RAD Surface Measurements

Surface, observation data

„Albedo“-protons also on Mars

Appel et al., 2017 (in prep.)
Radiation exposure on a mission to Mars:

Cruise: 662 +/- 108 mSv
Mars: 320 +/- 50 mSv

Total ~ 1000 mSv

For comparison:
6 months ISS: 75-90 mSv
radiation worker: 20 mSv/y
CT-scan: 8 mSv
Implications for human exploration

- Space particle radiation is complex!
- “Shielding“ primarily “magnetic“
- Space weather predictions are still very difficult
- Large variability (solar, heliospheric, seasonal, diurnal)
- Secondary radiation important (n/γ)
- Where should we live on Mars?

Implications for non-terrestrial life?
Exo-, astrobiology?

Preservation of bio-signatures?
Summary, Conclusions, and Thanks

- Radiation in heliosphere very variable
- Models are even more variable...
- First radiation measurements on another planet
- Radiation environment on Mars quite different than on Earth and important for future human exploration
- Modulation is an important „shielding“ factor
Destruction of Organic Compounds by Radiation

Ionizing radiation breaks chemical bonds and produces radicals and oxidants.

Result: Destruction of large organic molecules (if there is no repair mechanism)
How long could organic molecules survive ionizing radiation environment?

Previous models: 50 – 150 mGy/y
RAD measurements: 76 mGy/y

Organic molecules are efficiently destroyed at a depth of 4-5 cm. In 650 million years only 1/1000 survives.

How many after 3.8 Gy?

==> Half of the organics should still be around if the soil were only exposed for 65 million years.
Age determination with cosmogenic isotopes

Sheepbed was exposed for only 80 ± 30 million years!

(Farley et al., Science, 2013)
erosion by windblown sand

Future site of Cumberland drill hole

Average scarp retreat rate 1m/Myr

surface with youngest cosmic ray exposure

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Cumberland sample

Blank = no sample

Retention Time (s)

QMS Response (10^3 counts/s)
Summary, Conclusions, and Thanks

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- Radiation environment on Mars quite different than on Earth and important for future human exploration
- Organics can be and have been detected on Mars
- Mars was habitable – but is it still so?
Additional Slides
Yes, there are planets everywhere!
### Catalog

Showing 2107 planets / 1349 planetary systems / 511 multiple planet systems

<table>
<thead>
<tr>
<th>Planet</th>
<th>Mass $(M_{\odot})$</th>
<th>Radius $(R_{\odot})$</th>
<th>Period (day)</th>
<th>$a$ (AU)</th>
<th>$e$</th>
<th>$i$ (deg)</th>
<th>Ang. dist. (arcsec)</th>
<th>Discovery</th>
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<tbody>
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<td>0.095</td>
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<td>0.102</td>
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<td>2.18</td>
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<td>1189.1</td>
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<td>0.464</td>
<td>—</td>
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<td>0.036</td>
<td>—</td>
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<td>2016</td>
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<tr>
<td>TYC 3667-1280-1 b</td>
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<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
What is life?

Life multiplies

Life is self-organizing

Life adapts to its environment
Life must be described differently:
What does life need?
What is life?

Life multiplies

Life is self-organizing

Life adapts to its environment

Life – as we know it – requires:

Liquid Water | stable environment | trace elements | energy
Habitability in the solar system

<table>
<thead>
<tr>
<th>SURFACE HABITATS</th>
<th>Trapped oceans</th>
<th>DEEP HABITATS</th>
<th>Top oceans</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The Earth</td>
<td>Liquid Water</td>
<td>Ganymede</td>
<td>Europa</td>
</tr>
<tr>
<td>Mars</td>
<td>Stable Environment</td>
<td>Callisto</td>
<td>Enceladus</td>
</tr>
<tr>
<td></td>
<td>Essential elements</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chemical Energy</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Liquid Water**: Green indicates presence, yellow indicates absence.
- **Stable Environment**: Red indicates absence.
- **Essential elements**: Green indicates presence, yellow indicates absence.
- **Chemical Energy**: Green indicates presence, yellow indicates absence.
Earth

Mars

Earth: 6.378 km  
1 g

Mars: 3.397 km  
0.375 g
Mars – our neighbor planet
Mars – our neighbor planet
Mars – our neighbor planet

Morocco

Mars

or are both Mars?

or

Mars

Morocco
Mars – our neighbor planet

Mars
or
Morocco

or are both Mars, or are both Morocco ... ?
Mars – our neighbor planet

Mars atmosphere:

Surface pressure: approx. 0.6% Earth value
Temperature at surface: approx. -130 to + 30°C
Composition: 95% carbon dioxide; 2.7% nitrogen
Earth (for comparison): 78% nitrogen; 21% oxygen
Mars – our neighbor planet

Morocco or Mars or are both Mars, or are both Morocco ... ?
Despite Mars' very thin atmosphere, dust storms can cover Mars nearly completely.

'Everything is dusty'
Warum der Krater von Gale?
Sediments were deposited some 3.7 billion years ago. Most of them have been eroded away by wind and sand.
Curiosity landed in the remnants of a river environment...
… and drove on into the remnants of an early lake!
Measurements show that the drilled mudstone contained carbon, nitrogen, oxygen, and sulfur. These elements are needed for life to form.

(Ming et al., Science, 2013)
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Backup Slides
Why do we go to the trouble of predicting radiation?

Radiation health primer:

Average exposure: few mSv/year
Allowed additional exposure: 1 mSv/year
Variability of exposures: from ~1mSv/year to 440 (!) mSv/year

Variability mainly due to radon. CH: factor 240!

NASA: Cancer risk shall not increase by more than 3%.
Summary of DAN observations after Curiosity multiple traverses in the same area

Most H-rich area (Up to 10% water equivalent hydrogen)

Coordinates of colored curve correspond to the position under DAN instrument (back side of the rover)
Why does ionization increase with height?

Measurements show count rate increases with height.

Air pressure decreases with height.

If Earth's radiation were ionizing, count rate should decrease with height because there is less air to ionize.

Can only be explained by ionizing agent coming in from outside the Earth --> extraterrestrial origin! (Millikan)

Pfotzer maximum discovered by Pfotzer in 1932. (Grieder, 2002)
Where is Curiosity?
Where is Curiosity?
Where is Curiosity?

... and what did we find?
Transport of the CR

- Galactic Cosmic Rays
  - High Speed Stream
  - Anomalous Cosmic Rays
  - Solar Wind
  - Corotating Ion Events
  - Corotating Storm Region
  - Energetic Storm Particles
  - Solar Energetic Particles
  - Interstellar Neutral Gas

- Solar Wind
- Fast Solar Wind
- Slow Solar Wind
- Gradual SEPs
- Impulsive SEPs
- CIRs
- GCRs
- Suprathermal tail
  - Heated solar wind ions
  - Pick-up ions
  - Inner Source
  - remnant SEP, ESP, CIRs
  - Bow shocks
  - ...other?

- Contributions to the Oxygen Fluence (10/97 to 6/00)
- Kinetic Energy (MeV/nucleon)
- Particles/cm² MeV/nucleon

- 70 - 100 AU?
From Kiel to Space

Space missions with contributions from CAU Kiel

- **Ulysses (1990-2009)**
  Solar mission, which went outside of the solar system to explore the polar regions of the sun and explore the 3D structure of the heliosphere.
  - **Kiel Solar Telescope**

- **Galileo (1989-2003)**
  NASA mission, which orbited Jupiter and its moons. Also carried a probe which descended into Jupiter's atmosphere.
  - **Solar Particle Investigation (EPI)** on board the probe

- **SOlar and Heliospheric (BOHO, 1995-today)**
  Observations over a wide range of optical and in situ measurements of the sun and the heliosphere.
  - **Electron Proton Helium Instrument (EPHIN)**, CELIAS

- **Space Shuttle (1981-2011)**
  American spacecraft used for a wide variety of experiments and other tasks.
  - Several dosimetry experiments starting in 1982

- **STEREO A and B (2006-today)**
  Two spacecraft observing the sun from different angles, allowing a stereoscopic view of the sun, with optical and in situ instruments.
  - **Solar Extreme Ultraviolet Telescope (SEPT)**, Plasma and Suprathermal Ion Composition (PLASTIC)

- **International Space Station (1998-today)**
  Permanently occupied space station used for a wide variety of scientific experiments.
  - Dosimetry experiments including MOSAIC and DOSTEL

- **Chandra X-Ray Observatory (1999-today)**
  Observes supernovae, black holes and other high-energy cosmic events.
  - Includes EPHIN for a radiation monitor

- **Mars Orbiter (2018-?)**
  Inner heliosphere mission, successor to Mars Express, which will explore the sun with in situ and optical instruments from a distance of only 0.25 AU.
  - **Electron Proton Telescope (EPT)**, High Energy Telescope (HET) and SupraThermal Electrons and Protons (STEP)

- **Helios 1 and 2 (1974-1986)**
  Inner heliosphere missions, which approached the sun closer than any other spacecraft so far.
  - **Cosmic Ray Experiment**

- **International Sun-Earth Explorer (SEE-2, 1977-1987)**
  Studied the interaction between solar wind and Earth's magnetic field.
  - **Charged Particle Spectrometer**

- **Polar (1996)**
  Russian space station, which enabled the first long-term stays of humans in space.
  - **Cosmic Ray Telescope**

- **Mars Express (2003)**
  ESA's Mars orbiter, which carried a variety of instruments to study the planet.
  - **Mars Express SSC**

- **Planck (2009)**
  ESA's space observatory, which mapped the cosmic microwave background.
  - **Planck**

- **Phoenix (2007)**
  NASA's Mars lander, which studied the water ice on Mars.
  - **Electron Proton Helium Instrument (EPHIN)**

- **Masten Space Systems StarLiner (2019)**
  American spacecraft that provides an alternative to traditional spacecraft.
  - **StarLiner**

- **Solar Orbiter (2018-?)**
  Inner heliosphere mission, successor to Mars Express, which will explore the sun with in situ and optical instruments from a distance of only 0.25 AU.
  - **Electron Proton Telescope (EPT)**, High Energy Telescope (HET) and SupraThermal Electrons and Protons (STEP)

- **Balloon Flights (ongoing)**
  Participation in the BEXUS balloon program aimed at students with several instruments.
  - **BEXUS**
**Solar Orbiter**
Exploring the Sun-Heliosphere Connection

---

**Mission Summary**
- **Launch:** October 2018
- **Cruise Phase:** 2.5 years
- **Nominal/Extended Mission:** 3.5/2.5 years
- **Orbit:** 0.28–0.91 AU (P=150-180 days)
- **Out-of-Ecliptic View:**
  - Multiple gravity assists with Venus to increase out-of-ecliptic inclination to >33°

---

**Science Focus**
How does the Sun create and control the Heliosphere – and why does solar activity change with time?

1. **What drives the solar wind and where does the coronal magnetic field originate?**
2. **How do solar transients drive heliospheric variability?**
3. **How do solar eruptions produce energetic particle radiation that fills the heliosphere?**
4. **How does the solar dynamo work and drive connections between the Sun and the heliosphere?**
**EPD - The Team**

Led by University of Alcalá, Spain, PI: Javier Rodriguez-Pacheco (Alcalá)  
Co-PI: Robert Wimmer-Schweingruber (Kiel)  
Hardware contributions from:

**Main funding agencies:**  
Spain: Mineco  
Germany: DLR  
ESA funds SIS as a facility instrument

System Engineering:

![Sener logo](image)
Background: Radiation on Earth

In 1896 Henri Bequerel and others discovers non-chemical process capable of penetrating black paper and darkening photo plates. It also excites fluorescence.

Marie Curie discovers that uranium salt also ionizes air, strictly proportional to the amount of material.

Pitchblend is four times more effective, therefore, it must contain a new element. Discovery of polonium and radium.

Invention of the word 'radioactivity'.

Something can ionize air and penetrate paper. Ionization is a good measure of radioactivity.
Other early discoveries

In 1912 Victor Hess discovers 'Höhenstrahlung' at large heights. Degree of ionization increases with height.

Image credit: NY Times

(Grieder, 2002)
Why does ionization increase with height?

(Grieder, 2002)
Why does ionization increase with height?
Why does ionization increase with height?

Ionization rate:
- Total
- Protons
- Heavy nuclei

(According to Grieder, 2002)
Why does ionization increase with height?

OK, …, but where does it come from?

Millikan: cosmic rays

Pfotzer maximum

(Grieder, 2002)
Radiation exposure and altitude

- 224 Gm: SL/RAD 26 µSv/h × 260
- 420 km: SL/RAD 77 µSv/h × 770
- 10 km: DOSIS 3D 30 µSv/h × 300
- 3 km: ~ 4 µSv/h × 40
- 50 m: ~ 0.2 µSv/h × 2
- 50 m: ~ 0.1 µSv/h × 1

[D. Hassler et al. 2014, Mars’ Surface Radiation Environment Measured with the Mars Science Laboratory’s Curiosity Rover, Science], [Thomas Berger]