# CARI-7: Software for Calculating Cosmic Radiation Flight Doses

Presentation at:

NASEM Assessing Radiation Exposure, Health Outcomes, and Mitigation Strategies for Flight Crewmembers - First meeting

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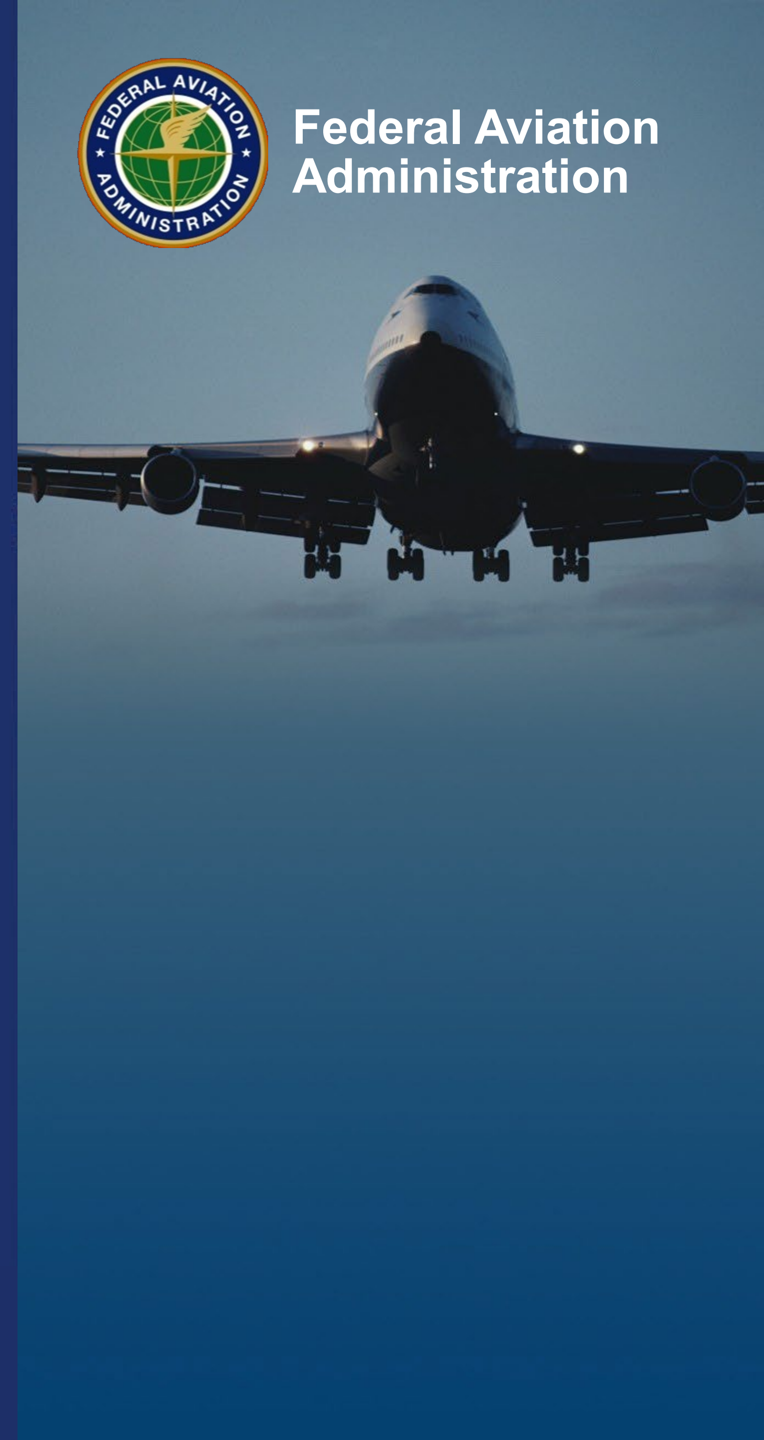
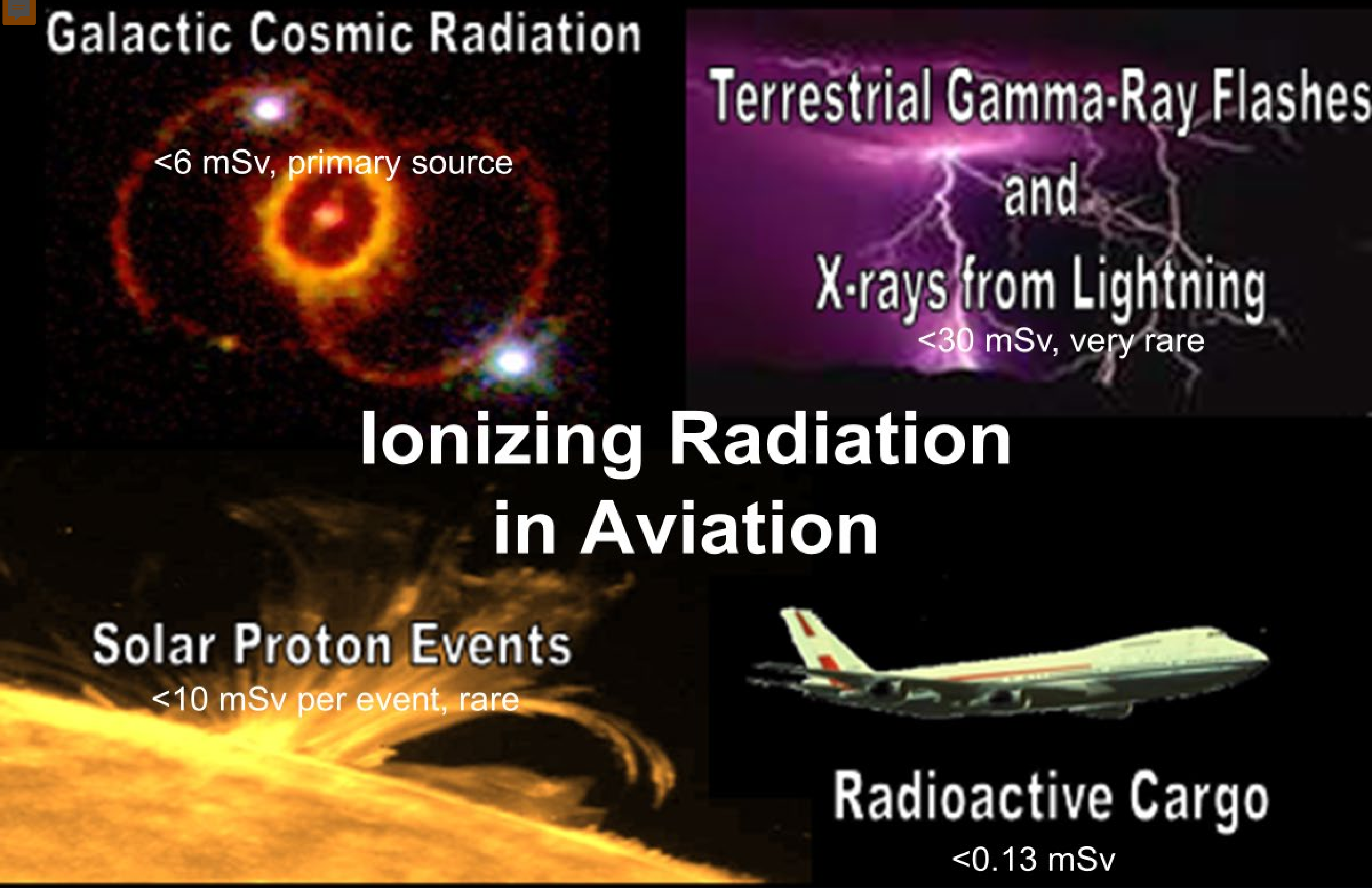



Galactic Cosmic Radiation
<6 mSv, primary source
Terrestrial Gamma-Ray Flashes
and
X-rays from Lightning
<30 mSv, very rare
Ionizing Radiation
in Aviation
Solar Proton Events
<10 mSv per event, rare
Radioactive Cargo
<0.13 mSv

# AIRCREW DOSES

Highest average annual effective doses among monitored workers worldwide (1990-1994) [UNSCEAR, 2000].

| Practice | Rank | Effective dose / $mSv \cdot y^{-1}$ |
|---|---|---|
| Above-ground radon from oil and natural gas extraction | 1 | 4.8 |
| Nuclear fuel mining | 2 | 4.5 |
| Nuclear fuel milling | 3 | 3.3 |
| **Aircrew** | **4** | **3.0** |
| Mining other than nuclear fuel or coal | 5 | 2.7 |
| Radioisotope production | 6 | 1.93 |
| Industrial radiography | 7 | 1.58 |
| Nuclear fuel reprocessing | 8 | 1.5 |

Annual Effective Dose from Natural Sources/mSv

| Radiation | Non-flyer: Non-Flying United States Resident | Non-flyer: Non-Flying Resident of EPA Region 8 | Airline Pilot*: Los Angeles-Tokyo (36 Round Trips) | Airline Pilot*: Chicago-London (48 Round Trips) | Airline Pilot*: Seattle-Portland (634 Round Trips) |
|---|---|---|---|---|---|
| Cosmic, airborne | ---- | ---- | 2.81 | 4.52 | 0.22 |
| Cosmic, ground level | 0.38 | 0.73 | 0.34 | 0.35 | 0.36 |
| Terrestrial gamma | 0.24 | 0.63 | 0.23 | 0.23 | 0.23 |
| Radon decay products | 1.31 | 2.55 | 1.12 | 1.13 | 1.23 |
| Radionuclides in body tissues | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |
| Total | 2.33 | 4.31 | 4.90 | 6.63 | 2.44 |

*Assumes 760 block hours

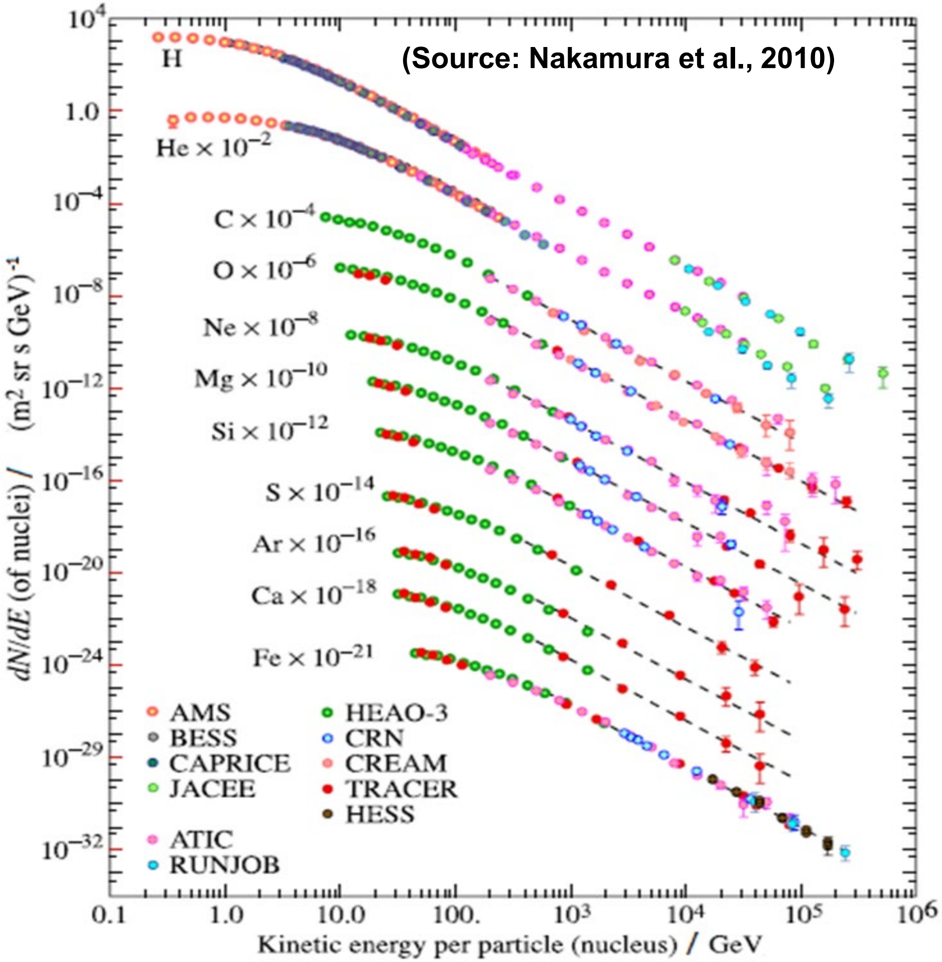
# Stochastic and Deterministic Health Effects

| | Increased lifetime risk* | |
|---|---|---|
| Stochastic Effect | Whole population | Age group 18-64 years |
| Genetic effects in first two successive generations (children and grandchildren), irradiation before conception. | 0.4 in 100,000 per mSv | 2.4 in 1,000,000 per mSv |
| Cancer (non-fatal or fatal) | 34 in 100,000 per mSv | 23 in 100,000 per mSv |
| Cancer (fatal only) | 8.0 in 100,000 per mSv | 6.3 in 100,000 per mSv |

*Risks assumes exposure to high-LET radiation (i.e., no DDREF) (ICRP, 2007)

| Deterministic Effect | Threshold Dose |
|---|---|
| None Significant | <0.1 Gy |
| Risks to conceptus (mental retardation, malformation, etc.) | 0.1-0.5 Gy |
| Transient mild nausea and headache in adults | 0.35 Gy |

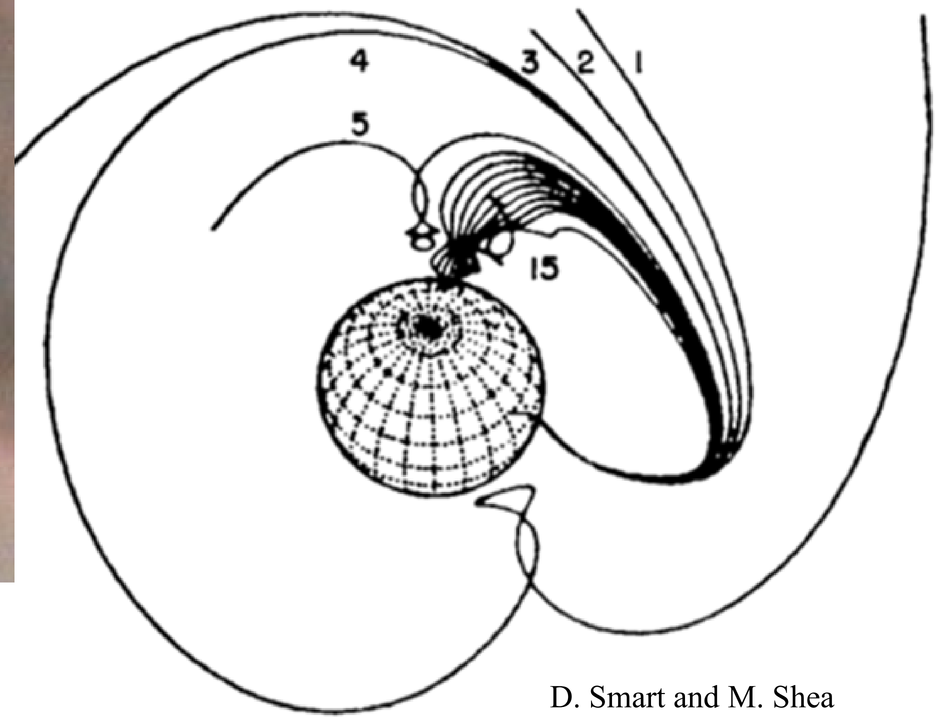
# Galactic Cosmic Radiation: What is it?

# Galactic Cosmic Radiation:
## How does it get here?


2. Solar wind

3. Earth's magnetosphere

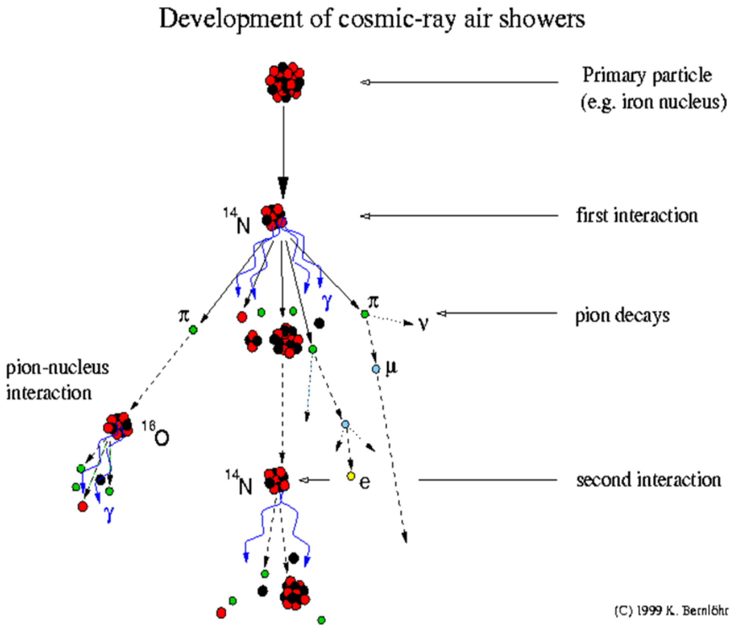


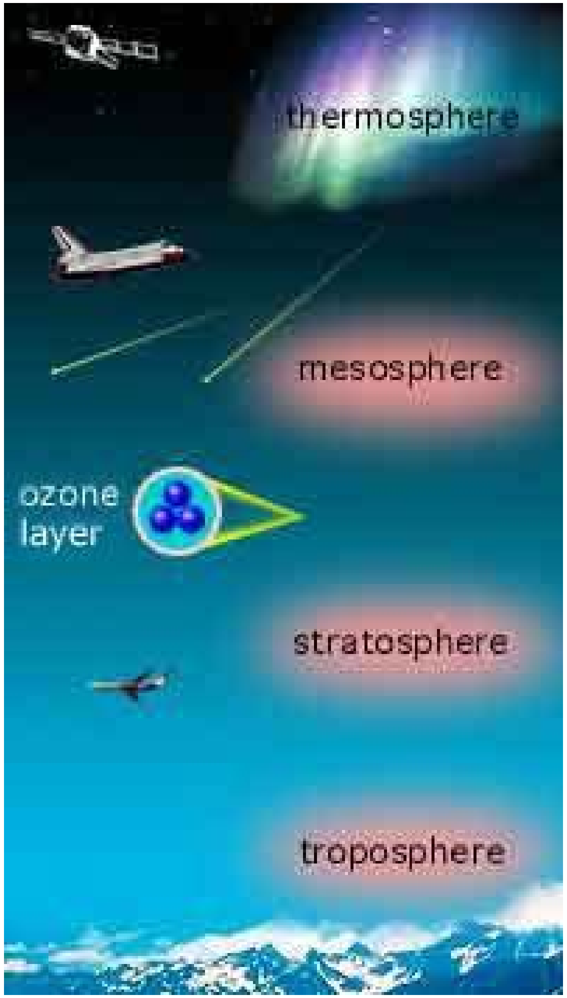

D. Smart and M. Shea

# Earth’s Atmosphere

Earth’s atmosphere is the final natural shield from cosmic radiation

It is very effective, equivalent to about 10 meters of water.




For CARI-7 the 1976 US Standard Atmosphere was used to create an input deck for MCNPX representing a set of 100 spherically concentric shells, each 1 km thick [Copeland et al, 2008]. The properties of the atmospheric model are:

| | |
|---|---|
| Maximum altitude above sea level | 100 km |
| Area of its uppermost surface | $5.262 \times 10^{18}$ cm$^2$ |
| Total atmospheric depth | 1035.08 g/cm$^2$ |

# Calculating a Flight Dose

## INPUTS

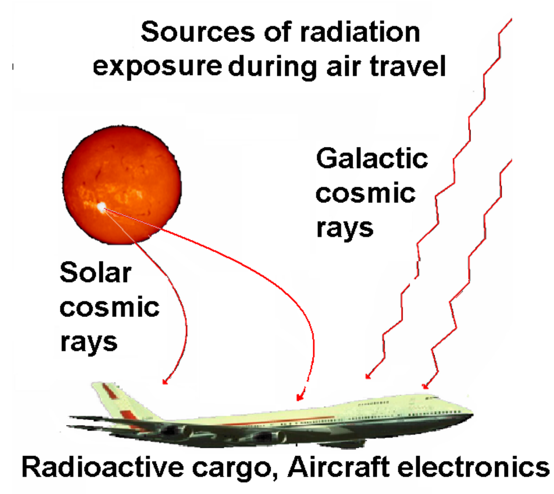
1. The GCR spectrum incident on the heliosphere.
2. The solar modulation during the flight, including Forbush effects.
3. The geomagnetic modulation along the flight route, including storm effects.
4. The mass shielding distribution throughout Earth's atmosphere.
5. Aircraft route information, including date and time of departure, altitudes, etc.

## USED TO

1. Calculate the location and altitude of the aircraft along its route.
2. Calculate secondary GCR particles fluxes at aircraft locations
3. Convert secondary GCR particle fluxes to dose rates.
4. Numerical integration of en-route dose rates.

# What is CARI?

- The first CARI program was released in the early 1990s. Based on LUIN transport code.
- First called CARRIER, then shortened to CARI.
- Each series of PC computer programs has a base version and some variants, e.g., for NIOSH.
- Used by pilots and airlines worldwide to monitor career radiation doses.
- Used by epidemiologists to estimate past exposures for radiation effects studies.




# FAA In-flight Cosmic Radiation Exposure Tools

**Galactic Cosmic Radiation:**

**CARI-7 with Galactic Cosmic Radiation Spectrum**

**Solar Cosmic Radiation:**

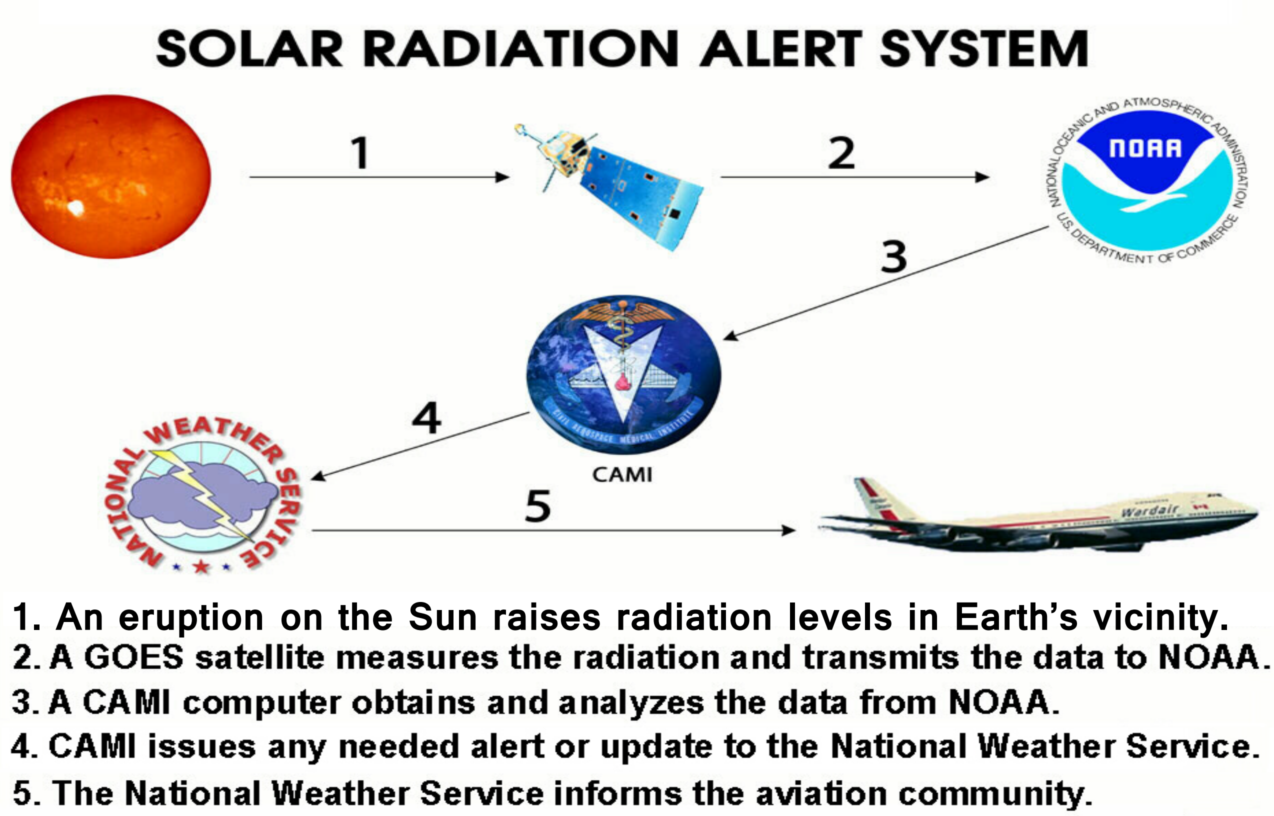
**CARI-7A with Solar Cosmic Radiation Spectrum**

Radiobiology Services | Federal Aviation Administration

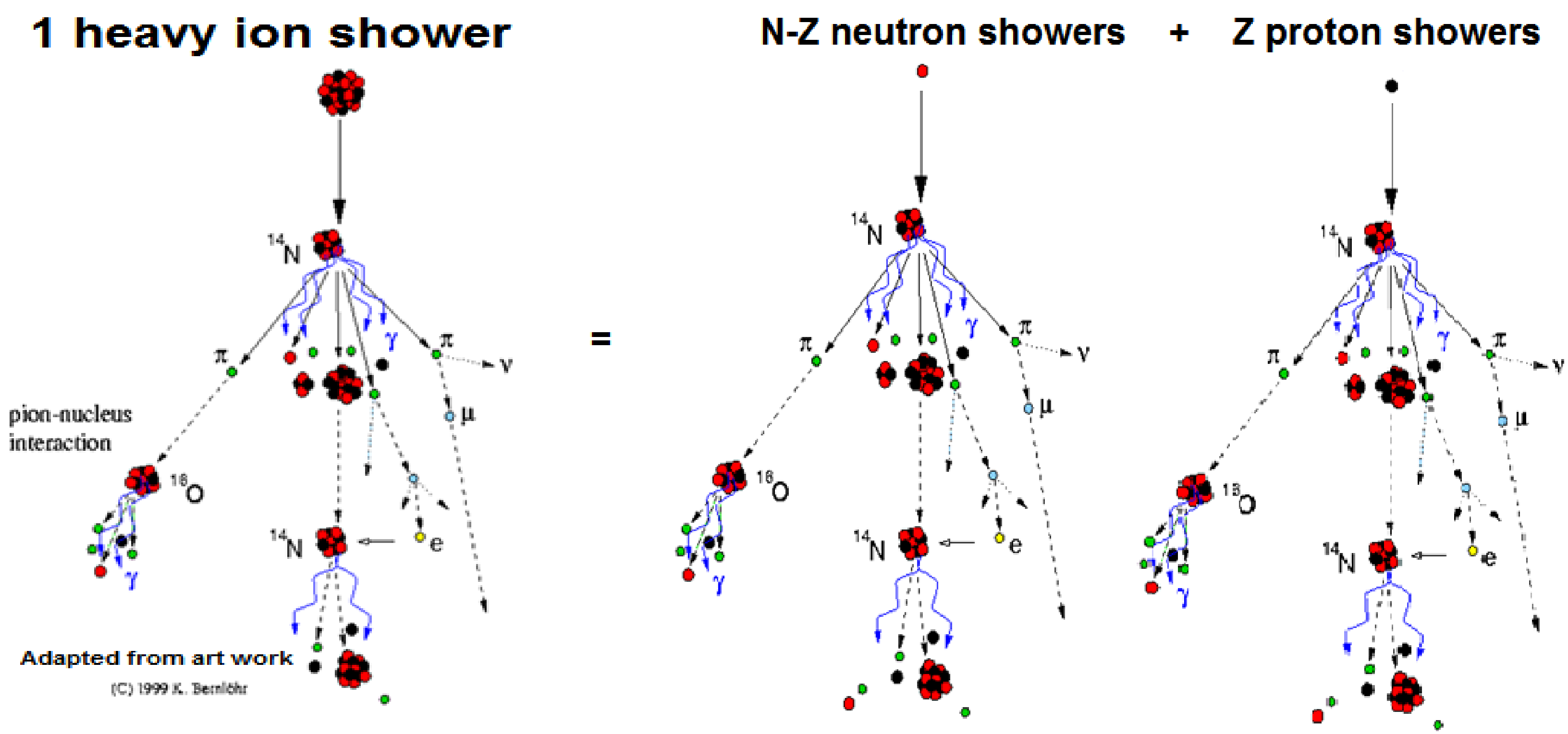
# CARI-7 Design

Up through CARI-6, altitude was limited to 60,000-87,000 feet. Uses LUIN [O'Brien 1978].

CARI-7 uses MCNPX2.7.0 (=MCNP6v1.0) and is an extension to GCR of the SPE dose calculation concepts used in the Solar Radiation Alert System [Copeland, 2014].



# The Superposition Approximation




Advantage: Eliminates the need for heavy ion transport in the atmosphere.
Cost: Inaccurate dosimetry where HZE flux is important.
In CARI-7A using the superposition approximation remains optional (it is no longer allowed in CARI-7).

# MCNPX 2.7.0
## (Monte Carlo N-Particle eXtended)

**Where does it come from?**

Los Alamos National Laboratory

**Why use it for cosmic ray research?**

It can transport all atomic species and dozens of subatomic particles and antiparticles at up to TeV ($10^{12}$eV ) energies.

**What is it?**

A general-purpose radiation transport code that uses Monte Carlo techniques.

Last Stable version of MCNPX.

Same physics as MCNP6v1.0.

# Particle Transport

MCNPX 2.7.0 was used to simulate cosmic ray showers for neutrons and primary GCR ions H-Fe.

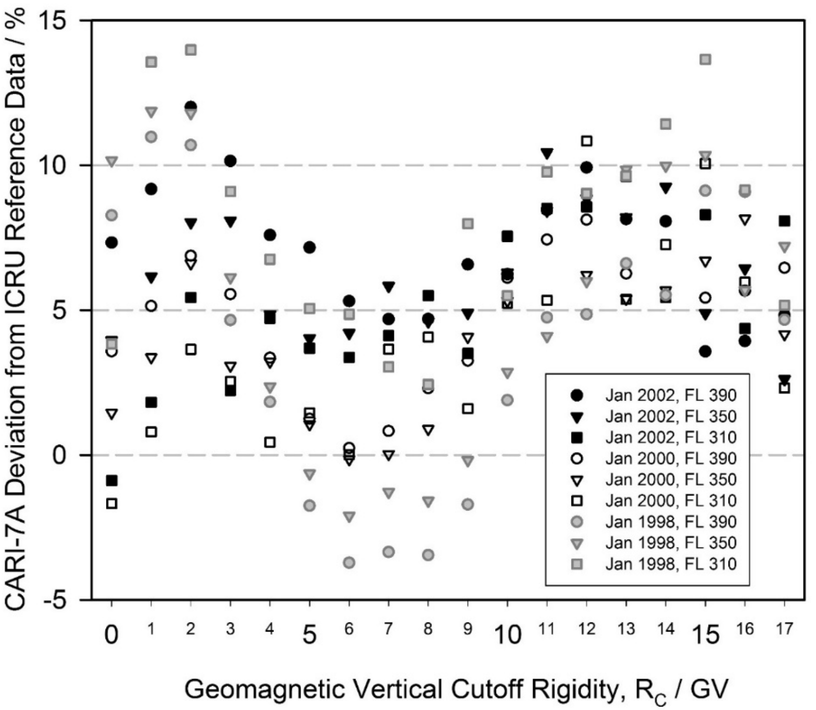
All modellable secondaries were transported, including particles that do not contribute significantly to dose (e.g., neutrinos).

Flux tallies were made throughout the atmosphere approximately every 3 km through 33 km, then more sparsely up to 100 km.

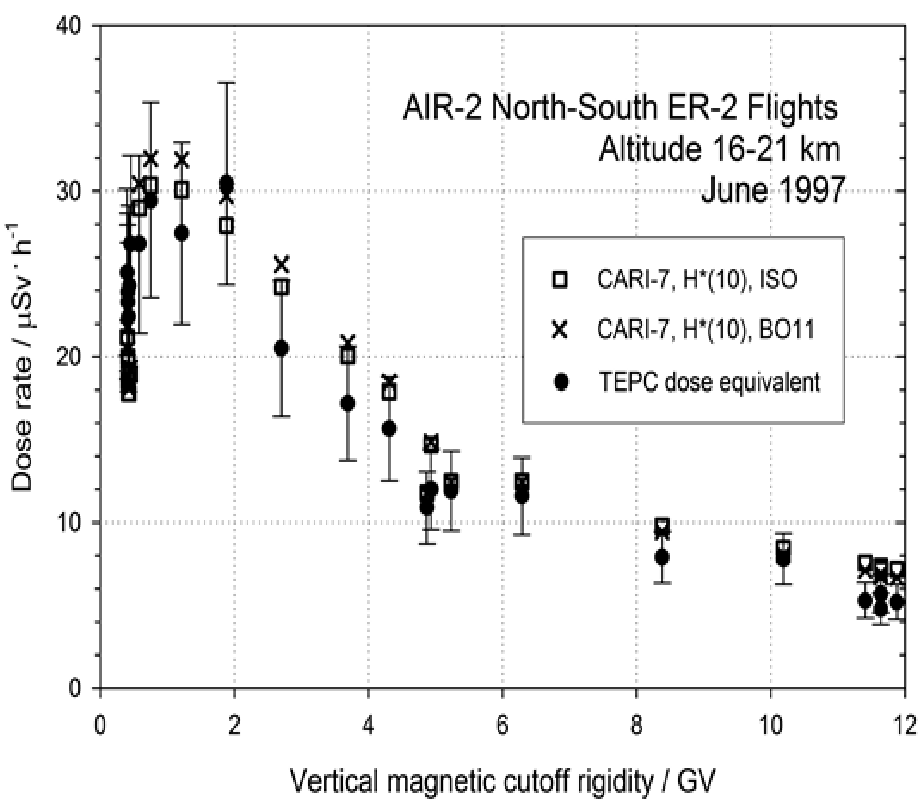
Tallies included n, e, gamma, pi, mu, p, d($^2H^+$), t($^3H^+$), alpha, $^3He$, and fully ionized Li-Fe.

Tally spectral energy range was 1MeV-1TeV for all particles, with additional lower-energy tallies for neutron and gamma spectra.

# CARI-7 vs Measurements




CARI-7 compares well with measurements




The largest uncertainty in CARI-7 is from the choice of cosmic radiation spectrum.

# CARI-7 Weaknesses

- Particles that escape cannot re-enter, even if they should.
- Shower data assume isotropic access to top of the atmosphere, which is an increasingly poor assumption at low geomagnetic latitudes and for early arriving solar energetic particles.
- The shielding approach is too approximate for spacecraft. It does not incorporate the details of internal structures.
- No trapped radiation modeling for spacecraft

# CARI-7 Strengths

- Superposition approximation in the atmosphere is avoided.
- Monte Carlo methods are used with modern physics models to build a fast and accurate simulation for atmospheric applications and Low-Earth orbit
- Results are consistently within expected uncertainties of measurements at aviation altitudes.
- Simple upkeep: just a few databases needed for a normal update
- CARI-7 is almost a plug and play replacement of CARI-6 in scripts

# Summary

CARI-7A provides accurate calculations of in-flight doses from galactic and solar cosmic rays.

Galactic cosmic radiation is omni-present background radiation in aerospace activities. On rare occasions, transient gamma-ray flashes, solar proton events, cargo related accidents, and terrestrial nuclear accidents can lead to additional exposure.

For current flight practices:

- Crewmember doses are typically a few mSv per year.
- This is well below the annual recommended dose limits of 20 mSv, but equivalent to occupational doses in other high exposure professions such a nuclear fuel processing.
- Rare events such solar proton events and transient gamma-ray flashes can raise this by 10s of mSv, which is still too low to cause life-threatening deterministic effects.

Considering future flights:

- CARI-7 and other modern calculations indicate effective doses from galactic cosmic radiation are much higher near the top of the atmosphere and at suborbital altitudes.
- Current annual limits will be attainable in a working year (<1000h).

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