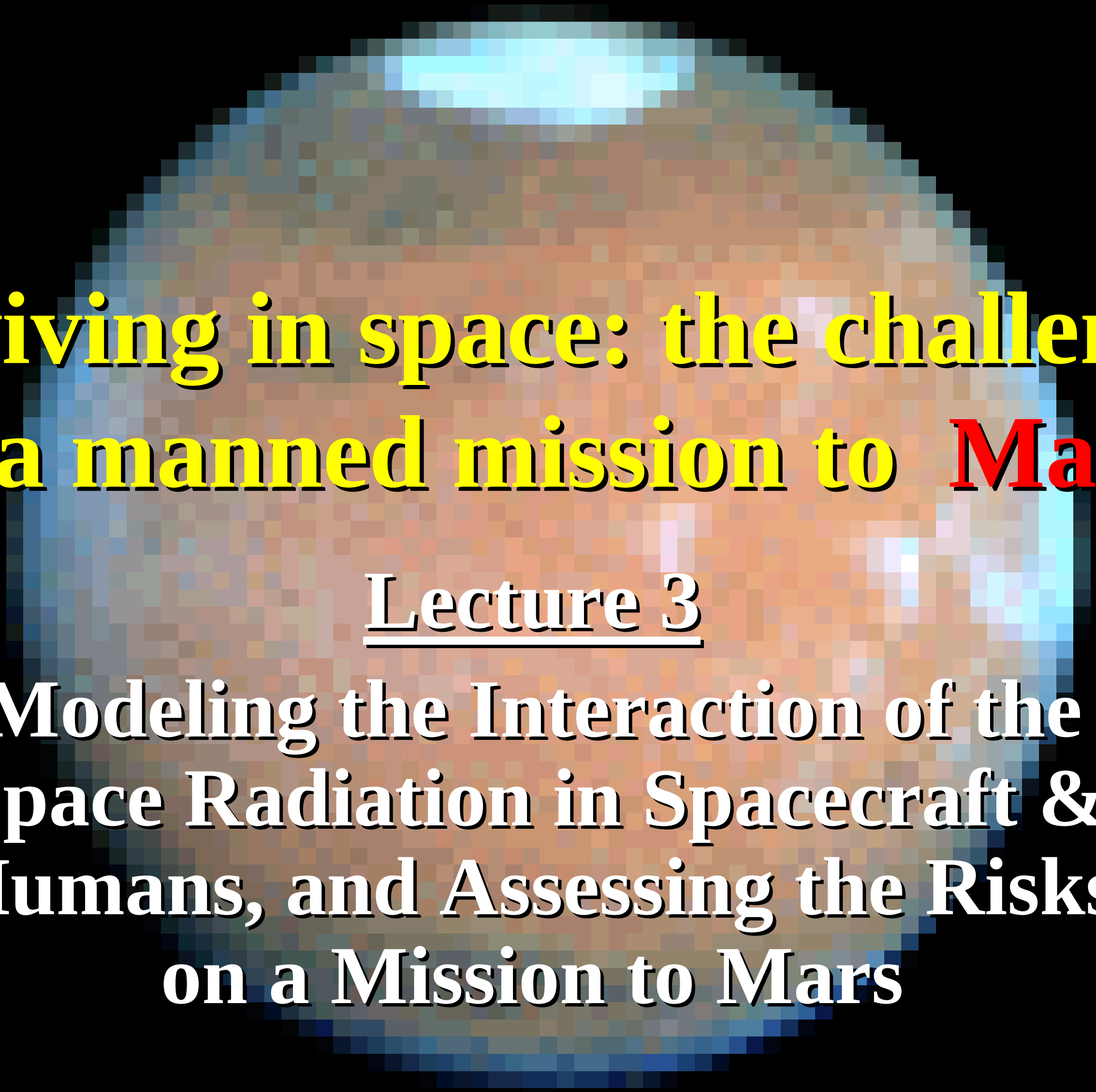


Surviving in space: the challenges of a manned mission to Mars

Lecture 3

Modeling the Interaction of the Space Radiation in Spacecraft & Humans, and Assessing the Risks on a Mission to Mars

Back to the Moon…
Then, On to Mars

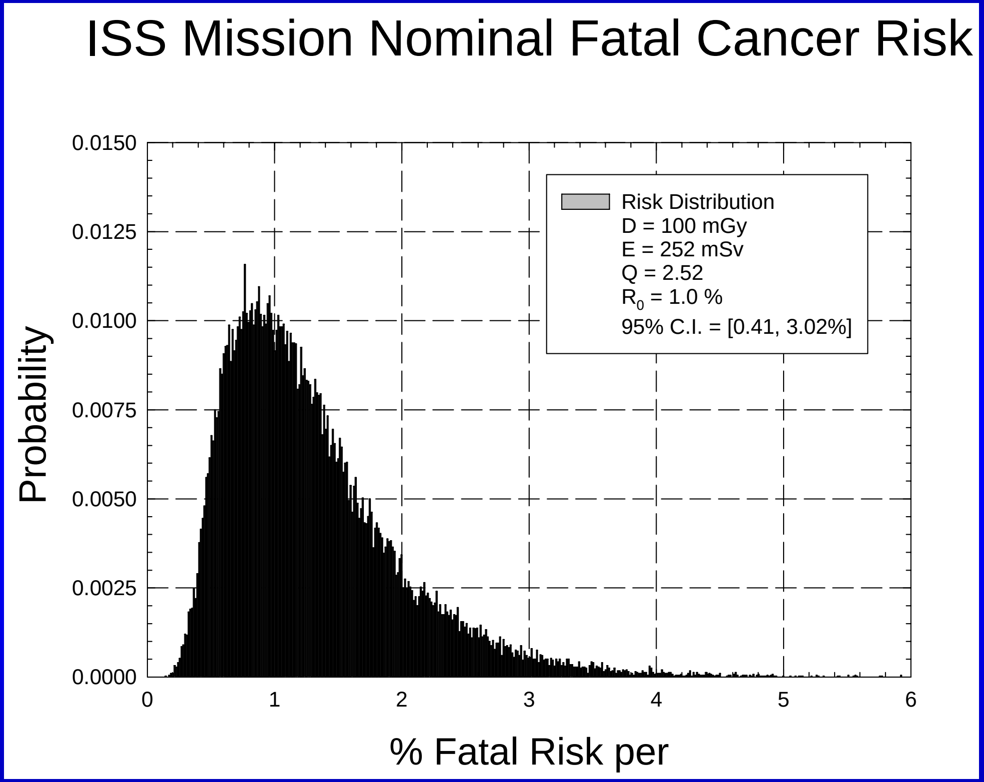
- President Bush has committed the US Space Program to going to Mars…
- The first step will be a return to the Moon to develop and test the techniques needed eventually to go to Mars…
- Crew radiation exposure has been identified as one of the major problems that must be dealt with to make this possible…

Radiation Exposure Guidelines

- Recall that astronauts will be held to the same exposure limits in terms of risk to health that ground-based atomic workers are!
- Nominally, for chronic exposure threats the biggest risk is radiation-induced cancer, and the current exposure guideline is to keep the Excess Lifetime Risk (ELR) to under 3%...

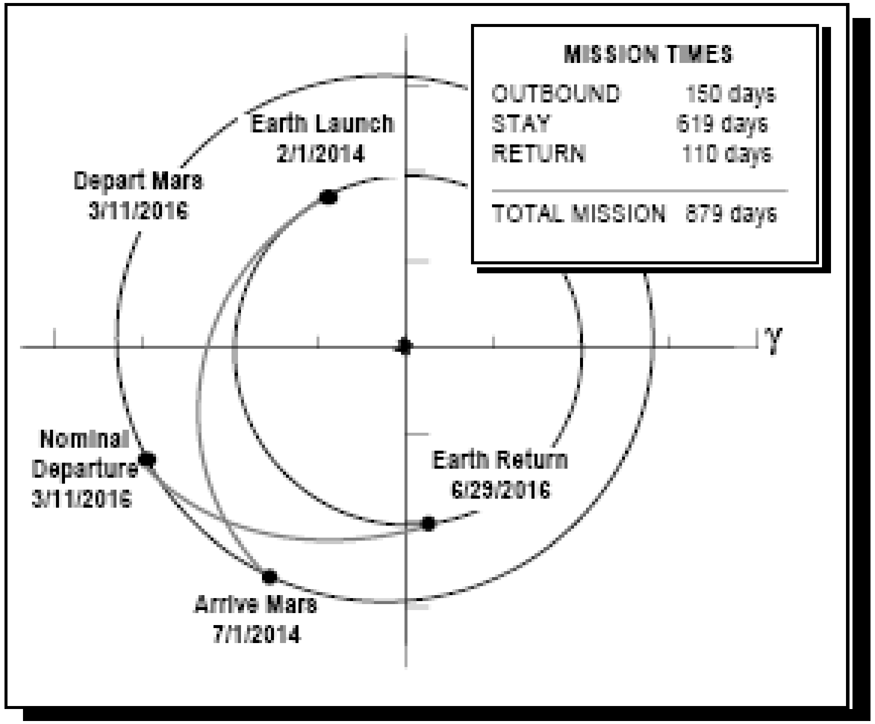
NASA Revised Standard for Radiation Limits

- Revised standard applies a 95% confidence level to the career limit of 3% risk of lifetime fatal cancer
    - Approved by NASA Medical Policy Board
- 95% confidence is conservative
    - Takes specific risk probabilities of individuals into account
    - Narrows range of increased risk
    - Epidemiology, DDREF (Dose and Dose Rate Effectiveness Factor), quality (QF) and dosimetry uncertainties part of evaluation
- “Lack of knowledge” leads to costs and restrictions



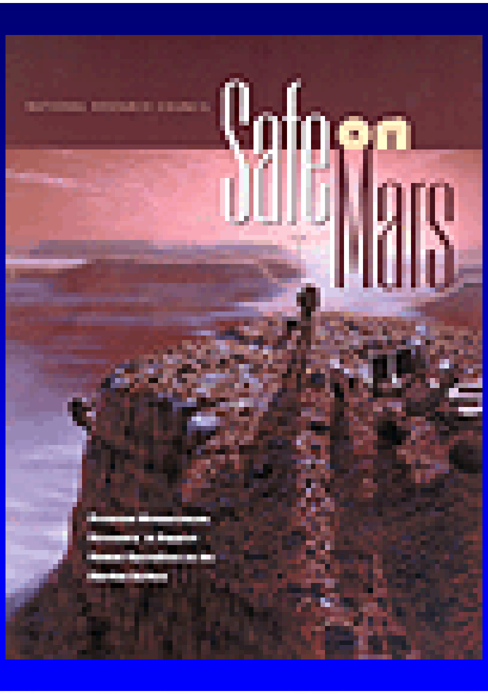
Slide Courtesy of F. Cucinotta, NASA/JSC

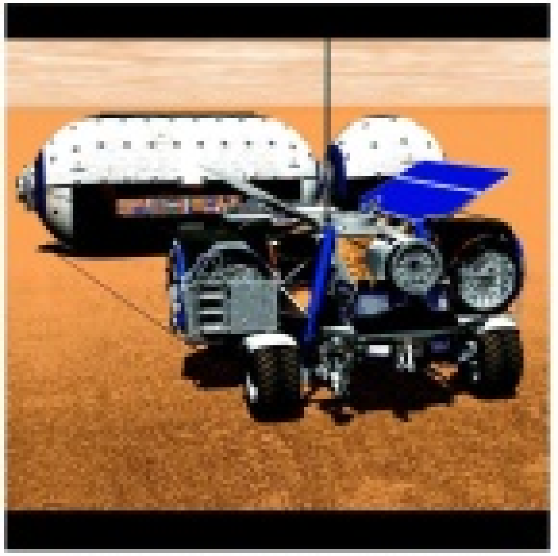
Mars "Reference" Mission



MISSION TIMES	
OUTBOUND	150 days
STAY	619 days
RETURN	110 days
TOTAL MISSION	879 days

Figure 1-1 Typical fast-transit trajectory.





Reference Mars Vehicles

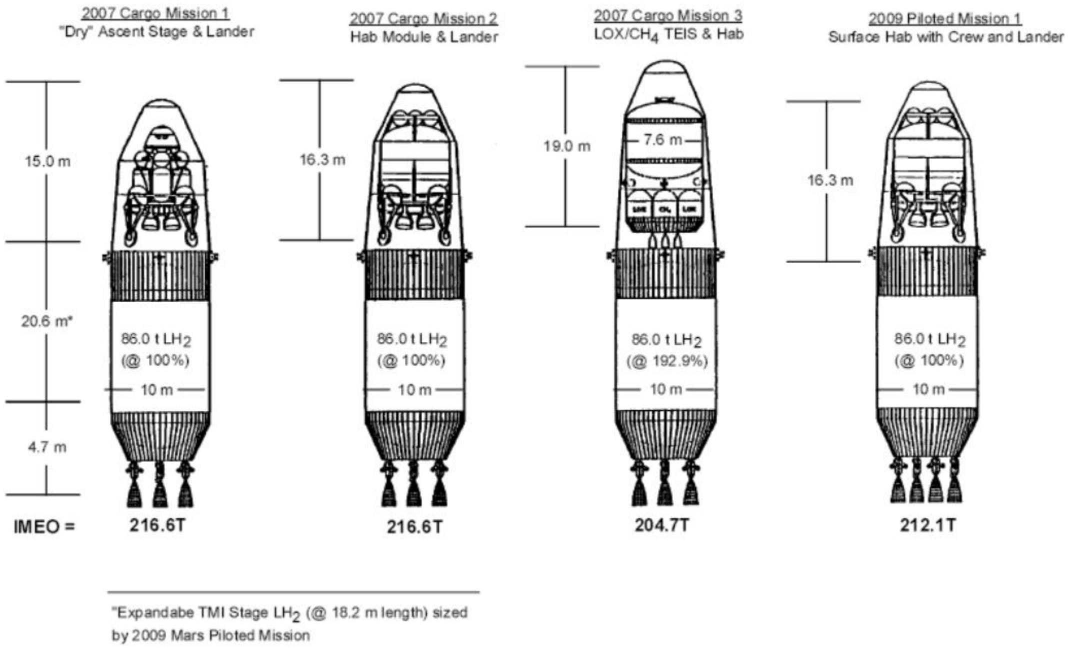


Figure 1-5 Reference Mars cargo and piloted vehicles.

Basic idea is to pre-position the ascent stage and habitats on Mars, along with the orbiting return vehicle before sending the crew with the descent stage… This is just a planning concept, and will likely be modified heavily in practice…


1 Robotic Sample Return Mission Demonstrates Mars Resource Utilization

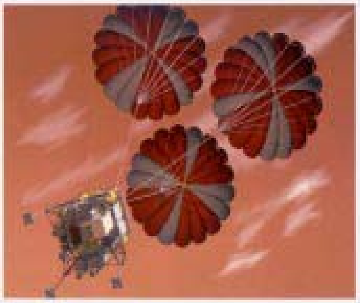

2 Energia Launches Mars Habitat Prototype

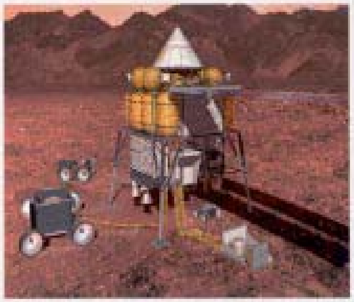

3 Mars Habitat Prototype Demonstrated on Space Station

Near Term Mars Precursor Strategy

Human Exploration of Mars

An Exploration Mission Concept


4 Ascent Vehicle and Outpost Cargo Arrives at Mars


5 Power Systems Deployed and Propellant Production Begins


6 Arrival of Initial Surface Habitat


7 Backup Ascent Vehicle and Exploration Systems

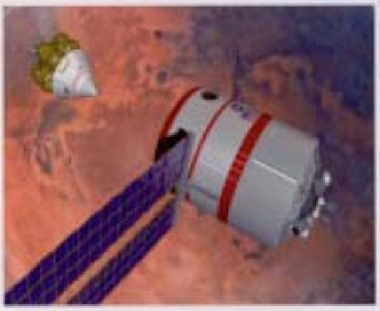

8 Crew Positions Habitation System


9 Pressurized Rover Docked with Habitation System

Human Exploration of Mars

An Exploration Mission Concept Continued


10 Crew Departs Mars After 500 Days on the Surface


11 Rendezvous with Earth Return Vehicle


12 Crew Returns to Earth

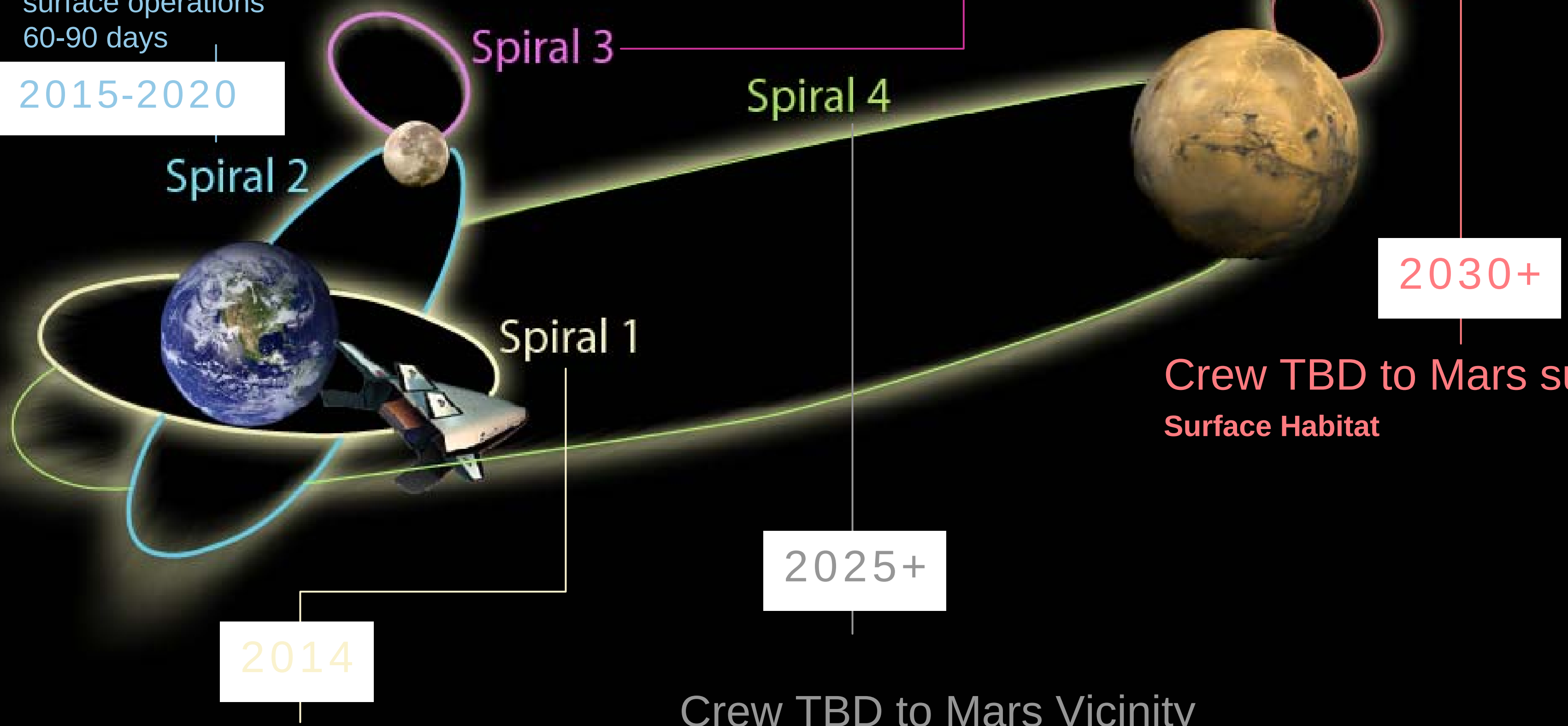
4-6 crew to lunar surface for extended-duration stay

CEV:Earth-moon cruise – 4 days
Low lunar orbit (LLO) operations- 1 day
Untended lunar orbit operations – 4-14 days
Low lunar orbit operations – 1 day
Moon-Earth cruise – 4 days

Lunar Lander: Lunar surface operations 60-90 days

4-6 crew to lunar surface for long-duration stay

Lunar Habitat: Lunar surface operations 60-90 days



Crew TBD to Mars surface

Surface Habitat

4-6 crew to Low Earth Orbit

Crew Exploration Vehicle: Launch Environment
LEO Environment
Earth entry, water (or land) recovery

Crew TBD to Mars Vicinity

Transit vehicle: Earth-Mars cruise – 6-9 months
Mars vicinity operations – 30-90 days
Mars-Earth cruise – 9-12 months

Slide Courtesy of F. Cucinotta, NASA/JSC

NASA ESMD

Mars Mission Exposure Regimes

- Trans-Mars & Trans-Earth Vehicle
  - Normal Crew Compartment
  - “Storm Shelter” within Vehicle
  - Spacesuit EVAs
- Martian Surface
  - Within Surface Habitat
  - Possible “Storm Shelter” within Habitat
  - EVA Vehicle
  - Spacesuit EVAs

DEEP SPACE GCR DOSES
Trans-Mars & Trans-Earth

- Annual bone marrow GCR doses will range up to ~ 15 cGy at solar minimum (~ 40 cSv) behind ~ 2cm Al shielding
- Effective dose at solar minimum is ~ 45-50 cSv per annum
- At solar maximum these are ~ 15-18 cSv
- Secondary neutrons and charged particles are the major sources of radiation exposure in an interplanetary spacecraft
- No dose limits yet for these missions

Courtesy of L. Townsend, US NCRP

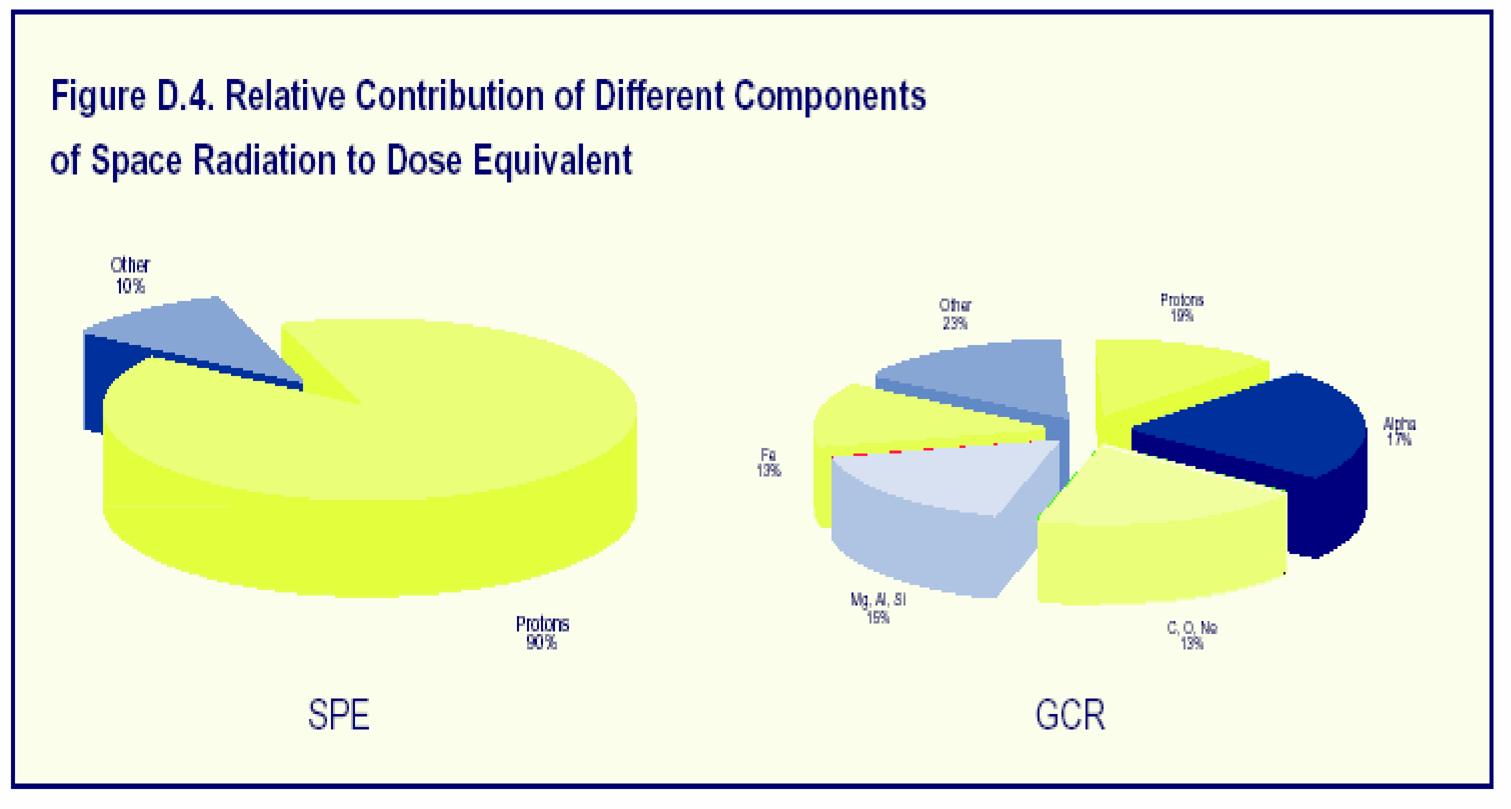
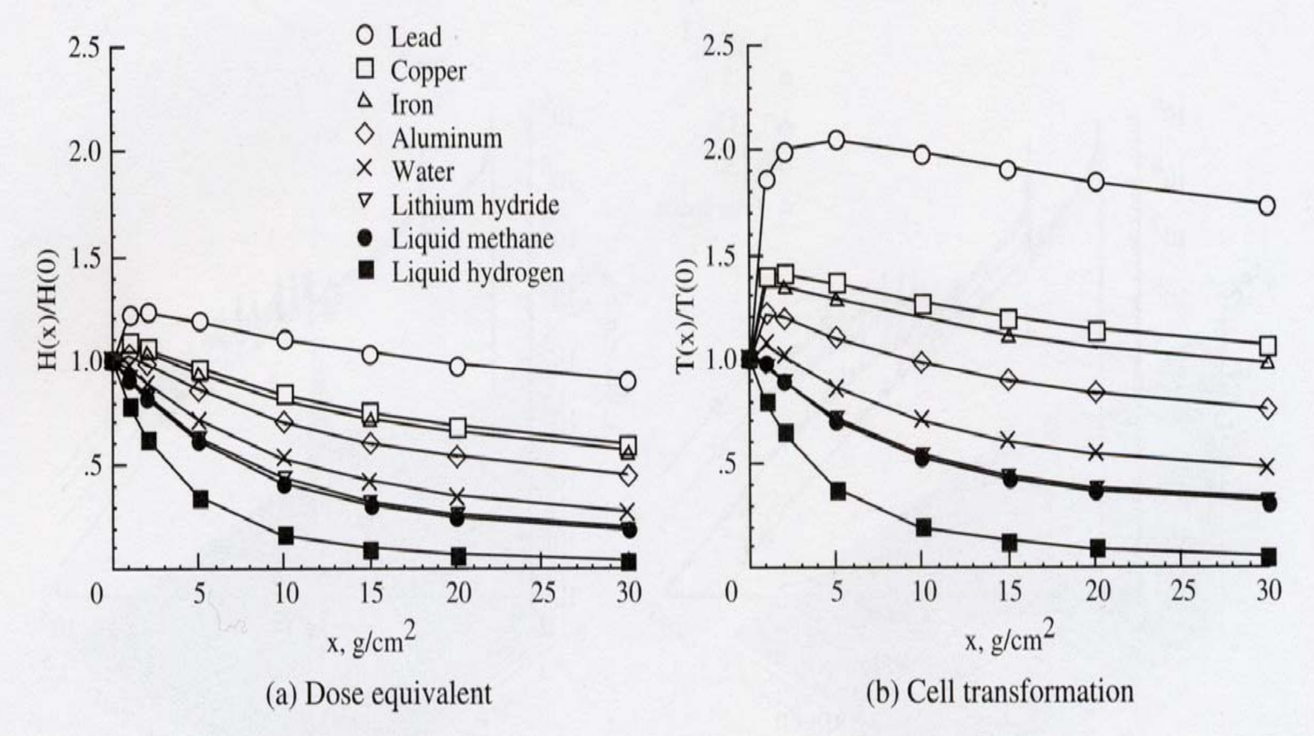


Figure D.4. Relative Contribution of Different Components of Space Radiation to Dose Equivalent

From NASA 1996 Strategic Program Plan

Dose v. Shielding Depth For Various Materials



(a) Dose equivalent

(b) Cell transformation

From NASA CP3360, J.W.Wilson et al., eds.

Cosmic Rays and Nuclear Physics

- NASA Sponsors Nuclear Modeling to Obtain Nucleus-Nucleus EVENT GENERATORS for use in Monte Carlo Transport Codes…
- Like **FLUKA**…
  - – We have embedded DPMJET 2.5 & 3 (for E > 5 GeV/A)
  - – as well as RQMD (for 100 MeV/A < E < 5 GeV/A)

…And, There is an Ongoing NASA-Sponsored Program to Improve the Accuracy of the Event Generators

- There is a Dual Program to Both Model and Measure Cross Sections…
  - The Focus is on the E < 5GeV/A Region…
  - Several Approaches are being taken…
  - The NASA-FLUKA Team is developing a new Hamiltonian QMD Formalism (HQMD).
- These Improvements will Directly benefit many Cosmic Ray Applicatons…
  - Air Shower Calculations…
  - Galactic Transport Calculations…
  - Experimental Corrections…

The FLUKA Monte Carlo code

- hadron-hadron and hadron-nucleus interactions 0-100 TeV
- nucleus-nucleus interactions 5 GeV/u-10,000 TeV/u (DPMJET)
- electromagnetic and μ interactions 0-100 TeV
- neutron multigroup transport and interactions 0-20 MeV

- nucleus-nucleus interactions below 5 GeV/u down to 100 MeV/u (by coupling with the RQMD 2.4 code)

- parallel development of an original non-relativistic QMD code down to ~ 20 MeV/u

Courtesy of F. Balarini

New Methods

Quality factors **Yields of “Complex Lesions”**

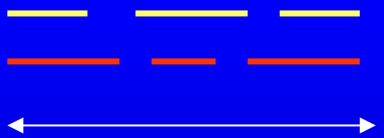
GCR and SPE spectra → **FLUKA** →

Dose

Equivalent dose

“Biological dose”

(Complex Lesions/cell)



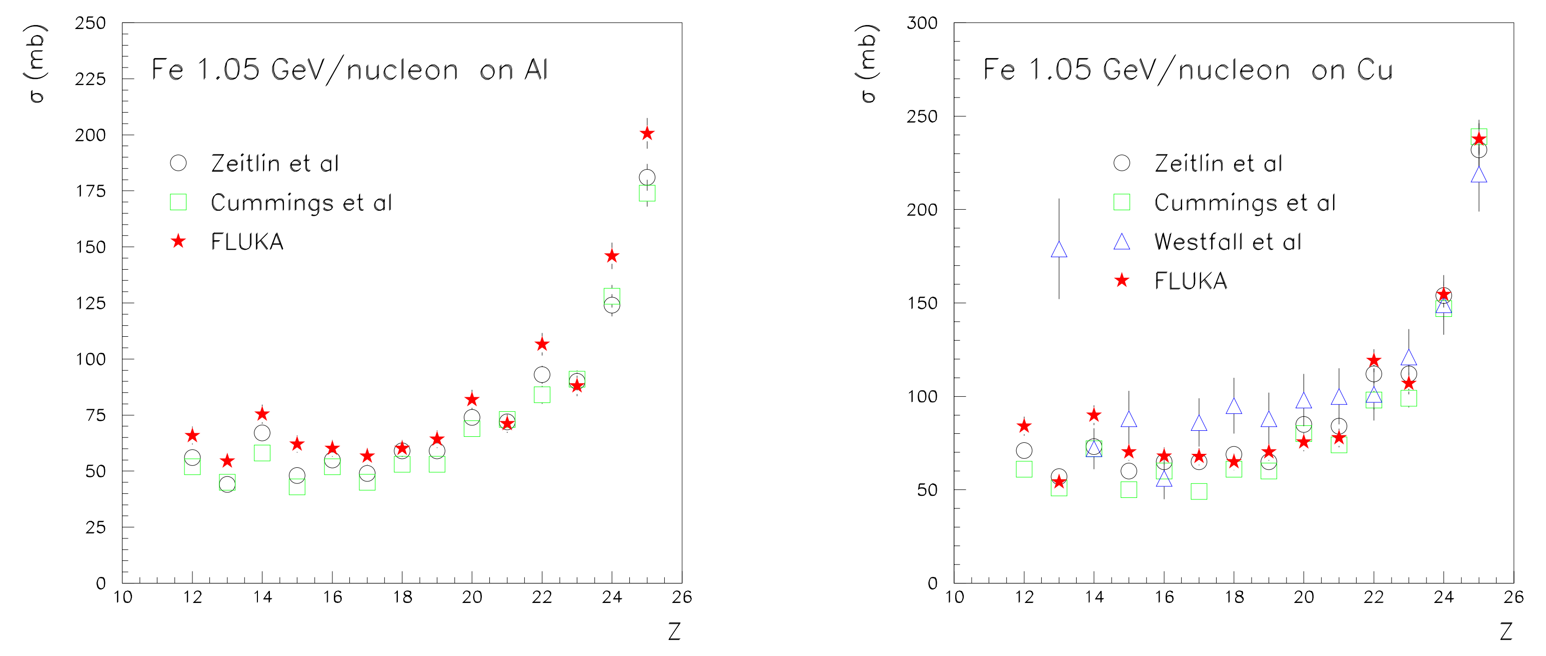
30 DNA base-pairs

Courtesy of F. Balarini

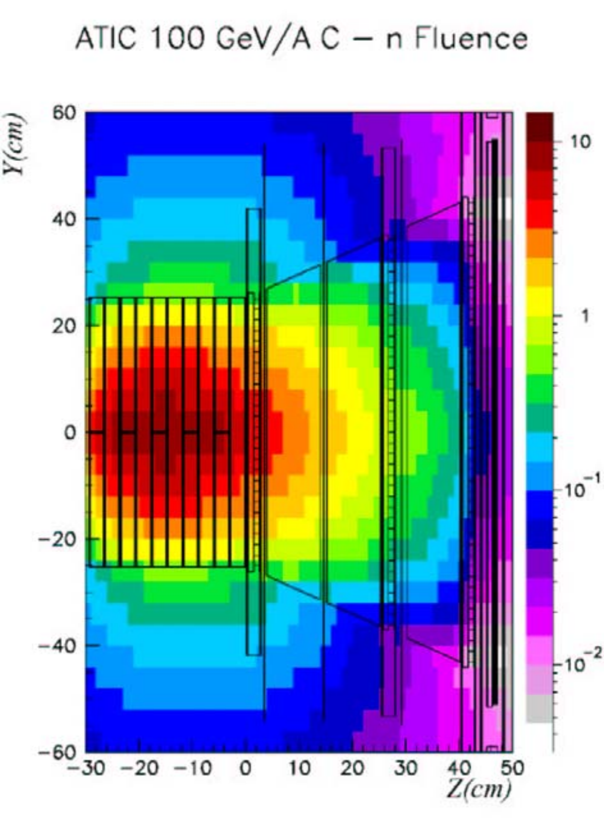
mathematical phantom (68 regions)

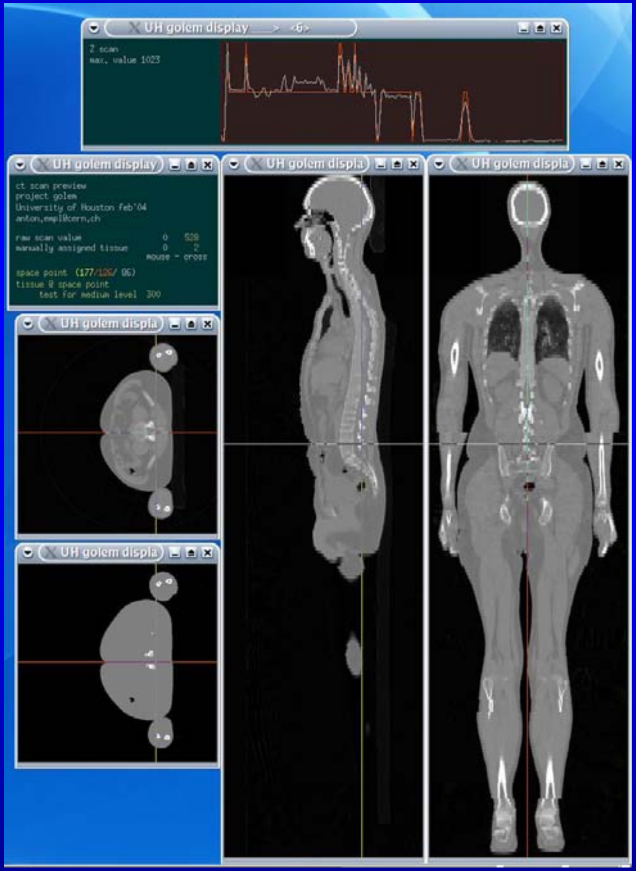
“voxel” phantom (287 regions, > 2x10^6 voxels)

FLUKA rQMD Fragmentation Yields



FLUKA Simulations





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Z scan
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ct scan preview
project golem
University of Houston feb'04
anton,empl@cern,ch

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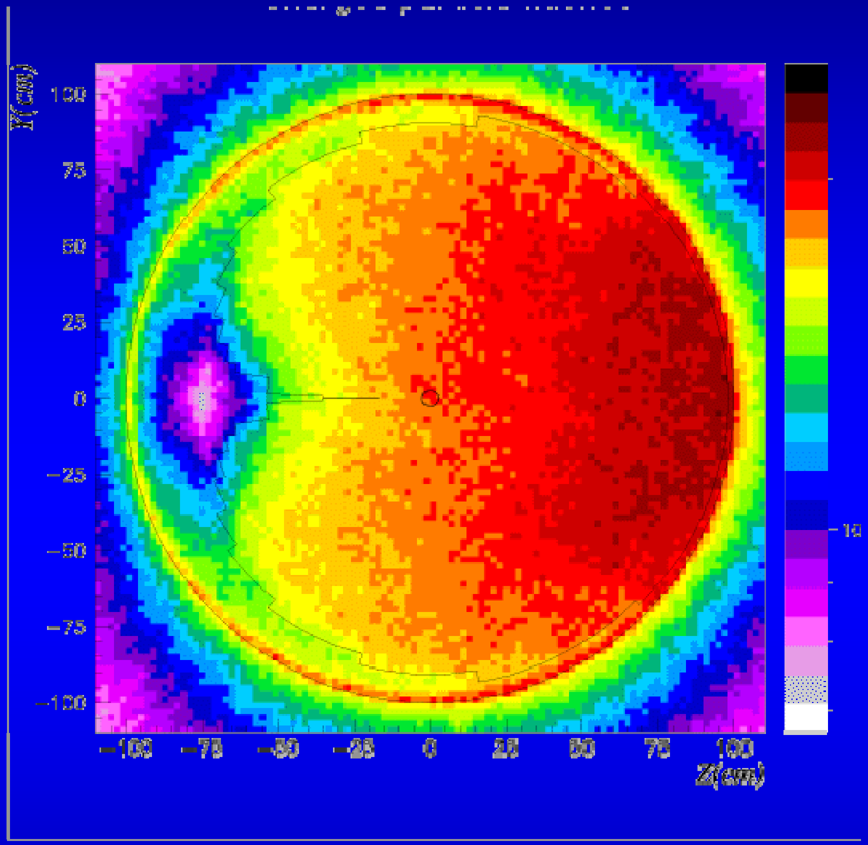
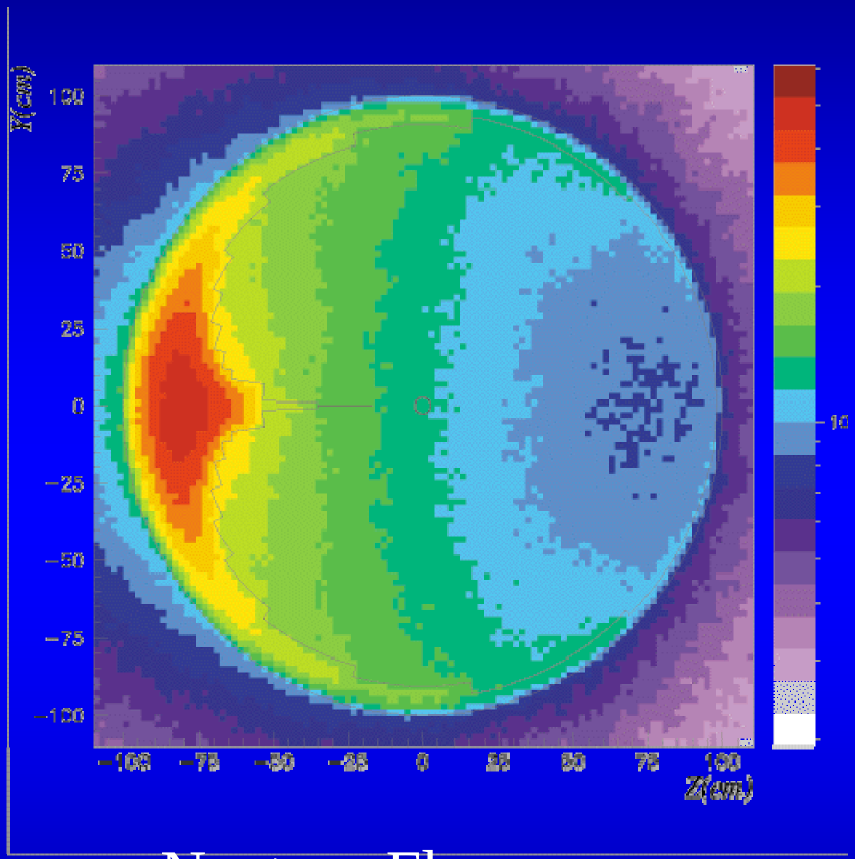
GOLEM Voxel Phantom in FLUKA

FLUKA MIR TPEC Simulations



Charged Particle Fluences

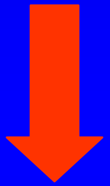


Neutron Fluences

(Note the albedo fluences outside of the phantom…)

Future developments

Further validation of the FLUKA Monte Carlo code in space radiation protection problems with simple shielding geometry



Repetition for more realistic geometries of shielding and spacecraft

Ultimately, we will need to assess the risk from this kind of radiation field, and that is a Biology Problem, not a physics challenge…

Annual GCR Doses

Al Shield (g cm^{-2})	Skin		Bone Marrow		Annual Effective Dose (cSv)
	Annual Dose (cGy)	Annual Dose Equiv. (cSv)	Annual Dose (cGy)	Annual Dose Equiv. (cSv)	
1970-71 Solar Maximum					
1	6.2	27.4	5.7	16.7	17.9
5	6.4	24.6	5.8	15.6	16.7
10	6.5	21.8	5.8	14.6	15.4

Courtesy of L. Townsend, US NCRP

Fatal Cancer Risk near Solar **Maximum***
(Males)

Slide Courtesy of F. Cucinotta, NASA/JSC

Mission	D, Gy	E, Sv	%REID	95% CI
		5 g/cm^2 Al		
Lunar (90 d)	0.45	0.69	2.7	[0.92,7.4]
Lunar (600 d)	0.63	1.21	4.4	[1.5,13.3]
Lunar (1000 d)	0.66	1.24	4.4	[1.5,13.0]
		20 g/cm^2 Al		
Lunar (90 d)	0.042	0.09	0.35	[0.11,1.2]
Mars (600 d)	0.22	0.54	2.0	[0.65, 6.8]
Mars (1000 d)	0.25	0.60	2.1	[0.69, 7.2]

**Phi=1100 MV (solar modulation) with Aug. 1972 SPE in transit*

Solar Min Annual GCR Dose

Al Shield (g cm^{-2})	Skin		Bone Marrow		Annual Effective Dose (cSv)
	Annual Dose (cGy)	Annual Dose Equiv. (cSv)	Annual Dose (cGy)	Annual Dose Equiv. (cSv)	
1977 Solar Minimum					
1	18.4	79.8	16.4	44.5	48.8
5	18.3	66.9	16.3	40.5	43.7
10	18.0	56.2	16.1	37.0	39.3

Courtesy of L. Townsend, US NCRP

Fatal Cancer Risk at Solar **Minimum**

(20 g/cm^2 Aluminum Shielding)

Mission	D, Gy	E, Sv	%REID	95% CI
		Males		
Lunar (90 d)	0.03	0.071	0.28	[0.09,0.96]
Mars (600 d)	0.36	0.87	3.2	[1.0,10.5]
Mars (1000 d)	0.41	0.96	3.4 (3.2)*	[1.1,11.0]
		Females		
Lunar (90 d)	0.03	0.071	0.34	[0.11,1.2]
Mars (600 d)	0.36	0.87	3.9	[1.2, 12.8]
Mars (1000 d)	0.41	0.96	4.1 (4.5)**	[1.4, 14.4]

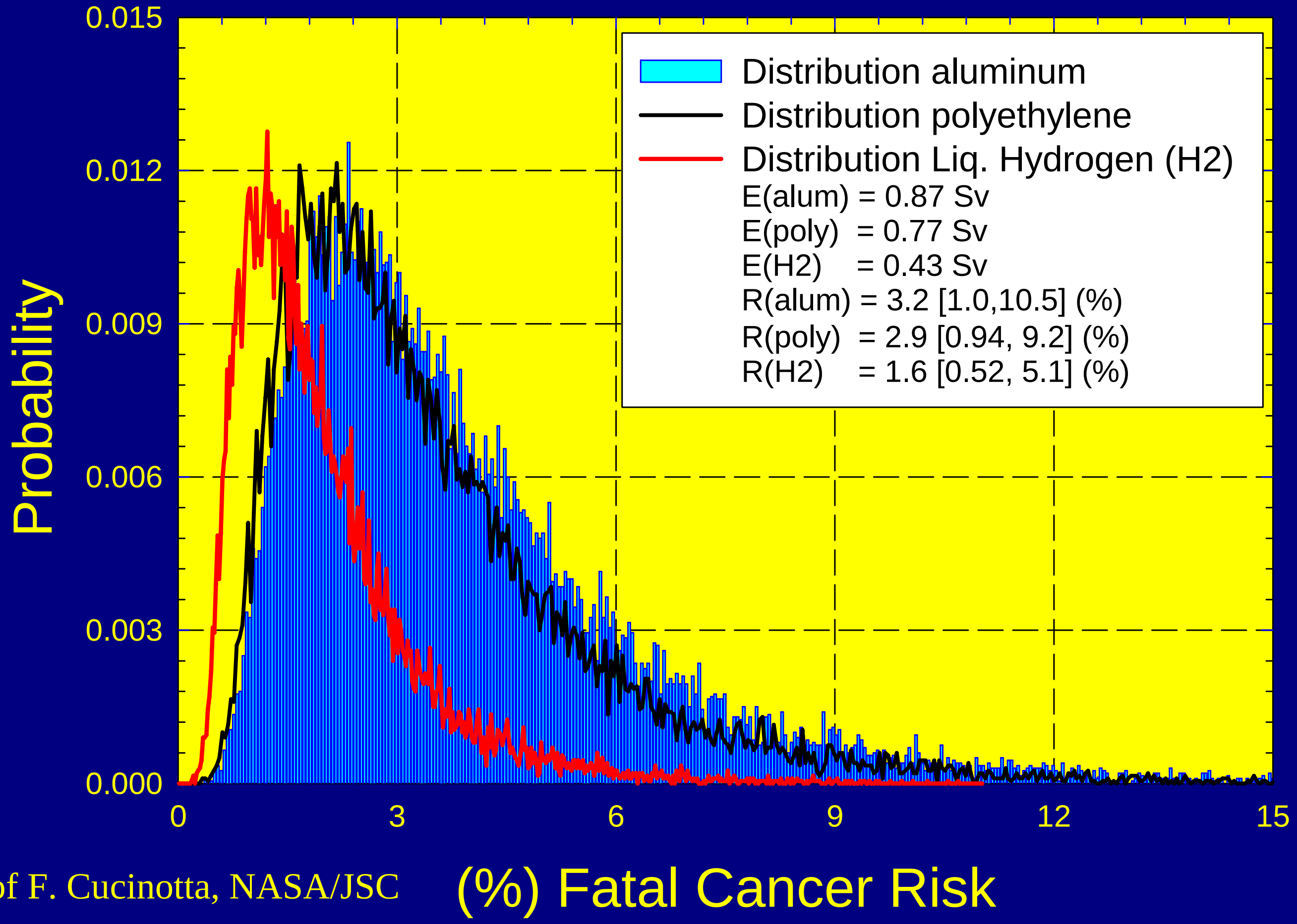
*Parenthesis exclude Prostate cancer; **Parenthesis LSS-report 12 (others report 13)

Slide Courtesy of F. Cucinotta, NASA/JSC

Material Shielding and GCR Risks

- Do materials rich in hydrogen and other light atomic mass atoms significantly reduce GCR risks?
- Possible advantages
  - High Z/A ratio increases stopping effectiveness
  - Higher projectile fragmentation per unit mass in hydrogen
  - Reduced target fragmentation per unit mass in hydrogen
- Possible physics limitations to GCR shielding approaches
  - GCR not stopped in practical amounts of shielding
  - Target fragmentation is largely short-range and correlated with projectile track
  - Target fragments in tissue occur for all materials and largely produced by relativistic ions not absorbed by shielding
- Do the biological uncertainties prevent us from knowing?

Significance of Shielding Materials for GCR
Spiral 4 (40-yr Males): 20 g/cm^2 Shields



Slide Courtesy of F. Cucinotta, NASA/JSC

GCR Risks

- **Clearly, annual doses < 20cGy present no acute health hazard to crews on deep space missions**
- **Hence only stochastic effects such as cancer induction and mortality or late deterministic effects, such as cataracts or damage to the central nervous system are of concern.**
- **Unfortunately, there are NO DATA for human exposures from these radiations that can be used to estimate risks to crews**
- **In fact, as noted yesterday, it is not clear that the usual methods of estimating risk by calculating dose equivalent are even appropriate for these particles**

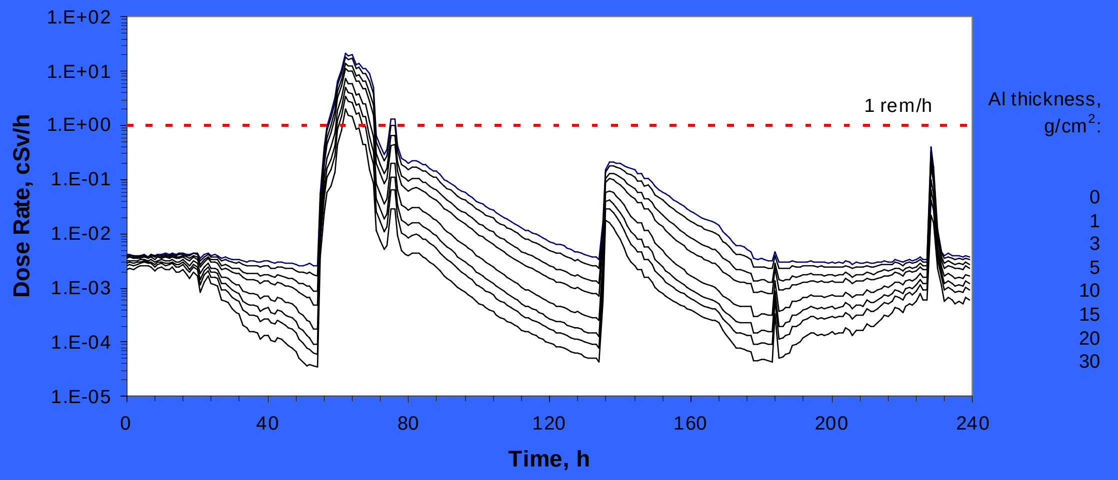
Courtesy of L. Townsend, US NCRP

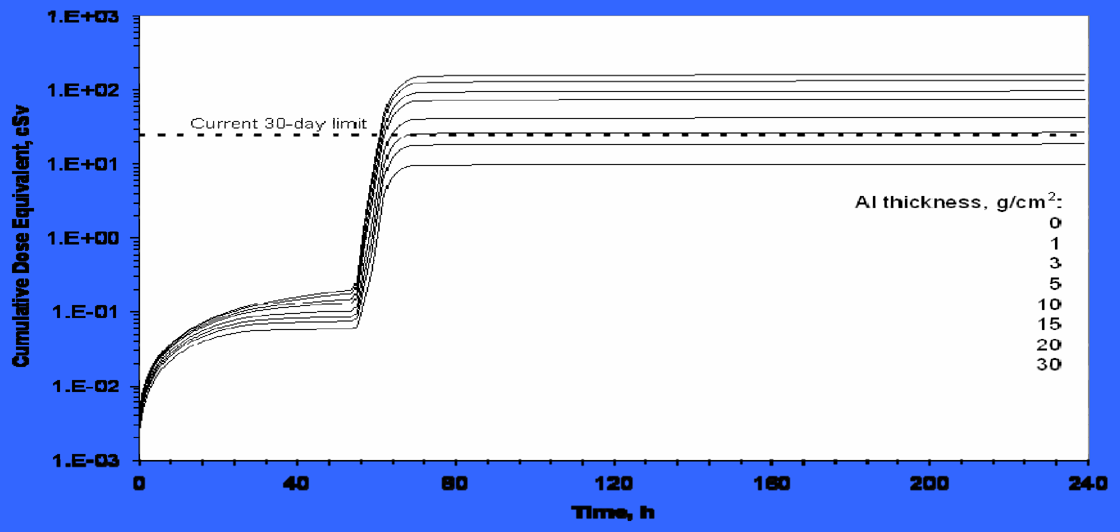
CONCLUSIONS - GCR

- Cancer risks for exploration missions
  - Risks from GCR are 2 to 5 percent mortality with upper 95% C.I. exceeding 10% for both males and females
    - Shielding will not significantly reduce GCR risks
    - Materials have unknown benefits because of biological uncertainties
  - **Risks from SPE are manageable with shielding approaches**
    - **Hydro-carbon shields offer a mass reduction over Aluminum shields of factor of two or more for acute effects from most SPE spectra**
    - **Benefits for cancer risk reduction are similar, however not significant for poly or similar materials again due to biological uncertainties**
- Uncertainty factors of 4-fold for GCR and 2.5 fold for SPE do not include several model assumptions
  - Uncertainties for Mars mission likely higher than estimated here
- Exploration vehicle shielding should focus on SPE not GCR

Slide Courtesy of F. Cucinotta, NASA/JSC

August 1972 Solar Particle Event





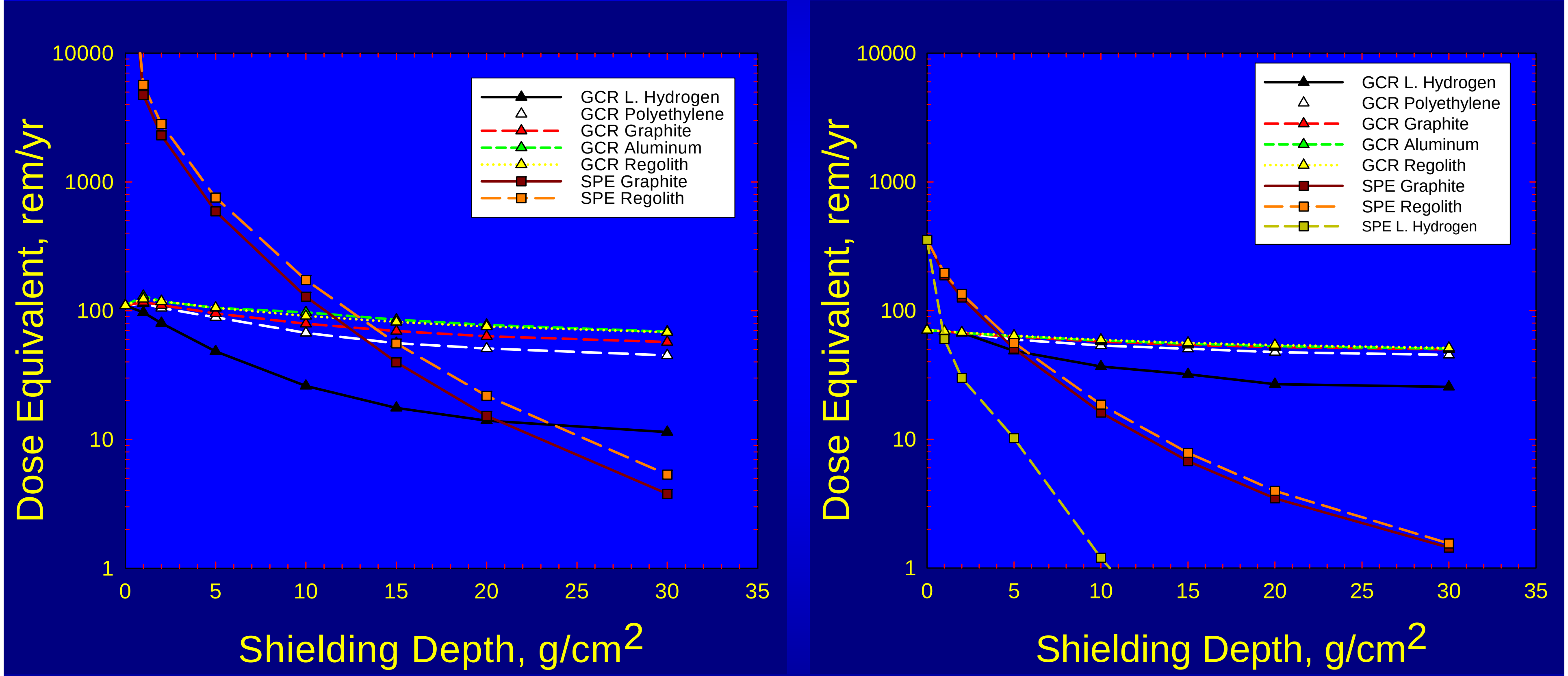
BFO Dose, rem (cSv)

Depth	Alum	Poly
5	61.1	39.1
10	20.9	10.7
20	4.57	1.83

Slide Courtesy of
F. Cucinotta, NASA/JSC

GCR and SPE Dose: Materials & Tissue

- GCR much higher energy producing secondary radiation



No Tissue Shielding

With Tissue Shielding

August 1972 SPE Slide Courtesy of F. Cucinotta, NASA/JSC

August 1972 SPE - comparison to NCRP limits

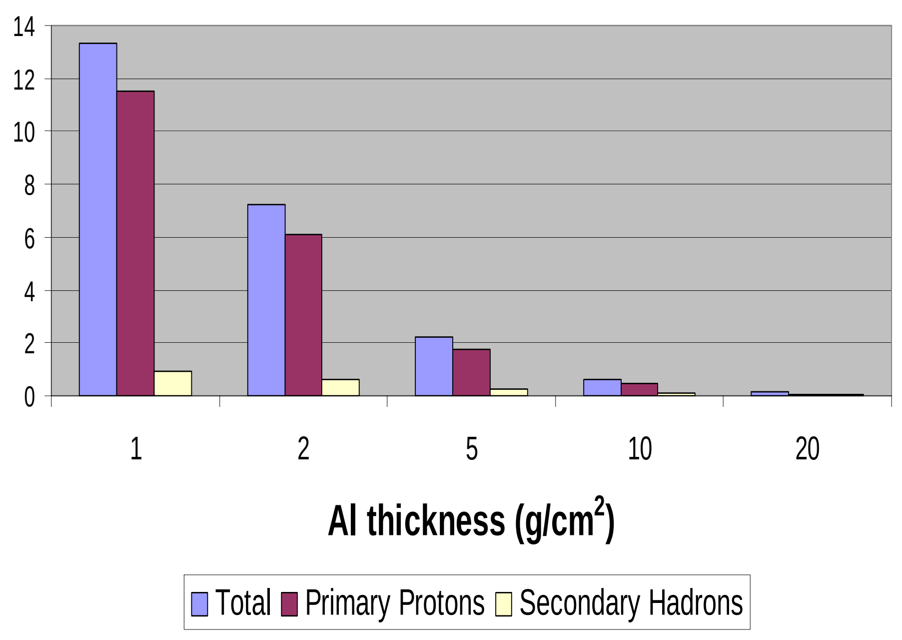
Al shield	**Skin**		**Lens**		**BFO**	
(g/cm^2)	*Erma*	*Golem*	*Erma*	*Golem*	*Erma*	*Golem*
1	**13.31**	**11.63**	**6.89**	**8.01**	**1.80**	**2.76**
2	**7.25**	**6.57**	**4.90**	**5.81**	**1.32**	**1.95**
5	**2.23**	**2.11**	**1.60**	**1.79**	**0.62**	**0.88**
10	***0.62***	***0.60***	***0.56***	***0.42***	***0.25***	**0.33 !!!**

NCRP limits for 30 days LEO missions: 1.5, 1.0 and 0.25 Gy-Eq for skin, lens and BFO, respectively ⇒ a 10 g/cm^2 Al storm shelter would provide adequate protection

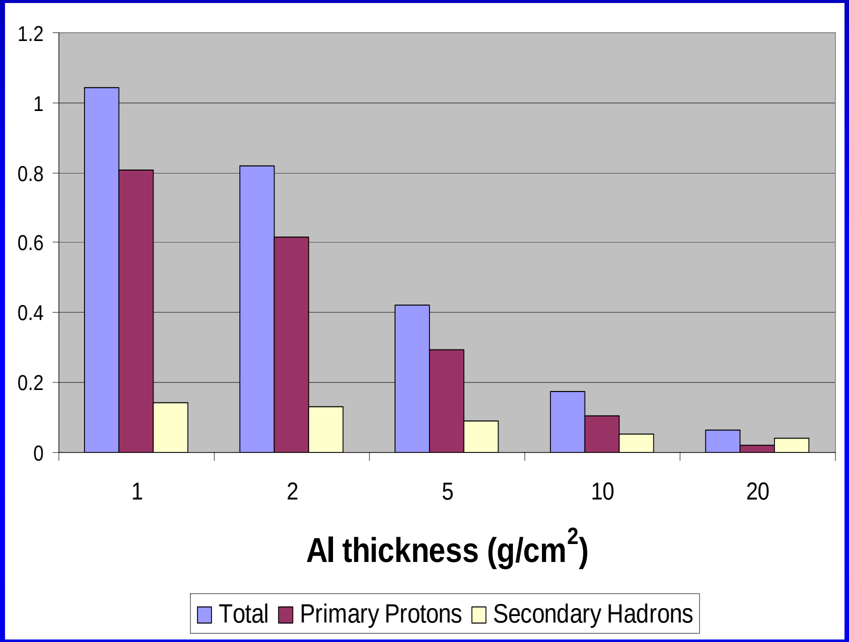
Courtesy of F. Balarini

August 1972 SPE - skin vs. internal organs

Equivalent dose to skin (Sv)



Equivalent dose to liver (Sv)



- much lower doses to liver than to skin (e.g. 1.0 vs. 13.3 Sv behind 1 g/cm^2 Al)
- larger relative contribution of nuclear reaction products for liver than for skin (e.g. 14% vs. 7% behind 1 g/cm^2 Al)

Courtesy of F. Balarini

Aug. 1972 and Oct. 1989 SPEs -Effective Dose (Sv)

Al shield	**August 1972** ***(Erma)***			**October 1989** ***(Erma)***		
(g/cm^2)	**E**	**E***	**E^*_{NASA}**	**E**	**E***	**E^*_{NASA}**
1	**2.04**	**1.35**	**1.31**	**1.11**	**0.78**	**0.78**
2	**1.43**	**0.95**	**0.94**	**0.79**	**0.55**	**0.58**
5	**0.63**	**0.43**	**0.52**	**0.42**	**0.30**	**0.33**
10	**0.23**	**0.17**	**0.27**	**0.20**	**0.15**	**0.18**

Courtesy of F. Balarini

- large contribution (33-50%) from gonads, especially with small shielding
- E* values (by neglecting gonads) very similar to those calculated with the BRYNTRN code and the CAM phantom *(Hoff et al. 2002, J. Rad. Res. 43)*

Conclusions - SPEs

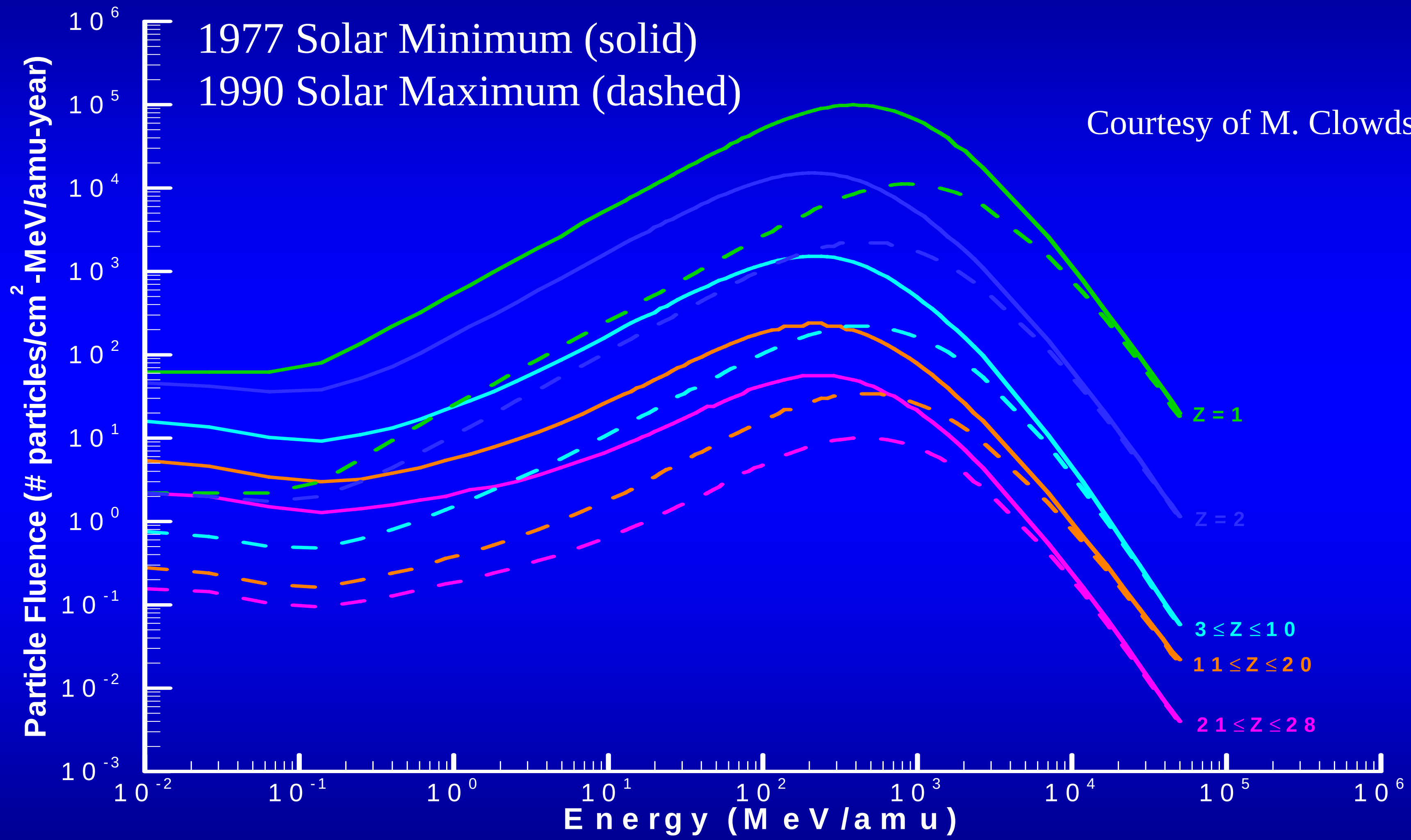
- calculation of:
  - dose decrease with increasing shielding
  - differences between internal organs and skin
  - relative contribution of primary protons and secondaries
  - contribution to effective dose from gonads
- Concludes that in case of an SPE similar to the August 1972 event, a 10 g/cm^2 Al storm shelter should allow us to respect the 30-days NCRP limit.

Courtesy of F. Balarini

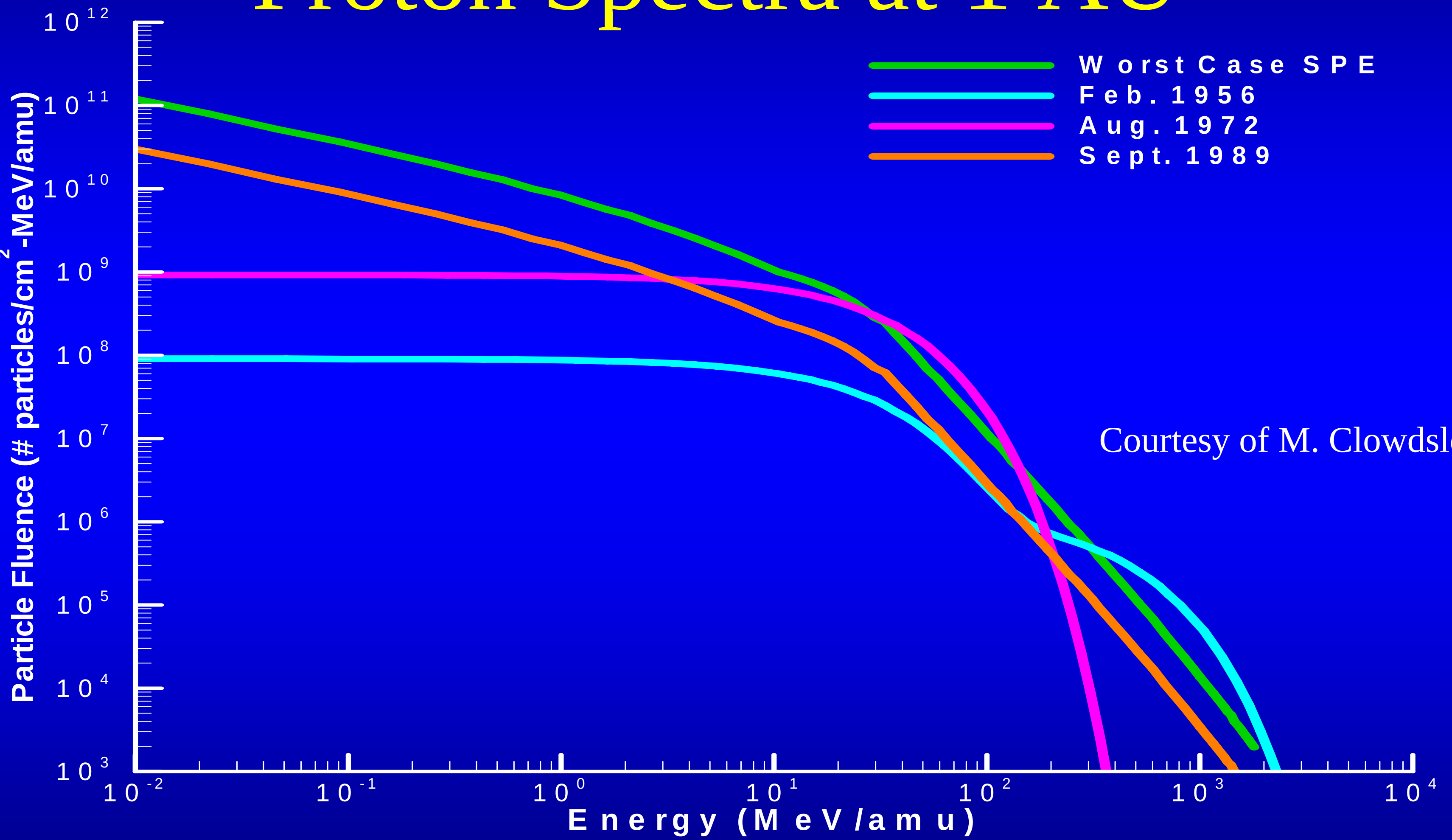
Modeling Lunar & Martian Surface Radiation Environments

- We need to start with the Free Space Fluences
- For the Moon, we can just calculate the albedo produced by the impact of the primary fluences and add one half the free space fluence to the albedo.
- For Mars, we have to propagate the free space fluence through the atmosphere to and into the surface materials. Then examine the field near and underneath the surface including all secondaries…

Free Space GCR Environments at 1 AU

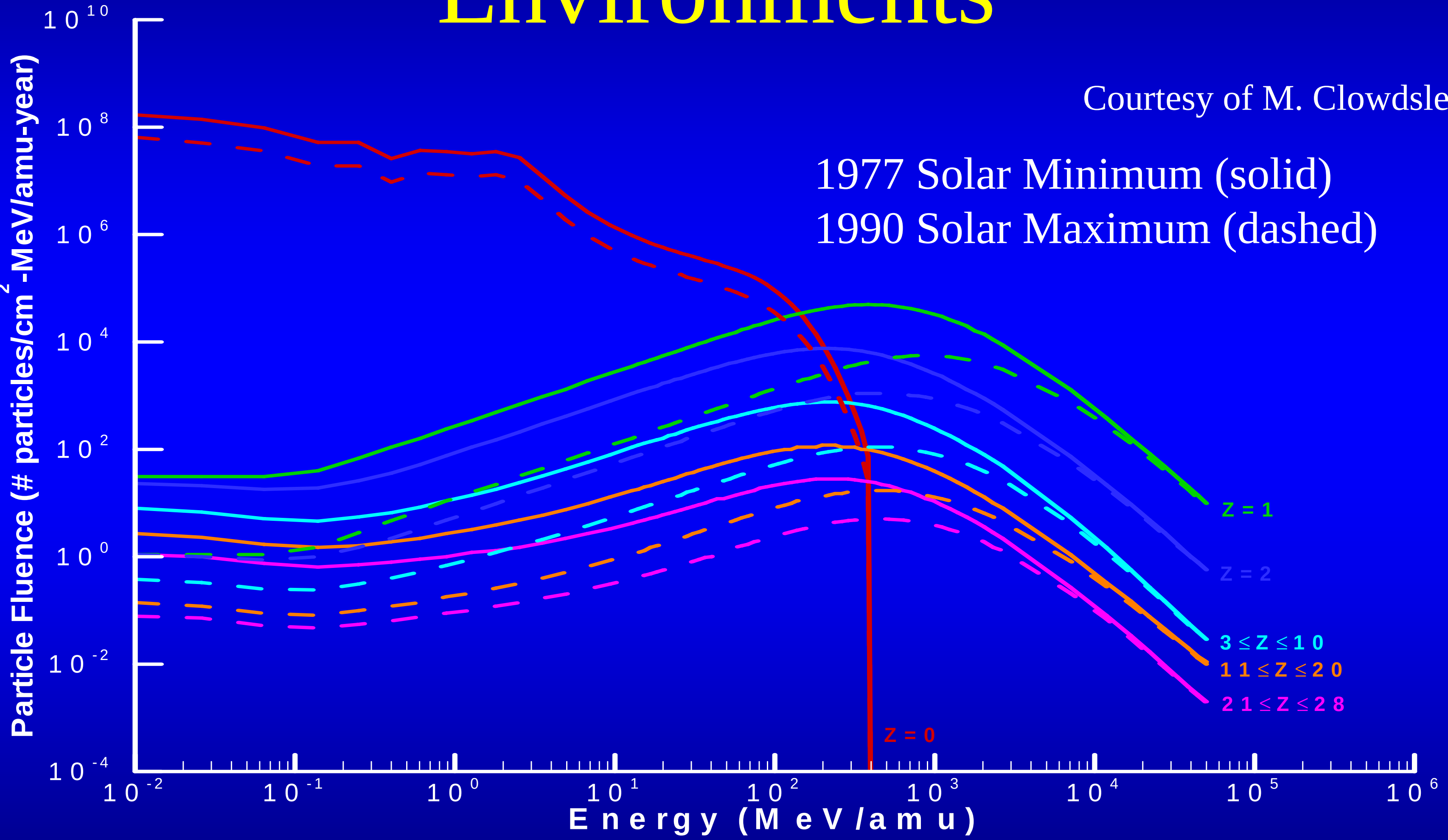


Free Space Solar Particle Event Proton Spectra at 1 AU



Courtesy of M. Clowdsley

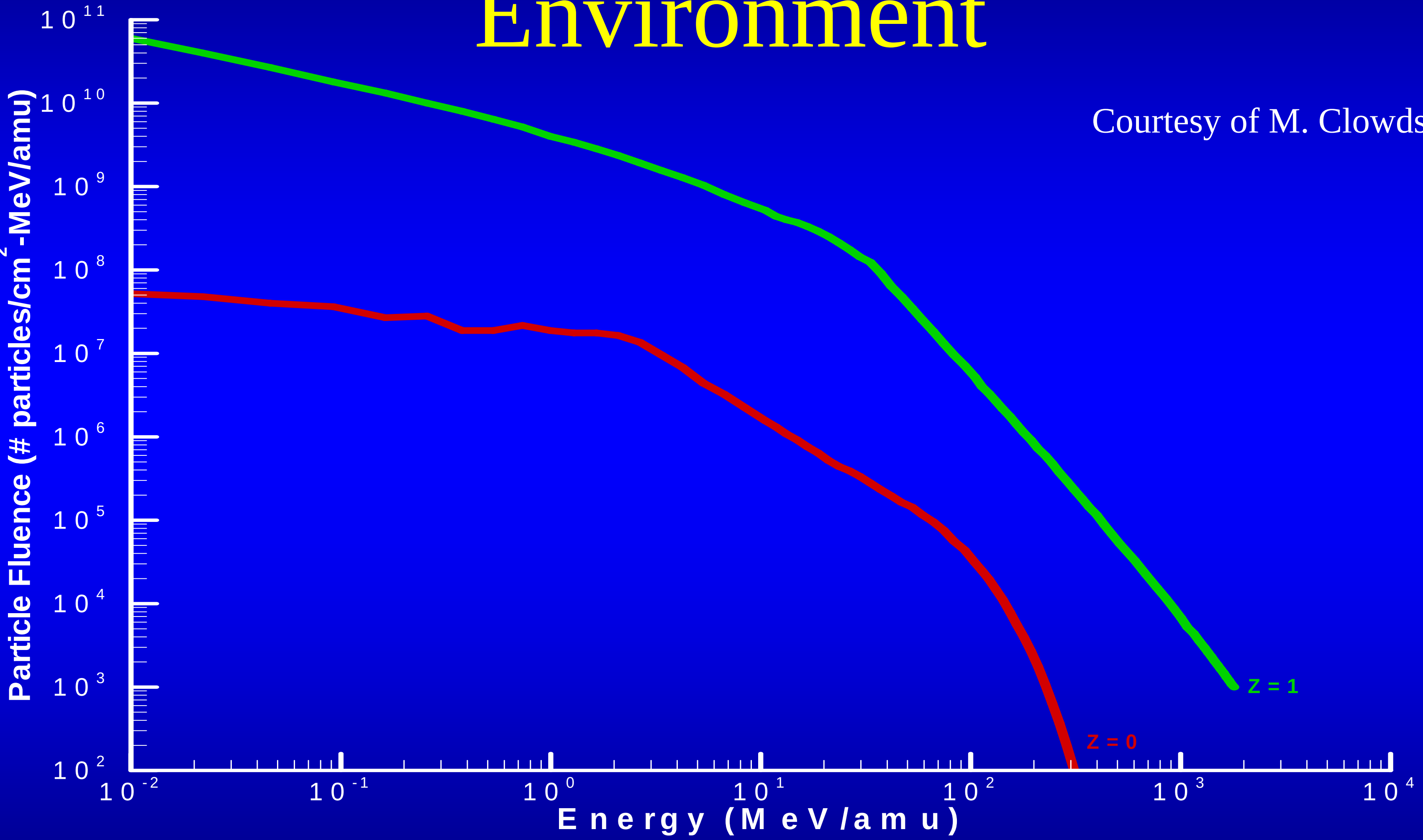
Lunar Surface GCR Environments



Courtesy of M. Clowdsley

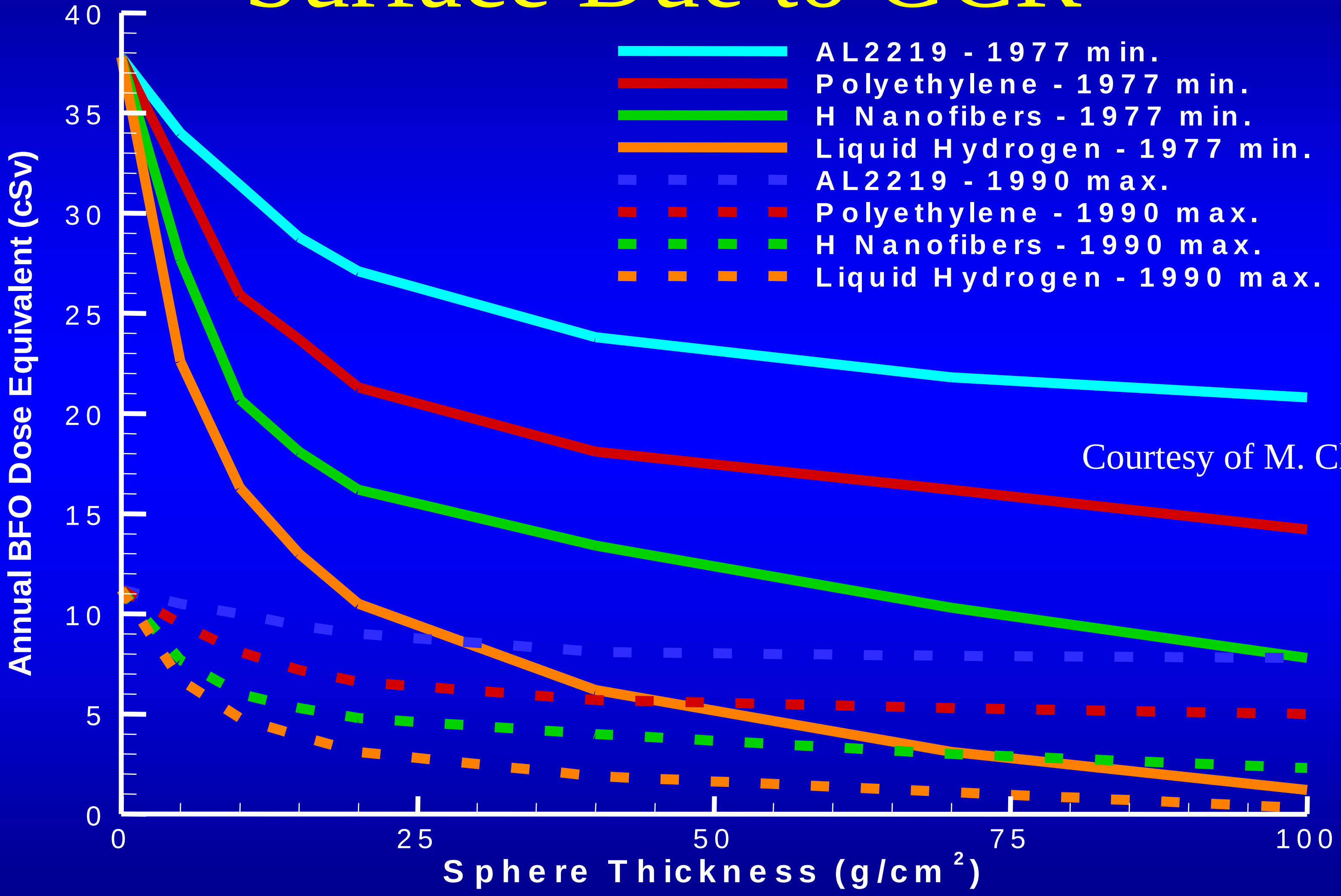
1977 Solar Minimum (solid)
1990 Solar Maximum (dashed)

Lunar Surface “Worst Case SPE” Environment

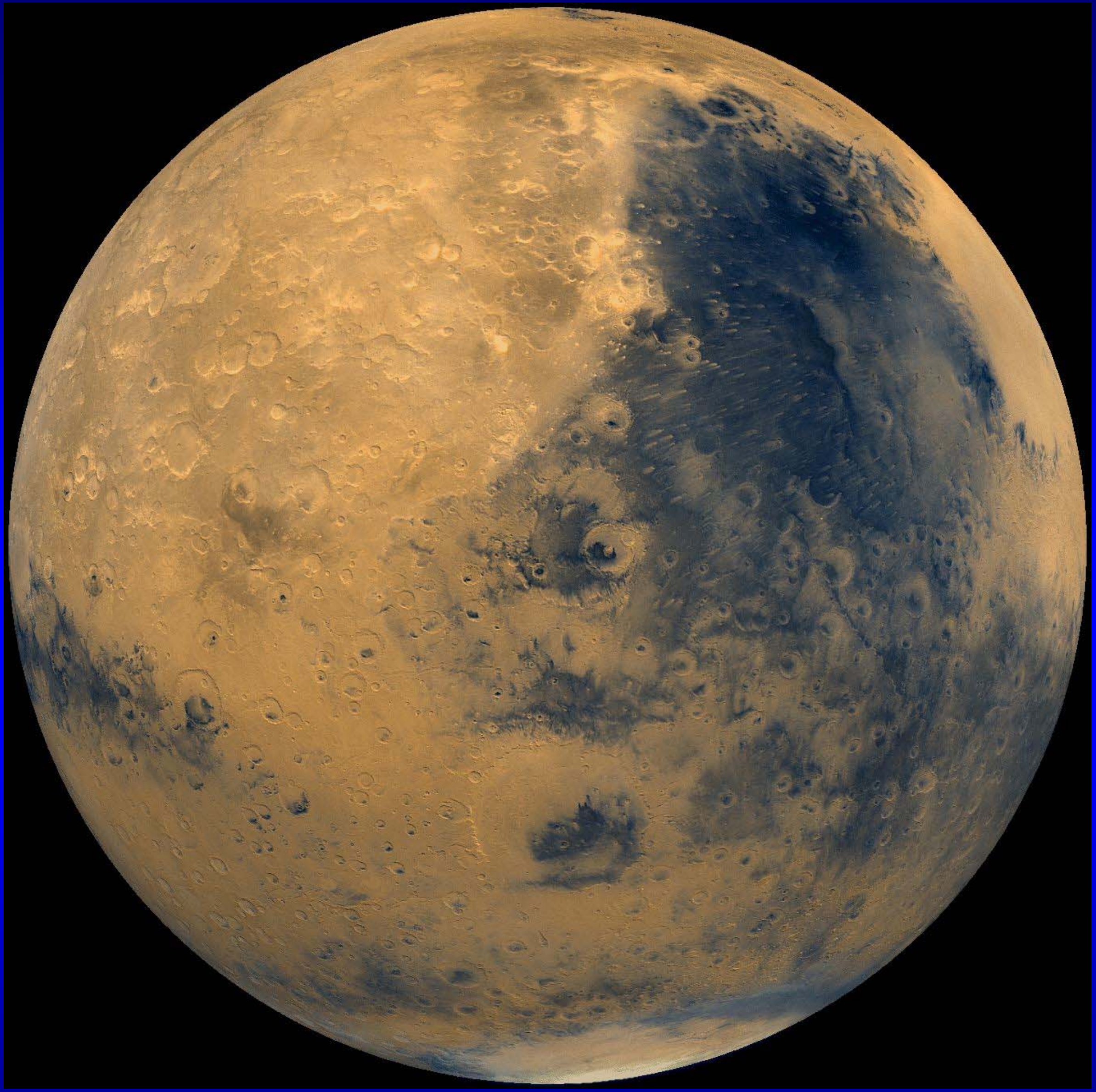


Courtesy of M. Clowdsley

Dose Equivalent on Lunar Surface Due to GCR



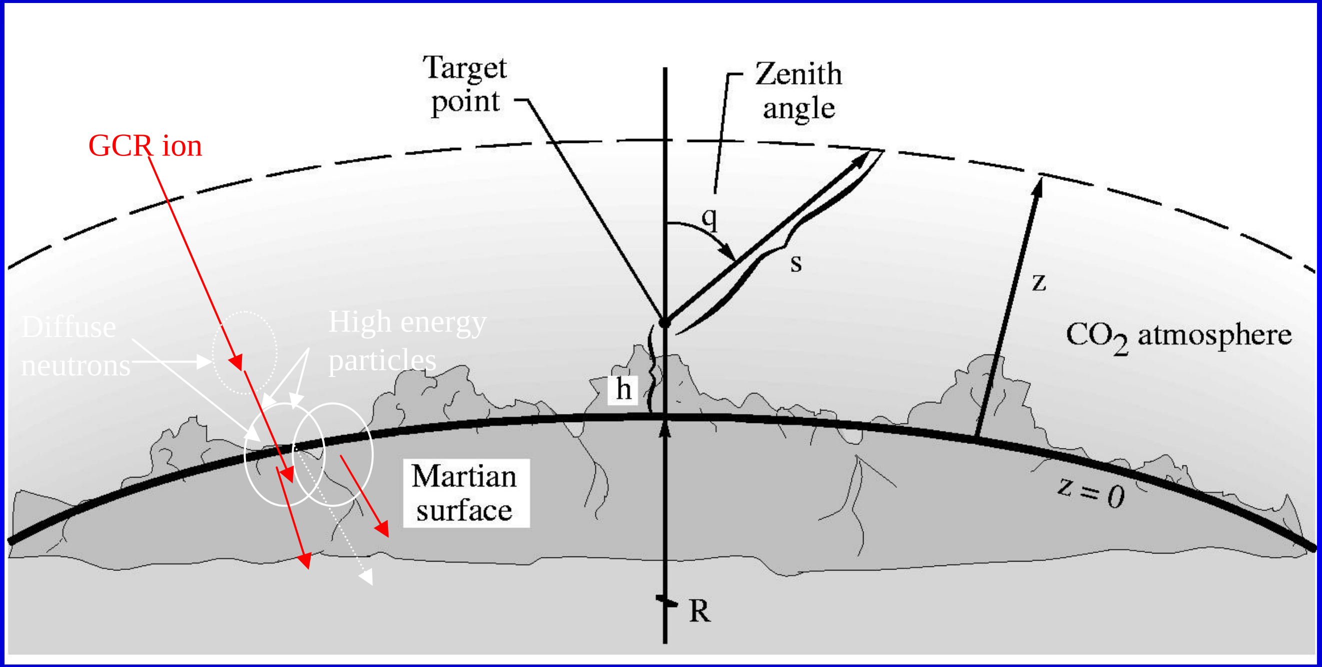
Courtesy of M. Clowdsley

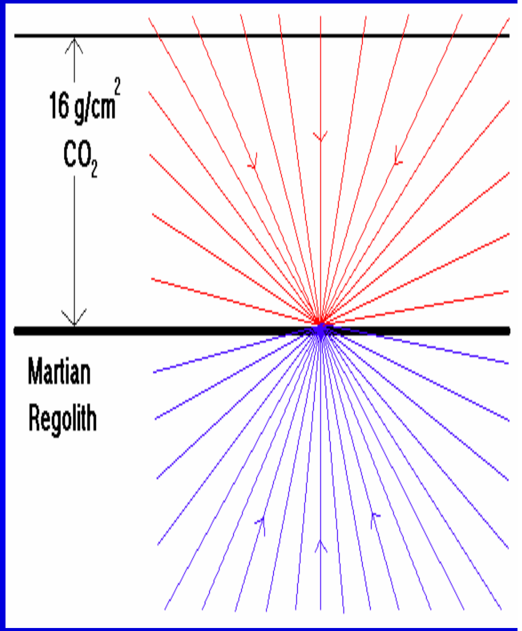


Modeling the Martian Surface Radiation Environment

Mars Induced Fields

Planetary Surface Material and Atmosphere





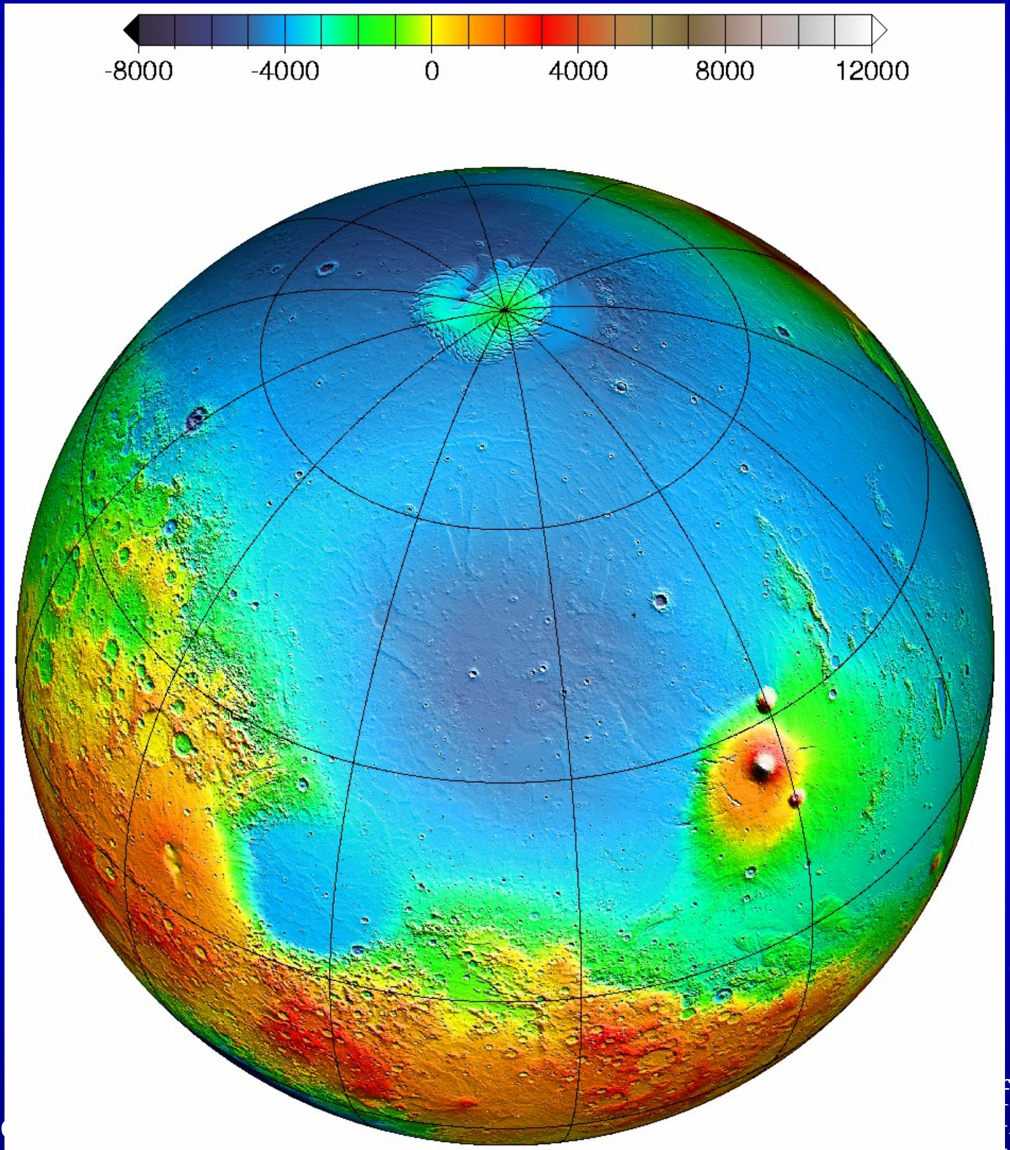
~15% of the primary GCR flux reaches the Martian Surface…

(From Simonsen et al.)

Courtesy of M. Clowdsley

Neutron albedos must be included in dose estimates…

Mars Surface Environment

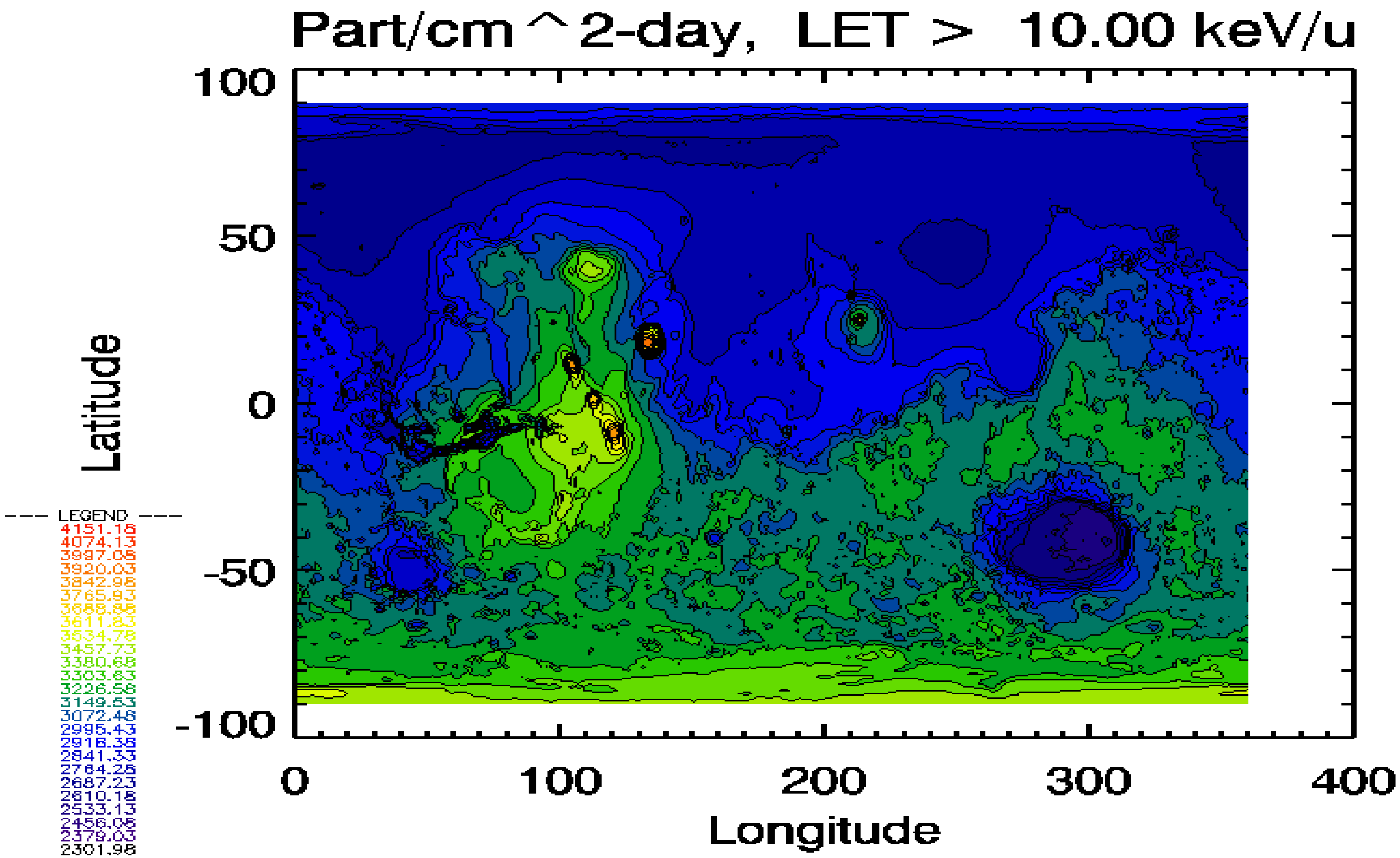


Courtesy of M. Clowdsley

Mars Surface Mapping

Charged Ions – 1977 Solar Minimum

Courtesy of M. Clowdsley

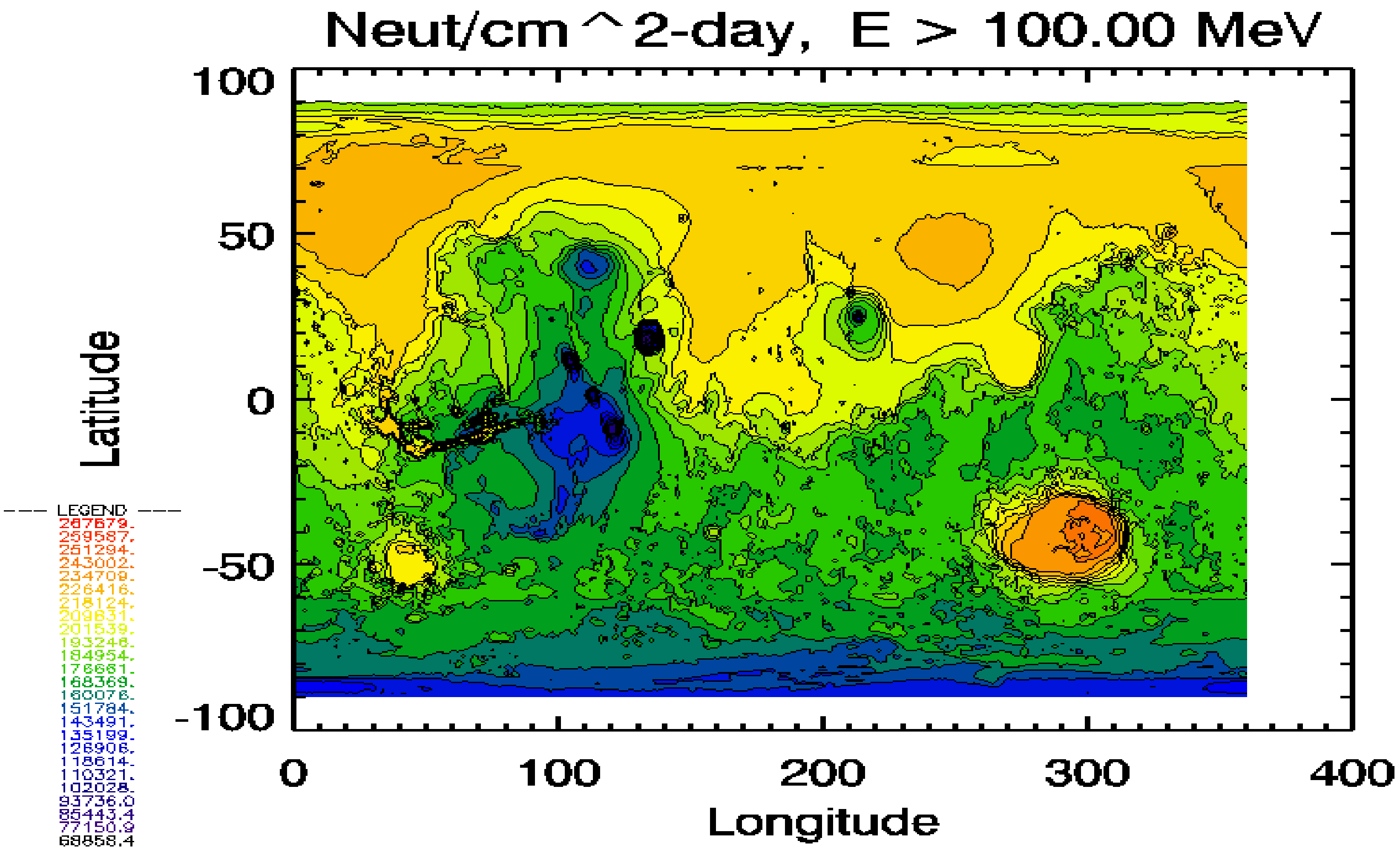


from Space Ionizing Radiation Environment and Shielding Tools (SIREST) web site http://sirest.larc.nasa.gov

Mars Surface Mapping

Neutrons – 1977 Solar Minimum

Courtesy of M. Clowdsley

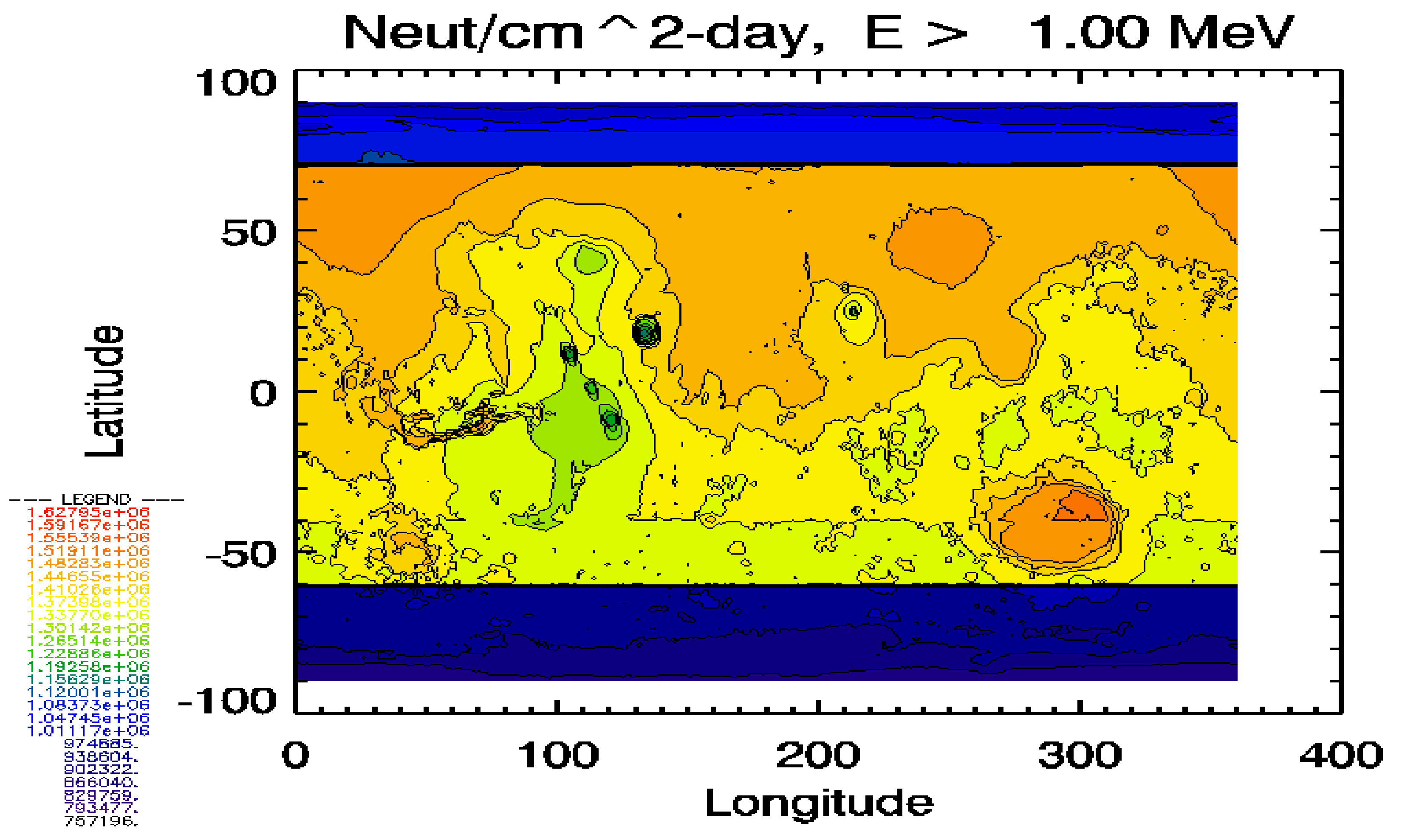


from Space Ionizing Radiation Environment and Shielding Tools (SIREST) web site http://sirest.larc.nasa.gov

Mars Surface Mapping

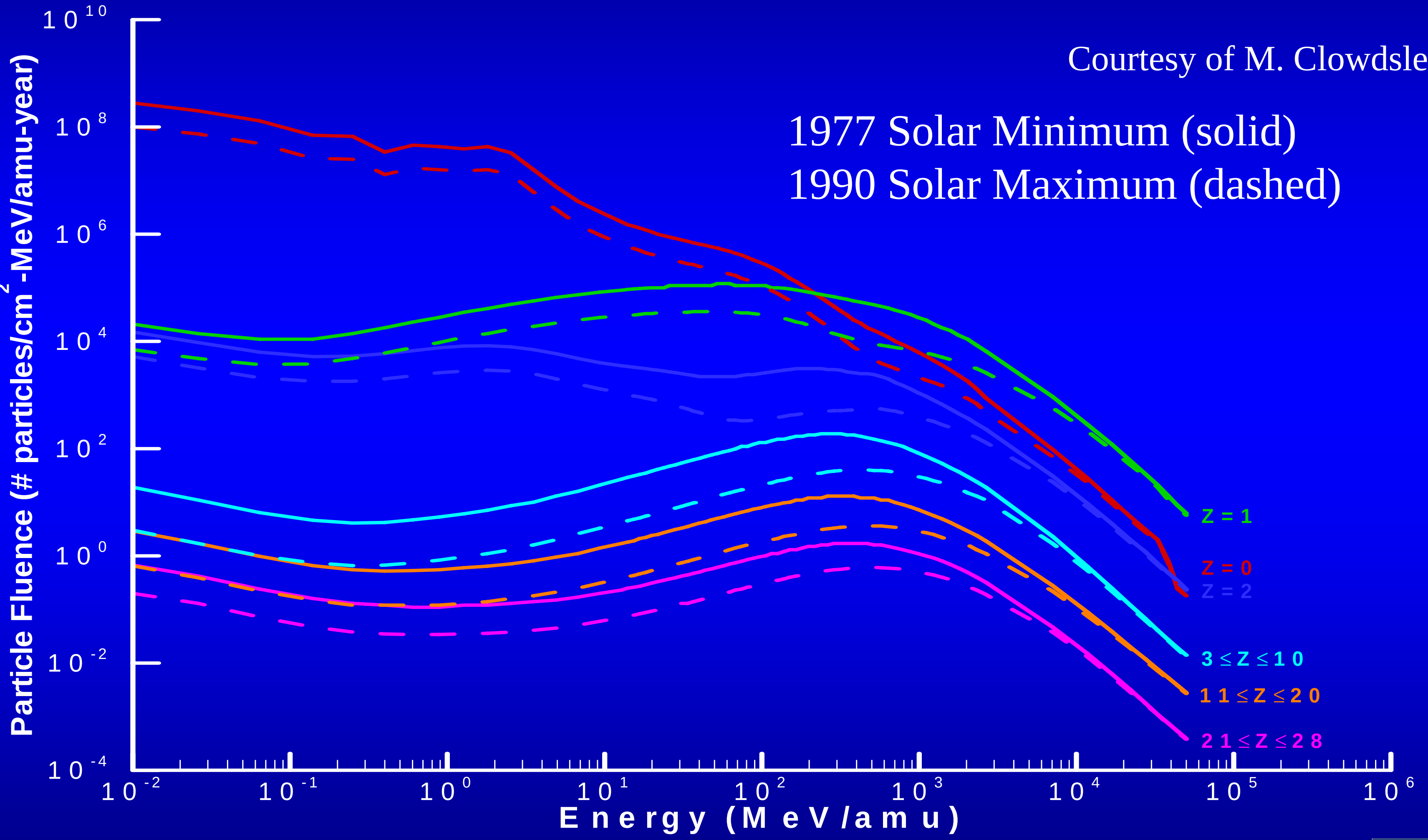
Low Energy Neutrons – 1977 Solar Minimum

Courtesy of M. Clowdsley

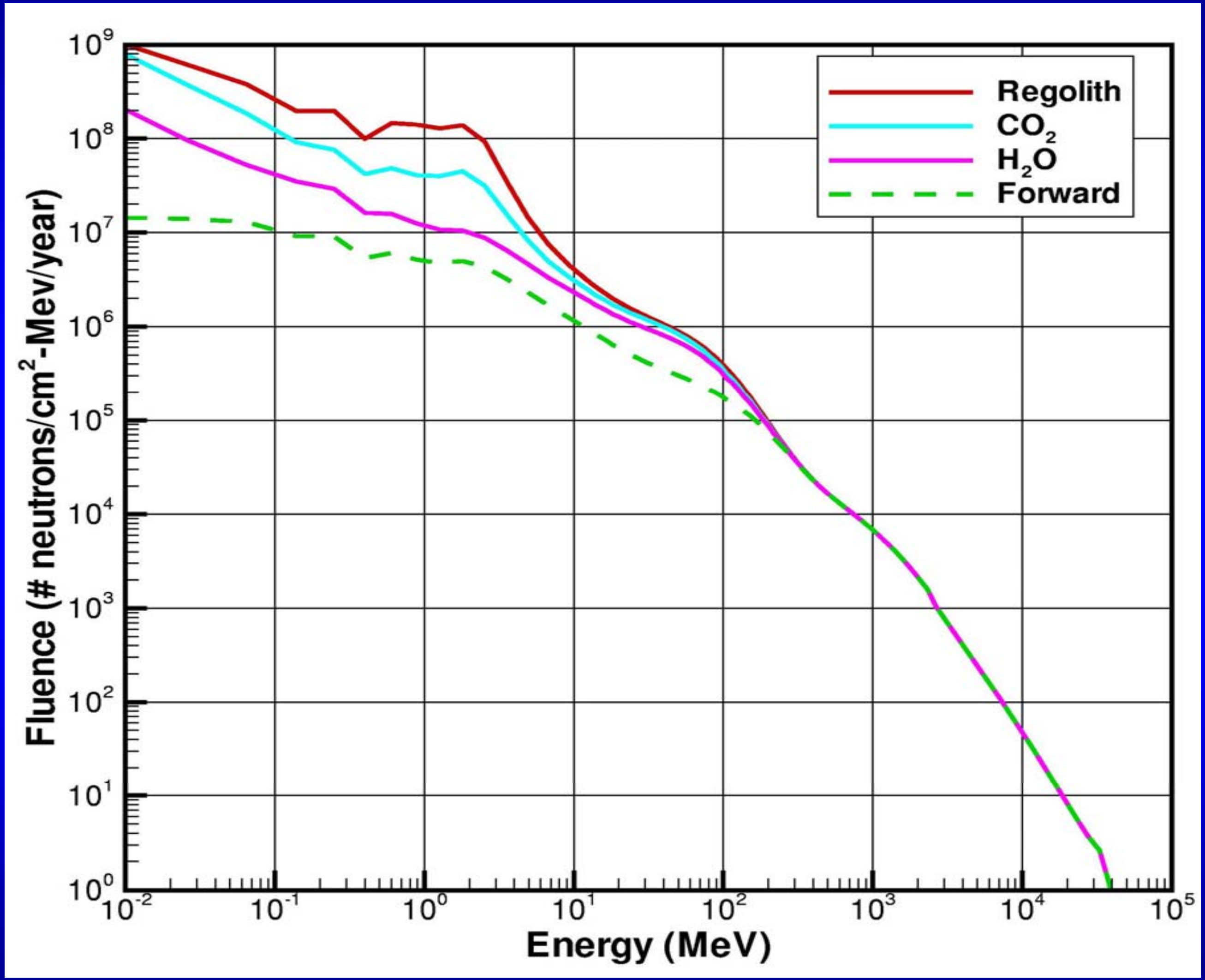


from Space Ionizing Radiation Environment and Shielding Tools (SIREST) web site http://sirest.larc.nasa.gov

Mars Surface GCR Environments

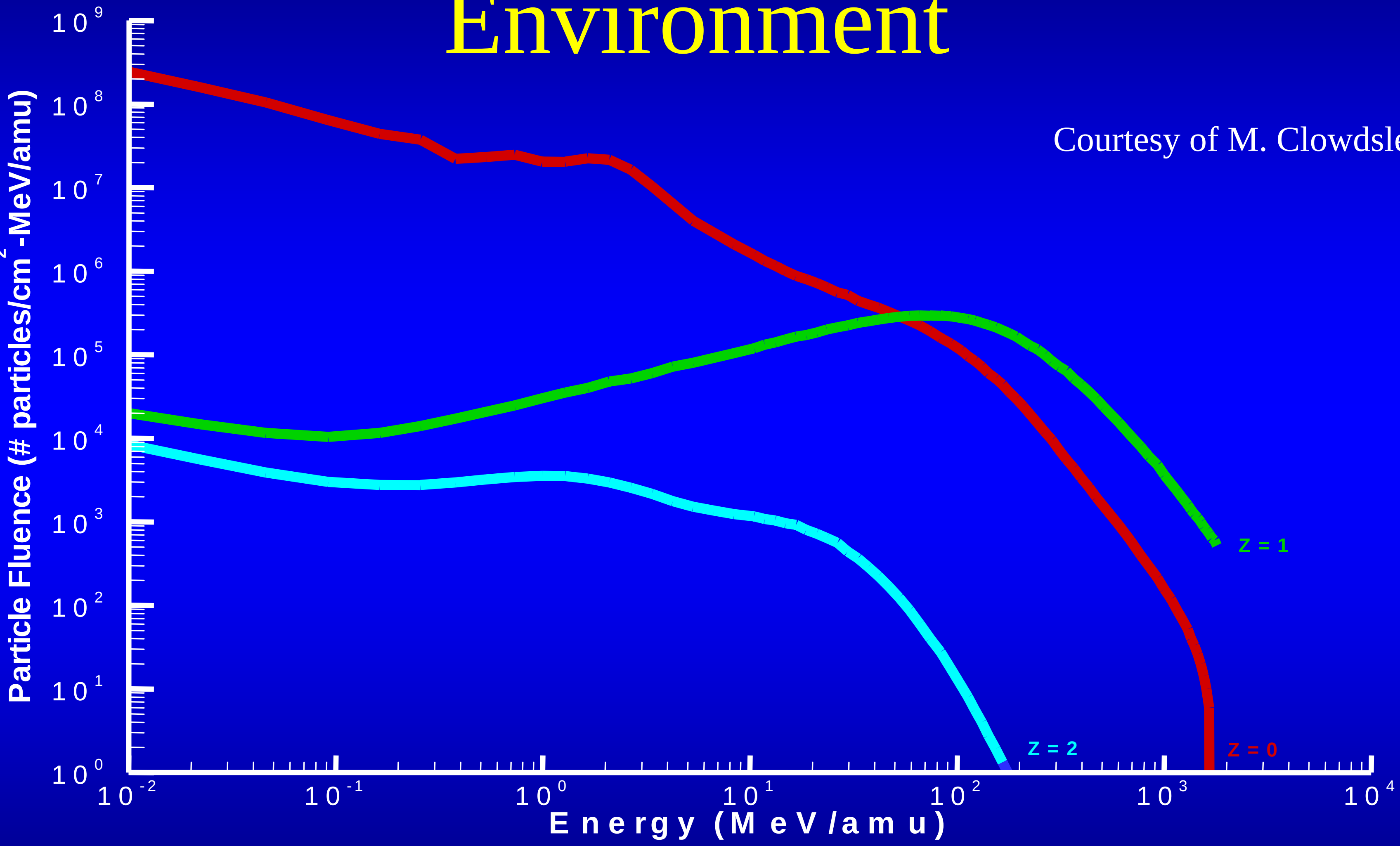


Mars Surface Neutrons



Courtesy of M. Clowdsley

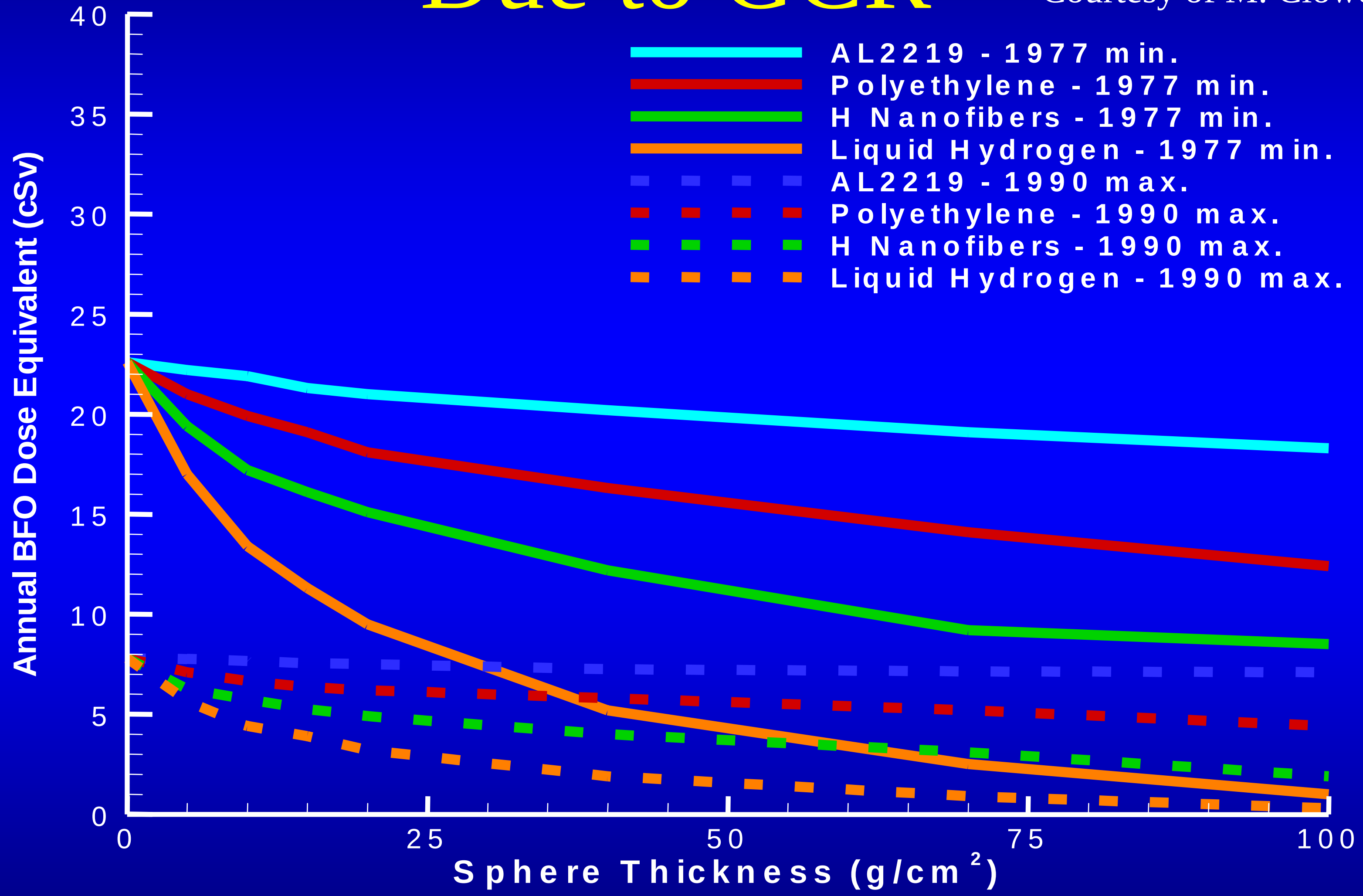
Mars Surface "Worst Case SPE" Environment



Courtesy of M. Clowdsley

Dose Equivalent on Mars Surface Due to GCR

Courtesy of M. Clowdsley



Summary and Conclusions

- SPE’s can probably be shielded against
  - …But only in “Storm-Shelters” or Protected Habitats on planetary surfaces.
  - Problematic during EVAs and in thinly shielded surroundings.
- GCR is more difficult to protect against in terms of keeping the Chronic Dose acceptable during a long mission, but enough shielding or a shorter mission could work…

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