The rough guide to the Moon and Mars

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ROUGH GUIDES

THE ROUGH GUIDE to

The Moon
& Mars

The Rough Guide to the Moon and Mars

Mike Lockwood and Mike Hapgood rough out essential physics for the astronaut intending to arrive alive.

Several space agencies around the world, notably in the US and China, are planning to return humans to the Moon, with a view to being the first also to visit Mars. The reasons are a complex mix of national prestige, economic spin-offs, technological capability and inspiration, in particular of potential young scientists and technologists. It is impossible to quantify the benefits that have accrued to the US in the decades following the Apollo lunar missions – but to doubt that they were of fundamental importance is to fail to understand the technological drivers of modern economies.

Two people who well understood both the aspirational and inspirational importance of manned space travel were John F Kennedy and his brilliant speechwriter Ted Sorensen. In his speech at Rice University on 12 September 1962, Kennedy delivered the famous words: "We choose to go to the Moon. We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard." The end of that speech acknowledged the hazards known at the time: "Many years ago the great British explorer George Mallory, who was to die on Mount Everest, was asked why did he want to climb it. He said, 'Because it is there.' Well, space is there, and we're going to climb it, and the Moon and the planets are there, and new hopes for knowledge and peace are there. And, therefore, as we set sail we ask God's blessing on the most hazardous and dangerous and greatest adventure on which man has ever embarked."

Since that speech, surely among the most significant in the history of humankind, we have achieved a much better understanding of both the inspirational power and the tremendous hazards of space travel. We know of primitive bacteria that might be able to tolerate the energetic particles that exist outside the twin protective shields of Earth's atmosphere and magnetic field: *Deinococcus radiodurans* can readily withstand radiation doses 500 times larger than a fatal dose for a human (Levin-Zaidman *et al*. 2003). We know of no similarly robust complex lifeforms.

ABSTRACT

Space is a dangerous place for humans, once we step beyond the protection of Earth's atmosphere and magnetic field. Galactic cosmic rays and bursts of charged particles from the Sun damaging to health happen with alarming frequency – the Apollo astronauts were very lucky. Understanding the physics of radiation from distinct sources in space will be useful to help future space voyagers plan journeys in greater safety, and produce effective shields for these unavoidable events on journeys to Mars or beyond.

We need to understand the mechanisms responsible for the acceleration of harmful particles and of their propagation through the heliosphere in order to develop systems and procedures to minimize the health risks of space travel. But it is also important to understand how a parent star and the atmosphere and magnetic field of a planet control the surface particle environment, in order to identify planets that could support advanced lifeforms. It is often assumed that the atmosphere is such an efficient shield for the surface that the magnetic field contribution is insignificant (e.g. Waddington 1967). Indeed, for the present-day Earth, cosmic surface radiation is limited to a very low flux of muons; heliospheric and geomagnetic modulations become factors for cosmic radiation doses only on high-altitude aircraft (Shea and Smart 2001). However, it is thought that the magnetic field has at least a partial role in preventing the loss of the atmosphere of an Earth-like planet (e.g. Dehant *et al*. 2007) and hence the atmospheric shield would also be weaker without the magnetic shield (Grießmeier *et al*. 2005). Furthermore, because oxygen has a strong modifying influence on radiogenic mutation rates, changes in the oxygen abundance during the history of the Earth means that radiogenic mutation rates in organisms have been up to 2.5 times greater than at present for most of the history of life (Karam *et al*. 2001). Such factors give credence to the idea that recent observations of cycles in Earth's fossil diversity over the past 542 Myr with period 62±3 Myr are induced by cosmic rays (Medvedev and Melott 2007). Studies of the importance of Earth's atmospheric and magnetic GCR shields for sustaining and developing life are likely to play an important part in answering the question that science is increasingly reclaiming from metaphysics: "Are we alone?"

The radiation hazard in space

The cover of Douglas Adams' wonderful *Hitchhiker's Guide to the Galaxy* carries (in large and friendly letters) the words "Don't Panic". While this is undoubtedly useful advice under almost all circumstances, it may not be specific enough for the space traveller. He or she will need to know all about the radiation health hazard in interplanetary space. The two main concerns are GCRs and SEPs. GCRs are galactic cosmic rays: particles ranging from protons to iron and heavier ions, moving at almost the speed of light having been accelerated, for example, at the shock fronts generated by supernovae explosions. SEP stands for solar energetic particle, some of which come directly from solar flares, but most are generated in the heliosphere at shock fronts ahead of CMEs (coronal mass ejections, e.g. Reames *et al*. 1996, Gopalswamy *et al*. 2 nd CIRs (co-rotating interaction regions, e.g. Mason *et al*. 1997). It is already clear that the *Rough Guide* will need a good glossary of TLAs – Three-Letter Acronyms – for in the *Hitchhiker's Guide*, SEP stands for Somebody Else's Problem. To those of us who remain safely in Earth's biosphere, SEPs are indeed both invisible and somebody else's problem, but to the space traveller they, like GCRs, pose a real danger.

The risks associated with GCRs and SEPs are quite different. For GCRs, chronic exposure time is important, whereas SEPs are acute bursts. Most of the biological dose (see "Radiation doses and risks" p6.12) for GCRs comes from the heavy ion component of the mass spectrum, not the protons. Heavy ions can generate a large track of damage in biological material and also generate many damaging secondary neutrons and ions in surrounding material (Terato and Ide 2004, Antonelli *et al*. 2004). On the surface of the Moon, secondary neutrons (the lunar neutron albedo) increase the effective biological dose by 1.5% for SEPs and by between 14 and 24% for GCRs, at solar maximum and minimum respectively. The dose from GCRs is

Radiation doses and risks

It is important to clarify the measures and units of radiation dose. *Absorbed* (or "*physical*") dose D is the energy absorbed by unit mass of matter due to ionizing radiation. The SI unit of absorbed dose is the Gray (Gy), defined as $1\,J\,kg^{-1}$ (but it is also sometimes expressed in rads $= 0.01\,Gy = 1\,cGy$).

The *dose equivalent* (or *biological* dose, H) indicates the risk of occurrence of biological effects due to the absorbed dose. It is defined as the absorbed dose multiplied by the relative biological effectiveness (RBE) factor (Q), which accounts for the radiation type (i.e. the energy and mass spectra) and characteristics of the affected body organ: $H = Q \times D$. The SI unit of equivalent dose is the Sievert (but is sometimes given in rem $= 0.01\,Sv = 1\,cSv$). To put these units in context, $1\,cSv$ is roughly three years' dose in a typical environment on Earth's surface,

a routine chest X-ray image gives $0.01\,cSv$, and a CAT scan gives $4\,cSv$. It is important to consider not only the total dose but also the dose rate (in $Gy\,s^{-1}$). A number of procedures have been developed to compute the doses, dose rates and dose equivalents in space for a given organ of the human body, and it is common to consider the values for the skin, ocular lens, and blood-forming organs (for example, Townsend *et al.* 2003, 2006). Such doses are evaluated behind different levels of shielding (e.g. Ballarini *et al.* 2004), the minimum being $1\,gm\,cm^{-2}$ of aluminium, for a (thick) space suit which is the only protection during extra-vehicular activity (EVA). Doses quoted for events are integrals over the duration of the event and the corresponding integral of the particle flux is called the fluence.

There are no completely safe levels of

human exposure to ionizing radiations – we have to set thresholds to unacceptable risks. The limits for astronauts inside Earth's magnetosphere (i.e. in low Earth orbit – LEO) are currently set at $0.5\,Sv$ per year (with a lifetime limit that depends on age and sex) and are based on a 3% excess cancer mortality risk. This limit for LEO is an order of magnitude higher than the corresponding limit for terrestrial radiation workers, e.g. in nuclear power plants, because of the shorter career lengths for astronauts (generally assumed to be no more than 10 years). Although there are concerns about EVA (Johnson *et al.* 2005), the shielding required to ensure radiation is held below these limits is readily achieved for an LEO mission. Outside Earth's magnetic protection, the situation is very different (Townsend *et al.* 1992, Cucinotta *et al.* 2005).

relatively small, only around $18.5\,cGy$ per year behind $1\,gm\,cm^{-2}$ at solar minimum (when they are largest), of which only about $7\,cGy$ comes from protons (Townsend *et al.* 1992).

Dose and dose rate are, however, important for assessing acute radiation sickness from large SEP events. In these cases, despite the presence of higher mass ions in SEPs, protons are the bigger concern because their flux is so high and they penetrate shielding more readily. The dose received during an SEP event varies greatly and studies have looked at the "worst-case scenario", the biggest event that we believe has occurred in the past 400 years (discussed below). This analysis takes the spectral characteristics of SEP events in recent times and scales them according to the proton fluence derived from ice-sheet measurements (Stephens *et al.* 2005, Townsend *et al.* 2006). For the shielding of $1\,gm\,cm^{-2}$ of aluminium and one of the "harder" spectral shapes observed in recent events, this event could have given doses to the skin and bone marrow of up to $12\,Gy$ and $0.8\,Gy$, respectively, in low-Earth orbit, and $45\,Gy$ and $2.8\,Gy$ in interplanetary space. It may be that the largest fluence events do not have the hardest spectra, which would reduce these estimates (Townsend *et al.* 2006). Using an appropriate relative biological effectiveness, this is a typical skin dose equivalent of $67\,Sv$, i.e. 20 000 years' dose on Earth's surface!

Galactic cosmic rays

Galactic cosmic rays interact with the magnetic fields of the Sun and Earth. The open solar magnetic flux, F_S, is the total magnetic flux that is dragged out of the solar atmosphere by the solar wind and permeates the heliosphere. Structure

1: Model spectra of galactic rays in near-Earth interplanetary space, fitted to observations for four different values of the open solar flux, F_S. The black line gives the inferred spectrum in local interstellar space (LIS).

LIS
$F_S = 2 \times 10^{14}\,Wb$
$F_S = 2 \times 10^{14}\,Wb$
$F_S = 2 \times 10^{14}\,Wb$
$F_S = 2 \times 10^{14}\,Wb$
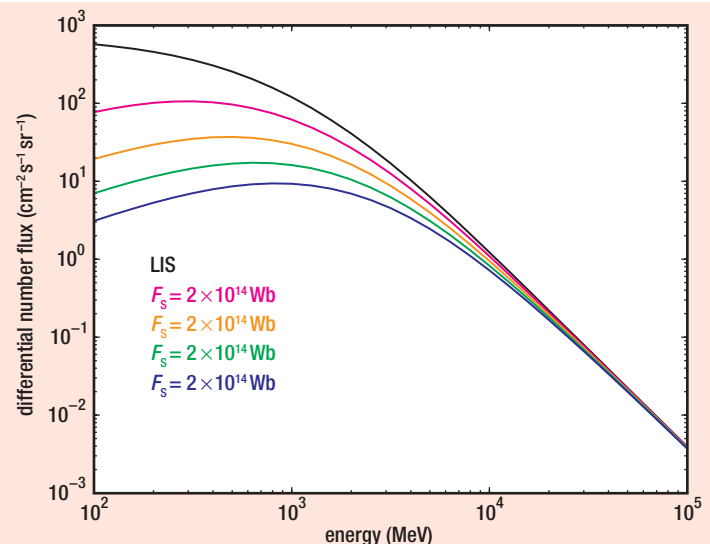
in the heliospheric field that scatters GCRs is the crucial component of shielding (e.g. Potgieter 1998). Rouillard and Lockwood (2004) demonstrated that there was an excellent anti-correlation between F_S and the cosmic-ray flux at various energies. Figure 1 shows modelled spectra of GCRs as a function of F_S, obtained as described by Lockwood (2006), and shows that it is the lower energies (below about $10^4\,MeV$) of the local interstellar GCR spectrum that is most modulated by F_S. Because F_S varies with the decadal solar cycle and on longer timescales (Lockwood *et al.* 1999, Rouillard *et al.* 2007), we expect corresponding variations in cosmic-ray fluxes in near-Earth interplanetary space.

GCRs are atomic nuclei, about 85% protons, 14% alpha particles and 1% heavier nuclei (Simpson 1983). The fluence distribution of protons is 10^3 times higher than that of, for

example, Fe ions, but the energy deposition – the dose of a single particle – depends on the atomic number squared, a factor of 56^2 for Fe.

In interplanetary space, GCR doses behind just $1\,gm\,cm^{-2}$ of shielding will give a total effective dose at solar minimum of about $50\,cSv$ per annum. At solar maximum this is reduced by the enhanced heliospheric shield to about $18\,cSv$. Given that, in Earth's biosphere, we typically receive $2\,mSv$ per year from cosmic radiation, the effective GCR doses in interplanetary space are greater than in the biosphere by factors of roughly 90 and 250 at sunspot maximum and minimum, respectively. With annual doses below $20\,cGy$, GCRs pose no acute health hazard to crews on deep space missions, but the concern is for stochastic effects such as induced cancers and mortality or late deterministic effects (for example cataracts or damage to the central nervous
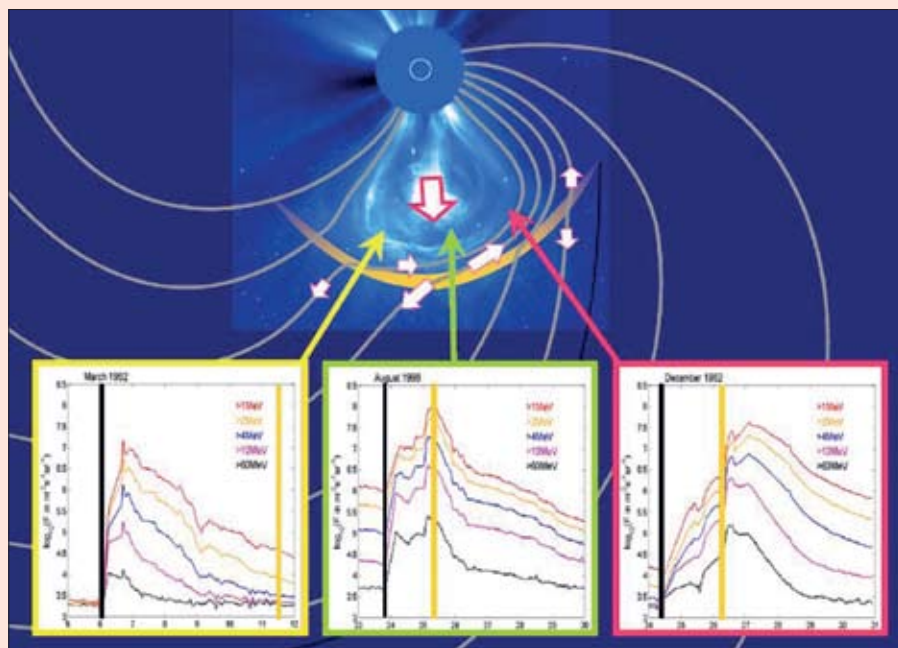
2: A large CME observed by the LASCO instrument on SOHO (Solar and Heliospheric Observatory) from near the ecliptic, used here as a schematic illustration of what a CME might look like when observed from over the solar pole. Parker spiral interplanetary field lines, perturbed by the CME, are shown in grey and the shock front at the head of the CME in orange. The white arrows denote fluxes of SEPs generated at the shock and propagating along the field lines, both away from and back toward the Sun. The boxes show SEP events observed at three different solar longitudes in: March 1982 (yellow box), August 1998 (green box), and December 1982 (red box). These data are taken from a variety of interplanetary spacecraft and merged into the intercalibrated "OMNI2" dataset by NASA's Goddard Space Flight Center. The longitude of the craft relative to the event on these three days was different in each case, such that as the event moved over them they had motions in the event rest frame as shown schematically by the corresponding coloured arrows. The fluxes of protons in energy ranges are given for: >60 MeV (black), >10 MeV (mauve), >4 MeV (blue), >2 MeV (orange) and >1 MeV (red). The vertical black and orange lines mark the event onset and time of shock crossing, respectively. (Based on schematics by Cane et al. 1988 and Reames et al. 1996).

system) from chronic exposure. Unfortunately, there are no data on the increased probability of these effects for prolonged human exposure that can be used to estimate risks to crews. Risk estimation is mainly based on epidemiological data from atomic-bomb survivors and victims of nuclear accidents, but these are very limited analogues for the space radiation environment. We have data on astronauts returning from long-term space missions such as on MIR and the Apollo missions, but thanks to Earth's magnetic field and good fortune, respectively, these are low-level doses. Accelerator experiments have also been performed with human cells. The induction of chromosome aberration is studied because it is thought to be the most accurate and sensitive indicator of genetic mutations, for cancer induction in particular. A special difficulty is the continuous or protracted irradiation with low doses in space: even the experiments on human cells are necessarily carried out with higher, shorter doses and then extrapolated.

During a mission to Mars lasting 600 days at solar minimum, there would be an estimated 220 proton and 22 He^{++} GCR traversals through the nucleus of each cell of the human body. Allowing for the mass and energy spectra, this would give an effective total dose of 30 cSv. This should be compared with estimated reasonably safe lifetime doses for 55-year-old males and females of 30 cSv and 15 cSv, respectively. In other words, even at the most favourable time, a trip to Mars would use up the lifetime radiation allowance for men and more than double that for women. Fujitaka (2005) estimates that a one-way trip to Pluto with maximum possible shielding would give 70 Sv, roughly equal to a cancer therapy dose over the whole body, killing all cells. We simply cannot travel beyond our solar system until we develop viable shielding.

Solar energetic particles

SEP bursts were first detected in ground-based ionization chambers during the large solar events of February and March 1942 (Forbush 1946). Because the flare was the main impulsive phenomenon on the Sun known at the time, it was natural to associate all SEPs with flares, a confusion that was not clarified until relatively recently when it was termed "the solar flare myth" (Gosling 1993). From radio bursts, Wild et al. (1963) indicated that there were two classes of events that are still termed "impulsive" and "gradual". These authors also noted that ion acceleration at a shock front was also probably involved; such acceleration is now well

understood (e.g. Jones and Ellison 1991).

The distinction between impulsive and gradual SEPs has been clarified using the ionization states and mass composition (see review by Reames 1999a). The fluxes of energetic ions are much higher and longer lived in gradual events and it is these that pose a health hazard. CMEs are transient events, more common at sunspot maximum, in which of order 10^{13} kg of coronal material is ejected into the inner heliosphere, typically moving at 350 km s^{-1}. Following the discovery of CMEs, it became apparent that the gradual SEP events were actually associated with the shock front ahead of the CMEs and not any associated flare (Kahler et al. 1984). Figure 2 shows three SEP events and what we now understand is their relationship to the CME shock front that generated them. In all three cases, the largest fluxes are seen when the satellite is magnetically connected to the strongest part of the shock. For the events on March 1982 (yellow box), August 1998 (green box) and December 1982 (red box), the peak fluxes are seen, respectively, before, as and after the shock passes the craft: in the third case the peak fluxes are seen travelling back towards the Sun.

The crew of Apollo 16 returned to Earth from the Moon on 27 April 1972 after an 11-day mission. Just three months later, on 4 August 1972, there was a large gradual SEP event. Four months later, on 7 December 1972, the final manned lunar mission, Apollo 17, was launched. Humans have not ventured out of the protection of Earth's magnetic field since.

Subsequent analysis of potential biological effects on human crews of the August 1972 event (e.g. Wilson and Denn 1976, Townsend et al. 1991, 1992, Wilson et al. 1997, Parsons and Townsend 2000) revealed that skin doses as large as 15 to 20 Gy would have arisen behind shielding of 1 gm cm^{-2}. Even inside a spacecraft, skin doses could have been as much as 2 Gy. In addition, the crew could have received bone marrow doses of about 1 Gy. Clearly this event would have had very severe consequences for either Apollo 16 or 17 if it had happened when astronauts were en-route to the Moon or, worse still, during EVA on the lunar surface. Figure 3 shows the estimated biological skin dose for all the SEP events detected during the Apollo era and shows their timing with respect to when the missions were beyond the safety of Earth's magnetic shield. Also shown are various thresholds: the green line shows the average annual dose received by UK residents of 2.2 mSv yr^{-1} (but note that natural radiation levels vary with location on the Earth's surface between about 1.5 and 26 mSv yr^{-1}); the yellow line is 20 mSv yr^{-1}, the legal limit for a radiation worker in the UK; the orange line is the 50 cSv level which (in an acute event) gives an estimated 3% enhanced lifetime risk of cancer (Brenner et al. 2003); the brown line is 2 Sv, which marks the onset of
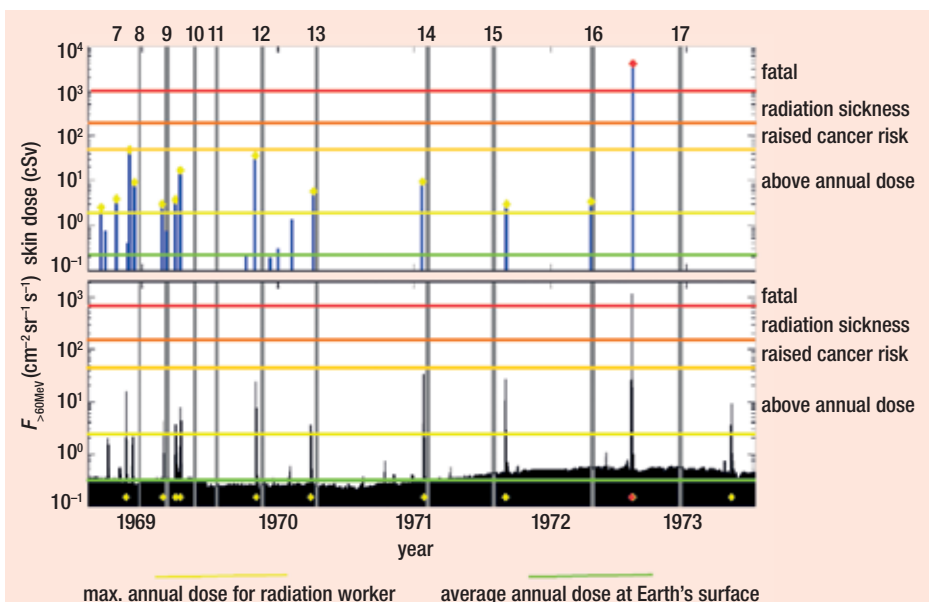
3: The variation of (top) cumulative-event skin dose behind a shield of 1 gm cm^{-2} of aluminium and (bottom) the flux of >60 MeV protons, both in interplanetary space. In both cases, the scale is logarithmic. The vertical grey bars give the times when the Apollo astronauts were outside Earth's magnetosphere in interplanetary space (the missions are numbered along the top). The horizontal lines show: in green, the average annual dose at the Earth's surface; in yellow, the maximum annual dose allowed for an employee working with radiation; a threshold for seriously enhanced long-term risk of cancers; in brown, a threshold above which most individuals will suffer severe radiation sickness and in red, a threshold above which doses are potentially fatal. These thresholds have been mapped onto the lower panel using the scatter plot presented in figure 5.

4: Scatter plot of modelled cumulative-event skin dose behind a shield of 1 gm cm^{-2} of aluminium as a function of the peak value of the daily means of proton flux (E > 60 MeV) during the event. The solid points are the events during the era of the Apollo missions, the open squares are values derived during some of the larger events seen in recent years. The thresholds used in figure 3 are also given, using the same colour scheme.
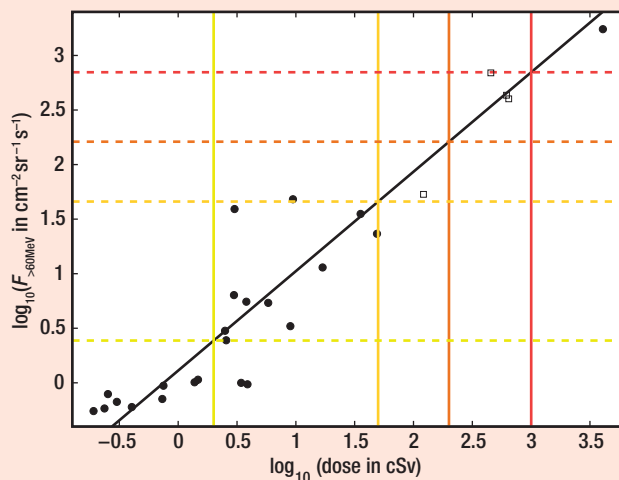
severe radiation sickness (tolerances vary from person to person) causing 35% fatality after 30 days (50% risk of vomiting for 1 to 2 days followed by a 7–14-day latent phase giving massive loss of white blood cells, greatly increasing the risk of infection – convalescence takes from one to several months); the red line is 10 Sv, which causes severe, debilitating radiation sickness in all humans, fatal in almost all cases within 7 days (McLaughlin *et al*. 2000). Figure 3 emphasizes how lucky the Apollo astronauts were not to encounter a major event.

SEP event statistics

Full modelling of the biological doses caused by SEP events in interplanetary space has been carried out for the largest events, but we do not

have a full database of the doses caused by all known SEP events. Because of their higher flux, protons deliver much of the dose of SEP events and because the mass spectrum does not vary too greatly in different events, integrated proton flux observations are a useful proxy for the event biological doses. However, we also know that the shape of the energy spectrum has a considerable effect on the effective dose (Townsend *et al*. 2001, 2003, 2006).

Figure 4 shows a scatter plot of the modelled cumulative-event skin doses deduced for the SEP events during the Apollo era (solid circles) and some recent events (open squares), against the peak value of the daily means of the integral proton flux (E > 60 MeV) during the event, $F_{>60MeV}$. It can be seen that there is scatter, as expected,

because of the variations in the shape of the energy spectra from event to event, but there is a general linear relationship. The thresholds used in figure 3 are also shown and mapped onto the proton flux levels, using best-fit least-squares linear regression, giving $F_{>60MeV}$ thresholds of 702, 162, 45.8 and 2.44 cm^{-2}s^{-1}sr^{-1}, roughly corresponding to the skin dose thresholds of 10, 2, 0.5 and 0.02 Sv mentioned.

The advantage of using the regression shown in figure 4 is that we have a continuous record of proton fluxes from 1968 onwards. Figure 5b compares the daily mean values to the counts of GCRs (shown in figure 5a from the Climax neutron monitor which detects cosmic rays of rigidity >3 GV). The solid black background in figure 5b is caused by cosmic rays and the variation shown in the upper panel has been used to calibrate the proton data to give a homogenous data series. The coloured dots give the classification of the SEP events using the thresholds and colour scheme in figure 3. After the August 1972 event, the only other events in the space age to cross the red threshold ($F_{>60MeV}$ > 702 cm^{-2}s^{-1}sr^{-1}, roughly corresponding to >10 Sv dose) took place in a fortnight in October 1989. However, events crossing the brown threshold ($F_{>60MeV}$ > 162 cm^{-2}s^{-1}sr^{-1}, roughly corresponding to >2 Sv dose) have been seen regularly and cluster around sunspot maximum when the GCR flux is most attenuated.

Hence figure 5 shows a broad anti-correlation between SEP events and GCR fluxes. This is not surprising because the CMEs that generate SEPs also cause reductions in GCRs called Forbush decreases. At Earth, few SEPs are generated by CIRs, although by the heliocentric distances of Mars the CIRs shocks have generally steepened sufficiently to make them significant. At greater distances, CMEs and CIRs combine to give global merged interaction regions that act as diffusive barriers and shield the inner heliosphere from GCRs (e.g. Potgieter 1998).

Figure 6 shows the fraction of time since 1968 that the daily mean flux of energetic protons (>60 MeV) exceeds the value given by the horizontal axis. The upper panel shows both the cosmic rays and the lower frequency, higher flux SEPs. The lower panel is the same as the upper, other than the scale has been changed to show the SEP event data more clearly. The thresholds used in figures 3–5 are also given, using the same colour scheme. The red, brown and orange thresholds are exceeded 0.03%, 0.16%, 0.43% and 3.12% of the time. Given that this is based on daily means, this tells us the probability of encountering events exceeding this threshold during a mission lasting just one day. Figure 7 gives the probabilities of encountering at least one event exceeding these thresholds for mission durations up to a typical return trip to Mars. That the probability of an event exceeding the annual UK safety limit is near unity is

not a surprise, but the chance of meeting at least one fatal 10 Sv event is 10% and the chance of meeting at least one 2 Sv event (which would be fatal for 35% of all individuals) is over 30%.

Century-scale variations

We have space measurements since 1968, but recent studies indicate that the space age may not have been typical of solar behaviour over the past few centuries (Lockwood 1999, Solanki *et al.* 2004, McCracken 2007a).

The work of McCracken *et al.* (2001a, b) gives an insight into the number of major SEP events over the past few centuries. These authors have studied impulsive increases in nitrates in polar ice cores. Nitrates are produced by the direct ionization of the upper polar atmosphere by SEP protons with energy >30 MeV (Jackman *et al.* 2000, 2001). The nitrates are precipitated within about 2 and 6 weeks in snow, particularly in the winter polar cap where they are compressed into ice sheets. Nitrates can also be generated during geomagnetic storms, but only at lower latitudes so ice cores from the polar cap give a good record of SEP proton fluxes. In addition, nitrates are generated by volcanoes, but this contribution can be identified because the ice layer also contains abundant H_2SO_4 from volcanic H_2S. The inferred fluence of >30 MeV SEP protons is shown in figure 8e, with the red line showing the 4 August 1972 event. This is far from the largest event in the past 400 years – that is the flare famously reported in white-light observations by Carrington in 1859 (Carrington 1860), with fluence about four times that of the 4 August 1972 event. Several studies have looked at the likely skin dose in that event (Townsend *et al.* 2001, 2003, 2006). Because the near linearity with dose, shown in figure 4 for >60 MeV protons, also applies to these >30 MeV fluxes, we can infer that in 440 years there were 32 events that would have exceeded the fatal skin dose limit of 10 Sv in near-Earth space, i.e. an average of one every 13.75 years. The 10% probability over a two-year mission shown in figure 7 is significantly lower than this long-term average.

Figure 8a shows the open solar flux, estimated from the group sunspot number using the method of Solanki *et al.* (2001), fitted to the values derived by Lockwood *et al.* (1999) from geomagnetic activity data. The production rate of the ^{10}Be cosmogenic isotope, predicted using the modelled spectra shown in figure 1 and the GEANT simulations by Masarik and Beer (1999) is shown in figure 8b (see Lockwood 2006). This isotope is generated by GCR bombardment of the atmosphere and stored in terrestrial reservoirs such as ice sheets and ocean sediments. The Dye-3 Greenland ice core data reveal it to be strongly anti-correlated with the estimated open solar flux variation (Lockwood 2001, McCracken 2007a). The variation of the inferred cosmic-ray spectra since the end of the
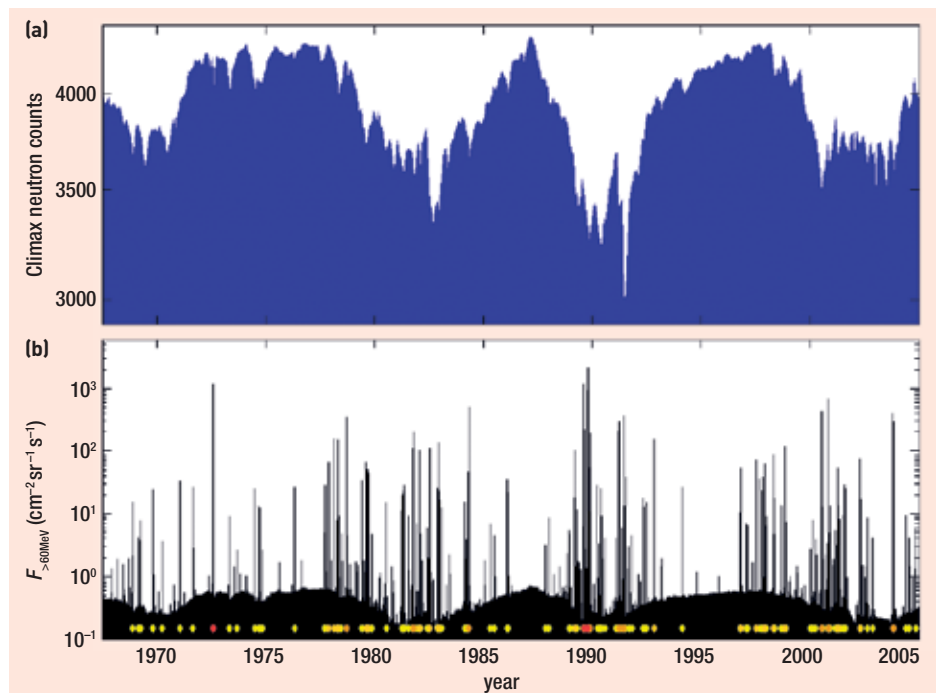
5 (a): The variation of cosmic rays (of rigidity >3 GV) deduced from counts detected by the neutron monitor at Climax, Colorado for 1968 to 2005. **(b):** The flux of protons at energies >60 MeV. The solid black background is caused by the cosmic rays and the variation shown in the upper panel has been used to calibrate the proton data and give a homogenous data series. The coloured dots give the classification of the SEP events using the thresholds and colour scheme given in figure 3.

6: The fraction of time that the daily mean flux of energetic protons (>60 MeV) exceeds the value given by the horizontal axis. The upper panel shows both the cosmic rays and the lower-frequency SEPs. The lower panel is the same as the upper other than the scale has been changed to show the SEP event data more clearly. The thresholds used in figure 3 are also given, using the same colour scheme.
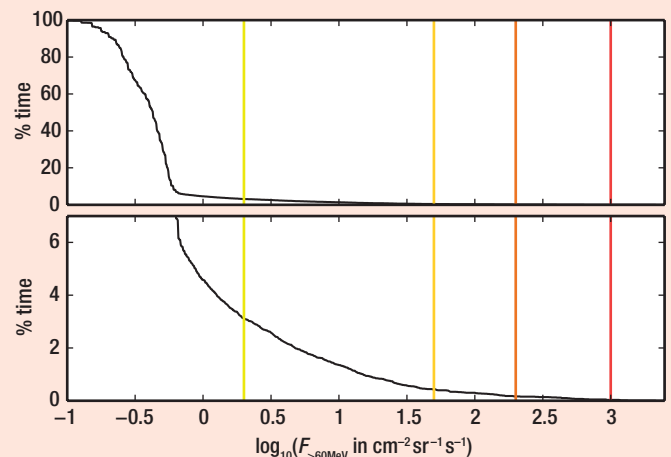
Maunder minimum in 1700 is shown in fig. 8c.

The occurrence frequency of inferred large SEP events shows some long-term variation, as demonstrated by the number N per solar cycle given in figure 8d, as derived by McCracken *et al.* (2001b). The occurrence does not appear to be linked in any simple manner to long-term cycles in the open solar flux (figure 8a). Nor, therefore, is there a simple connection with the corresponding variations in the sunspot number, GCR spectrum and abundance of the ^{10}Be isotope (figure 8b). If there is a link, it appears to be that neither very high nor very low solar open solar flux gives the strongest SEP events, but that they are most common during intermediate solar activity. From the inferred fluences of >4 GeV particles, McCracken (2007b) proposes that solar activity must be high enough to give

large flares but not so high that the open solar flux is large. The second effect is thought to arise because larger open solar flux raises the field and hence the Alfvén speed in the heliosphere, reducing the strength and number of the shock fronts. This may not be good news for the space traveller in the next few decades: it seems that we have recently passed through a significant grand maximum in solar activity and that a return to more moderate levels is underway (Lockwood and Fröhlich 2007). We can expect a reversion to the more frequent large SEP events seen just before the space age (McCracken, 2007b).

Shielding

Figure 9 shows the daily mean fluxes of >60 MeV protons during the August 1972 SEP event and

7: The probability of encountering an event as a function of the time spent beyond the protection of Earth's magnetic field. The curves are for events giving a cumulative skin dose exceeding the thresholds used in figure 3 (and are coloured using the same colour scheme).
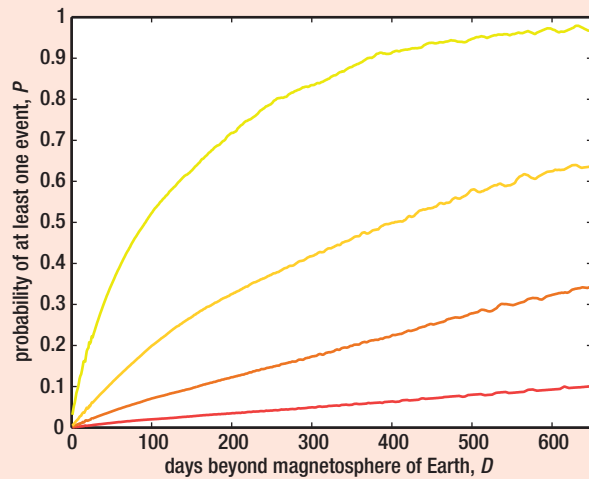
8: The variation of near-Earth radiations over century timescales. (a) The open solar flux F_S derived from sunspot data. (b) The variation of the production rate of the ^{10}Be isotope, P[^{10}Be], deduced from F_S and consistent with the Dye-3 ice-core data. (c) The integral flux of GCRs at energies above a threshold E_{TH} as a function of E_{TH} and time. (d) the occurrence frequency of the events shown in (e), given as the number, N, per solar cycle. (e) The fluence of 30 MeV particles deduced from nitrate abundances in ice cores by McCracken *et al.* (2001a, b). The event coloured red is the August 1972 event also shown in figures 3 and 9.
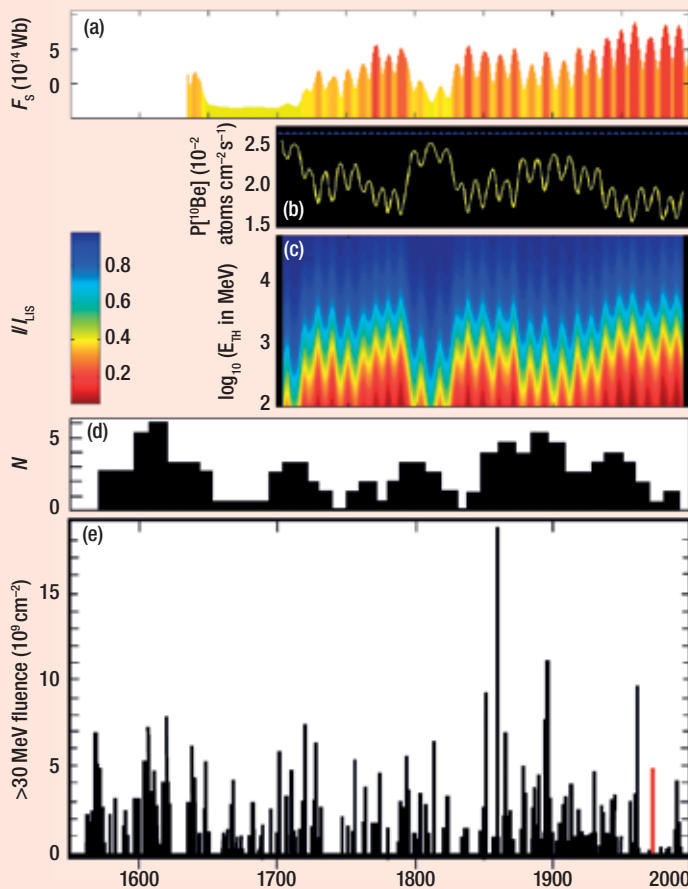
the growth of the cumulative skin dose behind shields of thickness (from dark to light blue) 1, 5, 10, 50 and 250 gm cm^{-2} of aluminium. The time profiles are as computed by Kim *et al.* (2005) and the final cumulative skin doses are computed by Hoff *et al.* (2004). A shelter giving 10 gm cm^{-2} is readily achieved and figure 9 shows that this is adequate to reduce the risks of a major event, such as the example in August 1972, to acceptable levels.

However, for GCRs, shielding is more problematic. The high-energy tail of the GCR energy spectrum is unaffected by the heliosphere and this is a problem for an effective shield: the cross-sections for nuclear fragmentation are still significant for the extremely high-energy GCRs,

so any shielding layer introduced to stop the low-energy GCRs particles also produces showers of nuclear fragments (including neutrons). Transport calculations for the GCR spectrum in various shielding materials show that after a small benefit from thin layers, thicker absorbers do not produce a net reduction of the biological effect: the decrease in low-energy particles is almost compensated by the increase in nuclear fragmentation (Wilson 1995).

The outlook for astronauts

It is clear from figure 9 that sufficient shielding can be effective at mitigating the radiation dose from a large SEP event. This also means that it is important to have adequate warning of the

onset and evolution of SEP events, along with a close-by safe haven when astronauts are on extra-vehicular activity or in an inadequately shielded part of their craft. During the space age at least, the proton intensities observed during the plateau ahead of the arrival of the peak fluxes and the shock itself present a minimal radiation hazard to astronauts and hazardous intensities only occur when the shock arrives at the spacecraft (Reames and Ng 1998, Reames 1999b). This limitation appears to be because protons streaming outward in the early phases of SEP events generate waves that scatter the particles and impede their flow. Hence we can be confident that this is a general characteristic of major SEP events and that 18–36 hours of warning should be available. This means that it is not necessary to attempt to predict the onset of an event before it occurs, although even this may become possible when we understand phenomena such as coronal dimming better (Bewsher *et al.* 2007). However, the ability to declare "all clear" intervals will need more studies of the source solar phenomena. We will need to measure or predict the intensities at the shock before it arrives at the spacecraft (Neal and Townsend 2001). Correlations show that the best parameter for determining the peak particle intensities is the shock speed, but we will also need to map the magnetic field of the inner heliosphere so that we can predict when a spacecraft will be magnetically connected to the shock. Until we have perfected a reliable prediction procedure, warnings for near-Earth space may be limited to the 45–60 minutes for observations taken by spacecraft in orbit around the L1 Lagrange point (Cohen *et al.* 2001, Cho *et al.* 2003). Studies will be needed to determine what kind of shelter is needed and how far astronauts will be able to venture from it. One problem we have is that opportunities to study major events are rare. Hence, although SEP events represent a real hazard, solutions using shielding and predictions should be viable. However, we have as yet no means to protect astronauts from GCR fluxes and this limits humankind's ability to travel through even our own solar system. Journeys to the Moon will have to be kept short to keep the radiation risks to acceptable levels; it is a matter of current debate and study whether trips to Mars can be made sufficiently low risk (Close *et al.* 2005).

Because shielding is much more difficult for GCRs, and because the space traveller will not want to spend the entire trip behind a shield, journeys beyond Earth's magnetosphere are likely to be planned for sunspot maximum when the heliosphere gives most protection from GCRs. Ironically, this is when SEP events are most common and our recent understanding of the long-term variations in the open solar flux and the occurrence of SEP events strongly suggests that large SEP events will be a greater

problem in the decades to come than they have been in the space age until now.

There are other hazards to space travel. For example, impacts of particles and objects in space are very damaging to spacecraft and so are also life-threatening for astronauts. In addition to naturally occurring dust, micro-meteorites and meteors, there is an increasing problem with man-made space debris. End-of-life procedures for "de-orbiting" space junk had halted the rise of this problem – until 11 January 2007 when the Chinese destroyed one of their old weather satellites, Fengyun IC, in a "Star Wars" military test. Such tests have almost certainly been carried out before, but on satellites at lower altitudes. The Fengyun IC test is significant because the satellite was at 850 km altitude: this makes it a considerable technical achievement of no small strategic significance, but it also makes space even more hazardous. By July, 2000 extra fragments of diameter >20 cm had been identified, increasing the known total by 50%. The spreading of the debris ring is being monitored by the EISCAT radars in Scandinavia (Markkanen 2007) and it is estimated that the number of fragments will have decayed by less than 20% in 100 years' time. The traveller to Moon and Mars will leave and return to Earth through this new and additional hazard.

The rewards of space travel are very high, both scientifically (advantages for astronomy were recently discussed by Lockwood, 2007) and in terms of spin-off benefits. But the hazards are also great. *The Rough Guide to the Moon and Mars* will need to contain many procedural do's and don'ts, but will also need to make it clear that Earth's biosphere is a remarkably benign place for advanced lifeforms and that the hazards beyond Earth's magnetosphere are great and real. JFK was right: doing these things is indeed hard. We now understand that his "greatest adventure" is even more dangerous than was envisaged then – and we will need all our inventiveness and knowledge to continue it safely and successfully. ●
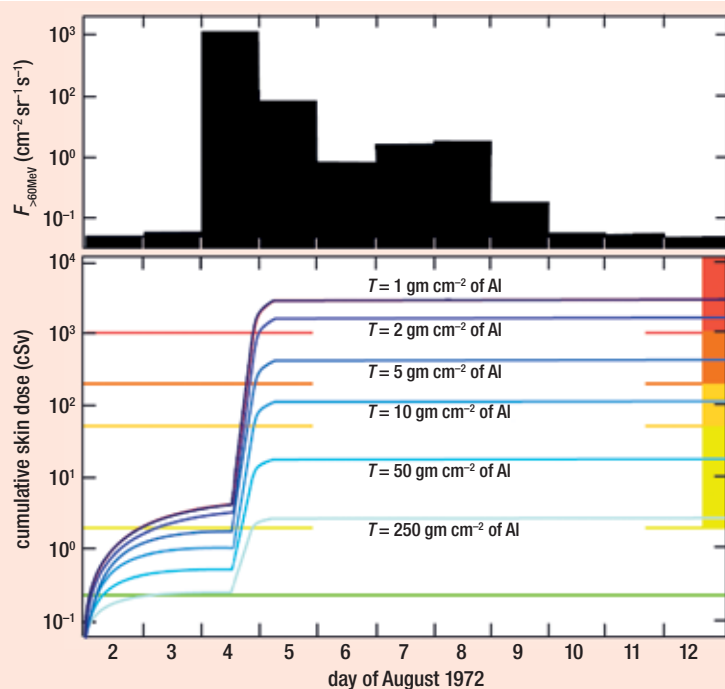
Mike Lockwood, School of Physics and Astronomy, Southampton University, and Space Science and Technology Dept, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire. Mike Hapgood, Space Science and Technology Dept, Rutherford Appleton Laboratory.

9 (a): The variation of daily mean values of the flux of protons with energies exceeding 60 MeV during the August 1972 SEP event (the largest event in figure 3).
(b): The growth on the cumulative skin dose behind aluminium shields of thickness (from dark to light blue) 1, 5, 10, 50 and 250 gm cm^{-2}. The thresholds used in figure 3 are also given, using the same colour scheme.

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Legend (within figure):

LIS
$F_S = 2 \times 10^{14}$ Wb
$F_S = 4 \times 10^{14}$ Wb
$F_S = 6 \times 10^{14}$ Wb
$F_S = 8 \times 10^{14}$ Wb

Axis labels:
- x-axis: Energy (MeV)
- y-axis: differential number flux ($cm^{-2} s^{-1} sr^{-1}$)