STATUS OF THE FEASIBILITY STUDY OF ASTRONAUT STANDARDIZED CAREER DOSE LIMITS IN LEO AND THE OUTLOOK FOR BLEO

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ABSTRACT

The International Academy of Astronautics has established, under the aegis of its "*Human Spaceflight Coordinating Group"* (HSFCG), a series of Cosmic Studies aimed at identifying a set of requirements for future human missions to Mars, within the context of future, global, cooperative scenarios. Among these, Cosmic Study SG 3.19/1.10 which is introduced in the present paper, considers the various career dose limits adopted by different space agencies for astronauts in ***Low Earth Orbit*** (LEO), having regard to the health risks imposed by the impingement of, naturally occurring, energetic particle radiation in this regime. These various limits raise the question as to whether the adoption of different limits can be justified or if they should, rather, be globally standardized, It is noted that standardization is not presently followed in the case of crew members of the International Space Station who individually adopt the career dose limits assigned by that agency with which they are affiliated. When a consensus is arrived at internationally regarding career dose limits for LEO, the question of how to assign such limits for missions ***Beyond Low Earth Orbit*** (BLEO) will be addressed. The deep space missions now envisioned to be implemented beyond the shielding provided by the geomagnetic field pose a different set of health risks to human crews than those prevailing in LEO and these risks will be carefully assessed and recommendations regarding them made. The biological responses of humans to high-energy particle radiation under microgravity conditions will, in addition, be investigated. An initial 25-page report describing the key scientific, technical and non-technical issues spinning off from the results relevant to human crews in LEO and BLEO, together with recommendations regarding the resolution, within a framework of multidisciplinary, international cooperation, of the related health hazards identified, will be prepared by all the Cosmic Study Team Members for joint submission to the Academy by October 2013. These initial recommendations will, thereafter, be prepared by the HSFCG for presentation at the Heads of Space Agencies Summit in Washington (January, 2014). An outline of those issues currently expected to be covered by the Team Report, together with associated recommendations that have emerged already from the study, are provided in the present paper. These items can, however, be expected to show ongoing modifications as the study progresses.

Keywords: Radiation Dose Limits, LEO, BLEO. Radiation Dose Modelling.

1 INTRODUCTION

With the aim of promoting future, coordinated global endeavours, the *International Academy of Astronautics* (IAA) invited the leaders of space agencies from around the world to meet in Washington D.C. on 17 November 2010 to consider enhancing international collaboration in four space related areas, namely: human spaceflight; planetary robotic exploration; climate change and disaster management. At this meeting, based on four studies already prepared within the Academy on these individual topics, the IAA presented its results to an audience composed of the heads of over 30 space agencies and more than 500 Academicians, as well as to world leaders and other stake holders. The study dealing with Human Spaceflight stated that "*Human missions to the surface of Mars are the long-term goal of space exploration in view of their scientific interest and strategic prospects for humankind"*. Recommendations from the IAA as to how human missions might be implemented were, in addition, set forth and these recommendations have come to be known collectively as the *IAA Summit Declaration* (see Pace and Reibaldi, 2010 and an earlier IAA publication Huntress, 2007).

Against this background, following succeeding extensive consultations with both Space Agencies and Academicians, the IAA, in preparation for making further recommendations at the upcoming Heads of Space Agencies Summit in Washington (January, 2014), established, under the aegis of its "*Human Spaceflight Coordinating Group* (HSFCG), a series of Cosmic Studies, including the one considered in the resent paper "*Feasibility Study of Astronaut Standardized Career Dose Limits in LEO and the outlook for BLEO*". This study, which was approved by the Board of Trustees in February, 2013, was assigned jointly to Commissions 3 and 1 of the Academy and given the designation SG 3.19/1.10.

2 OBJECTIVES OF SG.3.19/1.10

Study SG 3.19/1.10 was initially based on an observation of the present author in the course of preparing a book for the Academy on "***The energetic particle radiation hazard en route to and at Mars***" (McKenna-Lawlor et al., 2013) that different space agencies have adopted different values for their career dose limits in ***Low Earth Orbit*** (LEO). When for instance (using the pre. 2012 literature) 10 year Career Effective Dose limits which applied to astronauts in a > 50 year age bracket were compared for NASA and JAXA personnel, it was found that, in the case of NASA, limits of 1.7 Sv (female) and 3.0 Sv (male) were assigned whereas, at JAXA, the corresponding figures were 0.8 Sv and 1.0 Sv. In each case it was required that a 3% probability of lifetime excess cancer mortality risk was not exceeded at a 95% confidence level. Other agencies meanwhile adapted a recommendation of the *International Commission on Radiological Protection* (ICRP) which calls for a general life time limit for space personnel of 1 Sv (ICRP, 1991).

Against this background the first objective of study 3.19/1.10 is to investigate differences between career dose limits assigned by different space agencies with a view to determining either if these can be justified or a consensus reached regarding the adoption of limit standardization between international agencies. No Career Dose Limits for ***Beyond Low Earth Orbit*** (BLEO) have as yet been assigned and, when the problems regarding LEO have been resolved, a further objective of the study is to consider how to meet the challenge of assigning suitable career dose limits for BLEO. It was recommended by the HSFCG at a meeting in March, 2013 that the overall study be extended to consider the biological responses of humans to the impingement in space of high energy particle radiation. This was agreed and experts in this area were duly invited by the Academy to join SG 3.19/1.10 (A. K. Lal, A. K. Singhvi, A. Bhardwaj, F. Ferrari).

It is anticipated that a report (25 pages long) providing details of the overall results obtained in year 1 (2013) regarding career dose limits in LEO, will be jointly prepared by the SG 3/19/1.10 team for submission to the Academy in October next. This report will in addition contain recommendations spinning off from the investigation regarding future steps to be taken internationally to overcome those constraints due to radiation related health hazards that presently accrue to human space flight. Thereafter, these recommendations will be prepared by the HSFCG for presentation at the next Heads of Space Agencies Summit Meeting (January, 2014). In the second year, the problem of assigning suitable career dose limits for human crews in BLEO will be addressed and, based on biological considerations, recommendations for advancing further toward achieving successful human exploration of deep space will be made.

3 COMPOSITION OF STUDY GROUP SG 3.19.1.10.

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4 PHILOSOPHY OF ASSIGNING RADIATION EXPOSURE LIMITS

Early radiation effects in humans are generally related to the loss of a fraction of cells that exceeds the threshold for impairment of function in a tissue. These effects are called “deterministic” because the statistical fluctuations in the number of affected cells are very small as compared with the number of cells required to reach the threshold value. The appropriate assignment of dose limits can ensure that ‘early effects’ will not be experienced by the crew during a particular mission. Late effects can result from changes in a very small number of cells within which statistical fluctuations can be large, and some level of risk is incurred even at low doses. These are referred to as “stochastic effects. The relationship between radiation exposure and dose and risk is age and gender specific due to latency effects, differences in tissue types and sensitivities, and differences in average life spans between genders. Also, prior crew exposure is a relevant factor and cumulative exposure over several missions for individual astronauts should be taken into account in setting mission design requirements to ensure that the ***Permissible Exposure Limits*** (PELs) of individual crew members are not exceeded.

PELs for human crews are chosen to prevent in-flight risks deemed to be prejudicial to mission success, while also limiting chronic risks to acceptable levels based on legal, ethical and financial considerations. Exposures are required to be ‘As Low As Reasonably Achievable’ (ALARA) to ensure that astronauts do not approach their assigned radiation limits. The application of ALARA dictates that measures are taken during the design and operational phases of the spacecraft to manage, and limit, crew exposures to ionizing radiation.

4.1 CAREER DOSE LIMITS IN LEO

At the commencement of the present study, 10 year Career Effective Dose limits available in the pre 2012 literature which applied to astronauts in a > 50 year age group were compared and, in the case of NASA, limits of 1.7 Sv (female) and 3.0 Sv (male) were noted whereas at JAXA the corresponding figures were 0.8 Sv and 1.0 Sv. In each case it was required that a 3% probability of lifetime excess cancer mortality risk was not exceeded at a 95% confidence level). As the study progressed, within the context of an envisaged relatively short duration (~400 days cruise, 30 days short surface stay) human mission to Mars, it was decided within the team that figures for a one year mission should be considered rather than for a 10 year period.

Also, in place of the pre-2012 estimations previously used in the literature, revised NASA radiation limits in LEO (which are age and gender dependent) based on an updated methodology for evaluating cancer risks from space radiation were utilized in the study. This revised methodology which is called the ***NASA Space Cancer Risk*** model (NSCR-2012), see Cucinotta, et al. (2013), has already been reviewed and positively evaluated by a panel of experts under the umbrella of the U.S. National Research Council/NRC Space Studies Board of the National Academy of Sciences, having regard to issues in space physics, radiobiology, epidemiology, and risk assessment (NRC-2012).

As in earlier NASA methodology, it is specified (Cucinotta et al., 2013) that occupationally related sources of exposure throughout the career of any U.S. crewmember shall result in no more than a 3% probability of lifetime excess cancer mortality risk and NASA again assures that these limits are not exceeded at a 95% confidence level, based on a statistical assessment of the uncertainties that enter into the cancer risk projection model. The age and gender-dependent risk coefficients used to determine career dose limits are defined as those appropriate to individuals who have never smoked (referred to as Never Smokers in the methodology). A candidate for a specific flight is not eligible for selection if the sum of that astronaut’s career occupational exposure to date, plus the projected mission exposure associated with the proposed new flight, exceeds the lifetime career limits adopted by the agency.

Table 1 presents an example of the career dose limits currently adopted at NASA for a one year mission based on their NSCR-2012 model. These figures were provided by Team Member L. Townsend who also pointed out that the quoted NASA limit for a 60 year old male is slightly above the general value recommended by the ***International Commission on Radiological Protection*** - which calls for a general life time limit of 1 Sv (ICRP, 1991).

Table 1: NASA career effective dose limits (age and gender specific), for ionizing radiation exposure during a one year mission. It is associatively specified that a 3% probability of lifetime excess cancer mortality risk is not exceeded at a 95% confidence level based on a statistical assessment of the uncertainties that enter into the cancer risk projection model.

NASA Career Effective Dose Limits (Sv) for a one year mission				
Gender	Age at First Exposure			
	30	40	50	60
Female	0.60	0.70	0.82	0.98
Male	0.78	0.88	1.00	1.17

Table 2 presents equivalent JAXA career effective dose limits (which are also age and gender specific) for ionizing radiation. These data were provided by Team Member A. **Nagamatsu** who pointed out that these figures still require to be fully ratified within the Japanese Space Agency (ratification expected during 2013).

The JAXA 3% probability and 95% confidence level is estimated in the same way as that adopted at NASA. However, the evaluation system employed in the radiation particle transport system (which is based on the Monte Carlo method), can be differently handled in individual agencies For example, while JAXA uses the PHITS code or HTC-3-step code, ESA uses GEANT. It is thus of interest to investigate if remaining differences between the career dose limits result from mathematical methodology.

Table 2: JAXA career effective dose limits (age and gender specific) for ionizing radiation exposure during a one year mission. It is specified that an ~ 3% probability of lifetime excess cancer mortality risk is not exceeded at a 95% confidence level based on a statistical assessment of the uncertainties that enter into the cancer risk projection model.

Career Exposure Limits By Age And Gender Effective Dose Equivalent (Sv) / risk				
Gender	Age			
	27 – 29	30 – 34	35 – 39	≥ 40
Female	0.60 / 2.9%	0.80 /3.1%	0.90 /3.1%	1.10 / 3.1%
Male	0.60 / 3.2%	0.90 /3.1%	1.00 /3.1%	1.20 / 3.0%

In the Russian Space Agency, the occupational dose limit for cosmonauts is 1 Sv. Here the impact of X-radiology is included and the limit is independent of age and gender (information provided by Team Member V. Petrov). Details are contained in document (OOKOKP-2004). Other leading agencies have adapted a recommendation of the *International Commission on Radiological Protection* (ICRP) which calls for a general life time limit of 1 Sv (ICRP-1991).

As part of the present study, information is currently being compiled of the dose limits adopted in different agencies for various internal human organs (eye lens, skin, bone marrow etc.).These also will be intercompared and the outcome considered by the Team.

4.2 CAREER DOSE LIMITS ON THE ISS

Crew members on the International Space Station (ISS) are at liberty to adopt the career dose limits of their affiliated space agency. Through Team member Leena Tomi, a telecon link has been forged between Study Group 3.19/1.10 and the ***International Space Station Radiation Health Working Group*** so that information regarding dose limits can be mutually discussed**.** An account of activities conducted to mitigate the adverse effects of space radiation incurred aboard the ISS is contained in Straube et al. (2010). Medical monitoring of crew members continues after an ISS mission ends and these data, with corresponding archival information from the Russian Space Station MIR, are of great potential value in estimating career dose limits since recent results show that the response of the body to radiation appears to be different in microgravity than in gravity (there is a modified response of the immune system). Since there is limited relevant data in this regard, biological experiments carried out in micro-gravity are urgently required to help reduce present uncertainties in making predictive risk assessments for astronauts (Reitz, 2013).

4.3 MODELLING OF THE RADIATION ENVIRONMENT

The high energy particle flux originating outside the magnetosphere which is present in LEO at a particular orbit depends on: the orbital parameters concerned; the momentary position of the spacecraft along its trajectory and the associated magnetospheric disturbance. To calculate the particle flux penetrating to a chosen orbit it is necessary to combine models of the particle flux exiting the Earth's magnetosphere with models of particle penetration into the magnetosphere, thereby taking into account magnetospheric parameters that depend on local time as well as on magnetospheric disturbances caused by solar activity - the latter of which can result in changing the penetration of the particles along different parts of the orbit. This is especially important in the case of large SEP events. The available models of particle penetration into the Earth's magnetosphere differ in their methodological approaches. The most widely available models are combined in project NW1 764 "High-energy charged particle penetration inside the magnetosphere: Method of the effective vertical cut-off determination" ISO TC20/SC14-WG 4 ⌈Space Environment (Natural and Artificial)⌋ Project leader: R. Nymmik. Our Russian

Team experts who participate in these studies have offered to forge a co-operative link between WG4 and IAA SG 3.19/1.10 so that these issues can be jointly discussed.

Another group of models of energetic particle radiation developed in Europe (CREME2009 and MEREM) and in the USA (the BRYNTRN and HZ|ETRN codes) have already been utilized to estimate the particle radiation hazard in free space and at Mars. These models indicate that career limit values currently adopted by NASA for space personnel are already approached during a 400 day cruise to/from Mars. The hazard due to background isotropic GCR would be further increased if levels recorded prior to 1957 were to return (McKenna-Lawlor et al., 2011a, 2011b).The effect of the occurrence of a, presently unpredictable, hard spectrum SEP could be catastrophic (Townsend et al., 2011, McKenna-Lawlor, 2013). Inter-comparison of the results obtained using these and other models from countries that include China, Japan and Russia are now required as well as validation of the models predictions using in situ data: e.g. measurements made aboard shielded spacecraft in inter-planetary space; data from rovers on Mars, ground based networks etc.)

It was noted by M. Panasyuk and his group that certain of the presently available radiation models are highly controversial and that there is presently a pressing need to establish, and suitably support, international cooperation with regard to the development and validation of space radiation models, based on mutually agreed conceptions.

5 PROPULSION ISSUES

Comparisons of propulsion systems used for getting crew and mission equipment from Earth orbit to Mars orbit, descending and ascending from the surface, and returning to Earth orbit are presented in Thomas et al.(2009). Areas of comparison for each of these phases include crew size, mission mass, propellant mass, delta v, specific impulse, transit time, surface stay time, aero-braking etc. It has been debated as to whether it is preferable to launch a short duration (~ 400 day cruise; 30 day short surface stay) mission to Mars during the maximum or minimum of the sunspot cycle. At maximum the contribution from galactic cosmic radiation is reduced whereas at minimum the probability of encountering a hard spectrum SEP event is less (e.g. McKenna-Lawlor et al., 2013). Recent mission planning has been made using a fifteen year synodic cycle within which some launch dates are "easier" to implement than others (due to trajectory differences that occur in the course of sequential mission opportunities).

Types of propulsion proposed include: Chemical; Nuclear Thermal Rocket/NTR; Nuclear Thermal Electric/NTE; Solar Electric and Chemical-using-an-Aerobrake (SEP/Chem./Aerobrake). Fast propulsion systems and the feasibility of their technical realization have been claimed for, among others, the "*gas core nuclear rocket*" under development at Los Alamos National Laboratories (Howe et al., 1998). Also, fast propulsion using a methodology based on the momentum of nuclear fission products from thin films of the Am-242m isotope, was proposed by scientists from Ben-Gurion University (Ronen et. al., 2000). A downstream travel time to Mars based on the above and other innovative technologies is claimed by the developers to potentially be measured in weeks rather than months. Such a transfer performance if confirmed, would reduce the natural radiation hazard incurred by human crews on missions to Mars and markedly reduce the risk of late effects caused by heavy ions (Reitz, 2013). It is noted that shielding from SEPs would still present a difficulty (e.g. Cucinotta et al., 2006, Gonçalves et al., 2013).

6 GALACTIC COSMIC RAYS

Investigations by Mewaldt et al. (2005) based on measurements of Be-10 in polar ice cores and other data sets indicate that the intensity of cosmic rays was significantly higher at 1 AU in 1954 and yet higher prior to 1900 than has been the case since the space era began in 1957 (by a factor of ~ 1.7). See also McCracken et al.(2004). It is conjectured, based on dendrochronological and other evidence (Bonev et al., 2004), that the high radiation levels formerly present could return at any time. Studies of the variations in GCR radiation over a range of time scales (e.g. Gushchina et al.,2009, Swadron et al., 2010) are ongoing.

7 SOLAR PHYSICS

Hazardous hard spectrum solar particle events can occur at any phase of the solar cycle and they cannot currently be predicted (e.g. McKenna-Lawlor, 2013). Comparative studies between hard X-ray spectral evolution in solar flares and observations of energetic interplanetary electrons and protons were carried out by Kiplinger (1995) who reported that progressive spectral hardening can be a diagnostic of high energy particle events i.e. there appears to be an approximate relationship between the timescales (FWHM) of progressively hardening X-ray peaks and the cube of the interplanetary peak proton flux .See however the paper of Kahler (2012) where it is pointed out that several criteria must be quantified and applied consistently before a prediction tool based on “the Kiplinger Effect” can be deemed to be established.

Profound changes in magnetic fields and plasma velocities on the Sun were recently shown (through jointly utilizing the Synoptic Optical Long-Term Investigation of the Sun (SOLIS) and the NASA/National Solar Observatory Spectro-magnetograph) to mark the locations of coronal mass ejections (CMEs) prior to their eruption (Choudhary et al., 2001). Potentially this methodology can lead to the development of new predictive capability enabling early forecasting of CME events. This work is ongoing.

Other methodologies that involve (inter alia) the use of artificial intelligence, locally weighted learning or Bayesian inference to infer from early SEP development the course of future dose build up are presently under investigation by many groups to improve space weather predictions.

8 PRELIMINARY LIST OF ITEMS THAT WILL BE DISCUSSED IN OUR TEAM DOCUMENT

Introduction - Goals of the project (short term and long term)

- Establishment (if acceptable), of internationally agreed common career dose limits for LEO and, in the longer term, BLEO.
- Investigation of current knowledge concerning the deleterious impact on humans in space due to energetic particle radiation (based on ISS/MIR information and state of the art biological measurements).
- Recommendations regarding mitigating strategies against energetic particle radiation during deep space missions

Section I -The energetic particle environment in LEO and beyond

- Galactic Cosmic Radiation, Solar Energetic Particles/(SEPs), The Radiation Belts.
- Ambient radiation (primaries and secondaries), onboard radiation sources.
- Bio-wells, Habitats.
- Energetic particle radiation differences between LEO and BLEO.

Section II -Modelling of the Radiation Environment in LEO and beyond

- European, NASA, JAXA, Chinese and Russian Models.
- Consideration of the concepts on which these various models were developed
- Rigorous comparisons of the results of individual models as they become available.
- Model validation/ground truth obtained at Mars using phantoms and rovers (utilizing areas featuring different soil compositions; measurements made at different altitudes etc.).

Section III - Response of humans to particle radiation exposure

- Discussion of the effect of the presence/absence of gravity on biological responses to radiation.

- Discussion of the Bystander effect/Genomic instability/Adaptive response for low dose rate exposure etc.

Section IV-Discussion of career dose limits for space personnel in LEO

- Career dose limits currently adopted by different space agencies?
- Can risks in the limit differences identified be explained and quantified?
- What limits are adopted by different nationalities aboard the ISS?
- How should career dose limits be assigned for international crews on deep space missions?

Section V –Mitigating Strategies

- Fast propulsion, improved shielding, mission specific spacecraft design.
- On-board risk management and its backup requirements (software and hardware).
- Approaches to predicting the arrival at a spacecraft/Mars of hard spectrum SEPs

9 RECOMMENDATIONS ALREADY ARISING FROM THE STUDY

It is possible already to present recommendations arising from Study 3.19/1.10 regarding steps that can be made, within a framework of multidisciplinary, international cooperation, toward the amelioration of those health hazards potentially afflicting human crews in LEO and in BLEO. A useful source of information in this regard is contained in the Chapters and recommendations of “The energetic particle radiation hazard en route to and at Mars”(McKenna-Lawlor, 2013).

Propulsion:

Fast nuclear propulsion, that would allow the transfer time to Mars to be measured in weeks rather than in months, is claimed to be technically feasible. The danger to the crew from radiation pertaining to the use of nuclear propulsion requires a trade-off to be made between the benefits of a fast transit trajectory that would decrease the time of exposure to in-space radiation and chemical propulsion that requires a longer journey time with associated greater exposure to GCR and SEPs. It is recommended that the hazard due to nuclear propulsion and from other onboard radiation sources be carefully assessed and their contribution included in determining career dose limits.

Spacecraft Design:

It is recommended that risk calculations for individual human missions take into account all the components of the spacecraft to be utilized (walls, equipment and fuel) so that, through custom designing the vehicle for the mission envisaged, radiation safety levels can be provided that optimally address the career dose limits of the crew.

An important task regarding the transformation of primary radiation components due to its passage through spacecraft shielding, is the proper treatment of secondary neutrons generated in the numerous kinds of reactions concerned (e.g. fragmentation, spallation, evaporation, knock-on events etc.). When, in particular, heavy shielding is involved, the relative contribution of secondary neutrons to the biologically weighted radiation exposure can be significant. Also, the atmosphere and surface of Mars can act as a source of neutrons due to the impingement of primary ions associated with GCR and SEP radiation (McKenna-Lawlor et al., 2011b) The corresponding doses and biologically weighted dose equivalents therefore need to be incorporated in the production codes of radiation transport models so that exposure estimates for reference mission scenarios can be appropriately determined.

Modeling of Space Radiation

Several models of GCR and SEP energetic particle radiation (in LEO in free space and at Mars) have been produced, certain of which are controversial with regard to the basic concepts involved in their development. It is recommended that support for the establishment of broad international co-operation with regard to the fabrication of space radiation models be put in place, together with agreed procedures for downstream model validation using in situ measurements and ground truth.

Biological Considerations

Development of improved dose response functions and the assignment to them of upgraded biological quality values are critically needed to reduce current uncertainties in determining the risk to humans in space. These uncertainties arise due to the present lack of knowledge of those mechanisms that underlie biological responses to radiation impingement under micro-gravity conditions (Reitz, 2013). Recent results suggest that the higher pro-oxidant state to which the human body adopts under microgravity conditions may be part of a phase within which the deleterious action of ionizing radiation is mediated at a molecular, cellular and tissue level. This result currently needs to be verified or refuted using dedicated biological spaceflight experiments as well as long term monitoring of ISS crew members.

Onboard Risk Management

Risk Management aboard human missions requires the availability of reliable forecasts of the arrival at a spacecraft/Mars of dangerous particle radiation levels in order, in these circumstances, to optimally manage such undertakings as: Extravehicular Activity/EVAs; sojourns in the bio-well; re-orientation of the spacecraft in anticipation of extreme conditions, etc. It is recommended that physics based, predictive operational forecasts and now-cast capability to predict SEP events (including their intensities; the spectra of protons and heavy ions; maximum particle energies and their durations; SEP composition and cosmic ray intensities and plasma parameters – to include shock arrival times and their strength and obliquity) be further developed in order to enable the successful implementation of onboard risk management en route to and at Mars. A related improvement in the accuracy of radiation transport codes and enlargement of the empirical data base of required nuclear reaction cross sections is associatively required.

The provision to crew members of active and passive personal dosimeters based on, well-characterized, charged particle/neutron measurements is recommended. These measurements should be backed-up by a rapid response procedure to be followed in critical situations (e.g., rapidly accessing onboard zones with increased shielding). Overall, pre-planned risk management should ultimately constitute a significant part of the radiation risk mitigation program provided for individual missions.

Suitably positioned spacecraft to provide optimal information on activity taking place on the far side of the Sun could significantly enhance present-day forecasting capability. It is additionally recommended that communications to support the telemetry of real-time space weather information to a vehicle in deep space be appropriately put in place (through, for example, positioning scientific spacecraft at various solar longitudes in operationally viable positions to support the sending of real-time data to manned vehicles at an emergency frequency).

10 CONCLUSIONS

The assignment of energetic particle radiation dose limits for human missions requires reliable calculation of the risk involved based on extensive physical measurements and state of the art biological research.

Success in calculating health risks to human space crews requires support for co-ordinated, international research in many disciplines. Enabling-technologies, that include propulsion, spacecraft design and onboard risk management (with its complex underlying technical requirements), presently provide promising avenues for improving onboard safety.

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