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A. C. H. Glasse, D. Lee, P. Samara-Ratna, G. H. Rieke, "Modelling the path length of aluminium seen by the detectors in the MIRI instrument on the JWST," Proc. SPIE 11443, Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave, 114434D (13 December 2020); doi: 10.1117/12.2561035

Event: SPIE Astronomical Telescopes + Instrumentation, 2020, Online Only

Modelling the path length of aluminium seen by the detectors in the MIRI instrument on the JWST

A.C.H. Glasse*[a], D. Lee[a], P. Samara-Ratna[b], G.H. Rieke[c]
[a]UKATC, Blackford Hill, Edinburgh, EH9 3HJ, United Kingdom
[b]Space Research Centre, Department of Physics and Astronomy, University of Leicester, University LE1 7RH, United Kingdom
[c]Steward Observatory, University of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721, USA

ABSTRACT

The MIRI instrument on the James Webb Space Telescope is equipped with detectors which are susceptible to signal disruption by the charge deposited from impacting cosmic rays. In order to quantify the degree to which the structure of MIRI will shield the detectors, we have used an opto-mechanical ray tracing approach, whereby the solid bodies in a detailed 3D model of the instrument are substituted with an absorptive glassy material. By importing this modified model into a ray tracing program (Tracepro) and then launching many rays from the detector, we have been able to generate a map of aluminium path length as a function of direction. We find that there is a minimum thickness of 2 to 3 mm over a few patches which subtend no more than 1.5 % of the sky for the worst case, imager detector. We discuss the performance of the shielding provided by the MIRI structure, concluding that this minimum thickness of aluminium is sufficient to suppress the impact of low energy protons below the level of the unavoidable flux due to high energy cosmic rays.

Keywords: JWST, MIRI, infrared astronomy, space observatory, cosmic ray, solid modelling, optical modelling

1. INTRODUCTION

The James Webb Space Telescope (JWST) will spend its five year science mission at the second Lagrangian point 'L2', where it will be bathed in an isotropic flux of ionising cosmic ray particles. The flux is estimated[1] to cause charge to be deposited in the MIRI detectors at a rate which will cause an upset to signal detection at a rate of 55 pixels per second per (unshielded) detector. This figure is based on geometric scaling from the Spitzer observatory, based on the use of similar detectors (in the IRAC instrument) and its operating environment being similarly located in inter-planetary space well away from the influence of the Earth's magnetic field.

The MIRI instrument[2] provides dedicated shielding by means of the detector housing over about one hemisphere of the detector field of view. Over the other hemisphere, the instrument structure provides the shielding. The structure and optics are all built from aluminium with the primary design requirements being stability against launch loads and maintaining optical alignment independent of temperature, whilst conforming with stringent mass and volume requirements. The nominal thickness of metal shielding for the detectors against cosmic rays was considered to be a secondary concern, where it was understood that increasing the thickness of aluminium beyond 20 mm or so would be counter-productive, due to the increase in production of secondary charged particle showers. Detailed analysis (for example[3]) supports this view, with the optimum thickness of aluminium shielding shown to be around 20 g cm^{-2}, equivalent to a path length of 7.3 mm.

Because of the weight requirement, the instrument structure and optics are ribbed, with thin walled light-weighted pockets. As a result, determination of aluminum path length as seen by the detectors is complex, leading us to develop a novel approach to the problem which utilised the available resources; a detailed solid model of the mechanical elements comprising MIRI, and the ability of the Tracepro optical modelling programme to import and ray trace the solid model. We note that the following analysis does not account for the shielding provided by the observatory; the carbon fibre

Space Telescopes and Instrumentation 2020: Optical, Infrared, and Millimeter Wave, edited by
Makenzie Lystrup, Marshall D. Perrin, Proc. of SPIE Vol. 11443, 114434D · © 2020 SPIE
CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2561035

structure and enclosure closest to MIRI are not expected to provide significant shielding, and the system level design policy for JWST reflects this by placing the responsibility for cosmic ray shielding on the individual instruments.

2. THE MODEL

A mixed opto-mechanical modelling approach was adopted to estimate the path length of solid material between each of MIRI's three detectors and the external environment. Our starting point was the MIRI solid model shown in Figure 1, which includes the optical elements (mirrors) and their supporting structure, down to the detail of electrical connectors and filter and grating wheel mechanisms. We then imported the model into the Tracepro optical modelling programme, with all solid bodies defined to be made from a mythical glassy material with a refractive index of unity and a wavelength independent absorption coefficient '*k*' of 0.203 mm^{-1}. We note that the following analysis assumes that all modelled objects contribute to the aluminium path length, ignoring the 5 to 10 % of the mass which is estimated to be made of other materials (filters, motor bearings and so on).

Treating each detector in turn, 5 million rays were projected from a point corresponding to the central pixel towards a hemisphere external to all structures and whose symmetry axis was orthogonal to the detector surface. The rays were directed to uniformly sample the solid angle subtended by the hemisphere, with the irradiance confirmed to be uniform and all rays detected at the hemisphere with the MIRI solid model absent.

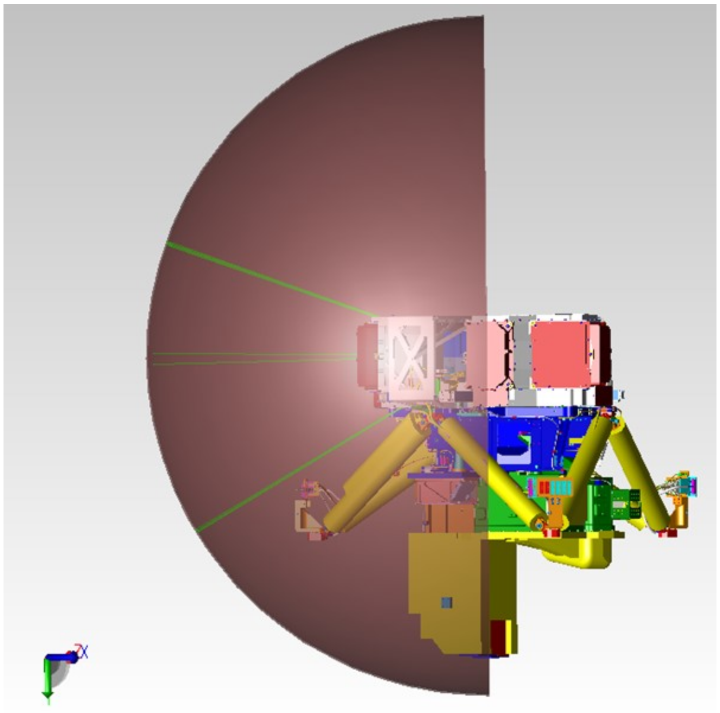

Figure 1. The MIRI solid model, including the central deck (blue), the imager, MIRIM (green) and the medium resolution spectrometer, MRS (white). The carbon fibre hexapod which supports and thermally isolates MIRI from the observatory 'Integrated Science Instrument Module' (ISIM) is shown in yellow. The brown hemisphere shows the surface used to map rays projected from the centre of the MRS long wavelength (LW) detector.

The symmetry of the MRS' short and long wavelength channel, and the knowledge that the aluminium path length in the hemisphere 'behind' the three detectors would be dominated by the three near identical Focal Plane Modules (FPMs) led us to run the model for three cases; the forward looking hemispheres of the MRS (LW) and the MIRI imager (MIRIM), and the hemisphere looking back through the detector into the FPMs.

3. ANALYSIS

The model generated a 2000 x 2000 grid of points, corresponding to an orthographic projection of the irradiance maps onto a plane orthogonal to the symmetry axis of the hemisphere. Each irradiance value ‘I’ was converted to a path length ‘t’ of aluminium using the attenuation formula, $I = Io \exp(-k\ t)$, where $k = 0.203\ \text{mm}^{-1}$ as defined above, to form aluminium path length maps which are plotted as the images in Figure 2.

In order to gauge the variation of shielding thickness with solid angle, we calculated the fraction of the total solid angle subtended at the hemisphere by rays passing through less than a thickness ‘t’ of aluminium. The results are plotted below the images in Figure 2.

4. DISCUSSION

In the direction of the Focal Plane Modules, which are near identical for all detectors, we see in Figure 2 that the path length is greater than 10 mm in almost all directions. For the MRS and MIRIM forward directions the maps show the web-like pattern of ribs and weight-relieving pockets in the MIRI structure and main mirrors which are so important in helping it to meet its stringent mass budget.

The thinnest regions (path length < 3 mm) are plotted in red, where for MIRIM, we see that there is a thin patch directly ‘above’ the detector boresight which is identified with the wall thickness being 2 mm in this region. For the MRS the thinnest region is through and around the final camera mirror in the spectrometer, close to the centre of the image.

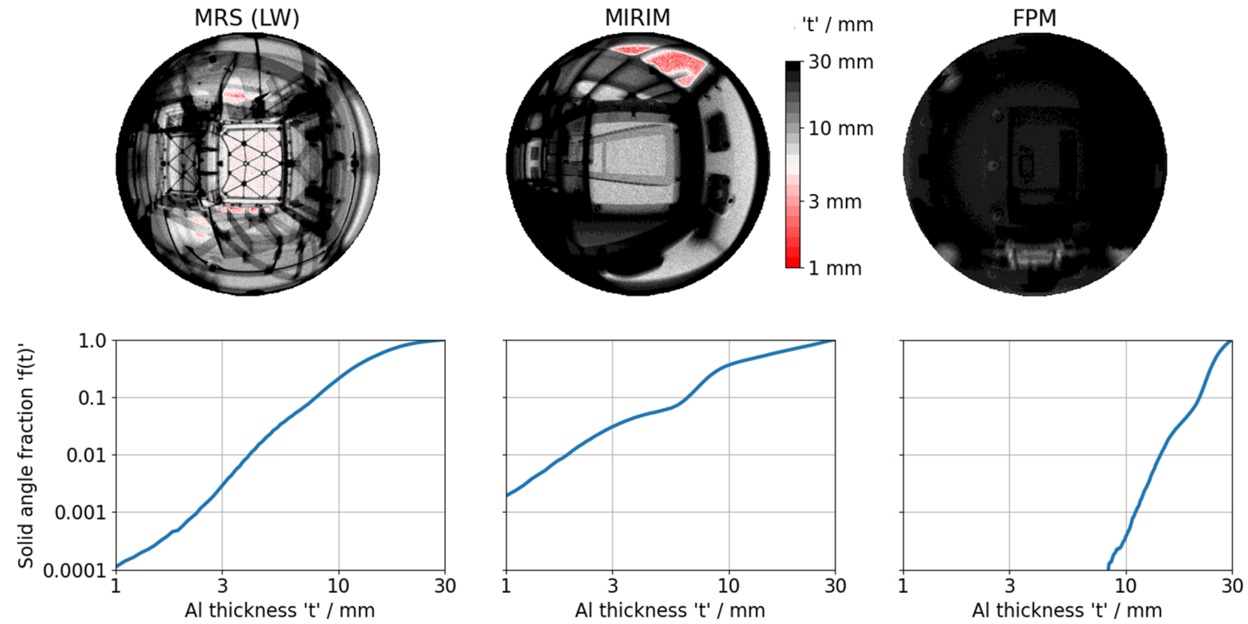

Figure 2. Aluminium thickness maps for the three modelled cases. The graphs plot the fraction of the solid angle for which the aluminium path length is less than the thickness ‘t’.

The plots of solid angle v aluminium thickness then show that the path length seen by the MRS detectors is less than 3 mm over 0.15 % of the full sphere, and less than 10 mm over 10.5 % of the sphere. For the MIRIM detector the corresponding figures are less than 3 mm over 1.5 %, and less than 10 mm over 18 % of the sphere.

5. SHIELDING PERFORMANCE

The ionizing particle spectrum consists of multiple components (we focus on the dominant species, protons). The particles in the solar wind itself have energies of ~ 0.5 – 10 keV. Solar energetic particles (SEPs), shock-accelerated in flares and coronal mass ejections, provide a steeply falling energy spectrum from about 1 keV to 100 MeV. Galactic cosmic rays (GCRs) have a very broad range of energies with a peak in the 100s of MeV and extending beyond 1 GeV. At 20 MeV and above, the flux is strongly dominated by the GCRs, and no plausible amount of aluminum shielding (within typical mass requirements) can significantly reduce their flux. In fact, as already mentioned, aluminum paths of more than a cm may be counterproductive due to production of knock-on particles and showering[3].

The range of 20 MeV protons in aluminum can be obtained conveniently from the stopping power and range tables provided by the U.S. National Institute of Standards and Technology (NIST), (https://www.nist.gov/pml/stopping-power-range-tables-electrons-protons-and-helium-ions). The range of 20 MeV protons in aluminum is 0.57 g/cm^2, or 2.11 mm. This value is an average, and the energy loss mechanism is multiple ionizations and hence a stochastic process. As a result, there is a distribution of ranges, sometimes termed path length straggling. Where the energy loss is small, this distribution can be significant relative to the average. However, the path of 20 MeV protons is characterized by a very large number of such interactions, and modeling of the effect[4] indicates that the standard deviation for 20 MeV protons in aluminum is 1.4 %. Adopting a 3-σ value, 2.2 mm of aluminum should be adequate to suppress the SEP flux well below that of GCRs.

The benefit from this level of shielding has been summarized by[5], who estimates that a path of 2.5 mm of aluminum will reduce the energetic proton flux by factors of ~ 3.1 and 6.6 respectively for Solar minimum and maximum.

ACKNOWLEDGMENTS

MIRI draws on the scientific and technical expertise of the following organisations: Ames Research Center, USA; Airbus Defence and Space, UK; CEA-Irfu, Saclay, France; Centre Spatial de Liege, Belgium; Consejo Superior de Investigaciones Cientcas, Spain; Carl Zeiss Optronics, Germany; Chalmers University of Technology, Sweden; Danish Space Research Institute, Denmark; Dublin Institute for Advanced Studies, Ireland; European Space Agency, Netherlands; ETCA, Belgium; ETH Zurich, Switzerland; Goddard Space Flight Center, USA; Institute d`Astrophysique Spatiale, France; Instituto Nacional de Tecnica Aeroespacial, Spain; Institute for Astronomy, Edinburgh, UK; Jet Propulsion Laboratory, USA; Laboratoire d`Astrophysique de Marseille (LAM), France; Leiden University, Netherlands; Lockheed Advanced Technology Center (USA); NOVA Opt-IR group at Dwingeloo, Netherlands; Northrop Grumman, USA; Max-Planck Institut fur Astronomie (MPIA), Heidelberg, Germany; Laboratoire d`Etudes Spatiales et d`Instrumentation en Astrophysique (LESIA), France; Paul Scherrer Institut, Switzerland; Raytheon Vision Systems, USA; RUAG Aerospace, Switzerland; Rutherford Appleton Laboratory (RAL Space), UK; Space Telescope Science Institute, USA; Toegepast-Natuurwetenschappelijk Onderzoek (TNO-TPD), Netherlands; UK Astronomy Technology Centre, UK; University College London, UK; University of Amsterdam, Netherlands; University of Arizona, USA; University of Bern, Switzerland; University of Cardiff, UK; University of Cologne, Germany; University of Ghent; University of Groningen, Netherlands; University of Leicester, UK; University of Leuven, Belgium; University of Stockholm, Sweden; Utah State University, USA. A portion of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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