Damage to Relativistic Interstellar Spacecraft by ISM Impact Gas Accumulation

Jon Drobny, Alexander N. Cohen, Davide Curreli, Philip Lubin, Maria G. Pelizzo, and Maxim Umansky

1 Department of Nuclear, Plasma, and Radiological Engineering, University of Illinois at Urbana Champaign, Urbana, IL, 61801, USA; drobny2@illinois.edu
2 Department of Physics, University of California—Santa Barbara, Santa Barbara, CA, 93106, USA
3 Consiglio Nazionale delle Ricerche—Istituto di Fotonica e Nanotecnologie (CNR-IFN), I-35131 Padova, Italy
4 Lawrence Livermore National Laboratory, Livermore, CA, 94550, USA

Received 2019 September 6; revised 2020 August 8; accepted 2020 December 16; published 2021 February 26

Abstract

As part of the NASA Starlight collaboration, we look at the implications of impacts with the interstellar medium (ISM) on a directed energy-driven relativistic spacecraft. The spacecraft experiences a stream of MeV/nucleon impacts along the forward edge primarily from hydrogen and helium nuclei. The accumulation of implanted slowly diffusing gas atoms in solids drives damage through the meso-scale processes of bubble formation, blistering, and exfoliation. This results in macroscopic changes to material properties and, in the cases of blistering and exfoliation, material erosion via blister rupture and delamination. Relativistic hydrogen and helium at constant velocity will stop in the material at a similar depth, as predicted by Bethe–Bloch stopping and subsequent simulations of the implantation distribution, leading to a mixed hydrogen and helium system similar to that observed within fusion plasma-facing components. However, the difference in depth of near-surface gas atoms with respect to the direction of exposure means that previously developed empirical models of blistering cannot be used to predict bubble formation or blistering onset. In this work, we present a model of the local gas concentration threshold for material blistering from exposure to the ISM at relativistic speeds. Expected effects on the spacecraft and mitigation strategies are also discussed. The same considerations apply to the Breakthrough Starshot mission.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Deep space probes (366); Space probes (1545)

1. Introduction

1.1. Motivation

If exploration beyond the outer limits of the solar system is to be conducted within reasonable fractions of a human lifetime, a radical shift in spacecraft propulsion technology is necessary. The radical shift proposed by Lubin (2016) and the NASA Starlight project consists of the directed energy propulsion of ultra-light spacecraft and a low-absorption reflective sail structure. The baseline system propels a low mass spacecraft via photon momentum exchange using a 1–10 km aperture, 100 GW class laser phased array to relativistic speeds. Such a system can be used with a wide variety of missions including the acceleration of a 1 g spacecraft to ∼c/4 or a 10 kg spacecraft to ∼c/40 or greater. This would enable the first robotic interstellar journey to the nearest star system, α Centauri, with a flight time of less than 20 yr. For this work, we use the term relativistic spacecraft to refer to this design and mission velocities greater than 0.1c. A spacecraft traveling at these speeds through interstellar space would experience the interstellar medium (ISM) in its rest frame as a nearly mono-energetic beam of particles, consisting primarily of protons, electrons, and alpha particles. Thus, in designing a spacecraft capable of surviving interstellar journeys, it is crucial to characterize, understand, and mitigate the damage that is caused by incident particles to ensure spacecraft survival through the ISM.

1.2. ISM Composition and Homogeneity

The ISM is composed of roughly 99% gaseous matter and 1% granular dust by mass. Of the gaseous matter, approximately 70% is hydrogen and 28% is helium by mass, while the remaining 2% is made up of heavier elements including carbon, oxygen, and iron (Draine 2011; Klessen & Glover 2016). Interstellar dust is composed of still heavier constituents including hydrocarbons, silicates, and ices in the form of crystalline and amorphous grains of size less than ∼1 μm (Draine 2011). Hydrogen in the ISM is observed in both neutral and ionized states, where the neutral state constitutes atomic and molecular hydrogen. The gaseous component of the ISM is commonly divided into five dominant phases which, since the phases are generally not in thermal equilibrium, drive large scale dynamics that produce structures like interstellar gas clouds of varying temperatures and often promote smaller scale gravitational phenomena such as star formation.

On large scales (∼10 to 100 lt-yr), the ISM is inhomogeneous and can vary greatly in density. While the majority of the ISM by volume is composed of ionized hydrogen with a density of approximately 1 cm⁻³, most of the neutral hydrogen is collected in large, cool clouds with densities between 0.1 and 50 cm⁻³ for neutral atomic hydrogen clouds and often greater than 1000 cm⁻³ for clouds cool enough to allow molecular hydrogen to exist in their cores (Draine 2011; Klessen & Glover 2016). These neutral gaseous phases are commonly referred to as cold and warm neutral media (CNM and WNM, respectively) depending on their temperatures, while the ionized phases are divided into the warm and hot ionized media (WIM and HIM, respectively).

For relativistic spacecraft for which α Cen or any other local star is the target, the ISM can be approximated by measurements of the Local Interstellar Cloud (LIC) due to the relatively short distance from the Sun to α Centauri. Common measurements of LIC densities, such as those performed by Gloeckler and Geiss, report combined H and He densities as low as ∼0.26 cm⁻³ (Gloeckler & Geiss 2004). Therefore, for our analyses we conservatively approximate the local ISM as a homogeneous gas of atomic hydrogen with a density of 1 cm⁻³ and a temperature of approximately 8000 K. Thus, to a relevant first approximation,
the local ISM falls within the WNM phase. However, distinct structures produced by the interaction of the ISM and stellar winds complicate the environment since they can create phases of matter that deviate greatly from the above approximation.

1.3. Stellar Winds

In addition to the various phases of the ISM that the spacecraft may experience, it may also be subject to the potentially damaging effects of stellar winds and the structures they produce as it approaches stellar targets. Specifically, in the simple stellar wind model consisting of a radial and isotropic outflow of material from the star, one would expect that, in the region where the stellar wind interacts strongly with the local ISM, there would exist a potentially different phase of material created by the interacting materials. In a NASA study by Linsky & Wood (1996), it is described how the $\alpha$ Centauri system, though consisting of a total of three stars, likely produces a solar wind and atmosphere similar to the Sun’s due to the proximity of the stars in the system, the main-sequence nature of the two dominant stars, and the similarity in relative velocity to the local ISM of the Sun and the $\alpha$ Centauri system. It was found, and later verified by a number of groups (Wood et al. 2004; Zank et al. 2013), that in the region surrounding the $\alpha$ Centauri astropause, and thus likely also around the heliopause of the Sun and the astropause of most stars in the local cloud, there exists a heated region of ISM material compressed by the outflowing stellar wind to a temperature $\sim 30,000$ K and density $\sim 0.3$ cm$^{-3}$, commonly referred to as the hydrogen wall. It is interesting to note that at 0.25 $c$, the spacecraft will likely pass through the hydrogen wall very quickly. Thus, we may be able to test this regime experimentally since the exposure time at hydrogen wall densities and temperatures may be small.

1.4. Relativistic Spacecraft Design

The baseline design for small relativistic wafer scale spacecraft consists of a single thin semiconductor or hybrid disk of radius between 25 and 100 mm depending on the mission with a nominal diameter of 100 mm (Lubin 2016). The spacecraft flies edge-on to reduce the number of ISM particle and dust impacts. The wafer houses the entire spacecraft bus, sensor suite, power system, and communication system on its surface, and would be manufactured from silicon or titanium using plasma etching technologies. It is to be extremely thin, $\sim 100$ $\mu$m, with a thin-walled honeycomb structure on the other side to reduce mass and enhance its structural integrity, as shown in Figure 1. The spacecraft wafer is then embedded within or attached to a light-sail structure made of an ultra-thin ($\sim 0.1–1$ $\mu$m) dielectric, reflective and low-absorption material that reflects the incident laser light, thus generating thrust. In other variants, the spacecraft could be a long thin “needle-like” structure with small forward-edge cross section. The lowest mass missions have a wafer and reflector mass of order 1 g, though the same launch system is capable of larger missions with higher mass spacecraft being slower with speed scaling as $m^{-1/3}$ (Lubin 2016).

In some proposed mission scenarios, the spacecraft design calls for a mechanism by which the reflector can be ejected from the wafer after the spacecraft has been accelerated to its cruise speed. In others, the reflector remains attached to the spacecraft for the duration of its journey or is removed passively by vaporization due to collisions with interstellar gas and dust.

Due to the extremely large distances to interstellar mission targets, the spacecraft communicates with Earth using a dedicated laser communications system to send data back to Earth. The spacecraft quickly enters a regime where the command delay time becomes exceedingly long, requiring largely autonomous operation with infrequent uplink commands. The spacecraft is powered by the heat given off by a small pellet of radioactive material such as plutonium-238, though the ISM impacts could conceivably be used as a source of power. In most mission scenarios, the spacecraft enters a low power hibernation mode during transit to its destination. The details of this are discussed in our other papers (Lubin 2016).

2. Cumulative Effects of ISM Impacts

2.1. Instantaneous Ion–Matter Interactions

ISM particle impacts will have a significant effect on relativistic spacecraft. Figure 2 shows a summary of particle-spacecraft interactions, including hydrogen/helium implantation, heavy species impacts, and secondary particle generation. Since
ISM particles incident upon a relativistic spacecraft will immediately lose their electrons on impact, we can treat the ISM in the frame of a relativistic spacecraft as a fully ionized, constant-velocity beam, composed primarily of hydrogen and helium. Ion–matter interactions span many orders of magnitude of energy-, time-, and length-scales and include the processes of sputtering, displacement of target atoms and damage, thermal spikes, and implantation. Contemporary understanding of these phenomena comes from a combination of theoretical, empirical, and computer models. Careful application of these models is necessary to understand the cumulative effects of ion bombardment. For example, a straightforward calculation of the analytic Bohdansky (1984) or semi-empirical Yamamura (Matsunami et al. 1984) formulas for the sputtering yield of relativistic ISM impacts will predict a negligible amount of material erosion during an interstellar journey, as shown in Figure 3(a).

Figure 3. (a) Sputtering yields from the Yamamura and Bohdansky formulas for hydrogen and helium on copper and silicon. (b) Total erosion from the Yamamura formula for sputtering yield, expected ISM fluence, atomic mass of the shield material, and mass density of the shield material, as shown in Equation (1).

Total one-dimensional erosion depths can be calculated based on the fluence and target material parameters with the expression

\[ \Delta x = \frac{\Phi_1 Y_{12}(E_1) M_2}{\rho_2}, \]  

where \( \Delta x \) is the depth of material eroded, \( \Phi_1 \) is the fluence of species 1, \( Y_{12}(E_1) \) is the sputtering yield for species 1 incident on species 2, \( M_2 \) is the atomic mass of species 2, and \( \rho_2 \) is the mass density of species 2. Using this approximation, erosion of silicon and copper by hydrogen and helium for a journey to α Cen at speeds between 0.1 and 0.5c is less than a single atomic layer, as shown in Figure 3(b). Erosion by physical sputtering is low for two reasons: first, energy transfer during collisions between energetic light ions and heavy atoms is inefficient, leading to low sputtering yields of heavy targets by light ions; second, at these energies, most of the ion–atom energy transfer occurs deep below the surface, where the nuclear stopping cross section becomes significant compared to the electronic stopping cross section. For atoms to be sputtered, momentum must be transmitted from this location to a free surface. A previous work (Hoang et al. 2017) has considered the damage caused by the cumulative effect of instantaneous ion–matter interactions, including sputtering and track-formation. However, damage from the accumulation of gas atoms is an unexplored, potentially threatening phenomenon for relativistic spacecraft. Gas atom accumulation negatively affects material properties, causes material swelling, induces surface morphology changes through blistering, and can drive erosion through exfoliation at rates exceeding physical sputtering.

2.2. Bubble Formation and Blistering

Bubble formation, blistering, and exfoliation are deleterious phenomena caused by the accumulation of relatively insoluble gas atoms in solids. Figure 7 shows an illustration of the bubble formation and blistering process. Insoluble gas atoms implanted in a solid, such as helium, can aggregate and form overpressurized bubbles (Donnelly 1985). If the local gas concentration exceeds a critical concentration, near-surface bubbles can deform the surface and burst, in processes called blistering and, when material is removed, exfoliation. When blistering does not occur, such as in the case of a subcritical gas concentration, the implanted gas atoms negatively affect material properties and can lead to swelling and crack nucleation (Condon & Schober 1993). Figure 4 shows examples of surface damage caused by implanted gas atoms, including blistering and exfoliation.

Blistering is a phenomenon typically encountered when materials are exposed to high-flux, high-fluence, intermediate energy (keV range), insoluble gas ions, such as in ion beam experiments and nuclear fusion (Bauer 1978; Behrisch 2010; Balden et al. 2013). Blistering by hydrogen and helium specifically has been extensively studied in these contexts (Erents & McCracken 1973; Das & Kaminsky 1975; Evans 1976; St-Jacques et al. 1978; Kaletta 1980; Guseva & Martyenko 1981). Blistering induced by low-energy protons has also been observed in extreme ultraviolet multilayer optics used in photolithographic systems (van den Bos et al. 2017) and space instrumentation (Pelizzo et al. 2011), and in metal films tested for space environmental conditions (Sznajder et al. 2018). In Figure 5 an example of blistering occurring in a thin gold layer is shown. The sample has been irradiated with 4 keV low-energy helium ions with a total fluence of \( 4 \times 10^{21} \) m\(^{-2} \); at
lower fluences, no clear evidence of bubbles was found. At higher energies (MeV range), blistering has been reported to occur at fluences an order of magnitude below the critical dose observed in analogous experiments at intermediate energies (keV range; Gavish Segev et al. 2017). In these situations, blistering occurs on the surface exposed to the ion flux, because the ions implant close to the surface.

In the frame of a relativistic spacecraft, the ISM appears as a low-flux, high-fluence, MeV-energy beam that spans the entire front-facing cross section of the spacecraft. During relativistic travel, the implantation depth distributions of ISM gas atoms will be strongly peaked many atomic layers below the surface. Additionally, due to the scaling of Bethe–Bloch stopping, at a constant relativistic velocity, hydrogen and helium will stop at approximately the same depth. From the prefactor of the Bethe formula, $S_0$, shown in Equation (2) with $Z_1$ being the atomic number of the incident ion, $Z_2$ being the atomic number of the target material, $m_e$ being the electron mass, and $v$ being the incident velocity, helium will experience a stopping power approximately four times larger than hydrogen. However, since helium is approximately four times more massive than hydrogen, helium at constant velocity will have approximately four times more kinetic energy, resulting in similar ranges in a given material. This will result in a thin layer of material spanning the entire exposed portion of the spacecraft, at the depth of the implantation distribution, where the local concentration of mixed gas atoms may form bubbles and

**Figure 4.** Diagram showing damage to materials in the intermediate fluence range, including material defects, blistering, and exfoliation, shown here for illustrative purposes. Reprinted by permission from Springer-Verlag: Scherzer (1983), 1983.

**Figure 5.** (a) Gold sample prior to irradiation. (b) Gold sample after irradiation with 4 keV He ions with a total fluence of $4 \times 10^{17} \text{cm}^{-2}$. Blistering is observed close to the surface at ions penetration depth. Reprinted with permission from Pelizzo et al. (2018). Copyright (2018) American Chemical Society.
may exceed the critical concentration necessary to form blisters.

\[ S_0 = \frac{4\pi e^4 Z_1^2 Z_2}{m_v v^2} \]  \hspace{1cm} (2)

In Figure 6(a), an illustration of bubble formation during a high-energy ion beam experiment is shown; the distance to the nearest surface from the location of bubble formation is approximately the range of the implantation distribution. In order to cause blistering or modify surface morphology, bubbles must travel to this surface or deform a layer of this thickness to have an effect. Figure 6(b) shows bubble formation caused by ISM gas accumulation. In this case, the smallest distance from bubble formation locations to a surface is effectively zero; gas atoms or bubbles do not need to travel any distance to begin having a deleterious effect on the nearest surface; Figure 7 shows an illustration of the bubble formation, migration, and blistering process. For this reason, swelling, blistering, and exfoliation may happen significantly earlier for the case of wide exposure. Previous work on blistering has produced an empirical formula (Gavish Segev et al. 2017) for predicting the dependence of critical dose on the incident ion energy; since this formula assumes blister formation at the surface directly exposed to ion flux, it is not applicable here. Instead, a more fundamental model of blistering onset must be used.

A simple theoretical model of blistering onset was described by Martynenko, and a reduced version is reproduced here (Martynenko 1977). In this model, a local pressurization is determined from the concentration of dissolved gas atoms, \( c_g \), and the dissolution energy, or energy change associated with the dissolution of a gas atom in the material, \( E_{d_i} \) of the gas species in the target material:

\[ p = E_{d_i} c_g. \]  \hspace{1cm} (3)

When more than one gas species is present, we assume that the pressures add linearly according to the partial concentration of each:

\[ p = \sum_{i=1}^{n} E_{d_i} c_i. \]  \hspace{1cm} (4)

A critical pressure for blistering onset is chosen as the pressure that exceeds the appropriate yield strength of the material, \( \sigma_y \), resisting the overpressurization in implanted gas bubbles. A critical concentration, \( c_{cs} \), is the local gas concentration at which this pressure is exceeded. Local gas concentration is
Table 1

Ranges and Stragglers of Hydrogen and Helium at 0.2c

| Material | C (graphite) | Cu | Si |
|----------|--------------|----|----|
| \( R_{\text{He}}(0.2c) \) | 1.9 mm | 0.72 mm | 2.1 mm |
| \( \Delta R_{\text{He}}(0.2c) \) | 30 \( \mu \)m | 15 \( \mu \)m | 35 \( \mu \)m |
| \( \Delta R_{\text{H}}(0.2c) \) | 13 \( \mu \)m | 7.2 \( \mu \)m | 14 \( \mu \)m |

Note. Ranges and stragglers obtained from SRIM simulations with 10,000 incident ions each. The “Ion Distribution and Quick Calculation of Damage” mode was used for these simulations.

approximately by:

\[
c_g = \frac{\Phi}{\Delta R}
\]  

where \( \Phi \) is the fluence and \( \Delta R \) is the width of the distribution. The width of the distribution is determined from the width of the implantation distribution and the diffusion length:

\[
\Delta R = \sqrt{\Delta R^2 + Dr}.
\]

Where \( \sqrt{\Delta R^2} \) is the straggler or standard deviation of the implantation distribution, \( D \) is the diffusion coefficient, and \( r \) is the irradiation time. In the case of gas implantation via ion irradiation, it is often assumed that irradiation damage produces enough defects to serve as trapping sites that the diffusion coefficient is negligible (Martynenko 1977; Scherzer 1983). In Section 2.5, an estimate of the effective diffusion in the presence of damage produced by relativistic light ion impacts is made. Lattice defects caused by ion irradiation also provide nucleation for fixed helium bubbles (Kornelsen 1972). We can assume additional trapping due to the interaction of hydrogen with helium in the material, since helium bubbles serve as trapping sites for hydrogen atoms through synergistic effects (Hayward & Deo 2012), leading to a lower critical dose in the case of mixed hydrogen and helium exposure (Guseva & Martynenko 1981). At temperatures well below the melting point, such as that expected for a relativistic interstellar spacecraft, high-flux hydrogen irradiation damage effects have been reproduced in low-flux experiments (Gao et al. 2019). However, for an interstellar probe, the flux is sufficiently low that diffusion effects may play a non-negligible role. Classical diffusion of individual gas atoms could lead to lower local gas atom concentrations as the implantation distributions widen, or increased gas atom concentrations around trapping sites such as grain boundaries; the effect of diffusion is discussed in Section 2.5. Helium bubble nucleation and migration could lead to increased gas atom concentrations and damage near surfaces, grain boundaries, and other defects (Nakamura et al. 1977; Goodhew 1983; Lane & Goodhew 1983). No single theoretical framework exists to summarily treat these effects. However, simple models such as that presented here immediately offer compelling mitigation strategies. To perform this analysis, we find implantation profiles of ISM gas atoms at relativistic speeds using an ion–material interactions code, calculate critical concentrations for blistering onset for hydrogen and helium individually assuming a worst-case scenario of negligible diffusion, and show the effect of non-negligible diffusion on local gas concentrations.

**2.3. Ion Implantation Distributions**

SRIM is a free-use but closed-source Monte Carlo, Binary Collision Approximation (BCA) code used to model ion–material interactions in continuous development since 1985 (Ziegler 2004; Ziegler et al. 2010). A detailed description of the BCA model can be found in Eckstein (1991) and Robinson (1994). For nuclear interactions, SRIM uses a universal interaction potential, the Ziegler–Biersack–Littmark potential, and the MAGIC algorithm to calculate the scattering angle of each binary collision (Biersack & Haggmark 1980). To model electronic interactions, SRIM includes an electronic stopping formula that includes Lindhard & Scharf (1953) electronic stopping at low energies (below approximately 25 keV amu\(^{-1}\)).
Bethe–Bloch (Ziegler 1999) stopping with corrections at high energies (above approximately 1 MeV amu$^{-1}$), and the empirical Andersen–Ziegler (Andersen & Ziegler 1977) stopping at intermediate energies between the ranges of validity of Lindhard–Scharff and Bethe–Bloch. Electronic stopping is evaluated along each path between binary collisions with target atoms. SRIM produces detailed information about stopped ions, including final resting positions in the material, from which we find implantation distributions.

Although SRIM has recently come under scrutiny for inaccuracies for low to intermediate energy sputtering (Wittmaack 2004; Shulga 2018, 2019) and sputtered atom angular distributions (Hofsiess et al. 2014), these issues do not affect the high-energy implantation distributions relevant to our analysis. From these ion implantation distributions we calculate the straggle and use this to estimate the local gas concentration in materials. Ranges and straggles of hydrogen and helium for a selection of materials are included in Table 1, and the straggle and use this to estimate the local gas concentration in materials. Ranges and straggles of hydrogen and helium for all presently considered shield candidate materials are included in Table 2. For this calculation, ISM particles are assumed to be mono-energetic for the duration of the mission, and the acceleration phase is not considered.

Figure 8(a) shows the implantation depth and straggle of hydrogen and helium in copper, an example shield material, from 0.1 to 0.5c. Copper was chosen as a representative metallic shield material in which hydrogen is relatively soluble, potentially mitigating hydrogen blister formation (Magnusson & Frisk 2017). Dissolution energies of hydrogen and helium for a variety of candidate shield materials are shown in Table 3. For velocities in excess of approximately 0.07c, the implantation distribution of helium out to one standard deviation from the mean fits entirely within one standard deviation of the hydrogen distribution. The inset in Figure 8(a) is a zoomed in figure showing this overlap at velocities relevant to a relativistic, interstellar mission (0.25–0.3c). Figure 8(b) shows the full implantation distributions of hydrogen and helium in copper at 0.1, 0.2, 0.3, 0.4, and 0.5c from SRIM simulations, normalized to unity. Any long duration, high velocity mission will be subject to a layer of mixed hydrogen and helium implanted many atomic layers deep below the surface. Table 1 shows the results of SRIM simulations for a number of other example materials at 0.2c. In each material, hydrogen and helium stop at the same distance. As the velocity increases, the straggle increases, due to the increased number of small-angle atomic collisions incident particles are subject to as they travel deeper in the material.
Over the course of a journey of 4.37 lt-yr, the approximate distance to α Cen, the fluence for hydrogen and helium will be $3.8 \times 10^{22}$ m$^{-2}$ and $3.3 \times 10^{21}$ m$^{-2}$, respectively, regardless of travel speed.

Using the model for determining blistering onset presented above, Figure 9 shows calculated critical concentrations of implanted gas atoms for a range of dissolution energies. Hydrogen, which dissolves readily in copper, has a dissolution energy near 0.5 eV (Magnusson & Frisk 2017). For gas–material combinations with lower solubility, the dissolution energy will be significantly higher. Dissolution energies of hydrogen and helium are not widely available for many materials; a collection of materials with available dissolution energies of hydrogen and helium is presented in Table 3. Determining dissolution energies requires carefully designed experiments or computational modeling. Additionally, this calculation assumes a constant ISM number density of 1.0 cm$^{-3}$; if the actual number density is larger, the fluence and thus implanted gas concentrations will increase linearly with increasing number density. From Figure 9, it is apparent that the local gas concentration of hydrogen and helium at 0.1c will be lower than at 0.2c; in other words, at higher relativistic velocities, incident ions will have traveled through significantly more material and will have experienced many more small-angle nuclear collisions, leading to increased straggles.

Determining the appropriate yield strength to use in the calculation of critical fluence presents some difficulty. Using the standard yield strength significantly underestimates the critical fluence for many materials at low to intermediate energy (keV range); one strategy is to estimate the yield strength as 10% of the elastic modulus (Martynenko 1977). Using this estimate to examine the case of gold irradiated with 4 keV helium shown in Figure 5, using 0.76 eV as the dissolution energy of helium in gold (Laakmann et al. 1987), 100 angstroms for the straggles, and 171 GPa as the elastic modulus of gold, we calculate a critical fluence of $1.4 \times 10^{21}$ m$^{-2}$; the observed critical fluence was $4 \times 10^{21}$ m$^{-2}$, with the next highest fluence $4 \times 10^{20}$ m$^{-2}$, showing no blistering. However, this estimate, chosen to match contemporary experimental results of low to intermediate energy ion irradiation, does not hold at higher energies (Gavish Segev et al. 2017). Tungsten targets irradiated with 2.2 MeV protons exhibited blister formation at $3 \times 10^{21}$ m$^{-2}$, well below the critical fluence suggested by the 10% of the elastic modulus estimate (using 405 GPa as the elastic modulus, 1.18 microns as the straggles, and 1.1 eV as the dissolution energy) of $2.7 \times 10^{23}$ m$^{-2}$. However, the critical pressure calculated using this method from the observed critical fluence is 448 MPa–within 20% of the yield strength. This suggests that, for high-energy irradiation, the correct choice of critical pressure is on the order of the yield strength of the material. Further experimental or computational investigation is necessary to determine the correct critical pressure for many materials, but for this work, as a best-available, order-of-magnitude estimate, we will use the yield strength as the critical pressure.

Values for these quantities are reported for copper in Figure 9 as vertical lines at 250 MPa and 13.3 GPa, representing the traditional yield strength, used as a high-energy estimate, and 10% of the elastic modulus, the low-energy estimate, respectively. Since we expect near-surface bubbles on surfaces perpendicular to ion exposure, choosing the correct yield strength will be critical for choosing target materials. For this work, we consider the standard yield strength as the best-available estimate of the critical pressure for blistering from high-energy light ion irradiation. Critical fluences using this value are presented for a variety of materials, including copper, in Table 4. Note that this figure shows the threshold for blistering, and that bubble formation, swelling, and changes to material properties are expected at fluences several orders of magnitude lower than the blistering threshold; these effects of gas accumulation will need to be mitigated.

### 2.5. Role of Diffusion in Cumulative Damage

Over the long timescales of an interstellar mission, diffusion will decrease the local implanted gas concentration by widening the implanted gas distributions. However, an interstellar spacecraft will have a relatively low equilibrium temperature, and the high-energy irradiation will produce significant damage in the spacecraft material, lowering the diffusion coefficient by trapping implanted gas atoms in vacancies and other radiation-induced defects (Langley 1984). As an example, in BCC metals such as tungsten, the hydrogen activation energy for diffusion is typically on the order of 0.1 eV. For tungsten, the binding energy of a vacancy, capable of holding many hydrogen atoms simultaneously, has been calculated to be as high as 1.2 eV (Johnson & Carter 2010). This deep trapping site is a significant barrier to diffusion.

Understanding the long timescale behavior of implanted gas atoms in spacecraft material including the effects of hydrogen–helium interactions, defect production by irradiation, and interactions of near-surface gas atoms with the material will be necessary to design materials capable of surviving an interstellar journey. Molecular dynamics and density functional theory simulations are appropriate tools to study these effects in silico, but including realistic fluences at high energy in atomistic simulations demands significant computational resources. Continuum modeling of bubble formation and bubble dynamics offers another approach, but relies on data from extensive HPC-scale MD and DFT calculations (Blondel et al. 2018). Barring terrestrial experimentation, a simple 0D quantitative analysis,

### Table 4

| Material | $\Phi_c(0.05c)$ (m$^{-2}$) | $\Phi_c(0.1c)$ (m$^{-2}$) | $\Phi_c(0.2c)$ (m$^{-2}$) |
|----------|---------------------------|---------------------------|---------------------------|
| Al       | 7.72 $\times 10^{20}$     | 5.64 $\times 10^{20}$     | 5.08 $\times 10^{21}$     |
| Cu       | 1.34 $\times 10^{20}$     | 6.74 $\times 10^{20}$     | 5.12 $\times 10^{21}$     |
| Mo       | 1.45 $\times 10^{21}$     | 7.59 $\times 10^{21}$     | 6.67 $\times 10^{22}$     |
| Nb       | 2.71 $\times 10^{22}$     | 1.62 $\times 10^{23}$     | 9.61 $\times 10^{23}$     |
| V        | 9.28 $\times 10^{21}$     | 5.24 $\times 10^{22}$     | 4.21 $\times 10^{23}$     |
| W        | 9.38 $\times 10^{20}$     | 3.87 $\times 10^{21}$     | 2.64 $\times 10^{22}$     |
| Ta       | 6.07 $\times 10^{21}$     | 1.25 $\times 10^{22}$     | 7.83 $\times 10^{22}$     |
| Li       | 1.46 $\times 10^{20}$     | 1.47 $\times 10^{21}$     | 1.34 $\times 10^{22}$     |
| Be       | 6.20 $\times 10^{20}$     | 4.97 $\times 10^{21}$     | 4.92 $\times 10^{22}$     |
| Ti       | 9.20 $\times 10^{20}$     | 6.14 $\times 10^{21}$     | 5.35 $\times 10^{22}$     |

**Note.** The relativistic spacecraft-relevant critical fluences are calculated using the high-energy version of the blistering onset formula (using yield strength as the critical pressure) from the material parameters in Table 3 and straggles from Table 2. Hydrogen and helium pressures are combined linearly assuming a 1:9 ratio of helium to hydrogen by number, with no synergistic effects taken into account. If a dissolution energy is negative, it is taken to add zero pressure.
presented below, may be used to investigate promising shield materials with a significant safety margin to compensate for the lack of a complete multi-scale model.

To estimate the effect of diffusion considering radiation damage, we use the Oriani model of diffusion in the presence of trapping sites (Oriani 1970; Hatano et al. 2013). An effective diffusion coefficient can be found from the lattice diffusion coefficient, 

$$D_{\text{eff}} = D_0 \exp(-E_a/kT)$$

where $E_a$ is the activation energy for diffusion, the equilibrium temperature $T_{\text{eq}}$, the binding energy for the trapping site, $E_b$, and the vacancy concentration, $c_T/c_L$, as shown in Equation (7). A calculation of the peak vacancy density production rate per unit fluence can be made using SRIMs damage calculation, following (Stoller et al. 2013). To estimate the equilibrium temperature of the spacecraft, we use the same formula as Hoang et al., reproduced in Equation (8). This analysis considers only the

effect of single vacancies on the diffusion coefficient and does not account for other radiation-induced defects, bubble formation and void production, or synergistic effects between hydrogen and helium, each of which would further lower the effective diffusion coefficient. The effective diffusion coefficient $D_{\text{eff}}$ and the corresponding equilibrium temperature $T_{\text{eq}}$ are given by

$$D_{\text{eff}} = \frac{D_0 \exp(-E_a/kT)}{1 + (c_T/c_L)\exp(E_b/kT)}$$

and

$$T_{\text{eq}} = \left(\frac{1.4n_{\text{ISM}}v_3}{2\sigma_{\text{SB}}}\right)^{1/4}.$$  

Using the lattice diffusion coefficient and peak vacancy production rates from SRIM, the effective diffusion coefficient at the damage and implantation peak can be calculated along the travel path of the spacecraft due to the incident fluence, as shown in Equation (9) and for copper and tungsten at 0.2$c$ in Figure 11. SRIM’s estimates of the peak damage production rate per unit fluence for copper and tungsten at 0.2$c$ are approximately $5 \times 10^5$ vac/meter-ion and $4 \times 10^5$ vac/meter-ion, respectively. We choose as negligible a diffusion coefficient below which the effective diffusion length, $L_{\text{eff}} = \sqrt{D_{\text{eff}} t}$, over an interstellar journey remains below 0.1 $\mu$m. At $-15^\circ$C, the equilibrium temperature for a spacecraft traveling at 0.2$c$ and an ISM particle density of $1.0 \text{ cm}^{-3}$, the diffusion coefficient dependence on vacancy concentration for copper and tungsten is shown in Figure 10. At temperatures and travel distances relevant to interstellar missions, the effective diffusion coefficient will be so low as to be negligible. A mechanism not taken into account in this analysis is vacancy saturation due to radiation. Defects cannot be produced in a material indefinitely; once there are enough vacancies present,

Figure 10. Effective hydrogen diffusion coefficients in tungsten and copper as a function of vacancy concentration, at the equilibrium temperature of a relativistic spacecraft traveling at 0.2$c$ through an interstellar medium density of $1.0 \text{ cm}^{-3}$. The value of the effective diffusion below which the diffusion length is negligible compared to the straggle is shown.

Figure 11. Effective hydrogen diffusion coefficients in tungsten and copper as a function of distance traveled for $n_{\text{ISM}} = 1.0 \text{ cm}^{-3}$ at 0.2$c$. The value of the effective diffusion below which the diffusion length is negligible compared to the straggle is shown.

Figure 12. Schematic of a wafer-like spacecraft geometry and four proposed shielding schemes. (a) Sintered granular material, (b) porous ceramic, (c) self-annealing liquid layer with heat exchanger (yellow), (d) metallic powder. Other shielding schemes involve plastics, oils, and/or circulating liquids.
the creation of further vacancies will induce recombination of vacancy-interstitial pairs. This value is not widely available
in the literature for many materials; for tungsten however, the vacancy saturation limit is known to be approximately
0.1 vac/atom (Hatano et al. 2013). At $-15^\circ$C, the effective diffusion coefficient is made negligible by a much lower vacancy concentration, approximately $10^{-8}$ vacancies per atom. Equation (9) shows the fluence required to lead to a
given effective diffusion length. As shown in Figure 11, for an ISM density of 0.3 particles per cm$^3$ and a spacecraft velocity of 0.2$c$, enough damage is produced in the spacecraft to reduce diffusion to a negligible level almost immediately. Per this analysis, at 0.2$c$ exposure to the ISM will result in a low
temperature and high vacancy production rate that will render diffusion negligible.

$$ \Phi = \frac{(D_0/L_{e,\text{eff}}^2) \exp(-E_a/kT)t - 1}{R \exp(E_b/kT)} $$

\text{(9)}

3. Discussion

3.1. Implications on Mission Success

The implications of the previously described phenomena are mission-threatening. For a 20 yr journey without an adequate shielding system, hydrogen or helium bubble formation and subsequent bursting may induce damage to the spacecraft’s leading edge which, as the damage continues to make its way into the spacecraft body, will eventually damage components and electronics essential to the spacecraft’s performance. Other spacecraft geometries, such as the needle-like spacecraft proposed by Lubin (2016), may help mitigate this issue by minimizing the front-facing surface area. If blistering and exfoliation does not occur, migration of gas atoms and bubbles into spacecraft components may lead to hardware failures. Additionally, overpressurized bubbles bursting at the surface will both drastically alter the surface morphology and induce torques on the spacecraft, both of which will alter the long-term trajectory and orientation of a gram-scale spacecraft. Torques induced by bubble rupture must be compensated for by the attitude control system (ACS), which might pose significant constraints on the design of the ACS and its authority over such perturbations. Moreover, secondary particle production and heavy species impacts have the potential to induce damage at a greater rate and severity than the common proton impact.

3.2. Mitigation Strategies

Various shielding schemes are proposed as mitigation strategies. Since the spacecraft is designed to fly edge-on into the ISM, a circumferential shield is proposed to protect the ISM-facing edge, as seen in Figure 12. The shield must satisfy three essential requisites: (1) block incoming proton radiation without structural failure due to hydrogen bubble formation, (2) stop any incoming heavier species, and (3) mitigate the production of secondary particles and their propagation through the spacecraft. Shield composition should be chosen to minimize the dissolution energy or maximize the effective yield strength, and minimize the total mass; these three parameters are summarized in Figure 13. Since the majority of the expected particle impacts will result in hydrogen build up at a localized depth below the surface, the Bragg peak, an effective shield would be at least two times as thick as the Bragg peak is deep.

A favored shielding scheme consists of a sintered material at the H/He Bragg peak. The sintered nature of the material makes it granular with a characteristic grain and hole size that enable a high resistance to bubble formation (Rossing et al. 1977). In a similar scheme, a porous ceramic material is used to surround the Bragg peak. The porous nature of the material acts similarly to the sintered material in that it makes it resistant to bubble formation and allows storage of the implanted hydrogen.

Figure 13. Comparison of materials discussed in this study, where $E_{d,H}$ and $E_{d,He}$ are the dissolution of energies of hydrogen and helium, respectively.

Figure 14. Proposed experimental setup for radiation studies using a linear accelerator or cyclotron. Top: the target is to be fabricated in a cylindrical shape so as to study implantation over a continuous range of incident angles. Bottom: in the ideal scheme, the target mount would house multiple targets of various materials and the accelerator facility would have the capability to control the temperature of the target.
in its pores. A favorable material for the shield is carbon due to its higher energy onset of secondary neutron production than most materials.

Schemes involving metal powder layers surrounding the Bragg peak are predicted to perform in a similar fashion to the sintered material shields due to the granular nature of the material. Other shielding schemes involve layers of self-annealing metals that can be induced from solid to liquid states and back again repeatedly, such as gallium or mercury. In these schemes, incoming protons are collected at the Bragg peak while the metal is in a solid state. Then, once the rotation of the spacecraft carries a particular circumferential region out of the direction of the incoming radiation, the metal is heated until it liquefies, allowing the implanted hydrogen, in the form of gas atoms or hydrides, to diffuse to the edges and escape the spacecraft. Similar schemes involve the use of long-chained polymers, plastics, or circulating oils or liquids to mitigate bubble formation and store implanted hydrogen.

More outlandish shielding schemes involve the deflection of incoming charged particles via electromagnetic fields about the circumference of the spacecraft. However, inherent issues such as high power consumption and strong field amplitudes necessary limit the viability of this approach on a small spacecraft.

3.3. Terrestrial Experimental Design

Terrestrial experimental investigation of the effect of ISM impacts on relativistic spacecraft will rely on an appropriate accelerator facility. A proposed target design for such an experiment is shown in Figure 14. Such a facility would need to meet the following requirements to be informative for this study:

1. High flux such that \( \sim 20 \text{ yr worth of ISM fluence} \) can be simulated in hours, days, or weeks. Since we expect a total fluence of approximately \( 4 \times 10^{22} \text{ m}^{-2} \), we would require a flux on the order of \( 10^{16} \text{ m}^{-2} \text{ s}^{-1} \) to achieve the target fluence with an exposure time of roughly 1.5 months.

2. Ability to defocus the beam such that the ion flux can span the forward-facing cross section of the target, investigating the possibility of blistering occurring on surfaces perpendicular to the direction of exposure.

3. Cooling capabilities to control target temperature. At laboratory-relevant fluxes, we expect significantly higher target temperatures than for a relativistic spacecraft.

4. Ability to implant hydrogen and helium at constant velocity. Simultaneous exposure may not be possible, so careful alternating exposures may be required.

There do exist facilities that meet many of these requirements. Material diagnostics would include TEM/SEM/AFM of front-facing and perpendicular surfaces to determine surface morphology and characterize any swelling, blistering, or exfoliation, and FIB to measure depth-dependent composition to determine diffusion coefficients.

Nuclear activation of the target due to proton irradiation is an additional concern for the spacecraft, but is also a concern for access to samples soon after experimental irradiations. A future paper will quantitatively address this issue.

4. Conclusion

In this work, we present the potentially mission critical phenomenon of damage to relativistic spacecraft by gas accumulation. Composed primarily of hydrogen and helium, exposure to the ISM at relativistic velocities will result in gas atoms accumulating many atomic layers below the front-facing surfaces of the spacecraft. Accumulation of hydrogen and helium in solids is associated with processes such as bubble formation, swelling, blistering, and exfoliation. Since the exposure will span the entire forward edge of the spacecraft, blistering may occur on surfaces perpendicular to the direction of travel. Using a zero-dimensional model of blistering onset, we have performed preliminary calculations in general and for copper, an example metallic shield material.

For a spacecraft velocity of 0.05c, this model predicts that all shield materials considered, including those in which hydrogen is readily soluble, will blister on a journey to \( \alpha \text{ Cen} \). At 0.1c, niobium and vanadium will be resistant to blistering, due to the negative energy of dissolution of hydrogen, low energy of dissolution of helium, and high yield strengths of these materials. At 0.2c, because of the widening of the implantation distribution function at higher velocities, only aluminum and copper will blister. However, these predictions neglect the synergistic effects of hydrogen and helium in materials, which may lower the critical fluence for blistering (Hayward & Deo 2012). Additionally, with each of these materials, the mass cost may be significant depending on spacecraft geometry, as can be seen from the wide range of densities in Table 3. There may be additional effects driven by the proximity of implanted ions to spacecraft surfaces perpendicular to the direction of motion.

Regardless of whether blistering occurs, the relatively high fluence suggests bubbles will form in the spacecraft shield. While no single theoretical framework exists to quantitatively explore bubble formation onset and the effects thereof, bubble formation in fusion plasma-facing components provides a qualitative understanding of this phenomenon. Bubble formation leads to swelling and a decrease in the structural integrity of the spacecraft shield. Experiments or atomistic simulations of gas implantation and bubble formation with a wide-beam geometry need to be performed to make informed engineering decisions on shield materials for relativistic spacecraft.

Our zero-dimensional analysis suggests a number of strategies to mitigate bubble formation and blistering. First, increasing the diffusion coefficient, either through heating or material choice, will decrease the local gas concentration, preventing bubble formation and blistering. Second, a material that can accommodate large amounts of trapped gas, such as granular and sintered materials, will be resistant to blistering and swelling. Third, liquid metals or potentially amorphous materials are particularly resistant to the effects of gas accumulation. Fourth, geometric optimization of the spacecraft such as high aspect ratio “needle-like” designs minimize the effective exposure area. Without accounting for the effects of bubble formation and potential blistering, spacecraft shields may erode or fail significantly sooner than instantaneous damage calculations or sputtering formulae would suggest.

Total particle fluence depends only on the travel distance and ISM number density. There exists no feasible mechanism, for low mass spacecraft, by which ISM particles could be deflected at relativistic speeds, so any interstellar mission must have a mitigation strategy to deal with gas accumulation. Determining
the ISM number density along the path of travel for an interstellar mission will be crucial for determining the fluence to which a relativistic spacecraft will be exposed. Blistering and exfoliation will erode the surface of any future missions to destinations significantly further than \( \alpha \) Centauri without appropriate mitigating strategies. Discussion of further mission targets can be found in Drobny et al. (2020). Regions of particularly high ISM number density will prove especially challenging to shield materials. Supercritical fluences for solids will require advanced mitigation strategies, such as self-healing, sintered, granular, or liquid metal shields that can accommodate the relentless accumulation of ISM particles incident upon future interstellar spacecraft traveling beyond \( \alpha \) Centauri.

Funding for this program comes from NASA grants NIAC Phase I DEEP-IN-2015 NNX15AL91G and NASA NIAC Phase II DEIS-2016 NNX16AL32G and the NASA California Space Grant NASA NNX10AT93H and a generous gift from the Emmett and Gladys W. Fund. We also acknowledge funding from ESA Contract No. 4000122836/18/NL/PS/gp and LLNL under Contract DE-AC52-07NA27344. P.M.L. acknowledges support from the Breakthrough Foundation as a part of the Starshot program.

ORCID iDs
Jon Drobny © https://orcid.org/0000-0002-9733-6058

References

Andersen, H. H., & Ziegler, J. F. 1977, Hydrogen: Stopping Powers and Ranges in All Elements (Oxford: Pergamon), I
Balden, M., Rohde, V., Lindig, S., Manhard, A., & Krieger, K. 2013, JNuM, 438, S220
Bauer, W. 1978, JNuM, 76-77, 3
Behrisch, R. 2010, J. Synch. Investig., 4, 549
Biersack, J., & Hagmark, L. 1980, NuclM, 174, 257
Blew, R. S., & Langley, R. A. 1976, JNuM, 63, 337
Blondel, S., Bernholdt, D. E., Hammond, K. D., & Wirth, B. D. 2018, NuclF, 58, 126034
Boldhusan, J. 1984, NIMPB, 2, 587
Condon, J., & Schober, T. 1993, JNuM, 207, 1
Das, S., & Kaminsky, M. 1975, Radiation Blistering in Metals and Alloys, Vol. 15 (Washington, DC: American Chemical Society)
Donnelly, S. E. 1985, RadEff, 90, 1
Draine, B. T. 2011, Physics of the Interstellar and Intergalactic Medium (Princeton, NJ: Princeton Univ. Press), 540
Drobny, J., Cohen, A. N., Curreli, D., et al. 2020, JBIS, 73, 446
Duan, C., Liu, Y.-L., & Zhou, H.-B. 2010, JNuM, 404, 109
Eckstein, W. 1991, Computer Simulation of Ion–Solid Interactions (Berlin: Springer)
EVENTS, S. K., & McCracken, G. M. 1973, RadEff, 18, 191
Evans, J. 1976, JNuM, 61, 1
Gao, L., Manhard, A., Jacob, W., et al. 2019, NuclF, 59, 056023
Gavish Segev, I., Yahel, E., Silverman, I., & Makov, G. 2017, JNuM, 496, 77
Gloeckler, G., & Geiss, J. 2004, AdSpR, 34, 53
Goodhew, P. J. 1983, RadEff, 78, 381
Guseva, M. L., & Martynenko, Y. V. 1981, SvPhU, 24, 996
Hatano, Y., Shimada, M., Alimov, V. K., et al. 2013, JNuM, 438, S114
Hayward, E., & Deo, C. 2012, JPCM, 24, 265402
Henriksson, K. O. E., Nordland, K., Keinonen, J., Sundholm, D., & Patzschke, M. 2004, PhyS, T108, 95
Hoang, T., Lazarian, A., Burkhart, B., & Loeb, A. 2017, ApJ, 837, 5
Hofsäss, H., Zhang, K., & Mutze, A. 2014, ApSS, 310, 134
Johnson, D. F., & Carter, E. A. 2010, JMatR, 25, 315
Kaletta, D. 1980, RadEff, 47, 237
Kirkcheim, R., & Pundt, A. 2014, in Physical Metallurgy, ed. D. E. Laughlin & K. Hono (5th edn: Amsterdam: Elsevier), 2597
Klessen, R. S., & Glover, S. C. O. 2016, Physical Processes in the Interstellar Medium (Berlin: Springer, 85
Kornelsen, E. V. 1972, RadEff, 13, 227
Laukmann, J., Jung, P., & Uehlof, W. 1987, Acta Metalurgica, 35, 2063
Lane, P. L., & Goodhew, P. J. 1983, PMagA, 48, 965
Langley, R. A. 1979, JNuM, 85-86, 1123
Langley, R. A. 1984, JNuM, 128-129, 622
Lindhard, J., & Scharf, M. 1953, Det Kongelige Danske Videnskabernes Selskab Matematisk-fysiske Meddelser, 27, 1
Linsky, J. S., & Wood, B. 1996, ApJ, 463, 254
Lubin, P. 2016, JBS, 69, 40
Magnusson, H., & Frisk, K. 2017, JESP, 36, 65
Martynenko, Y. V. 1977, SvJP, 3, 395
Matsunami, N., Yamamura, Y., Itikawa, Y., et al. 1984, ADNDT, 31, 1
Naito, S., Yamamoto, M., Doi, M., & Kimura, M. 1995, FaJ, 91, 1967
Nakamura, Y., Shibata, T., & Tanaka, M. 1977, JNuM, 68, 253
Oriani, R. A. 1970, AcMet, 18, 147
Pelizzo, M. G., Corso, A. J., Tessarolo, E., et al. 2018, ACS Appl. Mater. Interfaces, 10, 34781
Pelizzo, M. G., Corso, A. J., Zappella, P., et al. 2011, OExpr, 19, 14838
Quirós, C., Mounegou, J., Lombardi, G., et al. 2017, NME, 12, 1178
Robinson, M. T. 1994, REDS, 130-131, 3
Rossing, T. D., Das, S. K., & Kaminsky, M. 1977, JVST, 14, 550
Roth, J., & Schmid, K. 2011, PhyS, T145, 014031
Scherzer, B. M. U. 1983, in Sputtering by Particle Bombardment II, ed. R. Behrisch (Berlin: Springer-Verlag), 271
Shugla, V. I. 2018, ApSS, 439, 456
Shugla, V. I. 2019, J Synch. Investig., 13, 562
Slotnick, H., Cleary, R. E., & Kaplaner, S. M. 1965, The Solubility of Helium in Liquid Lithium and Potassium, Connecticut Advanced Nuclear Engineering Lab, Technical Report, TID-21583, https://www.osti.gov/biblio/4571248
St-Jacques, R. G., Terreault, B., Martel, J. G., & L’Ecuyer, J. 1978, J. Eng. Mater. Technol., 100, 411
Stoller, R. E., Tołoczko, M. B., Was, G. S., et al. 2013, NIMPB, 310, 75
Szajneder, M., Geppert, U., & Dukde, M. R. 2018, npMD, 2, 3
Terreault, B., St-Jacques, R. G., Veilleux, G., et al. 1978, CaJPh, 56, 232
You, Y.-W., Hou, J., & Sun, J. 2018, JNuM, 499, 1
Ziegler, J. F. 1999, JAP, 85, 1240