Field of Study:

I am a planetary space physicist and geophysicist specializing in four main areas: 1) energetic particles and their effects on planetary environments, 2) electrodynamics of planetary ionospheres, 3) the physics of atmospheric escape and climate evolution, and 4) crustal magnetism and its geophysical implications. Mars has been my primary focus, though I've also published on Mercury, Venus, and the Moon. My research approach is broad, encompassing data analysis, modeling and the development of both instrumentation and mission concepts.

Current Major Space Science Projects:

I am involved in three active planetary science missions (operational or in funded development):

- Escape, Plasma Acceleration and Dynamics Explorers (ESCAPADE), launching in 2024. Here I am the mission Principal Investigator, having conceived the mission concept and led the proposal effort.
- The Mars Atmosphere and Volatile EvolutioN (MAVEN) NASA Mars Scout, launched in 2013. Here I am a science team member, deputy lead of Solar Energetic Particle instrument, and a member of the Science Steering committee.
- The Emirates Mars Mission (EMM), launched in July 2020, for which I led the mission formulation in 2014/15. Here I am both a member of the ultraviolet spectrograph instrument science team, and PI for UC Berkeley's ~$11 million contribution to hardware, science, and operations.

Past & Present Research:

Planetary Effects of Solar Energetic Particles

Solar energetic particles (or SEPs), usually defined as charged particles with energies of 10 keV up to ~1 GeV, are accelerated by solar flares or interplanetary plasma shocks, their fluxes increasing by many orders of magnitude during punctuated episodes known as 'SEP events'. When they intersect planetary atmospheres, SEPs deposit energy and are known to cause heating, ionization and chemical changes in terrestrial planet atmospheres, driving dynamics and atmospheric escape. In addition, those with energies > ~30 MeV can penetrate spacesuits and skin, causing radiation damage to living tissue. **My contributions to this area of research are:**

1) ***Space flight hardware***. I am the deputy lead for the SEP instrument on the NASA MAVEN (Mars Atmosphere and Volatile EvolutioN) Mars Mission, proposed in 2006, launched in Nov. 2013 and still successfully operating in Mars orbit. My roles were a) design of the detector, attenuator, and electron/ion separation system (through GEANT4 simulation), b) optimal placement/orientation on the spacecraft, c) design and assembly of the magnet cage system, d) testing (vibration, thermal vacuum) and calibration of the instrument prior to integration and launch and e) design and testing of data processing pipeline. I also wrote the SEP instrument design publication in Space Sciences Reviews.
2) ***SEP effects on the Mars atmosphere.*** *I have authored eight (four as first author) peer-reviewed articles* dealing with SEP characteristics and effects on the atmosphere of Mars, focusing on

heating, ionization patterns, planetary shadowing and behavior over the 11-year solar cycle, using data from MAVEN, and prior Mars orbiters. My pre-MAVEN work formed part of the motivation for the inclusion of the SEP instrument on MAVEN. In addition, I mentored a UCB undergraduate, Rebecca Jolitz, to build a full Monte Carlo simulation of energetic ion transport in planetary atmospheres (including Mars), which I use and which she now uses in her PhD work at CU Boulder (Berkeley's primary academic partner institution on MAVEN).

3) ***Radiation effects on life at the surface of Mars and Europa.*** I recently designed a lightweight stacked radiation detector (called TRACE) sensitive to 20 keV - 80 MeV electrons and 20 keV-150 MeV protons, and proposed it to NASA's ICEE-2 (Instrument Concepts for Europa Exploration) in September 2018. Lastly, I collaborate with the Radiation Assessment Detector (RAD) team on the NASA Curiosity rover to correlate high-energy particle measurements in Mars orbit and the Martian surface, to understand radiation transport through the atmosphere.

Electrodynamics of Planetary Ionospheres

Ionospheric variability is important to understand as part of the earth system, and for radio communication and GPS navigation. Each planet, with distinct solar radiance, gravity, atmospheric composition, wind patterns, seasons and magnetic fields, forms a unique laboratory in which to study the physical processes which establish and maintain these ionized upper atmospheric layers. Most of my research here has concerned the Martian ionosphere, which differs from Earth in all of the above attributes. Perhaps the most interesting is that Mars lacks a global magnetic field, hence its ionosphere is directly exposed to the solar wind and is threaded by Mars' enigmatic and strong (relative to Earth) crustal magnetic fields, which interact with atmospheric winds and ionization from solar photons and charged particles, resulting in a rich and complex electrodynamic picture that is still very much being understood. **My contributions to this area of research are**:

1) ***Suprathermal electron transport into Mars' upper atmosphere.*** Electrons from the solar wind constantly bombard the upper atmosphere of Mars. As part of my PhD and postdoc work at UC Berkeley, I created a code called MarMCET (Mars Monte Carlo Electron Transport) to simulate a) the motion of electrons in Mars' unique magnetic environment and b) the results of their collisions with neutrals, e.g. ionization, auroral emission etc. This, along with data sets of electron fluxes and ionospheric densities from multiple Mars orbiters, has proved a useful tool for discerning spatial patterns of electron energy deposition, their variability with the dynamic solar wind, and their impacts on the Mars ionosphere and upper atmosphere. <u>*I have authored more than 10 (five as first author) peer-reviewed articles on this topic*</u> and continue to work on it with the data from MAVEN.
2) ***Solar wind hydrogen deposition in the Mars atmosphere.*** I co-authored a paper on the discovery of low-energy (~1 keV) 'Houdini' protons in the Mars lower atmosphere, turning into neutral hydrogen by charge exchanging with Mars' hydrogen exosphere, continuing into Mars' collisional atmosphere unaffected by Mars' induced magnetosphere, then being stripped of their electrons by further collision and being detected. <u>*I recently completed a $350k PI grant from NASA to fit the results of a model of this process to MAVEN proton data to quantify the amount and variability of hydrogen deposition, and to extrapolate this to the early solar system*</u>.
3) ***Dynamo current systems in the Mars ionosphere.*** Dynamo currents flow in ionospheres in the altitude range where ion motion is dominated by collisions with neutrals, but electrons (with

their much smaller gyroradii) are confined to move with magnetic fields. This results in differential charge motion and hence current flow. On earth, these currents cause magnetic fields small compared to the earth's global field, so can be approximated analytically. Mars' magnetic fields are highly inhomogeneous and typically too weak for this approximation to hold, and so currents must be simulated. *As a research scientist I led a successful NASA proposal to simulate these complex currents and have authored six articles on the topic*.

The Physics of Atmospheric Escape and Climate Evolution

The primary goal of the NASA MAVEN Mars mission is to make the measurements from orbit that are necessary to understand the physics of atmospheric escape from Mars and how escape rates depend on solar energy inputs, so that these rates can be extrapolated backward in time and placed in context with paleo climate modeling and ongoing geological studies, to provide important constraints on the history of the Martian climate. *I have been a core MAVEN team member since 2005 and have contributed to this field of research in the following ways:*

1) ***Developing the SEP instrument sensor*** for MAVEN as described in the second section.
2) ***Leading the MAVEN Science closure effort****.* At the direction of the mission PI, Dr. Bruce Jakosky, *I led the 'science closure' effort prior to Mars arrival in late 2014, i.e. organizing a team of ~20 scientists* to develop and reconcile several physical models of the Mars upper atmosphere and escape processes. This resulted in my leading a large paper in 2015 describing the strategy for achieving the mission's core goal.
3) ***Photochemical escape of oxygen and carbon from Mars***. Exothermic reactions in the Mars ionosphere can provide sufficient energy for the resulting neutral atoms to escape from Mars, but those hot atoms cannot be detected directly by existing instruments. I have used measurements of neutral and plasma temperatures and densities from three different MAVEN instruments to calculate a) the rates of production of these hot atoms, b) (using a Monte Carlo model I developed of hot atom transport and collisions) their escape probabilities, and from these two quantities c) escape rates of hot oxygen and carbon. *I am also the organizer of the MAVEN photochemical escape group and have published six papers on this topic*.
4) ***UV Spectrometry of Mars' atmosphere from the Emirates Mars Mission.*** This mission is the first to study links between the Mars lower and upper atmospheres. In April 2014, when SSL was approached by representatives of the United Arab Emirates Space agency to develop a scientific Mars mission concept from scratch, I took the lead in writing a detailed mission proposal when few others believed anything would come of it. After the mission was officially approved in August 2014, I led the development of the science goals and requirements document and have been a member of the ultraviolet spectrometer team (led by CU Boulder) since then. I secured a substantial role in the mission for UC Berkeley as local PI, including a $3M state-of-the-art ultraviolet detector and electronics board, systems engineering support and management of the ground communications network. *As a member of the EMUS (Emirates Mars Ultraviolet Spectrograph) team, I have been leading the investigation into Martian aurora and have responsibility for deriving an important data product: maps of oxygen column abundances in the Martian thermosphere.*

5) ***Leading a large NASA proposal and mission***. In situ plasma measurements at planets have always suffered badly from a single measurement platform, whereby spatial and temporal variations in measured quantities cannot be disentangled. In 2017 I secured a $400k NASA effort to develop a mission concept with identical spacecraft and plasma instrumentation in coordinated orbits to address this shortcoming. This concept became a <$55M proposal (called ESCAPADE) to NASA in 2018 led by myself, which was selected for funding in mid-2019. As PI, I am responsible for leading the science team and overseeing the technical and management teams.

Remote Sensing of Crustal Magnetism: a Window into Mars' Geophysical Past

Measurements of electron angular distributions were used by my graduate advisor, Robert P. Lin, in his postdoctoral work in the 1970s, to remotely sense lunar crustal magnetic fields via the magnetic mirror force such fields exert on electrons. This technique is relatively straightforward on an airless body where electrons either magnetically reflect back upwards or strike the hard surface, but is very challenging in a collisional atmosphere where multiple scattering occurs over a wide vertical distance. **As a PhD student and postdoc, I pioneered the technique of electron reflectometry in planetary atmospheres.** I used angular and energy spectra of upward-and downward-traveling electrons measured in Mars orbit to make a high sensitivity map of Mars' crustal magnetic field strength at 200 km altitude. **This magnetic map has been used for three main research purposes:**

1) ***First definitive history of Mars' global magnetic field.*** The loss of Mars' global geodynamo and magnetic field forms one of the most important topics in planetary science, bringing together interior, crust and atmospheric evolution. Crustal magnetic fields remotely sensed from orbit (i.e. my map) are a proxy, if an imperfect one, for crustal magnetization, which itself originates from shock or heating/cooling of the crust in an ambient magnetic field. I found that, of 28 identified large impact craters on Mars, those older than 4.1 billion years were all magnetized and those younger were all demagnetized, placing a hard constraint on the life of Mars' geo-dynamo. <u>*Altogether this work has produced seven related publications (four as lead author).*</u>
2) ***Martian giant impacts and crustal magnetic minerals***. Two important questions in Mars science are a) what minerals could be responsible for Mars' intense crustal magnetic fields? b) how large were the giant asteroid impacts in its early history that shaped its evolution? I used laboratory data of shock demagnetization and hydrocode simulations of impacts to predict demagnetization patterns in crustal field maps for different minerals and impact energies, then fit these model results to the map to place joint constraints on these important quantities. <u>*This resulted in a 3-year PI NASA grant & three related publications (two as lead author).*</u>
3) ***Mars Volcanic/magmatic history***. While volcanic flows can be mapped on the surface of Mars, typically more than 10 times this volume is intruded into the crust as magma. Magma thermally demagnetizes magnetic rocks and leaves a 'bite-out' signature in crustal magnetic field maps. <u>*In three separate lead-author studies with recognized volcanologists*</u>, I modeled this thermal demagnetization to constrain patterns, volumes and timelines of magma intrusion. These patterns mirror tectonic stress fields and, in concert with remote sensing of erupted minerals, can constrain models of magma chamber evolution, a key objective of planetary volcanology.

Recent Student Research Advising (all undergraduate)

Jesse Engel (2006-2007) used data from the Mars Global Surveyor MAG/ER instrument to constrain neutral densities in Mars atmosphere with electron reflectometry, assisting with a publication in Geophysical Research Letters in 2008.

Rebecca Jolitz (2013-2015) developed a detailed ion transport code for modeling the consequences of solar energetic particles as they precipitate into planetary atmospheres. This research resulted in a publication in the Journal of Geophysical Research in 2017. Ms. Jolitz is soon finishing a PhD at the University of Colorado.

Melissa Marquette (2016 - 2018) characterized and interpreted variability in the solar wind and interplanetary magnetic field at Mars over multiple timescales using data from the MAVEN SWIA and MAG instruments. This research resulted in a publication in the Journal of Geophysical Research in 2018. She returned in September 2021 to help construct an empirical model of suprathermal electron impact ionization in the nightside ionosphere of Mars and helping to integrate it into two Mars global thermal-ionosphere models run at U. Michigan and LMD, Paris.

Naomi Weiss (2021-) is investigating the high energy particle radiation environment in Mars orbit using data from two spacecraft: NASA's Mars Global Surveyor (1997-2006) and the European Space Agency's Mars Express (2004-present). She is characterizing the fluxes of both solar energetic particles and galactic cosmic rays in Mars orbit, how they change in space and time over the last two of the Sun's 11-year cycles of activity, and correlating these measurements made by two very different instruments on different spacecraft.

Laura Johann (2021-) is investigating solar wind hydrogen deposition into the Mars atmosphere, using a combination of Monte Carlo modelling and MAVEN SWIA data.

Summer students from the UAE (2015-2019) As part of my participation in the Emirates Mars Mission, I have mentored 5 students from the United Arab Emirates in 8-week summer research

- 2015 Hind Al Ali (electron precipitation patterns on the Mars nightside).
- 2016 Khalid Al Awar (Energetic particle precipitation effects on the Mars nightside ionosphere)
- 2017 Abdullah Al Muharrami (solar EUV variability at Mars).
- 2018 Ahmed Al Hamedi (simulating energetic electron transport in a stacked silicon detector)
- 2019 Maryam Al Hosani (sensitivity of 135.6 nm emission to Mars thermosphere conditions)

Future directions

As indicated above, my main areas of active research are and will be in the medium-term:

- **Leading the ESCAPADE science team and mission**. With confirmation by NASA behind us (August 2021), I will continue to lead the ESCAPADE project through fabrication, test, launch in 2024, and operations. As I also lead the science team, my focus will be on developing science data products and analysis techniques in anticipation of ESCAPADE's unprecedented data set in 2024-2025. This data set will represent a huge leap forward in understanding planetary upper atmospheres, representing many theses worth of science topics for potential students. With the exceptions of a few key review milestones, my PI responsibilities can be discharged remotely from Boston.

- **MAVEN data analysis** and related modeling studies of Mars' upper atmosphere and atmospheric evolution. There are at least a half-dozen thesis-ready data analysis research projects on the following topics.
    - Planetary ionospheres and their sources of energy and variability
    - Mars magnetospheric and ionospheric electrodynamics, aurora and their drivers.
    - Atmospheric escape and the climate evolution of Mars.
    - Solar energetic particle effects on planetary atmospheres.
- **UV Spectrometry** of the Martian atmosphere via the 2020 Emirates Mars Mission. As a member of the EMUS instrument team and Mission Science team, I have responsibility for data product generation and have funding for one student.
- **Planetary Crustal Magnetism**. I remain interested and have recently co-authored three papers ahead of the first magnetometer measurements from the martian surface from NASA's Insight mission and paleomagnetic studies of anticipated returned samples from the martian surface. Recent advances in magnetic mapping of Mars from MAVEN open up potential geophysical studies of magmatic/volcanic and impact processes, and dynamo history.
- **Instrument Development**. I intend to continue develop novel lightweight multi-aperture stacked solid-state detectors aiming at the 10 keV to 100 MeV energy range, for a range of planetary and heliophysics applications. I also have a keen interest in developing lower energy ion and electron sensors that use electrostatic optics, having worked closely with a) data from such sensors and b) several scientists who designed them. To take advantage of the increasing move towards science with small satellites, I am driven towards small (1 to 2 U), low-mass (< 1.5 kg) sensor designs that can be accommodated on small satellites (< 60 kg).
- **Science Mission Design**. Leading the ESCAPADE proposal to the SIMPLEX program, I learned much about the complex tradespace between scientific mission capability, destination, power, mass and cost, particularly in the light of rapid advances in propulsion technology, miniaturization in science instrumentation, and commoditization of subsystems. I would be happy helping out any BU students or faculty looking into designing or proposing planetary science missions, low-cost or otherwise.

Student Research opportunities

All of the above research topics contain opportunities for student research, both undergraduate and PhD. While it is not for every student, I believe that to get a true appreciation of planetary data acquired in space, it's important for students to "get their hands dirty" in the lab with instrumentation development, for which I foresee ample opportunity at BU. However, given the long time frame of space science missions, even these students must also get the opportunity to do real science and make discoveries with existing data collected through the hard work of their predecessors, as I was able to do as a student. In this, the MAVEN data set is truly a treasure trove, with 10 instruments on board operating for 7 years already and the surface barely scratched on many of the largest science questions. In addition, I anticipate significant funding for student involvement in analyzing data from the 2020 Emirates Mars Mission, and ESCAPADE starting in 2025.