Field of Study:

I am a planetary space physicist and geophysicist specializing in four main areas: 1) solar energetic particles and their effects on planetary environments, 2) electrodynamics of planetary ionospheres, 3) remote sensing of crustal magnetism and 4) the physics of atmospheric escape and climate evolution. I have studied several planets but **Mars is my primary focus**. My research approach is broad, encompassing data analysis, modeling and both instrumentation and mission development. I am involved in two active Mars missions: MAVEN (NASA) and the Emirates Mars Mission (UCB PI).

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 contribution to this area of research is threefold:**

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) 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. I currently advise ~10 active users of MAVEN SEP data.
2) ***SEP effects on the Mars atmosphere.*** <u>I have authored eight (four as first author) peer-reviewed articles</u> 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.*** First, I co-wrote a $100M NASA proposal for UCB to build a plasma instrument package, including energetic particle detectors to characterize the radiation environment near Jupiter's moon Europa. Second, 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. Lastly I am co-designing a lightweight stacked radiation detector in preparation for an expected NASA call for instruments for a Europa Lander, in order to better understand radiation effects on any putative Europan life.

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 recent 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 currently have 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. <u>*As a research scientist I led a successful NASA proposal to simulate these complex currents and have co-authored five articles on the topic*</u>.

Remote Sensing of Crustal Magnetism: a Window into Mars' Geophysics

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 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.** Using the MarMCET code (previous section), I used angular and energy spectra of upward-and downward-traveling electrons measured in Mars orbit to make two first-of-their-kind complementary measurements: a) I measured, over seven years, Mars' atmospheric density at ~200 km altitude *resulting in three lead-author publications* and helping to constrain global climate models and b) I derived 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. *Altogether this work has produced seven related publications (four as lead author).*
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. *This resulted in a 3-year PI NASA grant & three related publications (two as lead author).*
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. *In three separate lead-author studies with recognized volcanologists*, 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.

The Physics of Atmospheric Escape and Climate Evolution

Ample evidence exists that stable surface water flowed and stood on early Mars, > 3.5 Gyr ago, necessitating atmospheric pressures at least 10 times higher than the 6-9 mbar of CO_2 seen today. A lack of observed carbonate minerals argues that most of the atmosphere escaped to space. The primary goal of the NASA MAVEN Mars Scout 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 wind conditions and solar extreme ultraviolet flux, 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 first 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, models that are necessary to place in context, and interpolate between, the measurements MAVEN has made in order to constrain atmospheric escape rates. This resulted in 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 dissociative 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, performed during regular orbital passes through the upper atmosphere, 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'm also the organizer of the MAVEN photochemical escape group and have published four papers (two as first author) on this topic*.
4) ***UV Spectrometry of Mars' atmosphere from the upcoming 2020 Emirates Mars Mission.*** This mission will be 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, systems engineering support and management of the ground communications network. The total value to UC Berkeley will exceed $10 million over the course of the mission (2015-2024), including student opportunities starting in 2018*.
5) ***Leading a NASA-funded multi-spacecraft mission and hardware development effort***. In situ particle and fields measurements made by space plasma and aeronomy missions suffer badly from a single measurement platform, whereby spatial and temporal variations in measured quantities cannot be disentangled. *I am the PI of a NASA-funded, $400k effort at UC Berkeley to develop a low cost (<$50M) mission concept to bring, for the first time, multi-spacecraft measurements of atmospheric escape* to Mars (or Venus) by utilizing small satellites and miniaturized ion sensor and magnetometer technology. It is called MISEN (Mars Ion Sputtering Escape Network) and will become a full mission proposal to NASA in 2018, led by myself as PI.

Recent Student Advising

Though not mentioned above as an active research project, until June 2018 I mentored/advised a UC Berkeley Astronomy student for 18 months, Melissa Marquette (Berkeley class of 2017), in her project to characterize and interpret variability in the solar wind and interplanetary magnetic field at Mars over multiple timescales. This research resulted in a peer-reviewed publication in the Journal of Geophysical Research. I have greatly enjoyed working with her, the two other UCB undergraduates, and four undergraduate students from the UAE I've had the privilege of advising.

Future directions

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

- Instrument development, including high energy particle detectors for radiation characterization and lower energy ion sensors and magnetometers for atmospheric escape.
- MAVEN data analysis and related modeling studies:
  - Planetary ionospheres and their sources of energy and variability
  - Hydrogen deposition in the Mars atmosphere.
  - 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
- Development and formulation of the multi-spacecraft, low cost ESCAPADE Mars mission.
- Though less active in in planetary crustal magnetism over the last two years, I remain interested in the topic and have co-authored two papers currently in review, particularly with the first magnetometer due to land on the Martian surface in November 2018 with NASA's InSight mission.

Student Research opportunities

All of the above research topics contain opportunities for student research, both undergraduate and PhD. I believe it's important for students to "get their hands dirty" in the lab with instrumentation development, for which there is ample opportunity at the UCB Space Sciences Laboratory, either on the radiation detectors or ion sensors. However, given the long time frame of space science missions, 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. In this, the MAVEN data set is truly a treasure trove, with 10 instruments on board operating for 4 years already and the surface barely scratched on many of the largest science questions. In addition, there will be ample opportunity and funding for student involvement in preparing for, and analyzing, data from the 2020 Emirates Mars Mission.