Magnetic fields, Atmospheres, and the Connection to Habitability (MACH) NASA Heliophysics DRIVE Team Science Center

Strategic Plan

Mission Statement

The Magnetic fields, Atmospheres, and the Connection to Habitability (MACH) Center brings together a diverse group of scientists and STEM professionals with a shared purpose:

MACH will bring together the terrestrial, planetary, and exoplanetary heliophysics disciplines in a supportive team environment to develop an integrated method to combine observations and models to advance our understanding of atmospheric escape from any planetary body while engaging diverse science and non-science communities

This document describes our strategic plan for Research (Section 1), Management (Section 2) and Broader Impacts (Section 3) to attain the MACH Center's goals in Phase I and II of the program.

1. MACH Research

1.1 Research: Goal

The inspiration for the MACH Center comes from the current debate in the heliophysics community about whether planets require magnetic fields to be habitable. To adequately address this question, the MACH team will engage in a cross-disciplinary cohesive effort that is informed by information from all rocky planets and a variety of scientific approaches. Our research has the following goal:

MACH will construct a flexible methodology for estimating atmospheric loss from an arbitrary rocky planet given information about the planet and the space climate of its host star

Our focus is on *rocky* planets, which have surfaces on which life might form, evolve, and be detectable and for which the atmosphere provides pressure that may allow water to exist in a liquid state at the surface. Scientists studying magnetized plantes (e.g. Earth) currently utilize different methods for observing and modeling atmospheric loss than scientists studying unmagnetized planets (e.g. Venus and Mars). We will construct a *methodology* for estimating atmospheric loss from either type of planet (magnetized or unmagnetized), using a combination of observations and newly-developed and validated models that incorporate all necessary physics. This methodology will be *flexible*, allowing for new advances in our understanding of atmospheric escape to be incorporated at any time.

For our work to be truly relevant to the habitability of a planet, we must consider all atmospheric loss processes identified over many decades of terrestrial and planetary heliophysics research: ion escape, thermal escape, photochemical escape, sputtering, and hydrodynamic escape. In order to estimate escape for a given planet we must consider both *information about the planet* (size, mass, orbital distance, atmospheric thickness and composition, nature of its intrinsic magnetic field, and rotation period) and the *space climate of its host star* (the stellar EUV/Xray photon flux, the stellar wind, the Interplanetary Magnetic Field, and properties of extreme events such as Coronal Mass Ejections and flares).

Creating our methodology will unite the terrestrial and planetary heliophysics communities to develop new understanding about how atmospheric escape operates at any planet, while substantially impacting the community of scientists studying exoplanet space climate and habitability. As a service to all three communities we will construct a web interface that allows a user to specify a planetary situation (choosing both planetary and stellar parameters) and receive the current best estimates of instantaneous atmospheric escape rates based on our methodology, as well as information about how those estimates were obtained. In our work we will treat a range of planetary parameters that encompass both known planets as well as hypothetical examples.

1.2 Research: Key outcomes for Phase I

Eight key outcomes for the two-year Phase I effort are listed below, grouped into four categories. For each numbered item start with: **"*By the end of Phase I, the MACH team will have...*"**

Research planning

1. Set the scope of physical processes to be addressed by the Center

   We have identified the processes necessary to consider in our observational analyses and models of ion escape (e.g. wave heating), photochemical escape, and hydrodynamic escape. We will fully achieve this goal by adding new team members to address thermal escape and sputtering.

   ~60% Complete

2. Identified necessary model improvements

   We have determined that both electron pressure and wave heating should be included in MACH models. Other processes to be identified in #1 above may be added to this list, or may be better included by extrapolating from observations.

   ~60% Complete

Research in preparation for Phase II

3. Cross-calibrated published estimates of atmospheric escape from planets

   We have compiled all literature addressing observational and modeling work on escape rates from all planets, noting differences in the measurement techniques,

   ~50% Complete

external conditions, model used, etc. Our goal is to cross-calibrate the results, to apply to MACH's methodology for estimating escape from any rocky planet.

4. Prototyped global plasma models that handle a range of planetary magnetization states

   The MACH team has now implemented four different global plasma models that include planetary dipole strength as an input parameter, and have made initial qualitative comparisons of the model results. We continue to incorporate new processes into the models, and are working to use data to validate the results.

   ~80% Complete

5. Conducted a case study for a selected hypothetical planetary situation

   The MACH team is conducting a case study to refine our methodology for estimating atmospheric escape in Phase II. The case study planetary situation is Mars orbiting a moderately active M Dwarf star which provides estimates of escape via all processes with a clear methodology for arriving at each estimate.

   ~50% Complete

Team development

6. Identified and prioritized missing expertise required to fulfill MACH's research goals

   As the MACH research goals and approach were refined during Phase I, gaps in the expertise of existing team members became apparent. We identified the expertise currently missing from the team, and prioritized it based on its value to furthering MACH goals. This list is provided in Section 1.5.

   100% Complete

Engagement of the research community

7. Conducted a multi-disciplinary workshop to unify MACH science

   In Phase I, the MACH team successfully organized a workshop to bring together the heliophysics, planetary, and exoplanetary communities around a shared research goal of understanding atmospheric escape. The pilot workshop had ~150 participants, and generated momentum and community support for the MACH Center science and approach. We anticipate follow-on workshops every 1-2 years during Phase II to nurture and maintain community involvement.

   100% Complete

   "I think the topic of atmospheric escape under different conditions is one of the most compelling interdisciplinary topics in space physics and atmospheric evolution today. I enjoyed connecting with a diverse community to further advance our understanding of the topic." - Workshop Participant

8. Advertised the Center across disciplines at national and international meetings

   The MACH team has and will continue to make presentations about the work of the Center at multiple scientific meetings, reaching communities in Heliophysics, Planetary Science, and Exoplanetary astrophysics.

   100% Complete

1.3 Research: Key outcomes for Phase II

Thirteen key outcomes for the Phase II effort are listed below, grouped into three categories. For each numbered item start with: "***By the end of Phase II, the MACH team will have...***"

Methodology for estimating atmospheric escape

1. Established a flexible methodology for estimating atmospheric escape

   Our methodology will provide, for a broad range of planets, best estimates for escape rates via the five escape processes. Estimates will be based on a combination of scaling laws for escape derived from observations and interpolation of the results of validated models. The MACH methodology will be flexible - accommodating new theoretical, observational, and modeling advances and constructed so that the parameter space can be easily expanded.

2. Validated the methodology using observations from the solar system

   To ensure that we provide the best possible estimates of escape, we will validate it using observations from specific planetary bodies such as Venus, Earth, Mars, Titan, and Pluto.

3. Applied the methodology to both known and hypothetical planetary situations

   Our methodology can be used to explore specific planetary situations (e.g. early Earth), as well as hypothetical situations where detailed observations are not available (e.g. rocky exoplanets at different stellar distances). MACH will conduct case studies for both situations.

4. Had investigators outside of the MACH team use the interface to our methodology

   A clear sign that MACH has made a useful contribution to the community will occur when community members use MACH results in their own work. We will track web hits to the interface and citations to our results by scientists outside our team.

5. Archived the escape estimates and made the interface accessible beyond Phase II

   We will ensure that all MACH results (model and observation) that can be used to estimate escape from planets, as well as the MACH-developed interface to the framework remains accessible well beyond the life of the Center. We already have a tentative agreement with NASA's Community Coordinated Modeling Center (CCMC) to take on these tasks.

Understanding atmospheric escape

6. Created a global plasma model that adequately treats magnetized *and* unmagnetized planets

   Terrestrial models for escape have diverged from models for escape from unmagnetized objects - especially for the process of ion escape. MACH will develop and validate a 3D model that accurately estimates escape from both kinds of planets.

7. Described the region of parameter space for which planetary magnetic fields matter

   The question that inspired the creation of this Center is a current topic of community debate: "Do habitable planets require magnetic fields?" A better phrasing may be "For what kinds of planets does the magnetic field play an important role in atmospheric retention?”. We will answer this question by applying MACH’s methodology to a variety of planetary situations.

8. Used MACH results to prioritize future observations that would advance the field

   Leveraging the new expertise developed by the MACH team, we will identify and prioritize measurements that would most improve our estimates of escape rates from planets.

9. Predicted the influence of escape on exoplanet transit spectroscopy observations

   MACH estimates of escape rates from rocky exoplanets will be of limited use without some connection to exoplanet observations. We will close this loop by feeding results from our models for escape into radiative transfer models to make predictions for exoplanet transmission spectroscopy.

10. Written a book on atmospheric escape and evolution

    In addition to published papers, the MACH team will capture new information generated during Phase II in the form of model results, observational analyses, and theoretical understanding in a single place for the community by publishing a book or series of review papers on atmospheric escape from planets.

Community engagement

11. Allowed and encouraged community members to contribute to the framework

    MACH will host model results and escape rate estimates from investigators outside our team, and make them accessible through our interface. We will actively encourage members of the community to make their results available in this way.

12. Hosted multiple interdisciplinary workshops for the entire community

    With the successful community workshop from Phase I as motivation, the MACH team intends to host follow-on workshops on atmospheric escape from planets during Phase II, with a workshop at least every two years. A goal is to create enough momentum that the workshops continue beyond the lifetime of the Center.

13. Advertised the work of MACH to multiple scientific communities

    We will regularly engage the heliophysics, planetary science, and exoplanet communities through attendance at and organization of meetings. Our goal is to advertise the progress that MACH makes to scientists who are likely to be impacted by our work and encourage them to participate. In our interactions with communities outside of heliophysics, the MACH team intends to act as ambassadors for the discipline, demonstrating how it provides value.

1.4 Research: Planned Activities

The research activities of the MACH Center are dedicated to constructing and applying a methodology for evaluating atmospheric escape from planets via all heliophysics-related escape processes. The research tasks conducted in the Center can be grouped into six main categories, labeled A-F and described below. As new information becomes available (e.g. new observations, new model capabilities, new insight) the methodology will be adapted. Thus, new progress in any of A-D can result in modifications to B-F.

Construction of framework for atmospheric escape

A. Empirical observational escape rate scaling laws

   Observations of atmospheric escape from Earth, Venus, Mars, Titan, and Pluto will be analyzed to determine the response of each planet to different drivers of escape. Empirical scaling laws will be derived (or used and compared where available) for the purpose of validating MACH models for escape. This effort requires both terrestrial and planetary observers, and also modelers who can provide observed trends from their models for observers to verify in data.

B. Physical understanding of escape and its drivers

   Both observations and models will be used to improve our understanding of the integrated thermospheric-ionospheric-magnetospheric systems that supply and power atmospheric escape, as well as the relative importance of the different processes that influence it. This new insight could come from modeling results, data-model comparisons, or novel comparison of observations.

C. Development and validation of models for escape

   Outcomes from category B, above, will be used to inform model improvement and development. As a process and its importance for escape becomes better understood, modelers will work to refine the treatment of the process (or include it) in their models. Outcomes from category A, above, will be used to validate the improved models. This effort requires modelers, observers, and theoreticians.

D. Application of models over multi-dimensional parameter space

   Our validated models will be run over a multi-dimensional parameter space consisting of stellar and space climate conditions as well as planetary properties. For example, planets will range in size from Mercury to super-Earth, with magnetization ranging from 0 dipole field strength to several times stronger than Earth's. External conditions will vary from active M Dwarf to non-active F stars. The outcome will be a library of model results.

Application of framework

E. Develop a community interface to the framework

   We will develop a web-based interface to our estimates of escape, as well as the observational and model results used to derive these estimates. This interface will allow a community member to estimate escape for individual planetary situations spanned (but perhaps not specifically modeled) by the input parameters for the model runs. Individual case studies will be selected by the MACH team for detailed analysis.

F. Application to exoplanets

The MACH team will use existing observations of exoplanets to provide input conditions for selected case studies and model runs in categories D and E, above. The team will also take the outputs of MACH models for escape and use them to provide testable predictions for the community, via the web-based interface, about transit spectroscopy observations of exoplanets with escaping atmospheres as well as secondary eclipse measurements of rocky exoplanets that indicate the presence or lack of an atmosphere.

1.5 Research: Potential Partners

The MACH team has inventoried the research expertise represented in the current team and discussed both necessary and desired expertise to incorporate into the Center for Phase II. This list will be revisited annually during Phase II, and funding reserved to add additional team members if they become needed.

Necessary Expertise

We are actively seeking to add team members with expertise in the following areas before Phase II begins. All should be added before September, 2021.

- Creating repositories to host MACH models and estimates in an accessible format
- Plasma wave heating resulting in ion escape from planets
- Planetary thermospheric physics and chemistry
- Hydrogen escape and planetary exospheres
- Atmospheric sputtering

Desired Expertise

We will consider adding additional expertise in the following areas if resources become available. Doing so would further the research goals of MACH, but the Center can be successful even if these areas are not added to the team:

- 3D simulations of planetary thermospheres
- Numerics, optimization, and implementation of large 3D simulations
- Planetary habitability
- Energetic particle precipitation
- Ionospheric radar measurements
- Measurements of solar drivers of escape
- Astrophysical theory related to atmospheric escape
- Exoplanet observations relevant to escape

1.6 Research: Key Actions Table

Key actions for MACH Research include the following:

Action	Due Date	Responsible Party
Determine needed model improvements	End of Phase I	All team members

Compare published estimates of escape	End of Phase I	Strangeway, Peterson, Ramstad, Kistler, Ma, Seki
Complete case study of escape from Mars-like exoplanet	End of Phase I	Brain + MACH Team
Continue to identify and bring onto the team individuals with needed expertise	End of Phase I	Brain + MACH Team
Develop scaling laws for different escape processes with different drivers	Year 2 of Phase II	Ramstad, Kistler, Strangeway, Peterson, Cravens
Develop models to handle a range of planetary magnetization	Year 1 of Phase II	Ma, Glocer, Seki, Holmstrom
Validate, document, and archive models	Year 2 of Phase II	All team members
Provide inputs from exoplanet hosting stars	Year 3 of Phase II	France, Cohen, Vidotto
Apply models over multi-dimensional parameter space	Year 3 of Phase II	Ma, Glocer, Seki, Holmstrom
Develop interface to methodology for escape	Year 3 of Phase II	MACH Team
Run test cases for the MACH framework	Year 5 of Phase II	MACH Team
Provide predictions for exoplanet transit spectroscopy observations	Year 5 of Phase II	Vidotto
Organize a series of community workshops	Years 2-5 of Phase II	MACH Team
Write book on atmospheric escape from planets	Year 5 of Phase II	MACH Team

2. MACH Management

2.1 Management Goal

The MACH Center has multiple ambitious and interrelated goals that span research, communication, team development, community engagement, and broadening impacts - as befits a Team Science Center. Fulfillment of these goals require that the diverse skill sets of the MACH team members are applied with shared purpose. MACH's management plan has the following goal:

MACH will be transparently organized and managed to facilitate progress, promote participation by all team members, and foster trust across the entire team

Each MACH team member will understand how their tasks relate to those of the rest of the team and fit into the bigger picture goals of the Center. A *transparent* organizational structure is imperative for this to happen, and decisions about tasks must be made with input from all relevant team members. As management tools and processes are adopted and used within this structure, MACH must regularly ask itself "Will this make it easier to achieve success in our goals?". The answer to this question about whether progress is *facilitated* will guide decision making about how the Center is managed. Ultimately, progress is made by team members, both individually and working together. We believe that progress is best made when people feel valued and the work is rewarding. The MACH Center will be managed in a way that *promotes participation* and that celebrates the contributions of team members, achievement of milestones, and new breakthroughs. This participation can be partly inhibited by the reward system in science, which is set up in a way that often encourages individual achievement that in turn promotes competition and the protection of ideas. MACH will be managed in a way that *fosters trust* between the team members, and instills the idea that the entire team shares in successful outcomes.

2.2 Management: Key outcomes for Phase I

Fifteen key management outcomes for the two-year Phase I effort are listed below, grouped into four categories. For each numbered item start with: "***By the end of Phase I, the MACH team will have...***"

Leadership and Administration

1. Developed a Strategic Plan for the MACH Center

The MACH team developed a Strategic Plan for the Center that describes our goals and approach for research, management, and impact broadening activities. The Strategic Plan was developed with input from the entire MACH team, and will be revisited and updated annually during Phase II.

100%
Complete

2. Established and practiced transparency when making management decisions

We are implementing a process for making management decisions that impact the team and its activities that is transparent, allows for input from the team, and is equitable. During Phase I all major decisions have been presented to the team for comment before being adopted.

~75%
Complete

3. Developed a process for managing the financial status of the Center

We are working to formalize a process to manage the financial status of the Center. During Phase I, the PI and PM review the team expenditures each month, and meet regularly with the LASP budget analyst to compare the current spending plan to the actuals. The PI and PM take action to reassess and/or reallocate funds when appropriate.

~75%
Complete

4. Facilitated MACH Leadership discussions about Team Collaboration and Communication

MACH Leadership engaged the Toolbox Dialogue Initiative for a 2-hour workshop on collaboration planning, with a facilitated, structured dialogue on Team Functioning, Collaboration, and Communication and a co-creation activity focused on collaboration planning. — 100% Complete

Team structure

5. Revised the MACH Org Chart in preparation for Phase II

   Initially our science team was organized in a way that resulted in the siloing of expertise. We therefore restructured the team under six interdisciplinary tasks to encourage whole team involvement. New team members were added (and will continue to be added) to fill gaps in expertise in our multidisciplinary team. — ~75% Complete

6. Developed and used an evaluation and onboarding process for new members

   Based on best practices, MACH developed a process for selecting and onboarding new members that meets predefined selection criteria that is equitable and allows for input from the entire team. We have used this process to add Alex Glocer as a team member in phase I and will soon invite 4-5 more scientists with valued expertise to join the team. — 100% Complete

Establish team communication modalities and norms

7. Established MACH meeting structure, cadence, and timing

   During Phase I we established a meeting structure (whole team invited to every meeting to share expertise), cadence (weekly, rotating topics), and timing (8am Mountain time works best for our international group) that allowed for full team involvement. — 100% Complete

8. Adopted technology for meeting synchronously and asynchronously

   Communication challenges during the pandemic forced our team to be proficient in synchronous and asynchronous technologies. Our team successfully utilizes Zoom for virtual meetings and Slack, Google Docs, and email for asynchronous communication. We continue to explore technologies to improve communication pathways to ensure full team involvement. — ~75% Complete

9. Developed a culture for respect, inclusivity, equity, and open communication

   The MACH management team established a culture and expected norms of communication that encourages respect for all team members at all career stages, thoughtful consideration of all ideas, and participation by all regardless of sub-disciplines and cultures. The team is periodically reminded of these norms to ensure inclusivity and equity. — 100% Complete

10. Established a process for correcting communication and ethics issues within the team

The management team is working to establish a process for recognizing, reporting, and addressing these issues when they arise, following the AAS code of ethics and anti-harassment policy (https://aas.org/policies/ethics). This ensures that all team members are treated with respect and experience inclusivity and equity, and that our team diversity is honored and celebrated.

~25% Complete

11. Increased the team's interest and knowledge of diversity and inclusion

Using facilitated dialogues, questions during team meetings, and a team survey, the team's interest and knowledge about diversity & inclusion is being assessed. We have run two diversity and inclusion team workshops on gender bias and underrepresented scientists' experiences. We will run one more in Phase I.

~60% Complete

Coordinate and integrate team activities

12. Adopted tools and developed processes for tracking, adding, and descoping tasks

We adopted tools for tracking MACH tasks among the management team (all team members submit monthly PowerPoint Quad charts which are summarized by the PM into a fever chart for each task). We plan to adopt a task tool so the entire team can monitor the status of each task (e.g. Trello). We are developing criteria for adding and descoping tasks.

~50% Complete

13. Adopted management strategies to propagate MACH results through our methodology

We will develop strategies to track new or revised results and routinely disseminated them to the research team to ensure they are integrated into the MACH methodology (e.g. a new physical process is added to a model, requiring that our estimates of escape are re-run and the results updated in our interface).

~20% Complete

14. Adopted tools and processes for storing and archiving data

We use Google Docs for meeting slides and notes, and will revisit this choice before Phase II. We are considering different archival and storage platforms for our larger data products such as model or data results (e.g. Google Drive, MACH website, CU Scholar, CCMC).

~50% Complete

15. Facilitated communication between the research and broader impacts teams

We will develop a strategy for facilitating monthly communication between the research and broader impacts teams in order to ensure that the broader impacts tools of the MACH Center (e.g. website, outreach products) reflect the latest MACH research results.

~70% Complete

2.3 Management: Key outcomes for Phase II

While maintaining the management key outcomes established in phase I, there are five additional key management outcomes for Phase II, grouped into four categories. For each numbered item start with: "***By the end of Phase II, the MACH team will have...***"

Leadership and Management

1. Annually reviewed and updated the MACH Center Strategic Plan

   We will revisit the MACH Strategic Plan annually and with the entire team, updating it to identify successful outcomes, new outcomes or planned activities that need to be added or altered, and new key actions or potential partners.

2. Facilitated active participation of MACH Co-Investigators in Center activities

   We will hold quarterly check-in discussions with each MACH Co-I to facilitate and ensure progress and devise strategies for overcoming obstacles as they arise. This includes both the research and broadening impacts teams.

3. Surveyed the team annually about Center management

   We will survey the team annually about whether they feel the Center is being managed effectively and transparently and whether they feel that their work is being facilitated or hindered. This survey will be administered by a consultant outside of the MACH management team, and distilled results reported to MACH management for action.

4. Engaged the External Advisory Board every ~6 months

   We will engage the MACH External Advisory Board twice annually during Phase II to report on the activities of the Center and to solicit feedback and advice on whether the Center is making appropriate progress and moving in an appropriate direction.

Team Communication

5. Incorporated annual in-person meetings into the MACH meeting structure

   In-person meetings are invaluable for making progress on team building and team tasks in short periods of time. If the pandemic subsides sufficiently, then we will hold at least one in-person team meeting per year in Phase II, with a goal of >75% team attendance each year.

2.4 Management: Planned Activities

Management activities for the Center can be grouped into five categories, as follows.

Team development and function

In Phase I we are defining the full team that is necessary to complete MACH objectives (with the exception of the "MACH Fellows" program described in Section 3). We are also refining the organizational chart for the Center in response to a recommendation from our External Advisory Board. Our new organizational structure will reflect the six interdisciplinary research tasks described in Section 1.4, rather than the more siloed organization of “Observations”, “Modeling”, and “Theory” proposed for Phase I. We have added Dr. Aimee Merkel as the Deputy Project Manager.

In Phase II we will ensure that the team continues to function effectively. Our weekly management meeting will regularly address team participation and effectiveness of communication. We will identify areas of overlap and potential conflict between team members, taking steps as appropriate to make sure that all team members can make valuable contributions.

Team communications

During Phase I, we established an optical meeting pattern, and shifted the meeting topics to prevent the “siloing” of expertise. Now all weekly meetings are open to all team members and once a month we discuss a topic that involves synthesis from the entire team. We email meeting notes to the entire team after each meeting is complete, with links to slides from the meeting and a description of any action items. The MACH PI, PM, and administrative assistant meet weekly to discuss management issues and action items, and the MACH Co-I’s meet every 2-3 weeks to provide input on management decisions. We have established communication norms and provide regular reminders for our team members to give everyone space to participate. We expect to continue to revisit our team communication practices in the remainder of Phase I and into Phase II, especially as our team grows by ~30%.

In Phase II, we will continue to facilitate Diversity & Inclusion team dialogues that will occur annually, or bi-annually depending on need. Different topics (e.g. stereotype threat, lack of representation, generational cultural differences, imposter syndrome) will be addressed using external experts as resources with small group discussions and prompts, to share out in the big group. Topics will be determined in Phase II using an open-ended team survey administered by an external facilitator.

Management Process development

We are currently developing or formalizing processes for addressing communications and ethics issues within the team, tracking Center activities and tasks, adding and descoping tasks, management decision-making, and financial management. Each of these processes is described in Sections 2.2 and 2.3 above.

Tool adoption and maintenance

By the start of Phase II the MACH team will have decided which management, communication and task tools will be adopted during the life of the Center. These include tools for both collaboration and shared research.

Collaboration Tools

- Virtual meetings (current choice: Zoom)

- Asynchronous communication (current choice: Slack)
- Repository for team-relevant information (current choice: Google Drive)
- Reporting (current choice: PowerPoint quad charts)
- Task tracking (current choice: Excel fever chart + TBD (i.e. Trello))
- Team calendar (current choice: Google Calendar)

Shared Research Tools

- Data repository (current choice: Google Drive + CU Scholar + CCMC)
- Code repository (current choice: TBD (i.e. Github))

Task administration

In both Phase I and Phase II we will manage the tasks of the Center, and regularly evaluate whether tasks are on track. For tasks that are not on track we will determine whether the task requires additional resources (funds or time) or should be descoped. We are using monthly quad charts for each team member, distilled to a fever chart organized by task.

2.5 Management: Potential Partners

We list below (in priority order) potential partnering opportunities that would augment our management activities in Phase II. We view the first two items as essential, and the remaining two as desired.

- Evaluator and advisor for Center management
- Workshops for junior scientists
- Strategic planning facilitation
- Virtual workshop support

A potential partner who provides all of the above is the Center for Interdisciplinarity (C4I) at Michigan State University. We have already been collaborating with representatives of this Center on each of the topics above during Phase I. If funded for Phase II, MACH and C4I could enter into a long-term collaboration in order to (1) guide the creation of a "living" collaboration plan, (2) monitor and improve communication and collaboration within MACH through surveys and workshops, (3) offer workshops for undergraduates, graduate students, and postdocs, and (4) help MACH to develop and deliver engaging meetings and events both in-person and virtually. We will also consider leveraging management consulting resources at the PI's home institution (CU Boulder).

2.6 Management: Key Actions Table

Key actions for MACH Management include the following:

Action	Due Date / Frequency	Responsible Party
Finalize MACH Organizational Chart	October 27, 2021	PI / PM
Select and onboard new MACH team members	October 27, 2021	MACH Team
Write a successful Phase II proposal	October 27, 2021	MACH Team

Develop, implement, and maintain team communication processes for the Center	Develop: End of Phase I Maintain: Ongoing	PI / PM
Adopt and maintain technology for MACH task management and exchange of research information	Adopt: End of Phase I Maintain: Ongoing	PI / PM
Financial status check-in	Monthly	PI / PM / LASP BA
Facilitate communication between research and BI teams	Monthly	PM / Peticolas
Hold check-in discussions with each MACH Co-I	Quarterly	PM / Co-Is
Engage the External Advisory Board	Bi-annually	Pi / PM
Revisit the MACH Strategic Plan	Annually	All team members
Survey the team and evaluate management	Annually	External facilitator

3. MACH Broader Impacts

<u>3.1 Broader Impacts: Goals</u>

Our broader impact goals are motivated by a desire and sense of social justice to nurture and prepare a robust and diverse next generation of professionals in the space sciences and an appreciation for the challenges that students, historically marginalized communities, and postdoctoral researchers face in joining the scientific community (AAAS, 2020; Morris, 2021; Sowell, 2015; NASEM, 2021).

MACH's impact-broadening activities have the following overarching goal:

MACH will engage teens, students, and professionals in MACH research and discoveries, inspired by the question, "Do Habitable Worlds Require Magnetic Fields?"

This overarching goal can be broken into specific goals, listed below. Note that the diversity and inclusion activities promoting and supporting diversity within the center's overall team are partially included in the Management Section 2.

- G1. When engaging and communicating with students and early career professionals, MACH will leverage its own diversity and inclusivity processes to ensure that best DEIA practices are followed.
- G2. Inspired by the idea that habitable worlds may require magnetic fields, under-represented and historically marginalized groups will engage in MACH's research discoveries and scientific practices.

G3. MACH will inspire the public to learn more about whether habitable worlds require magnetic fields.

G4. MACH will prepare the next generation of heliophysicists and science educators by mentoring and training students and postdoctoral researchers

G5. MACH will gain new expertise and knowledge from participating researchers through our MACH Fellowship program, while fostering their careers.

<u>3.2 Broader Impacts: Key outcomes for Phase I</u>

Key outcomes for Phase I are listed below and connected to each of the impact broadening goals (G1-G5) in Section 3.1. For each numbered item start with: "***By the end of Phase I, the MACH team will have...***"

1. Collected information from students and postdoctoral researchers to iteratively improve team, training, and mentoring activities, as described in Section 3.4 (G1, G4)

   Data are gathered from students and postdoctoral researchers using journal entries, a Toolbox Project Workshop, and surveys (described in Section 3.4). Data will be analyzed in order to make modifications to activities to better align them with the broader impact goals.

   ~40% Complete

2. Developed a plan for engaging teens from under-represented groups in its research, discoveries and scientific practices, inspired by whether habitable worlds require magnetic fields (G2)

   MACH team members are interested in supporting historically marginalized and under-represented teens in their communities. A TRIO-NASA MACH partnership has begun discussing plans. Initial ideas on possible activities and partnerships with MACH team members in California, Colorado, Kansas, New Hampshire, and Massachusetts are described in Section 3.4.

   ~60% Complete

3. Used formative evaluation about MACH communications and outreach to the public in Phase I to iteratively improve communication and outreach activities for Phase II (G3)

   Communication and outreach activities described in Section 3.4 engaged the public in MACH-related science via virtual presentations using a variety of formats and partnerships. Metrics, evaluation and education research methodologies are being analyzed.

   ~60% Complete

4. Developed and implemented a training framework for the MACH Center (G4)

   The interdisciplinary nature of the MACH Center provides a challenging and exciting opportunity to build a framework for training all students in relevant knowledge and skills. By Phase I, a plan for the development and iterative

   ~5% Complete

testing of the training framework will be created, including the foundations needed to do research in the MACH Center.

5. Had research presentations from 5 undergraduates, 5 graduate students, and 3 postdocs at MACH team meetings, the MACH virtual workshop, or at AGU (G4)

To date at least 4 PhD students and 1 master's degree student presented their science results at the MACH workshop, and 5 undergraduate students presented to the MACH team at team meetings.	~80% Complete

6. Developed mentoring plans for students, postdocs, and their mentors (G4)

Mentoring agreement templates for undergraduates are drafted. Mentoring plan templates have been reviewed. Final plans need to be completed.	~50% Complete

7. Mentored at least two undergraduate students desiring a career in science education (G4)

One UNH physics student with a plan to be a high school science teacher participated in the Summer Undergraduate Research (SUR) activity. An SSU physics student furthered her career aspirations through a mentored Senior Project (Capstone). The research protocol was completed and opened for data collection.	100% Complete

8. Devised an implementation plan for the MACH Fellows program (G5)

Given the interdisciplinary nature of the center, MACH's research requires a constant influx of new expertise and perspectives. At the same time, scientists at all career stages often look for opportunities to take their research in new directions or join a new network of collaborators to explore innovative new ideas. Our concept for the MACH Fellows program will meet these needs, but the implementation plan remains to be completed.	~50% Complete

3.3 Broader Impacts: Key outcomes for Phase II

Seven key broader impacts outcomes for the Phase II effort are listed below, grouped into three categories. Each outcome is associated with one of the BI goals (G1-G6). For each numbered item start with: "***By the end of Phase II, the MACH team will have...***"

Diversity and inclusion

1. Increased the team's ethnic, racial, and gender diversity (G1, G5, G6)

   Team and Broader Impact activities described in Sections 2.4 and 3.4 ensure that barriers are removed to engaging with under-represented and/or historically marginalized research team members and partners. Additionally, processes are in place to support these team members, and to enable an increase in team diversity.

2. Provided programming via outreach and training/mentoring activities to over 7,000 first generation, low-income teens (80% Hispanic/Latinx) (G2)

   This outcome is met through partnerships with TRIO programs: Talent Search (TS) and Upward Bound (UB), at MACH Universities, as described in Section 3.4. For this collaboration, we will add assessments that measure students' increased interest and readiness for computer science, science, and mathematics majors and careers, such as completion of advanced coursework in high school. TS programs at SSU, KU, and UNH currently have 3,612 teens enrolled in their programs (~7,000 total assuming 50% engagement for 4 years).

3. Collaborated with at least 6 MACH fellows, at least a third of whom will identify as a member of an under-represented community in Heliophysics (G6)

   The MACH team is reserving funds for two Fellows per year in each of the 5 years of the Phase II effort, with the possibility that some Fellows may be able to renew for a 2nd year. We will actively reach out to minority serving institutions when soliciting Fellowship applications.

Communications and outreach

4. Communicated MACH Center discoveries to more than 80,000 people (G3)

   The MACH Center expects to communicate discoveries to a variety of audiences ranging from the general public to scientists. Specific targets include readers of Sky & Telescope, attendees of public talks, readers of the AGU publication EOS, NASA SciAct program leads and their audiences, and informal Science Education and Think Tank communities. See Section 3.4 for more information. The number in the outcome using online information about readership, and experience giving public lectures, and working with informal science education communities.

Training and mentoring

5. Trained at least 1,000 under-represented teens in computational skills and MACH-related content inspired by whether habitable worlds require magnetic fields (G2)

   Upward Bound Math & Science programs at SSU, KU, and UCLA currently have 268 teens enrolled in their programs. Assuming full engagement for 4 years (1,072 total). The Upward Bound programs at SSU, KU, UCLA, CU Boulder, and UNH have an additional 1,035 teens enrolled in those non-math & science programs. Some Upward Bound programs are open to including science in these programs. See Section 3.4 for details on the program elements.

6. Trained at least 36 students and post-doctoral researchers in Heliophysics computational modeling, data analysis, and professional development skills (e.g. oral presentation skills) in the context of MACH research (described in Section 1) (G4)

   At least 5 undergraduates, 4 graduate students, and 3 postdoctoral researchers will be trained by MACH scientists each year. This will yield a total of 36 students/postdoctoral researchers if turnover occurs every other year, not counting additional students from other Universities who engage in conferences and workshops with MACH team members.

7. Mentored at least 45 undergraduates, graduate students, and postdoctoral researchers (G5)

   We make a distinction between training (providing professional skills, described in #6 above) and mentoring (supporting scientists as individuals as they navigate the early stages of their careers). As part of the total above, we will mentor 1 student per year in science education.

8. Brought early career team members into leadership roles within MACH (G4)

   By the end of Phase II we will have provided at least three early career scientists the opportunity to develop leadership skills within the MACH Center. Examples could include assigning early career scientists as Deputies or Leads for our 6 broad research tasks (or taking over as leader) or leading the organization of the recurring MACH workshop.

3.4 Broader Impacts: Planned Activities

The MACH BI suite of activities are designed to achieve the BI Key Outcomes. Each activity uses the interests and expertise of the current team and potential partners, as well as research relating to successful implementation of such activities, when relevant. The BI management of these activities uses the Plan, Do, Study, Act (PDSA) process model to ensure iterative design and improvement over the years of the MACH Center's broader impact activity implementation.

Implement a MACH Fellows program

The MACH Fellows program will bring scientists from all career stages into the MACH team for periods of 1-2 years. We will assess whether the selected Fellows meet our multi-dimensional diversity criteria and the impact of their contributions to the MACH program. We will collaborate with minority-serving institution partners in the design of this program. Additional minority-serving institutions will be contacted when recruiting applicants.

Communication and Outreach activities

We will conduct a Think Tank that engages an interdisciplinary group to examine the societal and cultural impacts of MACH's essential question (whether or not magnetic fields are required for habitability). Workshop participants will include MACH scientists, external scientists, informal science educators (e.g., YouTube influencers, Exploratorium and other science center education specialists), and science communicators. Topics will include habitability, evolution, astrobiology, space exploration and industry, diversity & inclusion, education, and possibly even science fiction. The group will initially meet for one day in conjunction with a MACH Community Workshop.

To combat the prevalent idea that it is already known that planets require a magnetic field to retain an atmosphere, we will write at least two popular science (e.g. Sky & Telescope) articles and one scientist-focused article (e.g. AGU EOS). Outreach to two NASA SciAct program leads each year will help us to find synergies between the MACH broader impacts programs and ongoing SciAct initiatives.

Academic workshops and MACH webinars for high school-aged teenagers

MACH has the potential to partner with the TRIO Programs (TRIO), which are Federal outreach and student services programs designed to identify and provide services for individuals from disadvantaged backgrounds. TRIO includes the Talent Search program, aimed to motivate, inform, and assist low-income, first-generation students towards higher education preparation and enrollment in college, and degree completion. The Upward Bound program has the same aims as the Talent Search program with an additional support of academic preparation. In SSU's partnership with the Talent Search leadership, virtual presentations (outreach) appropriate and relevant to these students would be created and presented to teens. SSU will test out curriculum for the Upward Bound Saturday academic workshops leveraging computational simulation tools developed for 9th graders by the SSU team. The number of low-income, first generation students currently enrolled in the Federal TRIO programs at each MACH institution is listed below in a table. These students enroll from primarily Latinx, African-American (80%) and other historically disadvantaged populations. Rural and Native American students are also represented.

	Talent Search # Students	Upward Bound Math & Science # Students	Upward Bound # Students
SSU	1,520	80	413
UCLA	0	62	321
CU Boulder	0	0	103
KU	932	126	94
UNH	1,160	0	104

Graduate student, post-doc, and Fellow research at Co-I Institutions

During Phase II we will incorporate graduate students and postdocs in the activities of the Center, including engaging in research, making presentations at professional meetings, appropriate mentoring, and engaging in BI activities. MACH will train students in Heliophysics computational modeling, data analysis, and oral presentation and other professional development skills in the context of MACH research (described in Section 1.)

Summer Undergraduate Research Recruit, Select, Implement, Evaluate

MACH's BI team is developing a Summer Undergraduate Research (SUR) program leveraging the structure and offerings of LASP's impactful Boulder Solar Alliance REU program. Activities for students will include a week-long boot camp for skill development, professional development, elevator pitches, use of Slack to communicate, computational programming tutorials, weekly journal entries, and final oral or poster presentations in a culminating virtual student research symposium. Recruitment will be done via the Broadening Participation non-profit portal; Physics and Astronomy Departments at MACH institutions; MESA, AISES, and SACNAS chapters at MACH institutions; and partnering minority institutions' Physics and/or Astronomy Departments. MACH undergraduate students and their MACH mentors will complete mentor-mentee agreements, in line with best practices identified by NASA. Mentors will be trained to recognize implicit biases and to avoid bullying and sexual harassment.

Senior Projects (Capstones) in science education

Science students at MACH institutions interested in a career in education will engage in MACH broader impact evaluation or research as a Senior Capstone project. These projects will include submission of an IRB protocol through the institution's IRB process. They will leverage evaluation efforts already taking place or needed by the MACH team.

Evaluate BI activities

An external evaluation team will provide both interactive formative evaluation and summative evaluation of all broader impacts activities.

3.5 Broader Impacts: Potential Partners

The MACH team has followed the same procedures as in Sections 1.5 and 2.5 for potential partners.

Necessary Expertise: We are actively seeking to add team members with expertise in the following areas before Phase II begins:

- TRIO program leaders at PI and Co-PI Universities.
- Faculty at minority-serving institutions
- Evaluator team for formative and summative assessments of Center's broader impacts

Desired Expertise: We will consider adding additional expertise in the following areas.

- Science writer
- Native American educators working with teens
- Broadening Participation in Science Non-Profit

Removing Expertise: After pilot testing a variety of activities, we have determined that we no longer need expertise in the following areas:

- Spherical displays of scientific data

3.6 Broader Impacts: Key Action Items

In order to achieve the BI Key Outcomes, the planned activities in 3.5 and the diversity & inclusion activities in 2.5 are scheduled according to the following timeline:

Action	Due Date / Frequency	Responsible Party
Diversity & Inclusion Facilitated team dialogues	Bi-annually: Winter & Summer	Peticolas + New Partner
Work with HS-aged teens and TRIO program leadership	Bi-annually: Fall & Spring	Peticolas / Co-Is
Implement a MACH Fellows program	Year 1 of Phase II / Annually	PI / PM / Peticolas
Communication and Outreach activities	Bi-annually: Fall & Spring	PI / Peticolas + New Partner
Bring early career members into leadership roles	Year 2 of Phase II	PI / PM / Co-Is
Outreach: Think Tank on topics to engage informal science educators and external scientists	Year 3 of Phase II	Peticolas / PI / PM
Student, post-doc, and fellow research at Co-I Institutions	Ongoing	PI / Co-Is
Summer Undergraduate Research Recruit, Select, Implement, Evaluate	Annually: Spring & Summer	Peticolas / PI / Co-Is
Senior Capstone science education activities	Annually: Spring	Peticolas
Evaluate BI activities	Annually	External evaluator

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