The Magnetosphere-Ionosphere Observatory (MIO)

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Summary: The MIO mission concept is to operate a powerful relativistic-electron accelerator (beam energy 1 MeV, beam power 1 kW) on a main spacecraft in the equatorial nightside magnetosphere with the beam directed into the atmospheric loss cone to deposit ionizing electrons in the atmosphere sufficient to optically illuminate the magnetic footpoint of the spacecraft while 4 nearby daughter spacecraft make magnetospheric measurements. A network of ground-based imagers will locate the optical beamspot thereby unambiguously establishing the connection between equatorial magnetospheric measurements and ionospheric phenomena [cf. Borovsky et al., 2020a,b] Critical measurements will be made to discern magnetospheric generator mechanisms. This enables the magnetospheric drivers of various aurora, ionospheric phenomena, and field-aligned currents to be determined. The MIO mission will conclusively fix a gap in our understanding of the magnetosphere-ionosphere system: that we don't know what magnetospheric processes are connected to what ionospheric processes. MIO is the result of substantial technology development and will provide the magnetospheric, ionospheric, and atmospheric communities with a unique scientific facility.

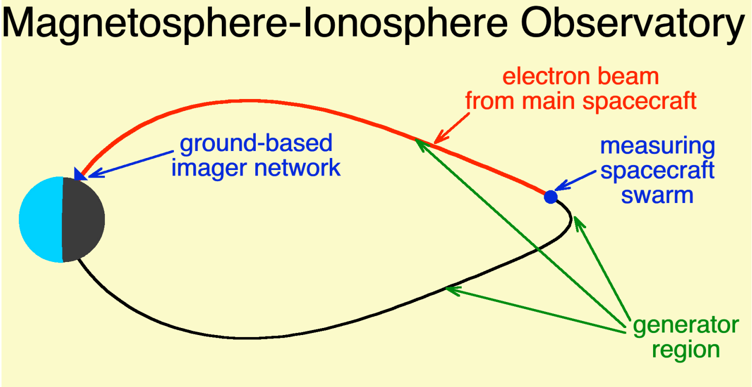

Figure 1. A sketch of the MIO swarm of spacecraft (blue) in the equatorial magnetosphere, the relativistic electron beam (red) marking the magnetic footpoint, and the TREx imaging network (blue) locating the optical beamspot in the atmosphere.

1. Science Goals and Objectives

The MIO mission is designed to conclusively fix a major gap in our knowledge of system-level dynamics: we don't know what fundamental magnetospheric processes drive the diverse auroral and ionospheric phenomena and we don't know what form of energy is extracted from the nightside magnetosphere and transferred to the ionosphere and atmosphere.

Specific science goals of the MIO mission are to determine: (1) What are the magnetospheric mechanisms that drive the specific types of auroral forms? (2) What magnetospheric processes drive critical ionospheric phenomena such as SAPS/SAID, STEVE, ionospheric irregularities, convection reversals, and the Harang discontinuity? (3) What are the magnetospheric counterparts of ionospheric boundaries and vice-versa? (4) What are the dominant magnetospheric gradients that drive field-aligned currents? (5) In the coupled magnetosphere-ionosphere convection pattern, who drives whom, when and where?

The overarching objective of MIO is to unambiguously connect equatorial magnetospheric measurements to ionospheric phenomena. Specific objectives are to achieve the above 5 science goals and to support ground-based scientific campaigns and spacecraft-conjunction campaigns with the ionospheric, atmospheric, and magnetospheric communities.

2. Impact and Relevance to the Solar Terrestrial Probes Program

Relevant to the ST Probes program, MIO addresses the fundamental physical processes of current driving in any astrophysical system and of coupling in a magnetospheric system. It addresses unsolved scientific questions about the physics of energy flow within the interconnected magnetosphere-ionosphere system. MIO focuses on our "weakest link" in the coupled system, which is the fact that we don't know what is coupled to what! MIO will conclusively fix that key knowledge gap throughout the complex, rapidly varying, nightside magnetosphere-ionosphere system. Without MIO, magnetosphere-ionosphere-coupling research could remain at an impasse.

The MIO mission will determine what forms of energy are converted in the magnetosphere to drive ionospheric phenomena, enabling us to better understand the impact on the magnetosphere of its driving of the ionosphere. Tests of the diverse theories of auroral generators can finally be made. And the MIO mission will test ideas about who is driving whom in the coupled magnetosphere and ionosphere convection patterns. Suspected connections between the ionosphere and the magnetosphere can be definitely confirmed or refuted. Finally, by determining what nightside processes drive the diverse forms of aurora, the MIO mission will provide the "Rosetta Stone" that will enable us to fulfill the longstanding desire to use auroral observations as a "TV screen" to monitor ongoing magnetospheric processes.

Via scientific campaigns with the magnetospheric, ionospheric, and atmospheric communities MIO will serve as a meta-instrument for Earth System Science.

3. Planned Research Methods

Measurements are taken continuously by the main spacecraft and by the 4 daughter spacecraft in the equatorial magnetosphere. These measurements are designed to measure critical gradients in the magnetosphere, including flow shear ω. A key concern is how the magnetospheric generator drives field-aligned currents $j_{||}$ that connect the magnetosphere and the ionosphere. In the magnetosphere the $j_{||}$ current generation is described by the "Vasyliunas formula"

$$\begin{aligned}\nabla_{||}(j_{||}/B) = {} & (2/B^3)((\nabla P_i + \nabla P_e) \times \nabla B)_{||} + (2\rho/B^3)((d\underline{v}/dt) \times \nabla B)_{||} \\ & - (1/B^2)((d\underline{\mathbf{v}}/dt) \times \nabla\rho)_{||} + (\rho/B^3)\,\underline{\omega} \bullet d\underline{\mathbf{B}}/dt \\ & + (\omega_{||}/eB^3)(\nabla k_B T \times \nabla\rho)_{||} + (\rho/B^2)\,d\omega_{||}/dt\ .\end{aligned} \tag{1}$$

All of the gradients on the right-hand side of eq. (1) are gradients perpendicular to the magnetic field. This equation motivates the measurements that must be made in the magnetosphere by the array of daughter spacecraft: radial and azimuthal gradients in the ion and electron pressure, the magnetic field, the flow velocity, the mass density, etc. These measured gradients will determine which terms in eq. (1) dominate the driving of the field-aligned current, thus identifying generator mechanisms. Further, in the magnetosphere there are finite-gyroradii effects where Hall currents can be generated: this requires independent measurements of the ion flow velocity (made with plasma instruments on the daughters) and the electron flow velocity (made with an electron drift instrument (EDI) on the main spacecraft).

The unambiguous connection between magnetospheric measurements with ionospheric phenomena is accomplished by firing an energetic-electron beam from the main spacecraft in the equatorial magnetosphere into the atmospheric loss cone and optically locating the electron beamspot in the atmosphere with a ground-based imaging array.

Community campaigns utilizing MIO as a scientific facility could involve incoherent-scatter radar, ionospheric heaters, imaging riometers, ionosondes, Fabry-Perot interferometers, TEC arrays, lidar, ionospheric-tomography experiments, DMSP conjunctions, Iridium-AMPERE conjunctions, and SuperDARN. The MIO orbit will be chosen such that the MIO magnetic footpoint passes near PFISR, Poker Flats Research Range, and HAARP once each day.

4. The Mission Concept

The MIO mission has a 1-MeV electron accelerator mounted on a 3-axis-stabilized main spacecraft in an equatorial orbit with a 24-hr period. The main spacecraft is surrounded by four spinning daughter spacecraft with separations of 100's of km making radial and azimuthal gradient measurements. Through each 24-hr interval the spacecraft's magnetic footpoint in the ionosphere will wander across an array of ground-based optical imagers in Western Canada and Alaska. The firing of the electron beam into the atmospheric loss cone will deposit energy in the atmosphere, producing an optical spot marking the location of the spacecraft's magnetic connection to the ionosphere in the context of auroral images and other ionospheric phenomena. The daughter spacecraft will carry scientific instrumentation to measure the properties of the magnetosphere sufficient to identify the regions and boundaries of the magnetosphere and to determine and quantify the physical mechanisms that drive field-aligned currents, the various types of aurora, and other ionospheric phenomena.

To know the direction to the loss cone, the main spacecraft carries a magnetometer. To mitigate beam-driven spacecraft charging, a xenon plasma contactor on the MIO main spacecraft will be initiated prior to the accelerator operation with the ion and electron currents of the contactor exceeding the electron current of the accelerator.

A 24-hr-period elliptical orbit for the spacecraft will be selected to cross through the equatorial magnetospheric regions that are believed to be the generator regions of various types of aurora and other ionospheric phenomena while the ionospheric magnetic footpoint of the spacecraft passes over a North American ground-based optical imager array.

The scientific instruments needed for MIO are off-the-shelf: EDI, electrostatic analyzers, and magnetometers. The ground-based imager array will use the TREx camera design. The major design work has been the development of a 1-kW space-based compact relativistic-electron accelerator, a LANL-SLAC partnership. Some components of the accelerator design will be flown on a NASA LCAS rocket (BeamPIE) in 2022. The charging-mitigation technology for MIO will be demonstrated in an LCAS rocket flight B-SPICE in 2023. The estimated mission cost for MIO is $500M with a detailed mission point design being performed at APL ACE Lab.

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