Multi-point Assessment of the Kinematics Of Shocks (MAKOS)
Pre-study Report

We propose the Multi-point Assessment of the Kinematics Of Shocks (MAKOS) mission concept with the objective to ***"understand the partition and conversion of energy at collisionless shocks under various conditions."*** This mission must not only fully resolve the solar wind particle populations but must also disambiguate spatiotemporal dynamics and connect the microphysical measurements to the contextual macrophysical observations over a broad range of solar wind conditions.

To achieve its objective, MAKOS will seek to address the following science questions:

1) *What is the partition of energy across collisionless shocks?*
2) *What are the processes governing energy conversion at and within collisionless shocks?*
3) *How and why do these processes vary with macroscopic shock parameters?*

A shock is a spatial discontinuity that forms when a supersonic flow encounters an obstacle. Its overall effect is to slow the flow to subsonic speeds via energy conversion, allowing the flow to travel past the obstacle. Shocks are a ubiquitous physical process that can occur in any media. In many space environments, e.g., heliospheric and astrophysical plasmas, shocks are collisionless. The conversion of bulk flow to particle thermal energy cannot be mediated by particle collisions alone but requires mechanisms such as wave-particle interactions, particle acceleration, dispersive radiation, and energy cascades.

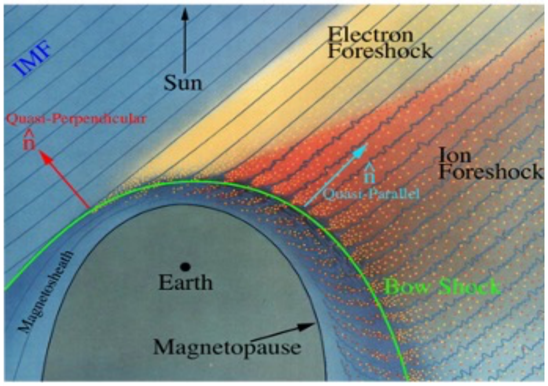

Figure 1 MAKOS is a multi-spacecraft mission specifically instrumented to probe Earth's bow shock.

Our current understanding of collisionless shocks has been achieved through decades of observations of Earth's and other planetary bow shocks, solar and interplanetary shocks, and the heliospheric termination shock. Those observations were all supported by increasingly sophisticated numerical simulations. Numerous observations of the terrestrial bow shock were obtained through missions including ISEE, AMPTE, *Cluster*, *Wind*, THEMIS, and MMS. While much has been learned through these missions, the detailed energy partition across collisionless shocks remains poorly understood.

Despite many observations of Earth's bow shock (Figure 1), the question of how energy is partitioned across it remains open. None of the aforementioned missions were able to simultaneously measure the upstream and downstream conditions required to determine the full energy budget of the shock. Since the shock's driving conditions can vary rapidly, it is difficult, if not impossible, to relate upstream and downstream measurements from a single spacecraft time-series dataset, as the conditions change faster than the spacecraft transitions across the full shock structure. Moreover, none of these missions have the instrumentation capable of fully separating both the thermal and nonthermal components of the solar wind proton distribution.

To fully understand the energy partition of collisionless shocks, a purpose-built mission is required. This mission must not only fully resolve the solar wind particle populations but must also disambiguate spatiotemporal dynamics and connect the microphysical measurements to the contextual macrophysical observations over a broad range of solar wind conditions.

MAKOS is particularly appropriate for the Solar and Terrestrial Probes (STP) Program, both in its scientific scope and its engineering ambition. The STP Program seeks to investigate fundamental processes that determine mass, momentum, and energy flow in space. It is generally accepted in the space physics community that the majority of energy transfer in space occurs due to one of three processes: turbulence, magnetic reconnection, and/or collisionless shocks.

Shocks are a universal phenomenon that provide an accessible astrophysical laboratory to study a host of fundamental physical processes, from wave-particle interactions to particle acceleration. However, they have not received the same level of attention as other processes from the spacecraft mission community. As a result, there are several gaps in our understanding regarding energy conversion within plasma shocks. These gaps include the specific energy conversion processes that occur within shocks, their dependence on different driving conditions, and their energy transfer efficiency. The implementation of MAKOS will close these gaps.

MAKOS will achieve science closure via case studies and statistical analyses of the in-situ particles and fields measurements that it will obtain at the bow shock and interplanetary shocks. To achieve closure on science question (SQ)-1, accurate measurements with high resolution must be made simultaneously upstream, in the shock transition layer, and downstream of the shock. The measurements include the thermal, suprathermal, and energetic particle populations combined with electric and magnetic fields. The thermal particle data must have sufficient angular and energy resolution to fully resolve the solar wind core, which no current missions can sufficiently measure in the shock to the level of detail necessary for MAKOS science closure. The fields must be well resolved and continuous from DC- to AC-coupled, where the latter should include measurements of sufficient cadence to observe in-situ Langmuir waves. The fields must be three vector component time series measurements. Only after measuring all quantities can the total energy budget in and out of the shock be properly quantified. With all these measurements, the energy flux densities of the fields and particles in the upstream, ramp, and downstream can be properly calculated to fully track the energy components across the shock.

To achieve closure on SQ-2, the same measurement requirements necessary for SQ-1 will be required at minimum plus detailed observations within the shock transition region (with simultaneous observations in either the upstream or downstream regime). The additional requirement is that full 3D VDFs must be returned to ground. Full 3D VDFs are required in each region to provide contrast and allow separation between transport and in-situ effects. That is, the VDFs must be examined in multiple locations simultaneously to distinguish between a local effect (e.g., waves heating the particles) and transport effects (e.g., hot population propagating from one region to another). The time resolution must be sufficiently high to clearly distinguish the effects of high frequency waves from quasi-static fields. Simultaneous multipoint measurements are also required for examination of the accuracy and reliability of Liouville mapping to constrain estimates of the cross-shock electric potential.

To achieve closure on SQ-3, again the same measurement requirements necessary for SQ-2 will be required at minimum but for the subset of all cases in which upstream data are available (i.e., two MAKOS S/C upstream with the other two at either the shock transition region or in the downstream regime). These observations will be used to determine the local and larger-scale, average shock geometry. A combination of efforts toward SQ-1 and -2 with a broader scope to examine numerous shock crossings under different driving conditions will be required to address SQ-3. Observations and quantification of the above processes and energy flux densities for hundreds of shocks will be required for closure on SQ-3. Closure will be enhanced comparing the MAKOS observations with particle-in-cell (PIC) and Vlasov simulations to provide additional context and more immediate comparison to theory.

A preliminary, notional MAKOS mission design comprises at least four spacecraft (S/C) with varying spatial separations in high-altitude, slightly elliptical Earth orbits with both the apogee and perigee >15 R_E to maximize the number of bow shock crossings, even when apogee is on the nightside. A potential orbital solution, utilizing a pair of five-to-one (5:1) lunar resonance orbits (LROs) with opposite lines of apsides is shown in Figure 2. Each of the two orbits has two co-orbital S/C with separations on the order of approximately 1000 km to obtain the required simultaneous upstream and downstream shock observations and multipoint observations at ion-kinetic scales through every shock transition layer crossing. The separations between the S/C on the different orbits range from ~4 to 7 R_E. Such an architecture provides year-round crossings of the bow shock with simultaneous multipoint separations ranging from ion kinetic (~1000 km; each pair) to MHD (several R_E; the pair of pairs) scales *plus* prolonged dwell time in the solar wind, enabling MAKOS to simultaneously probe both ion-kinetic- and MHD-scale processes during every shock crossing.

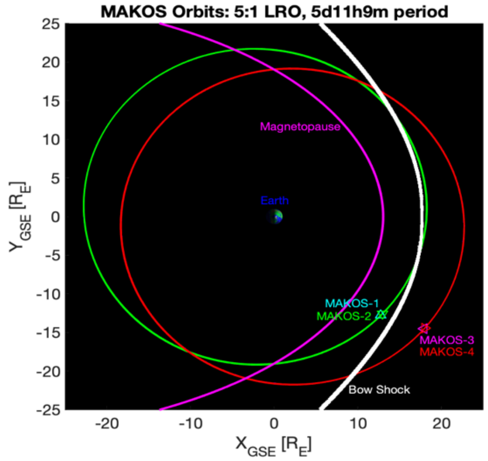

Figure 2 Initial orbit design for four MAKOS spacecraft.

MAKOS requires each S/C to carry a comprehensive science payload of particles and fields instruments specifically tailored to measure the in-situ processes at play at collisionless shocks. The need to fully characterize the plasma populations upstream and downstream of the shock drives a mission requirement that the complete electron and ion velocity distributions be sampled at temporal resolutions faster than 15 s. This could be achieved by either carrying fewer sensors on a rapidly- spinning S/C or instrument platform, or by accommodating additional sensors on a S/C with a lower spin rate. This is a trade to be conducted during the proposed concept study. This is complicated by the fact that commercially- available star trackers cannot handle such high spin rates. The proposed study will need to investigate how best to achieve the MAKOS attitude determination and control (ADC) requirements given the need to make high-time-resolution particle measurements.

A major goal of the proposed concept study will be to develop a baseline mission design that identifies a suitable launch vehicle(s) (LV) that can achieve a necessary orbital configuration for the MAKOS S/C (like that shown in Figure 2) or investigate the possible trade of implementing the mission via a rideshare launch(es) to GTO or GEO. For a rideshare launch, the ΔV required to get to the desired orbits would be high and the necessary kick-stage or onboard propellant would likely significantly drive design of the S/C. For this reason, the proposed study will consider the most suitable implementation to achieve the necessary MAKOS orbits – e.g., use of a single or multiple LVs, use of an orbit maneuver vehicle(s), S/C deployment options, details of the LV accommodation and interface, etc.

The proposed study will provide baseline solutions for the S/C bus, mission design (including LV), payload, and all S/C subsystems, including power, propulsion, communications, thermal, mechanical, avionics, guidance and control, navigation, and attitude determination and control. The details of these subsystems, along with the final science and mission requirements will be used to develop a notional concept of operations (CONOPS) and assess science closure for the mission.