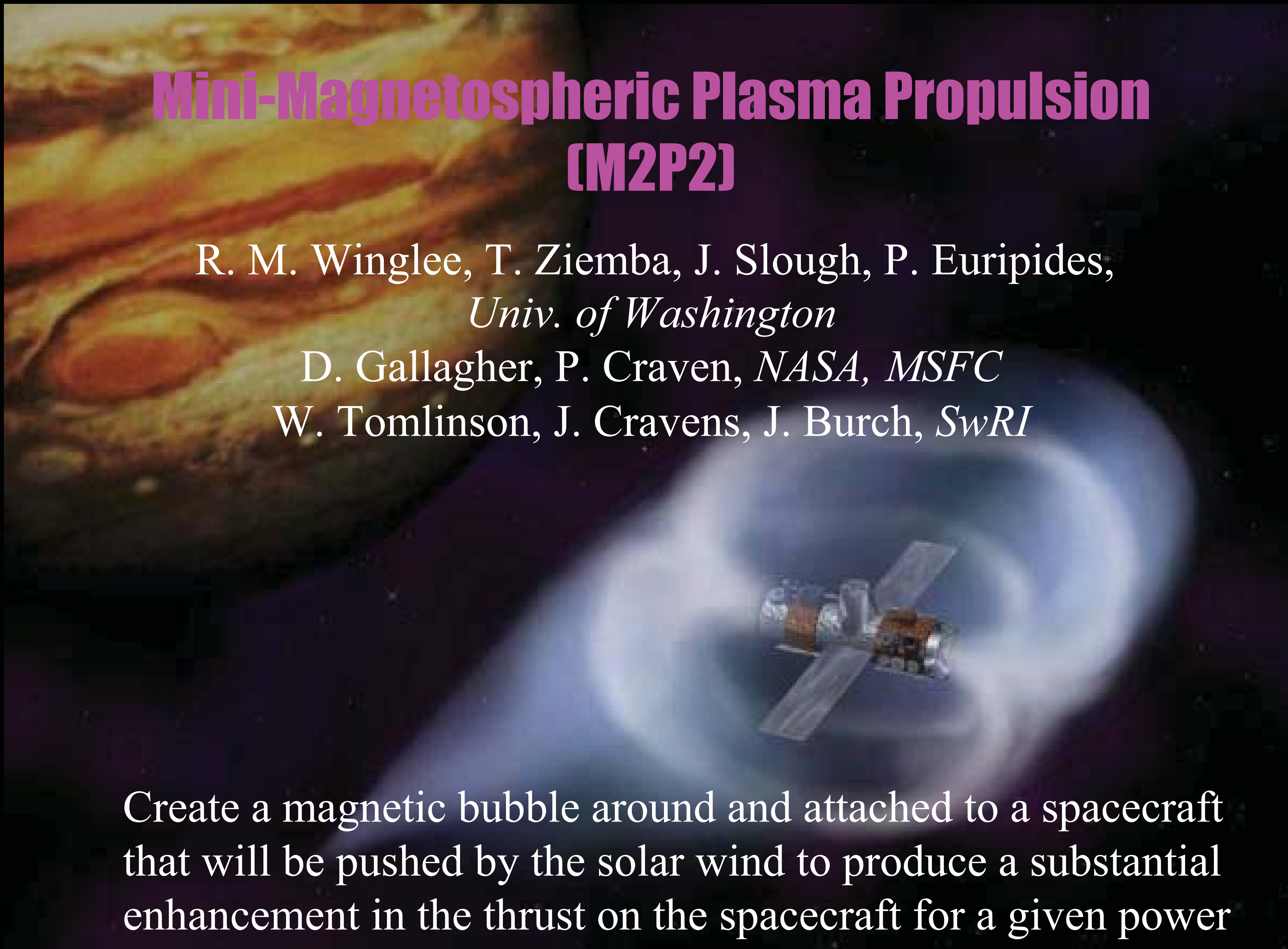
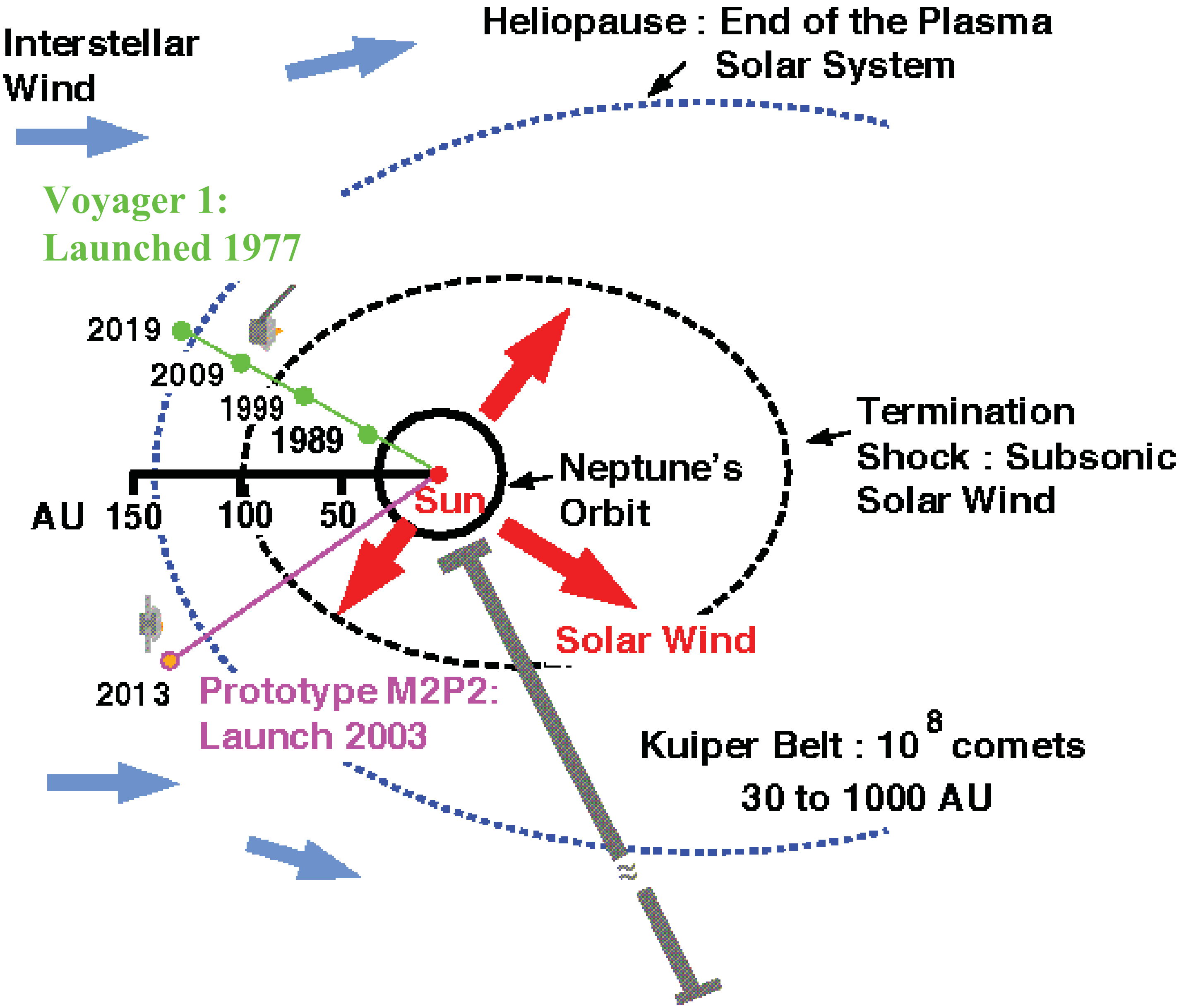


Mini-Magnetospheric Plasma Propulsion (M2P2)

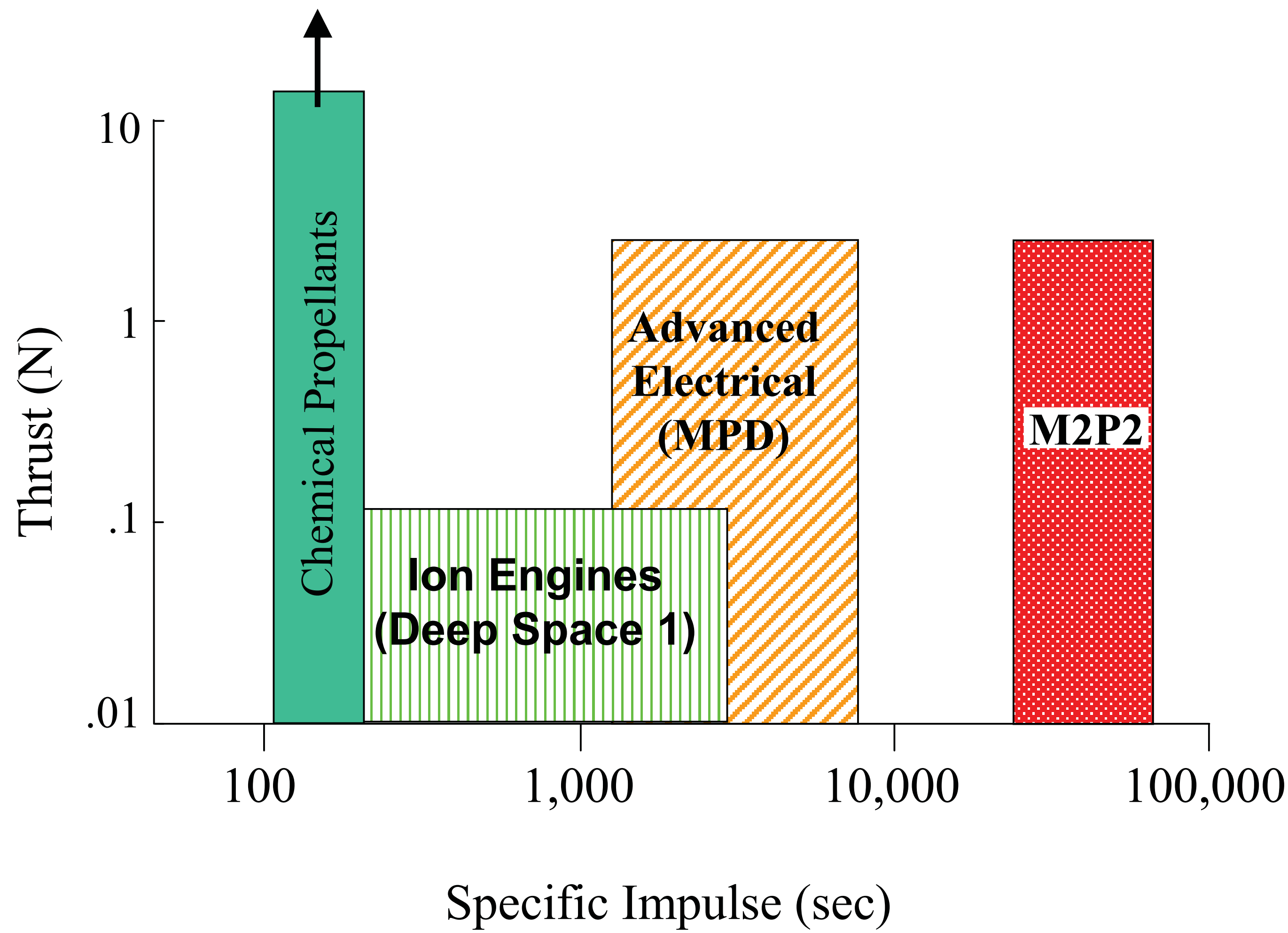
R. M. Winglee, T. Ziemba, J. Slough, P. Euripides,
Univ. of Washington
D. Gallagher, P. Craven, *NASA, MSFC*
W. Tomlinson, J. Cravens, J. Burch, *SwRI*

Create a magnetic bubble around and attached to a spacecraft that will be pushed by the solar wind to produce a substantial enhancement in the thrust on the spacecraft for a given power

The Solar System : A Large Unexplored Region

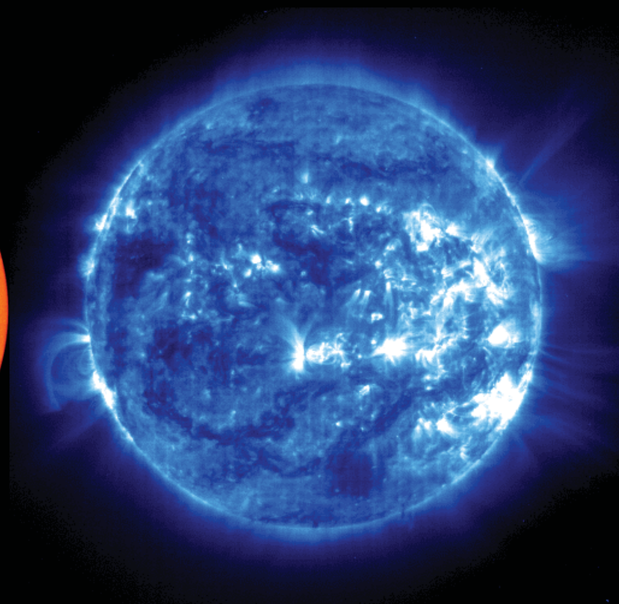


The Need for Advanced Propulsion Systems

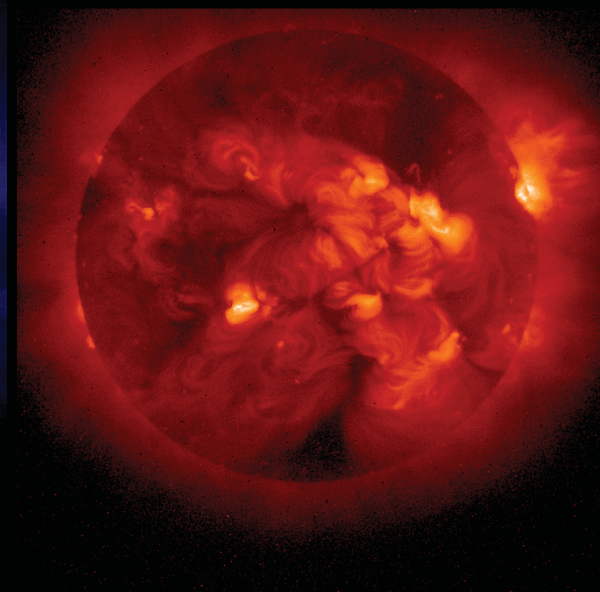


The Dynamic Sun:

Visible



UV



soft X-Rays

Electrical Storms raising the solar corona
(solar atmosphere to 2 million degrees)

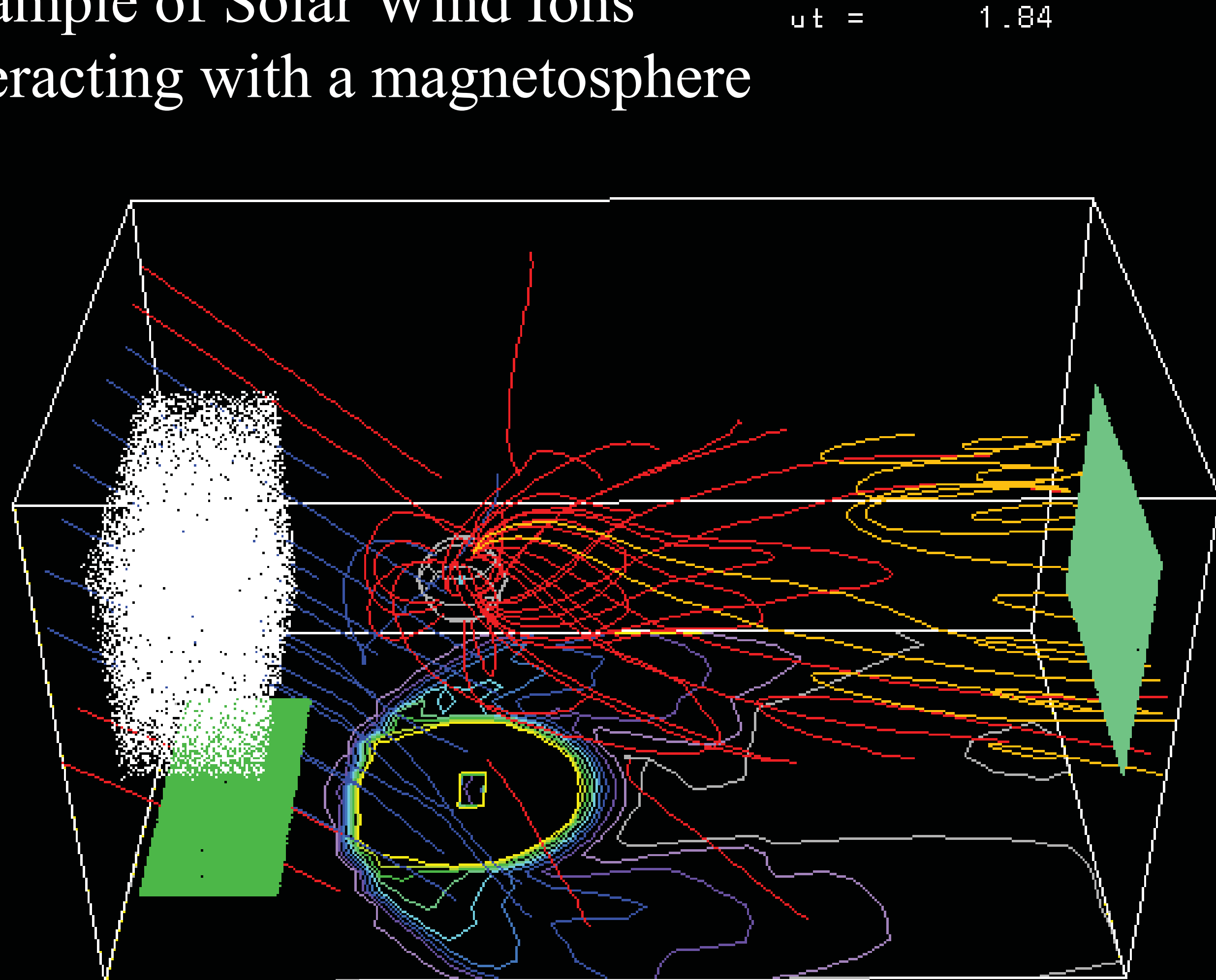
Expanding Magnetic Flare Loops seen by Yohkoh

The Solar Wind

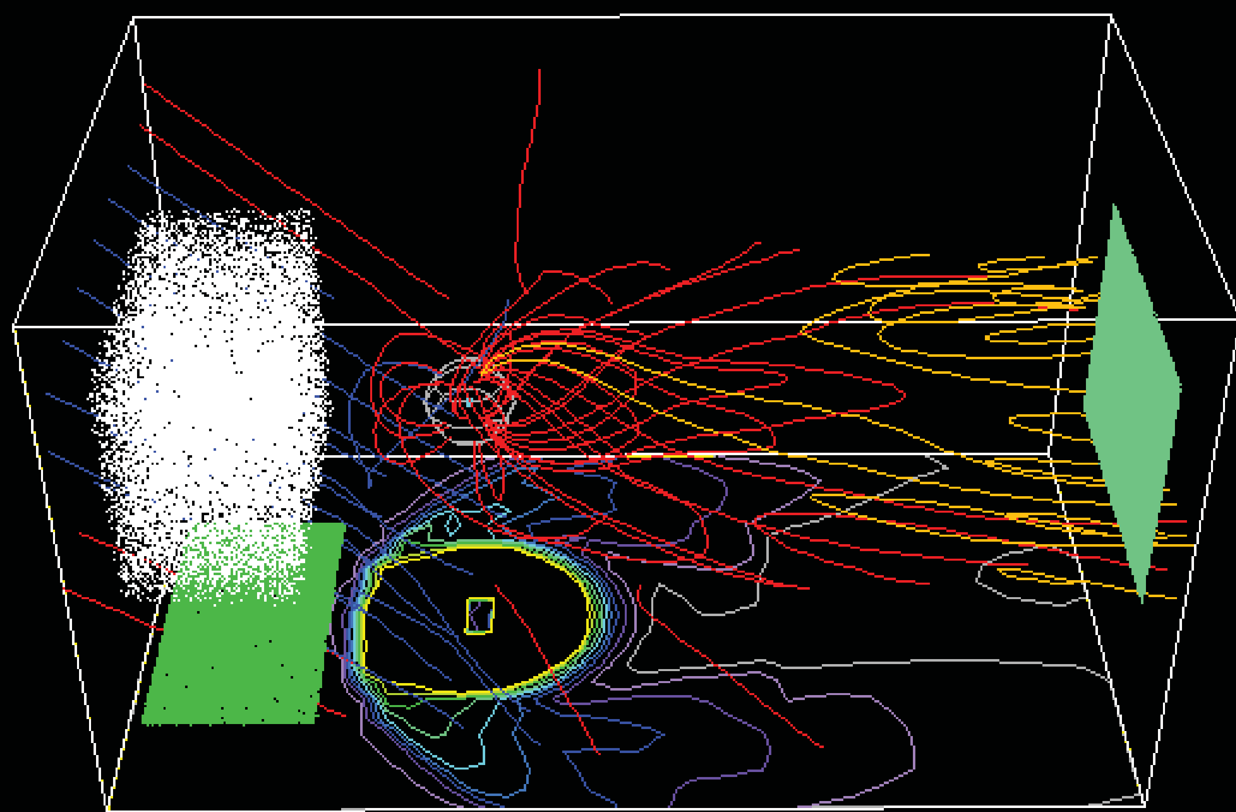
- Charged Particles: Ions and electrons
- 300-800 km/s
- Tenuous being only about 6 particles per cubic cm at Earth

Magnetosphere: Magnetic field, usually attached to a planet or moon, that is able to deflect the charged particles of the solar wind

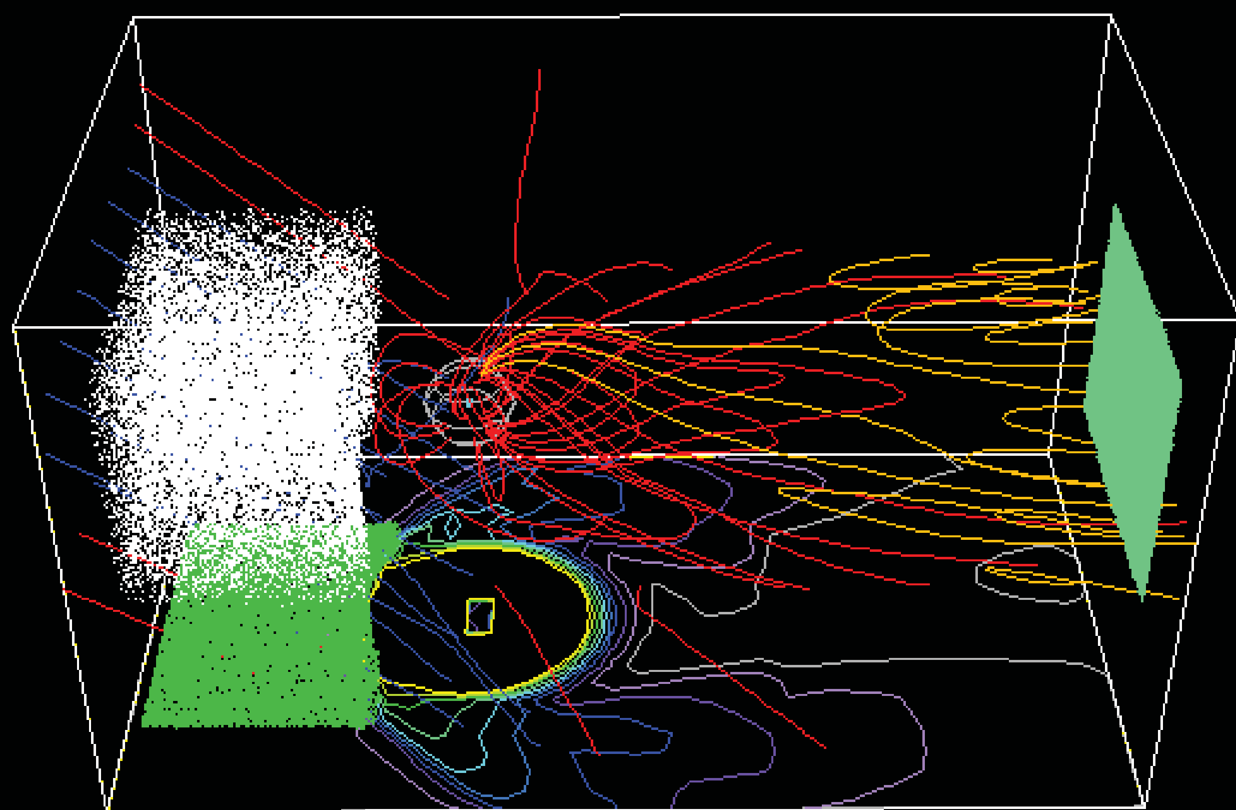
Example of Solar Wind Ions interacting with a magnetosphere



Example of Solar Wind Ions interacting with a magnetosphere



Example of Solar Wind Ions interacting with a magnetosphere



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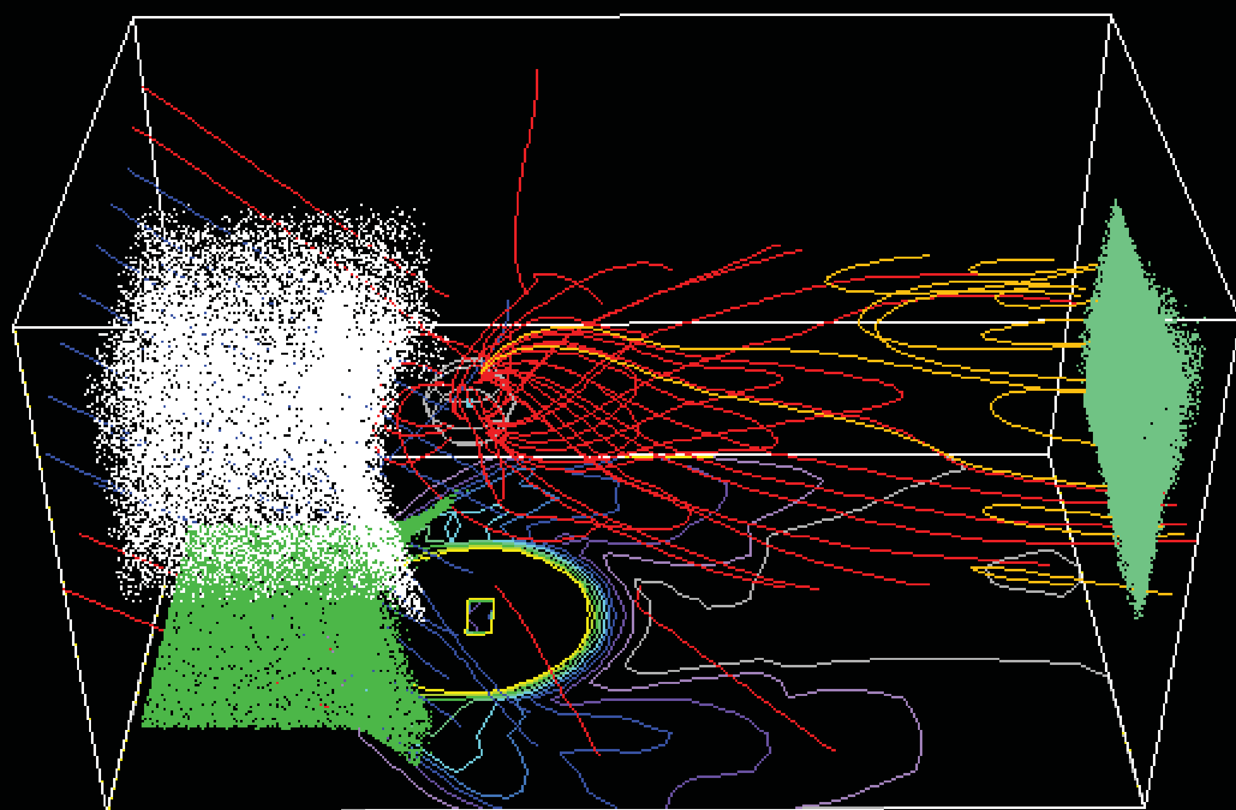

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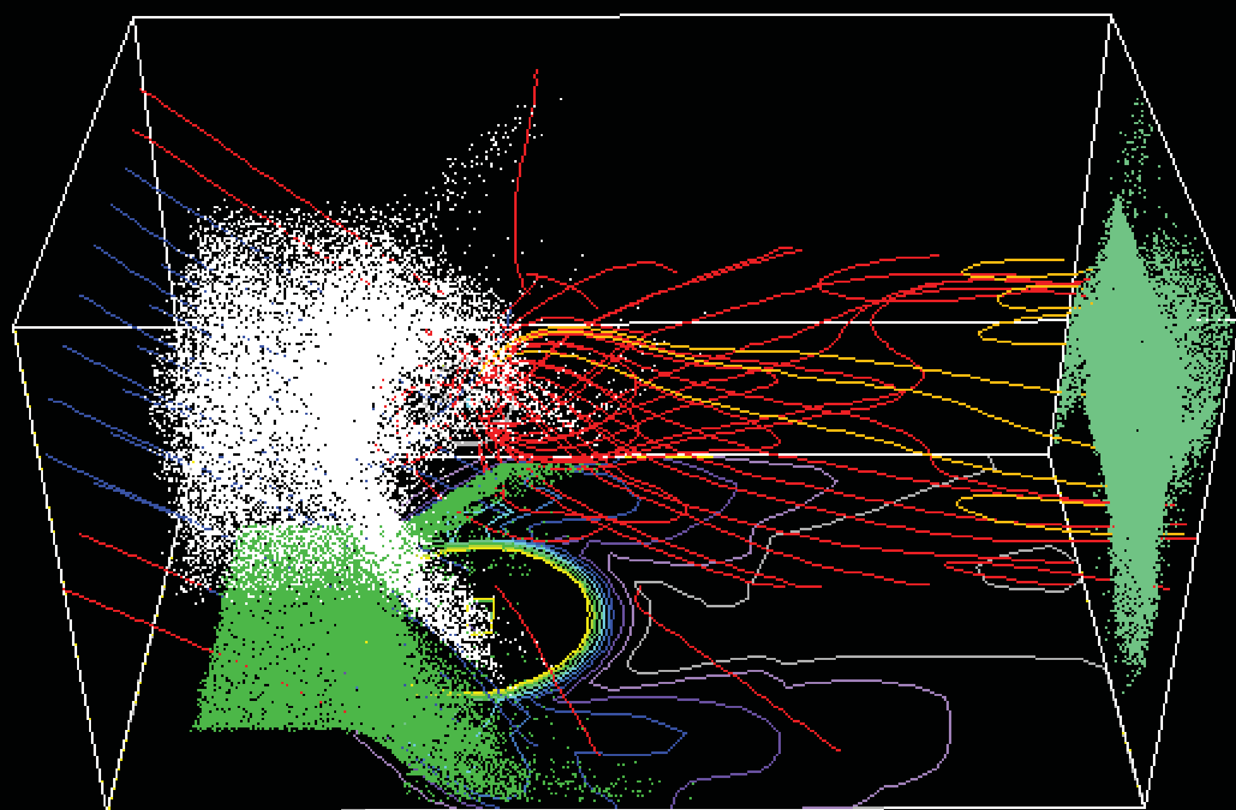

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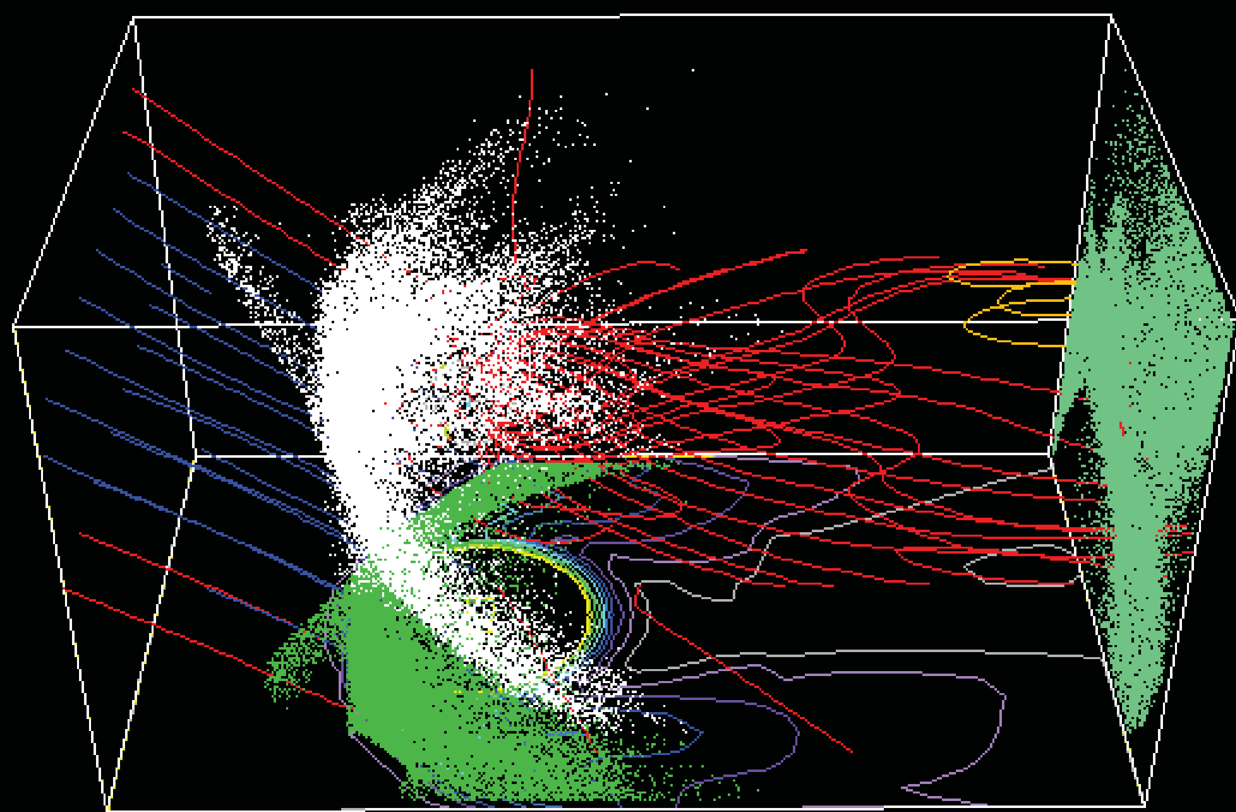
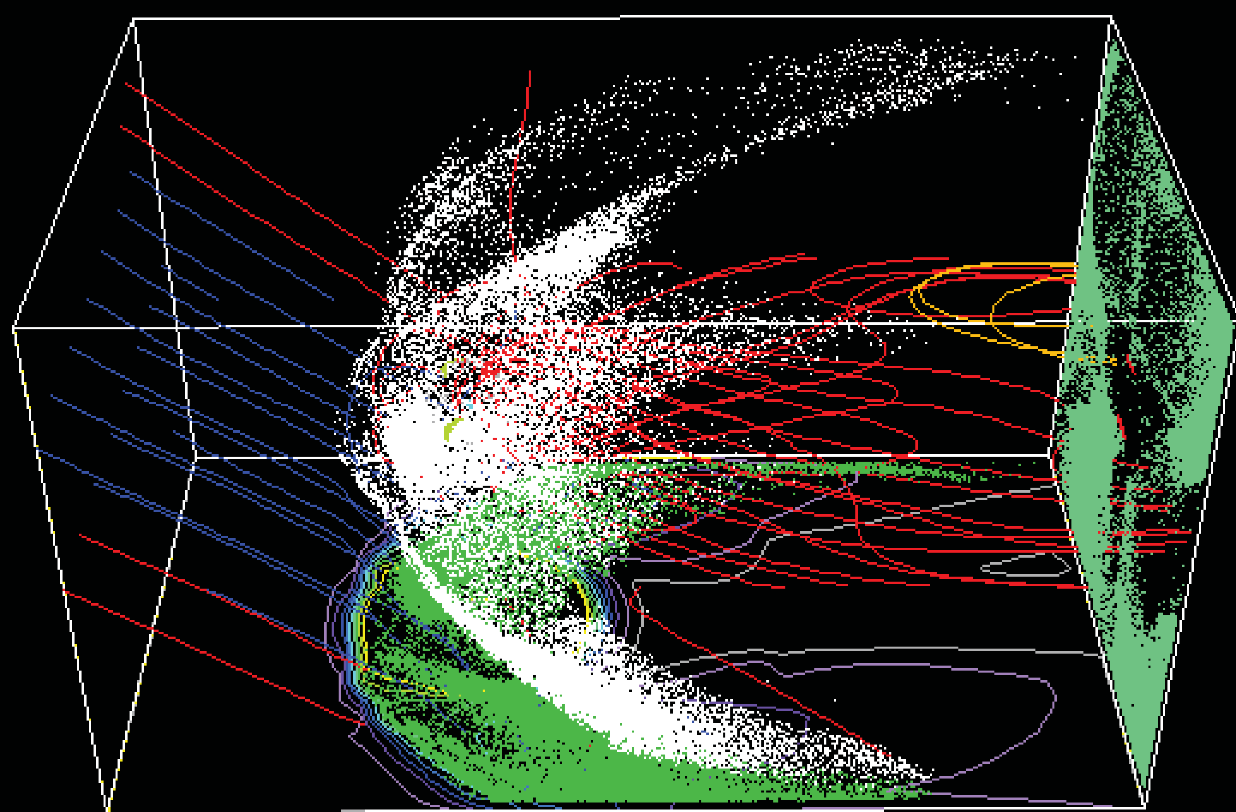
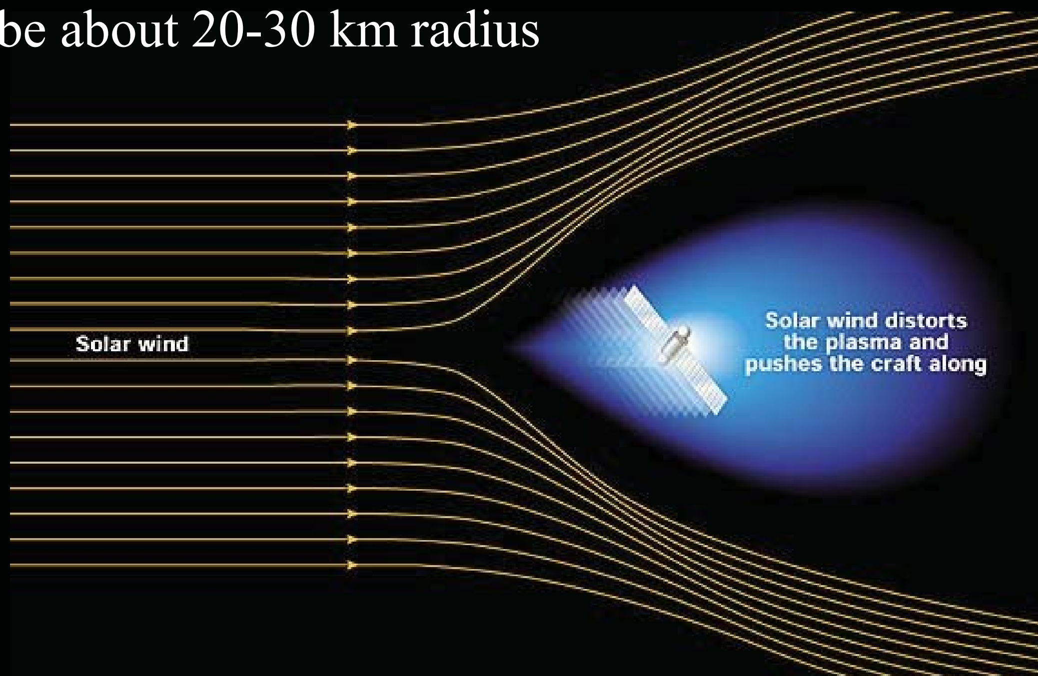


Example of Solar Wind Ions interacting with a magnetosphere



M2P2

- Seeks to create a magnetosphere around the spacecraft
- Enhanced the size of the magnetosphere by the injection of low energy plasma
- Size needs to be about 20-30 km radius



- Advantage is that the inflation is done fully electromagnetically, and deployment of large scale structures in space

Magsail: Simple Dipole

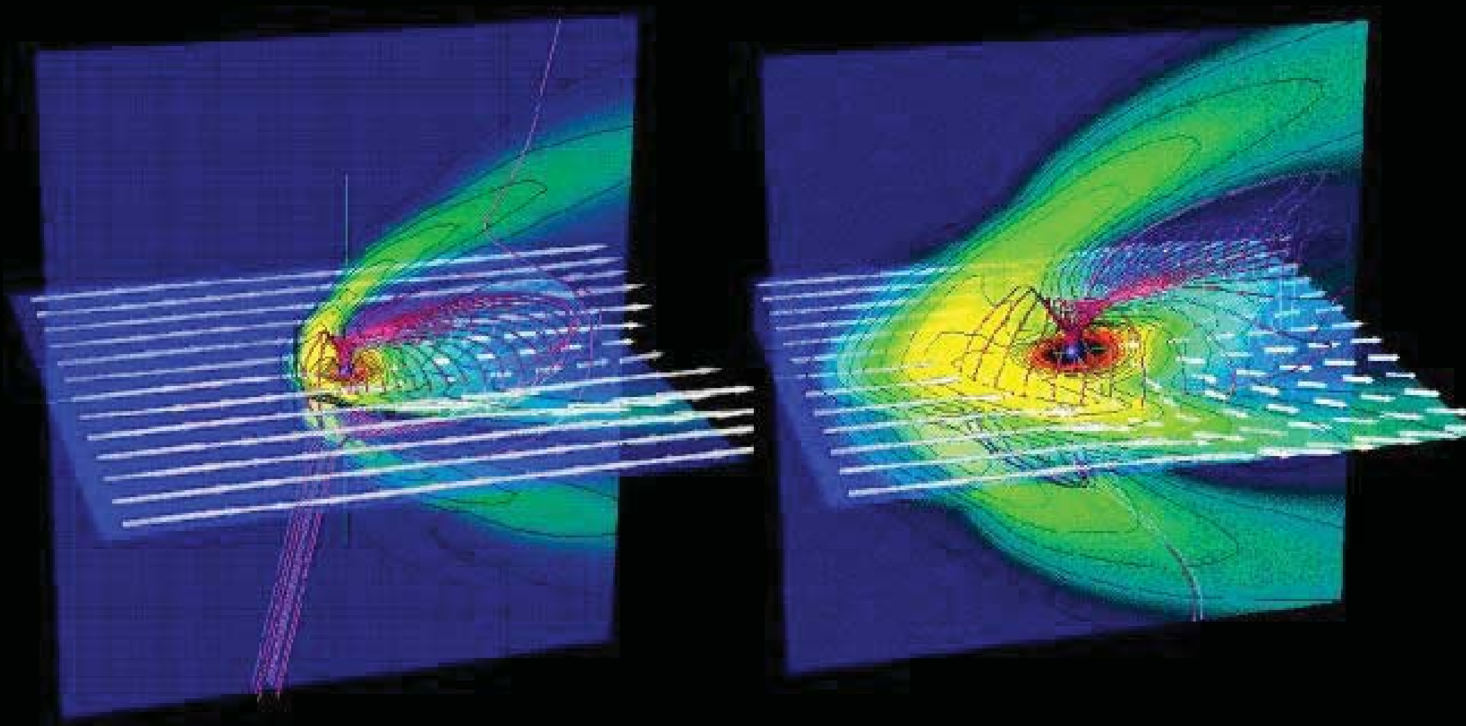
→ $B \sim R^{-3}$

→ <u>Limited</u> Interaction Region

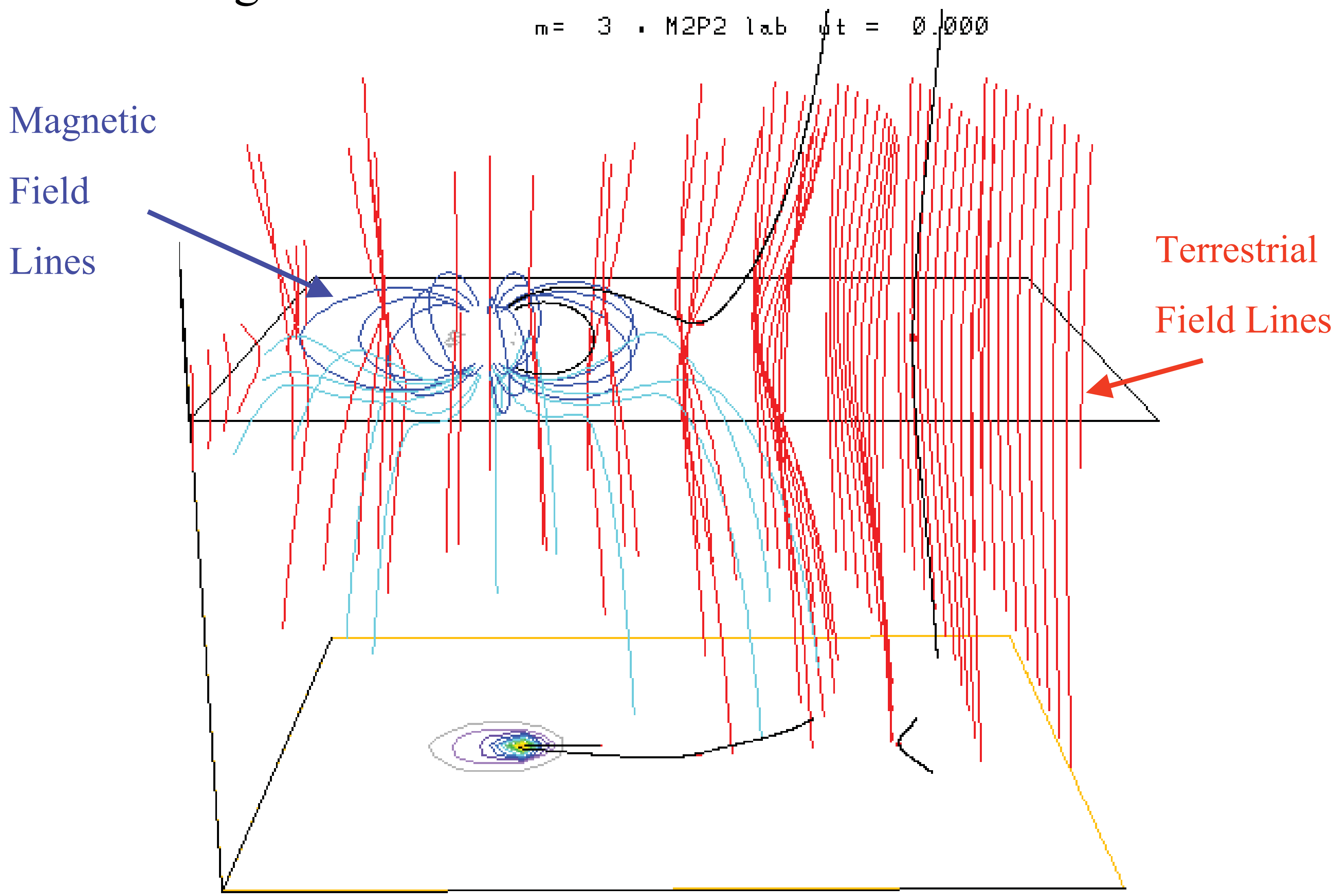
M2P2: Dipole+ Plasma

→ $B \sim R^{-1}$

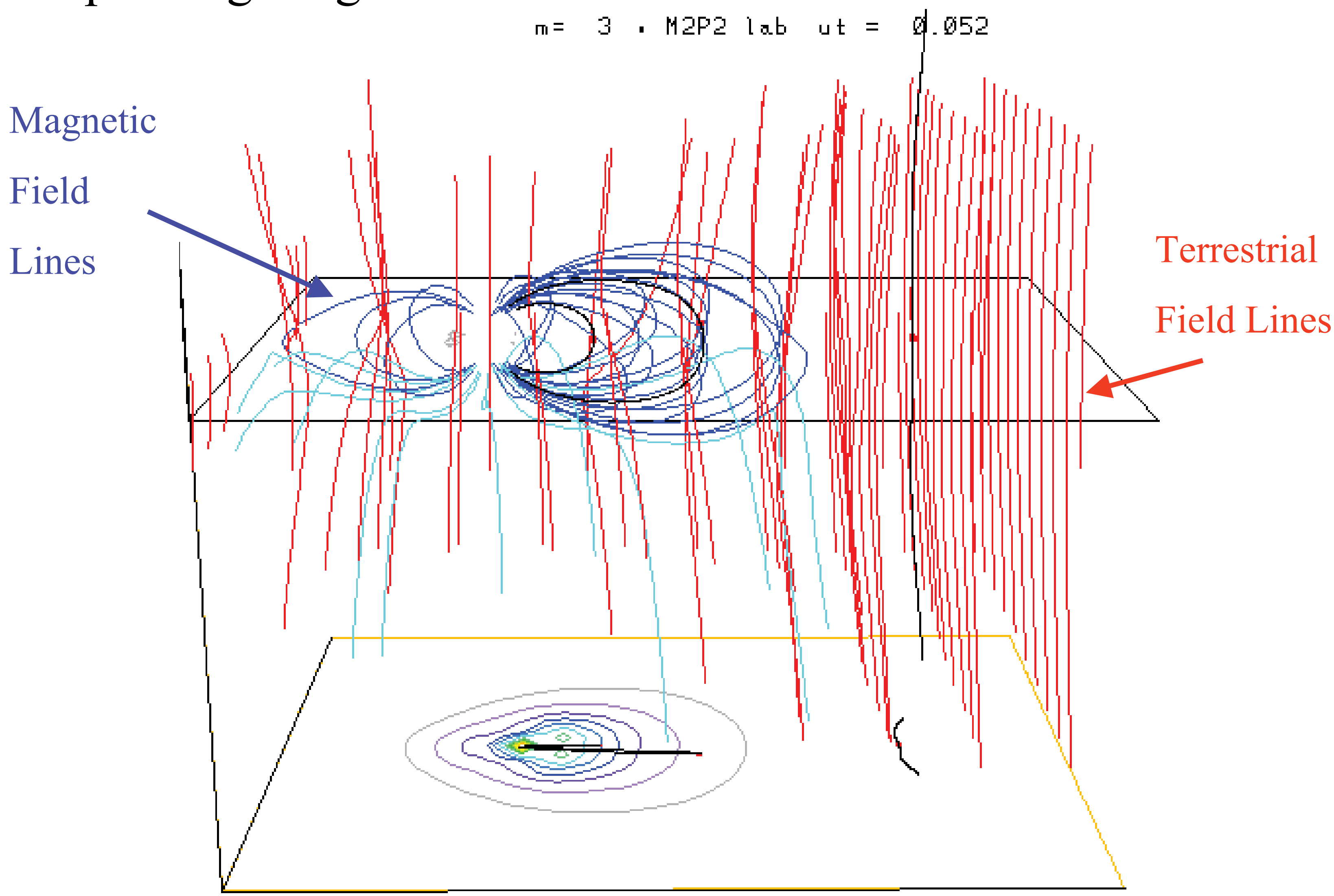
→ <u>Enhanced</u> Interaction Region



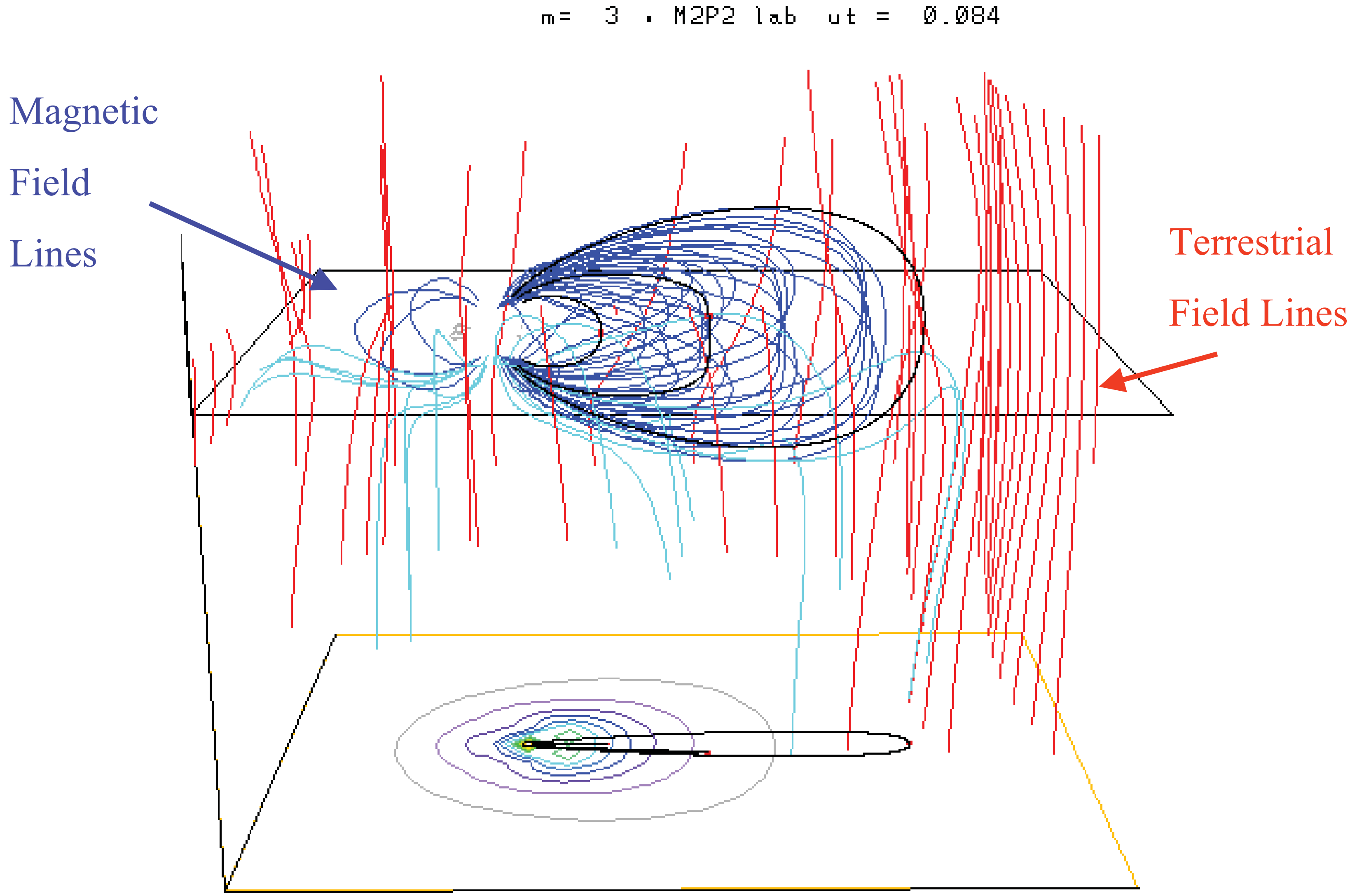
Initial Magnetic Field



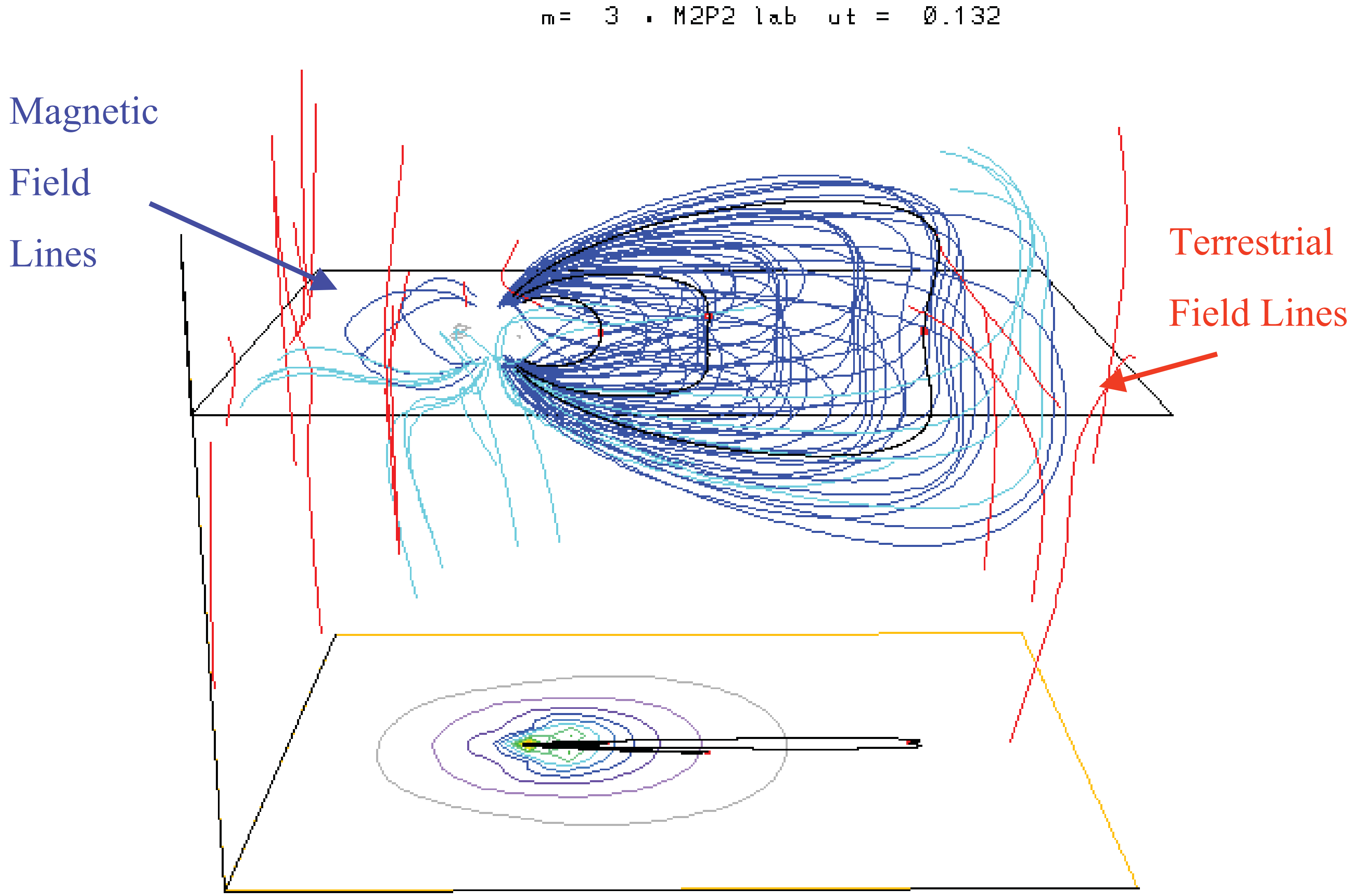
Expanding Magnetic Field



Expanding Magnetic Field



Expanding Magnetic Field



M2P2 Milestones:

✓**Prove Feasibility through Computer Simulations**

✓**Generation of *High Density, Strongly Magnetized Plasma***

- $>10^{11}$ cm^{-3} **plasma density**
- **> 300 G magnetic field**
- **< 1 kW of Power**
- **~ 0.25 to 1 kg/day fuel consumption**

✓**Demonstrate *Inflation* of Magnetic Field**

✓**Demonstrate *Deflection* of an external Plasma Wind**

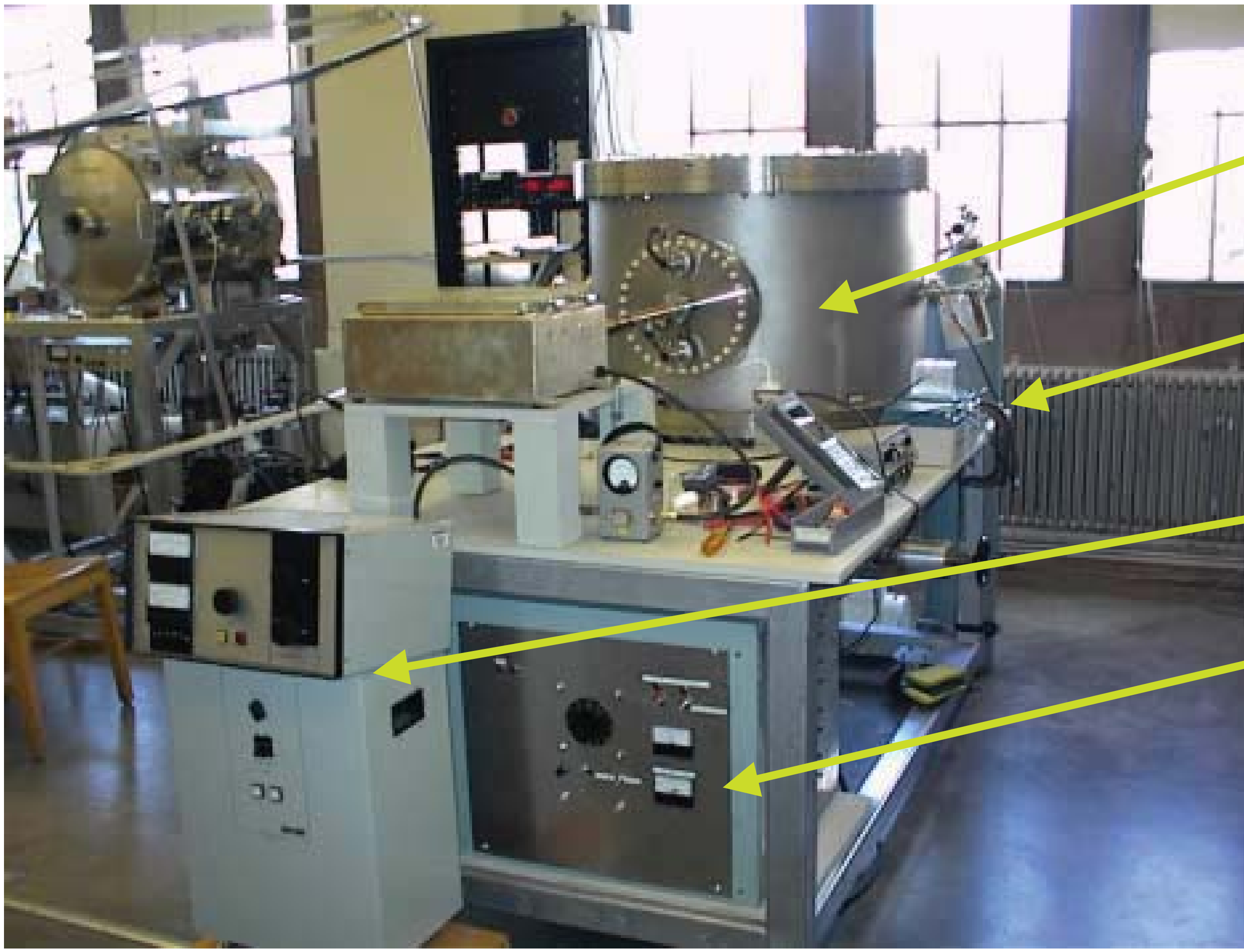
➢**Test Performance of *Different Propellants***

➢ **Measure Thrust and verify Efficiency**

M2P2 Capabilities

- **Mini-Magnetosphere (Single Unit) :** ***20-30 km Radius***
  - **Inflation is *Purely Electromagnetic***
  - ***No Large Mechanical Struts* have to be deployed**
- **Intercept**
  - **~ *1-3 N* of Solar Wind Force**
  - **~ 0.6 MW of Solar Wind Energy using only ~ 1kW**
- **Scientific Payload of 100 to 200 kg would attain**
  - **50- 80 km/s in 3 month acceleration period**
- **Economies of Scale for Multiple Units**

Experimental Arrangement



400 Liter Vacuum Chamber

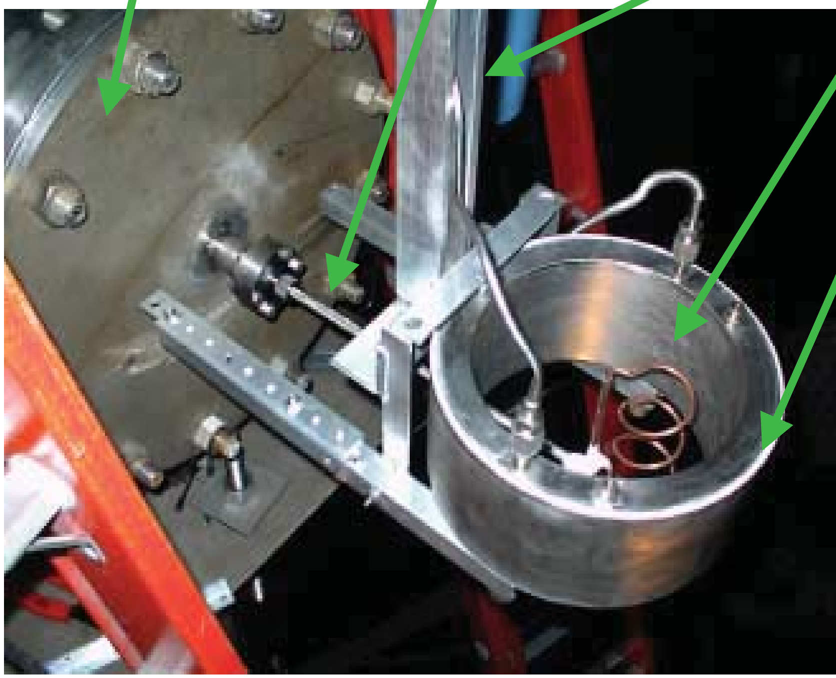
Propellant Bottle

RF Amplifier

Power Supply

Mini-Magnetospheric Plasma Propulsion:

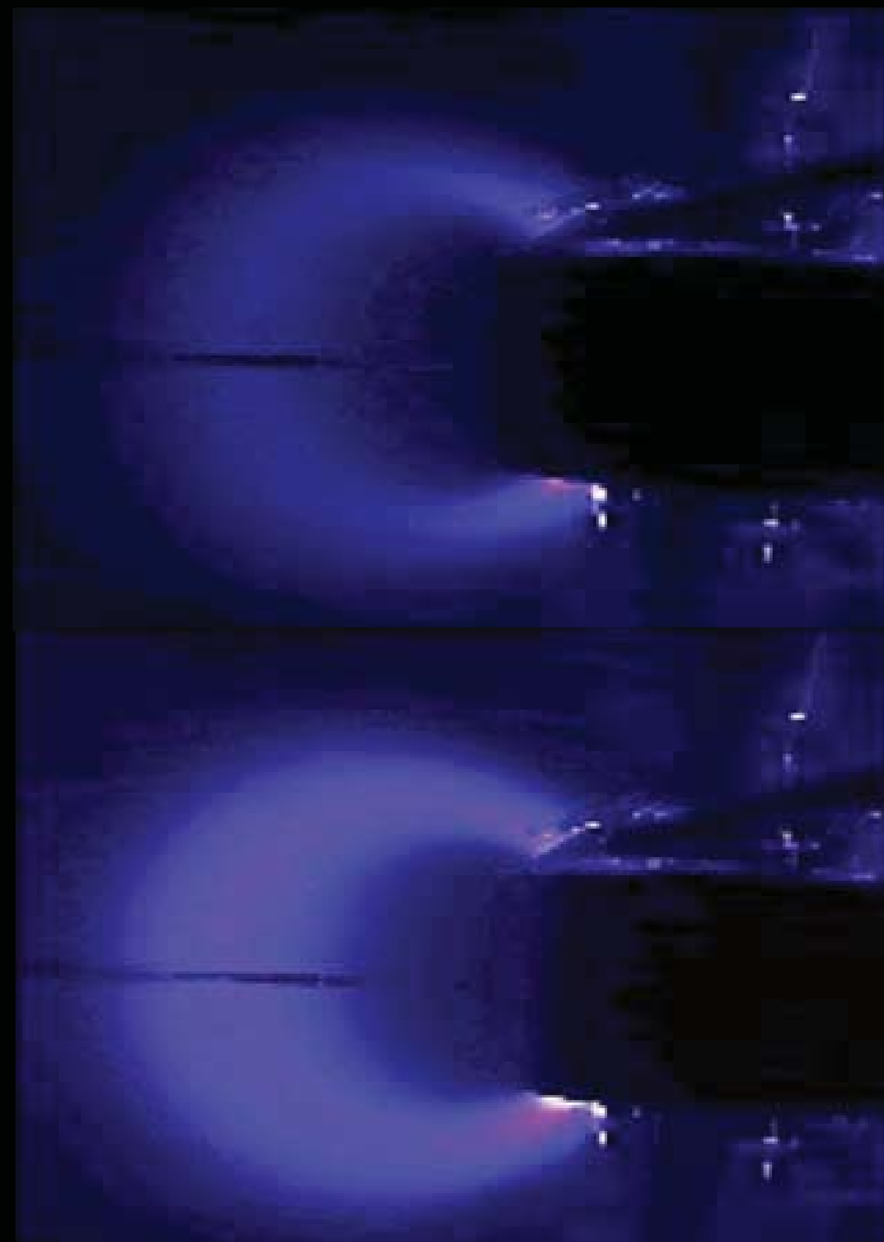
Prototype Development and Performance

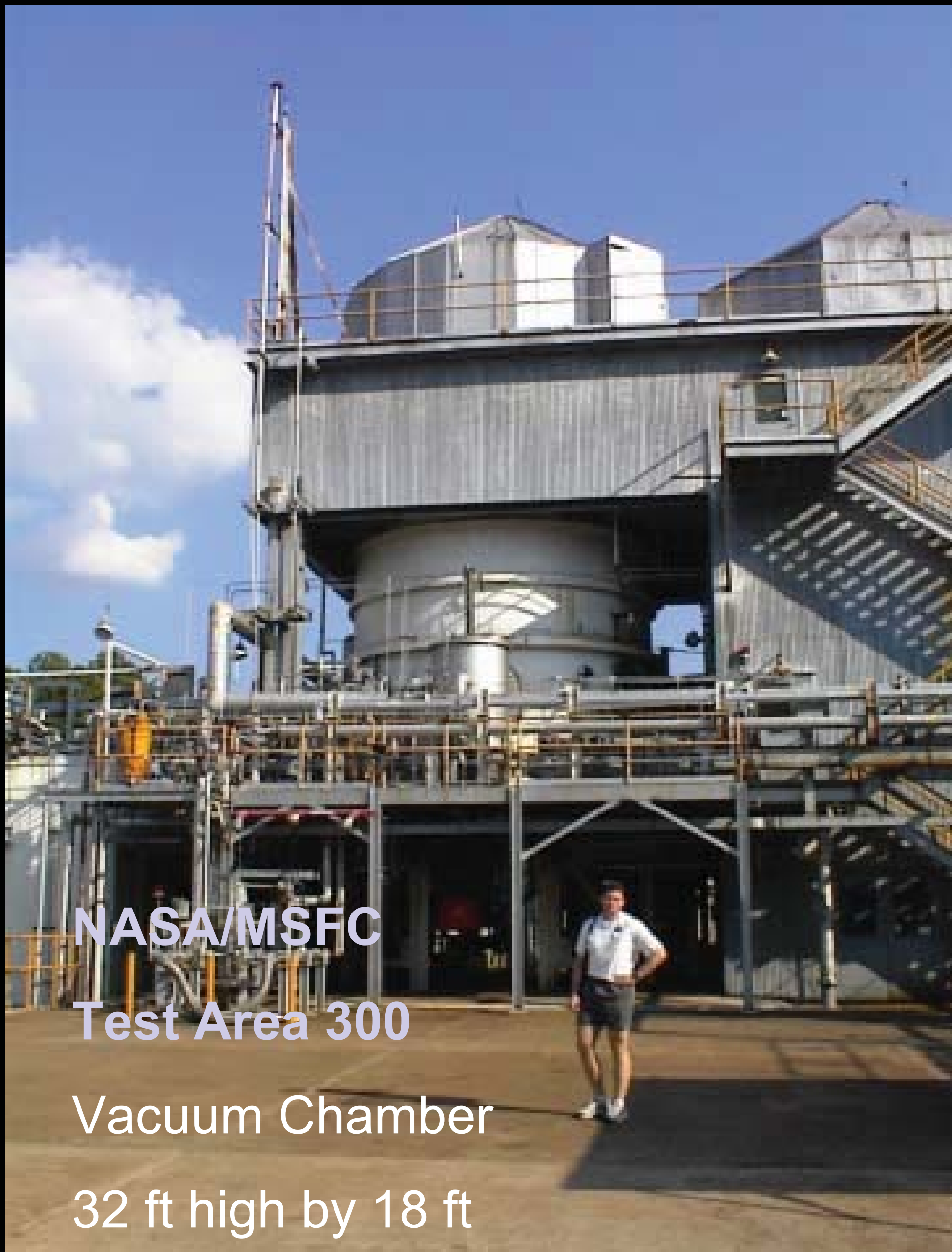


- Prototype Specifications
  - 11 cm radius magnet, 300-1000 G
  - Antenna, small (1.5 cm radius) and large (2.5 cm radius), ~ 1kW
- Prototype Performance
  - Sustained densities of 10^{13} cm^{-3}
  - Temperatures of 4 – 12 eV
  - Small Antenna: 0.4 kg/day (5.4 mg/s) @ 25% gas efficiency, for 3.3 amps of plasma and 4 mN
  - Large Antenna: 0.8 kg/day (11 mg/s) @>50% gas efficiency, for 12 amps and 16 mN

- Variety of Propellants Possible
  - Argon or Helium (for lab use)
  - Nitrogen/Hydrogen
  - Water – refueling in space
  - Other light weigh fuels : CH_4, NH_3 CO_2,

Examples of Plasma Inflation

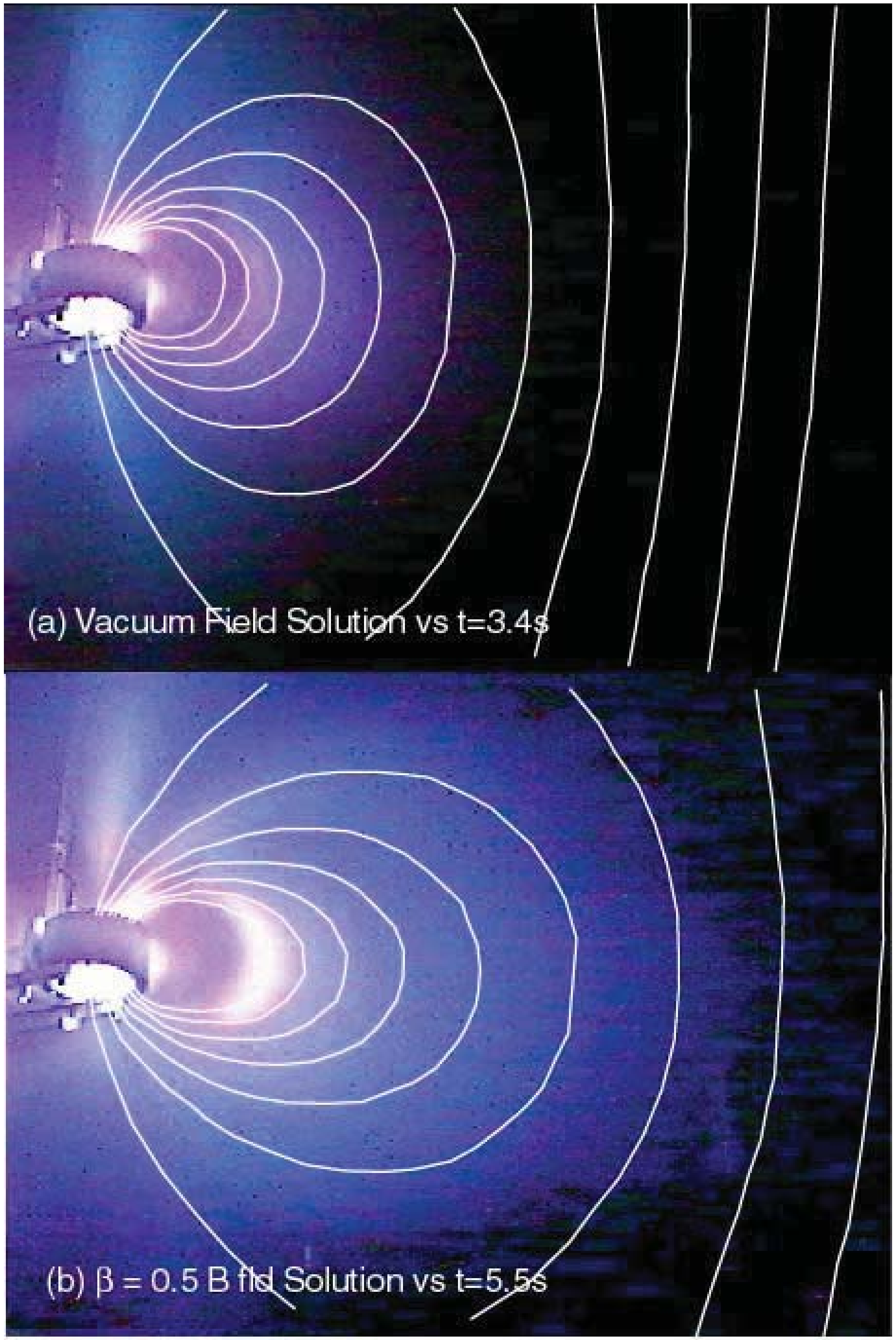




Objectives:

- Demonstrate Magnetospheric *Inflation*
- Demonstrate Magnetospheric Plasma *Deflection*

Demonstration of Plasma Expansion of a Mini-Magnetosphere:



- Large Chamber Tests at MSFC
  - Helium plasma @ 350 G
  - –Vacuum field solution shows no closed field lines within ~ 3ft
  - –Plasma emissions initially seen to closely match the vacuum field solution
  - –Expansion seen as plasma β approaches unity.
  - –Expansion out to at least **30 times** the magnet radius demonstrated.
  - –Main limitation due to recombination with chamber neutrals

M2P2: MSFC Operation

Demonstration of Plasma Deflection by a Mini-Magnetosphere: M2P2 vs SEPAC

- SEPAC (right hand side)
  - 4 Amp Xenon ion source
  - 800 W @ 1 eV
- M2P2 (left hand side)
  - ~ 4 Amps of Argon @ 400 W
  - the two sources separated by about 14 ft (only 6ft field of view around M2P2 shown in figures)
- Deflection
  - Permanent barrier (magnetopause) seen better the two plasmas
  - Barrier moves to the right as the magnetosphere is inflated
  - Barrier moves to right with increase magnetic field

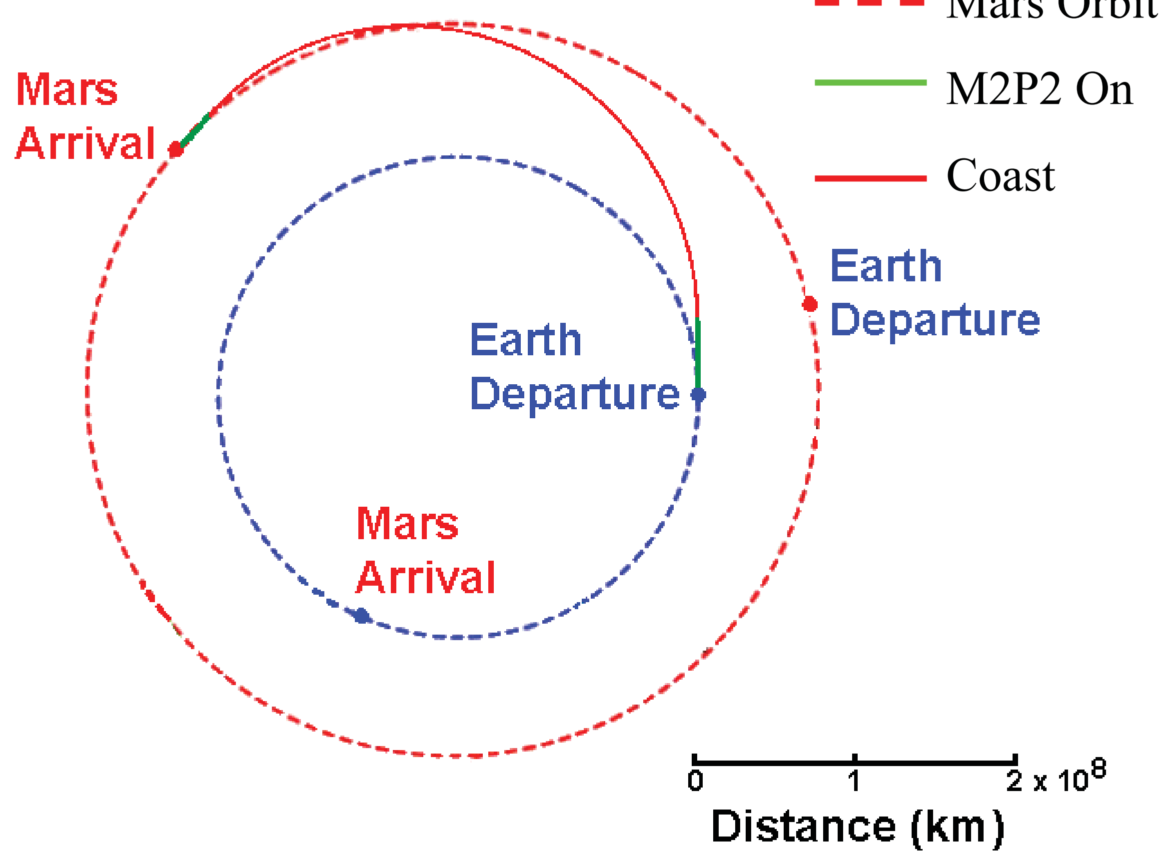
M2P2 vs SEPAC

Mission Designs:

- Mars Return (1.8 yrs)
- Jupiter Orbital (1.3yrs)
- Saturn/Titan (5.6 yrs)
- Pluto (6.2 yrs)
- Heliopause (10 yrs)

Example M2P2 Mission

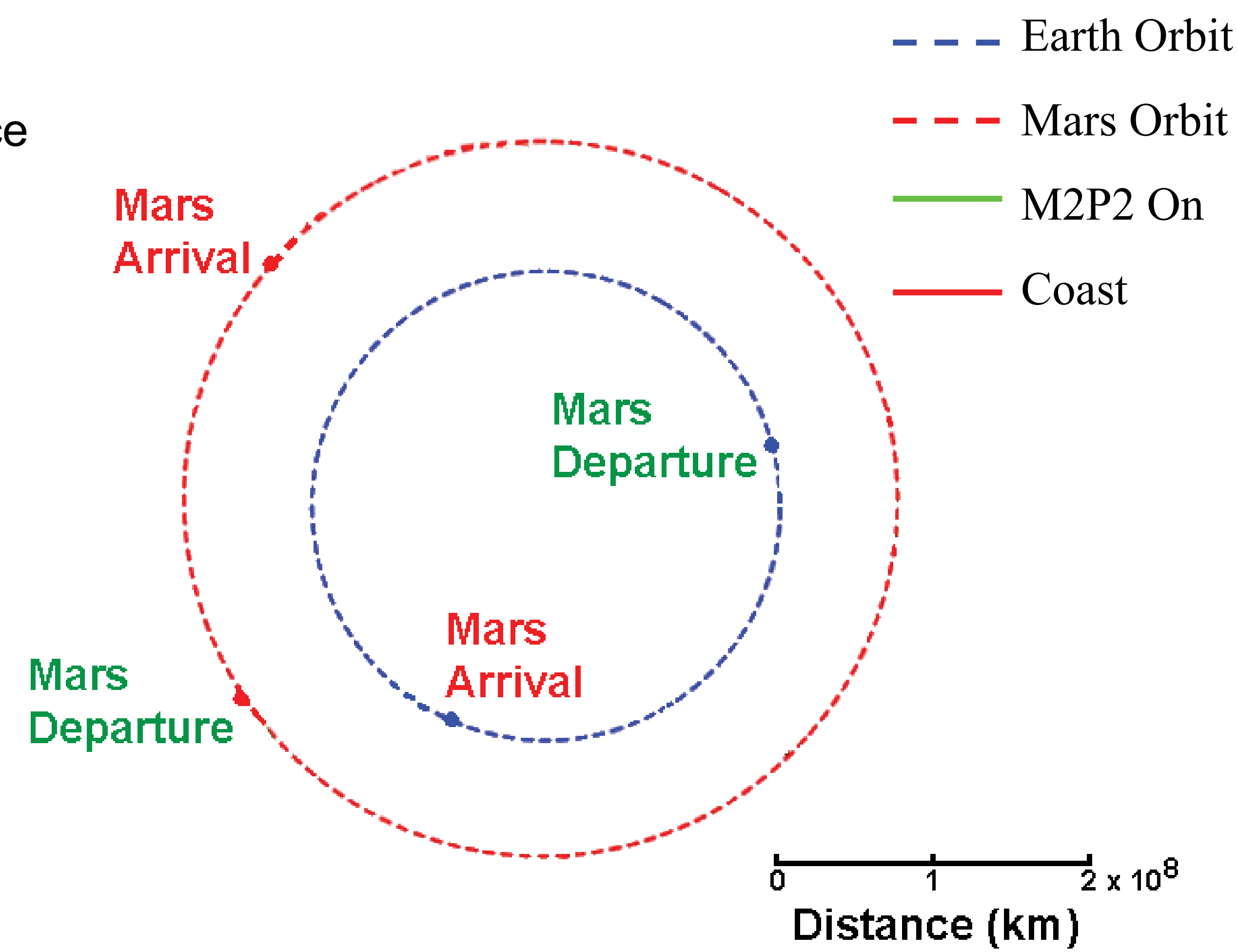
250 Days to Mars



Example M2P2 Mission

250 Days to Mars

130 Days on Surface

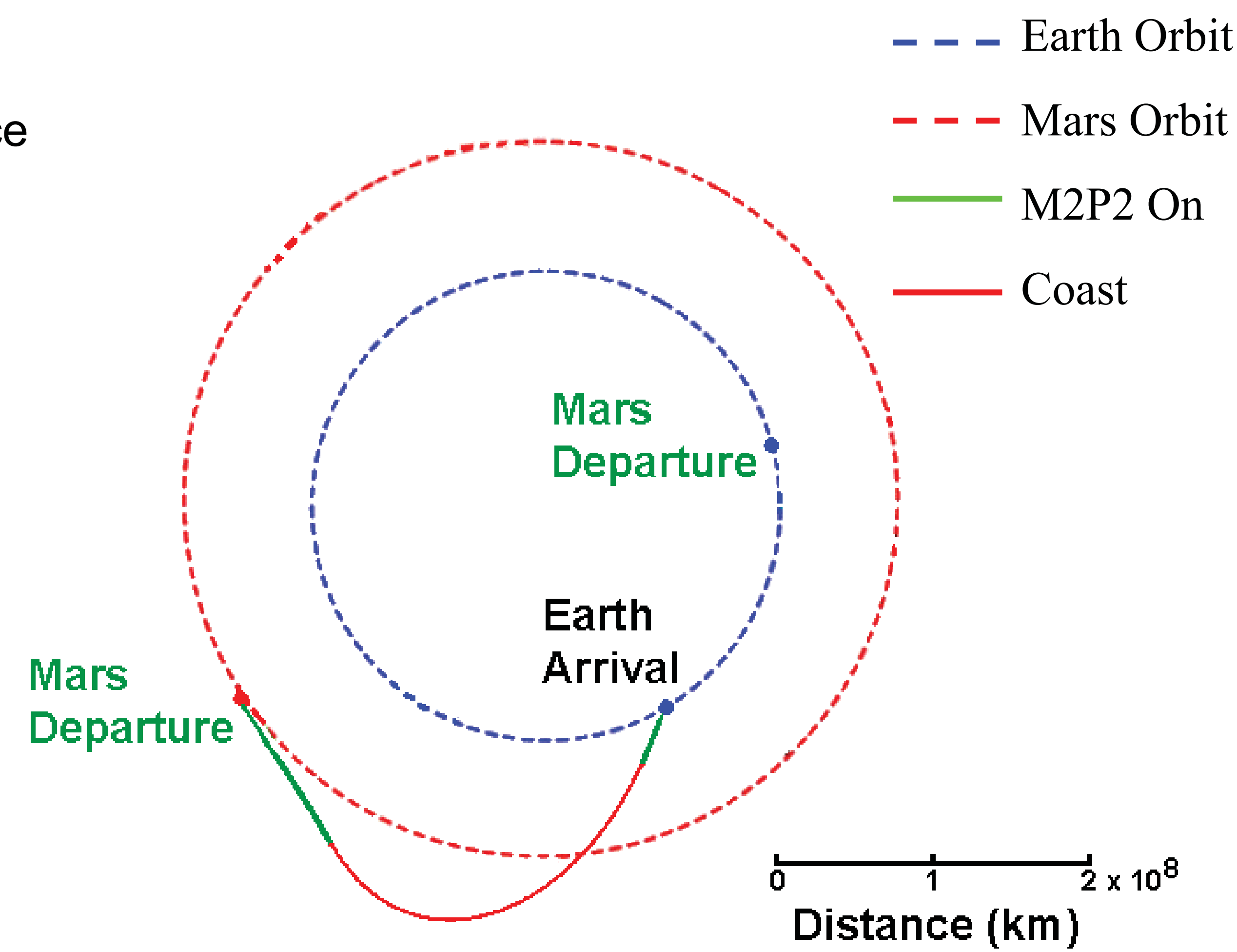


Example M2P2 Mission

250 Days to Mars

130 Days on Surface

290 Day Return



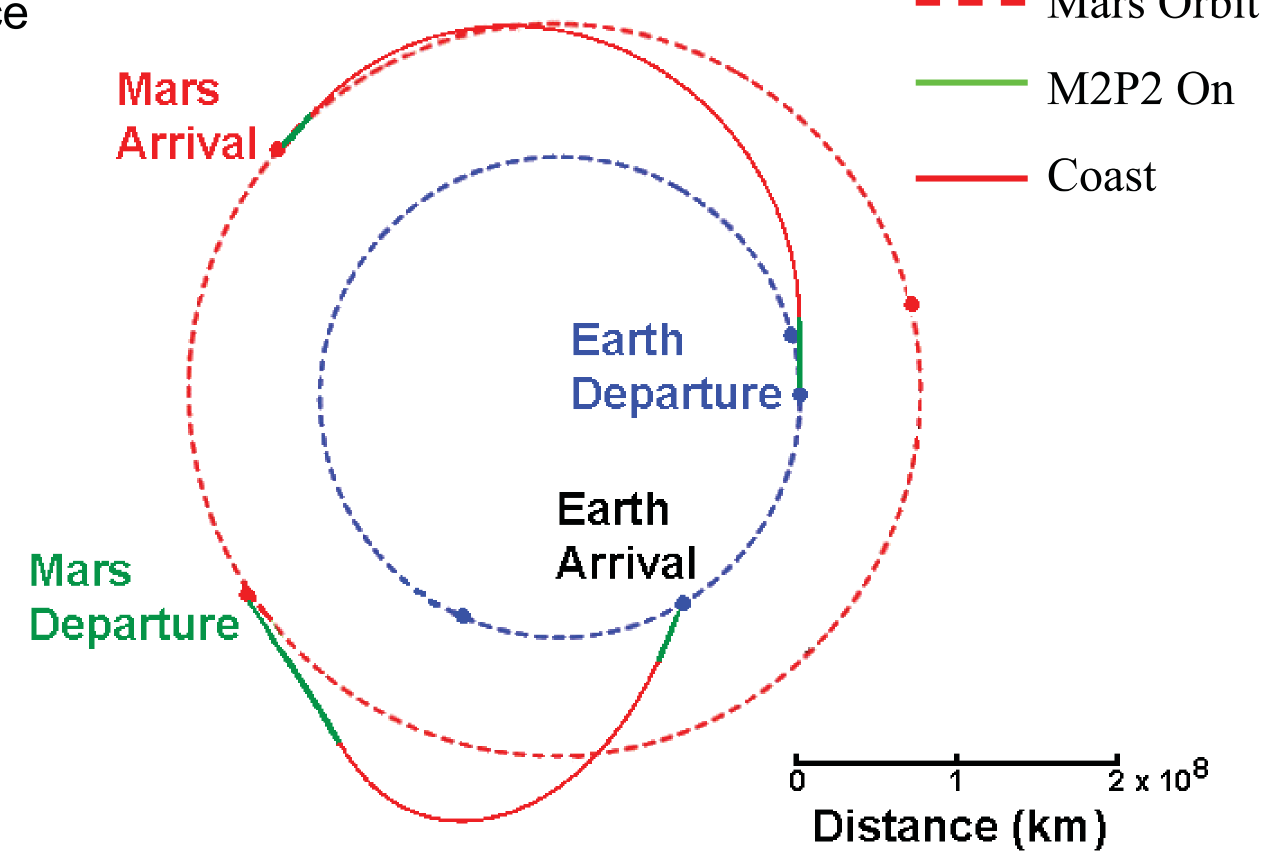
Example M2P2 Mission

250 Days to Mars

130 Days on Surface

290 Day Return

Total: 1.8 Years

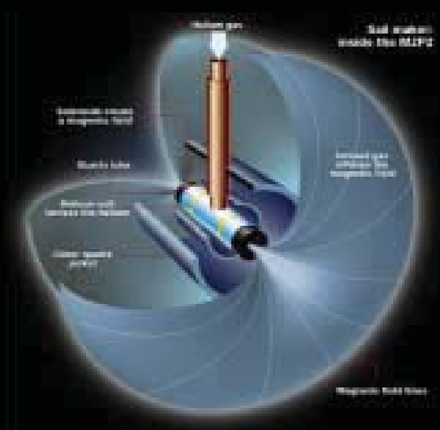


NIAC Timeline

Concept

1st Prototype

Mar.,99



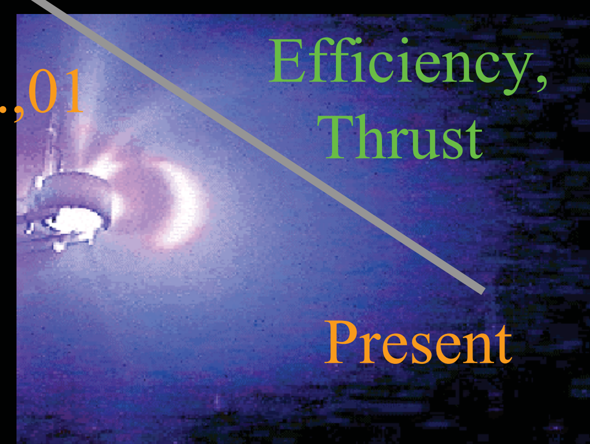
Large Chamber Testing

Dec.,99

Verification of concept

Aug.,00

Feb.,01



Efficiency, Thrust

Present

Phase I

Phase II