Extra-Zodiacal Exploration (EZE):

An Architecture for Servicing-Sustained Cosmic Discovery

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Mission architecture design objectives

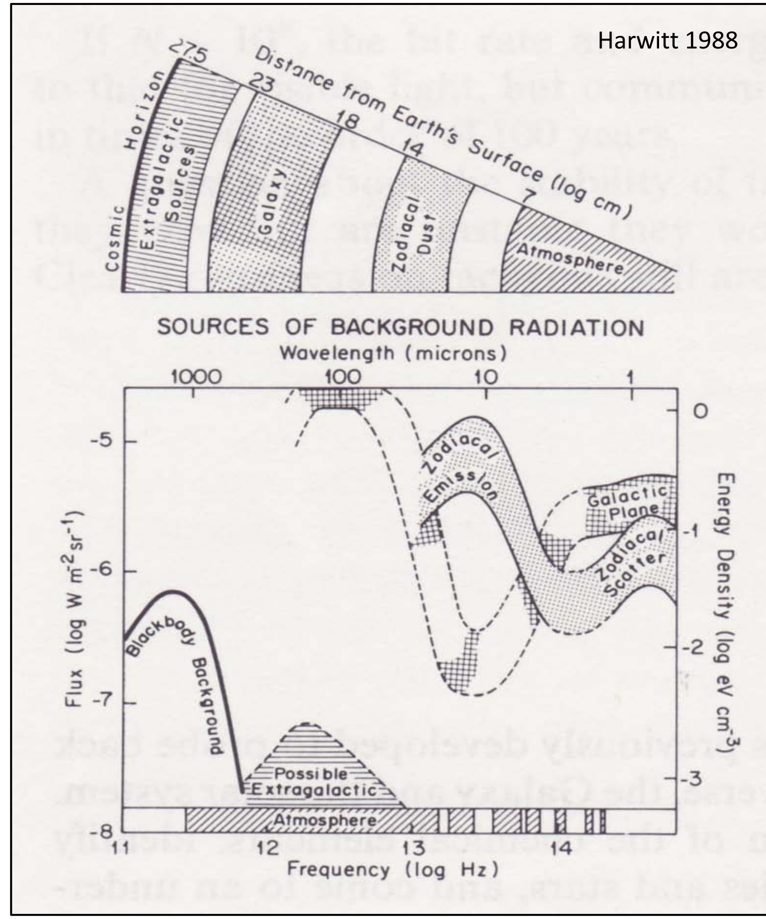
- Enable a substantial advance in scientific discovery potential over JWST without significantly increasing telescope size
  - Selection of an elliptical science orbit that takes observatory outside of the Zodical dust cloud
- Enable a long duration (20 year) mission lifetime and science instrument upgrades via on-orbit servicing
- Develop a high level architecture that can meet the above objectives and:
  - enable a wide range of JWST follow-on observatory concepts:
    - any flagship class observatory with sensitivity limited by Zodiacal light
  - be implemented with currently proven technology concepts

Architecture design approach

- Focus on observatory-independent factors that limit sensitivity
  - Zodiacal background emission
    - Produced by dust grains that occupy inter-planetary space in the inner Solar system
    - Controlled by selection of extra-Zodical elliptical orbit
      - Trade space spans: high inclination 1 AU to zero inclination 3 AU
- Limit consideration to existing EELV launch systems
- Use JWST as straw man for key observatory accommodation requirements
  - ~3400 kg science payload (telescope & science instruments)
  - ~2000 W science power
  - ~500 Gbits/day science data volume

Exploiting the darkness of space for the first time

- The Earth is imbedded in a cloud of dust grains that produce a background light through which space observatories must observe.
  - Cloud spans heliocentric radii of 0.9 – 2 AU and extends 0.6 AU above and 0.4 AU below the elliptic plane.
- This zodiacal background can be ~10^3 times brighter than astronomical sources and adds photon noise that limits the sensitivity of observatories at Sun-Earth L2.
  - Analogous to ground-based astronomers observing during daylight hours
- **In the visible to far-infrared spectrum, it has never been nighttime for space astronomers.**

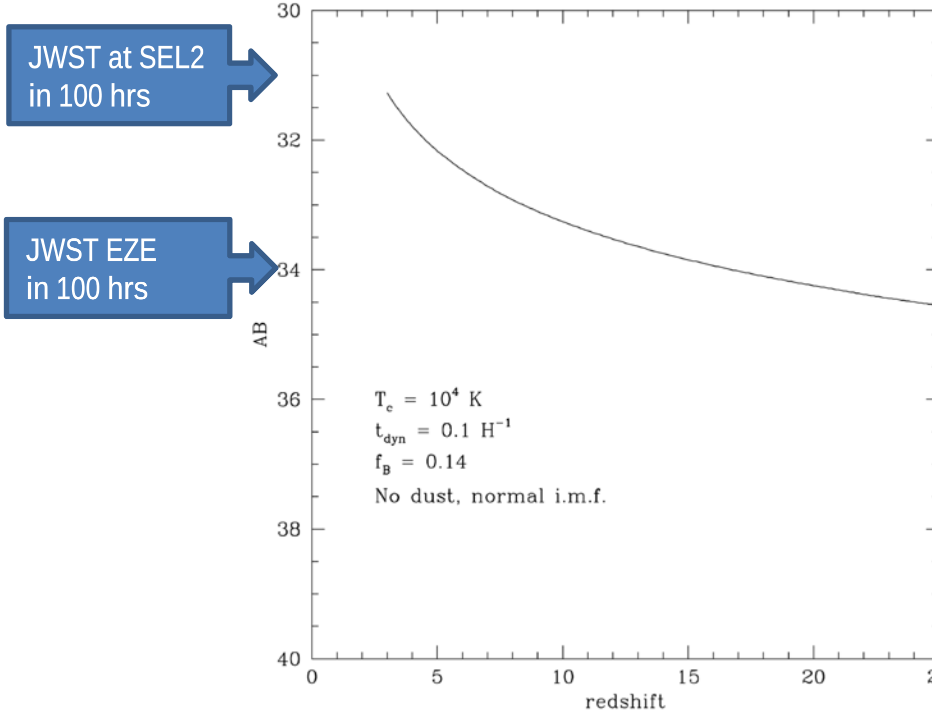


The future of visible/infrared space astronomy lies outside the Zodical cloud

- An Zodical light-limited observatory can achieve a 5-15 fold increase in sensitivity over JWST <u>through orbit choice alone</u> with no increase in telescope aperture or improvement in detector technology.

- The cosmological reach of a 6 m class observatory in an extra-Zodical orbit would span the galaxy formation epoch.
  - Hence, it would not be necessary to replace it with a larger aperture system to probe deeper into the past.
  - **Particularly if it were sustained for a HST-like 20 yr lifetime by servicing**

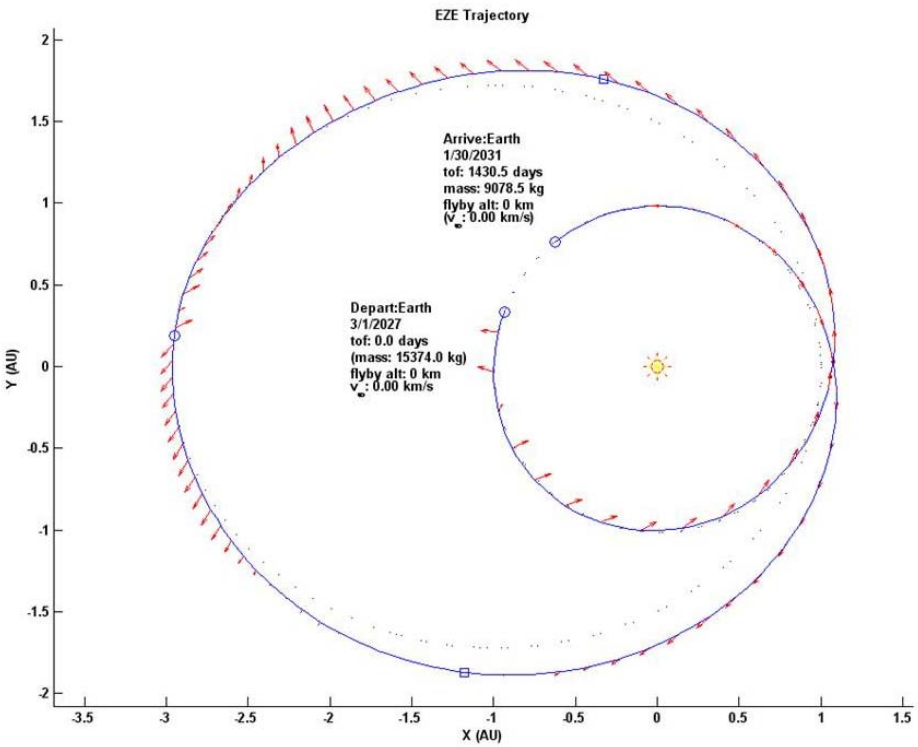
Minimum brightness of the first galaxies

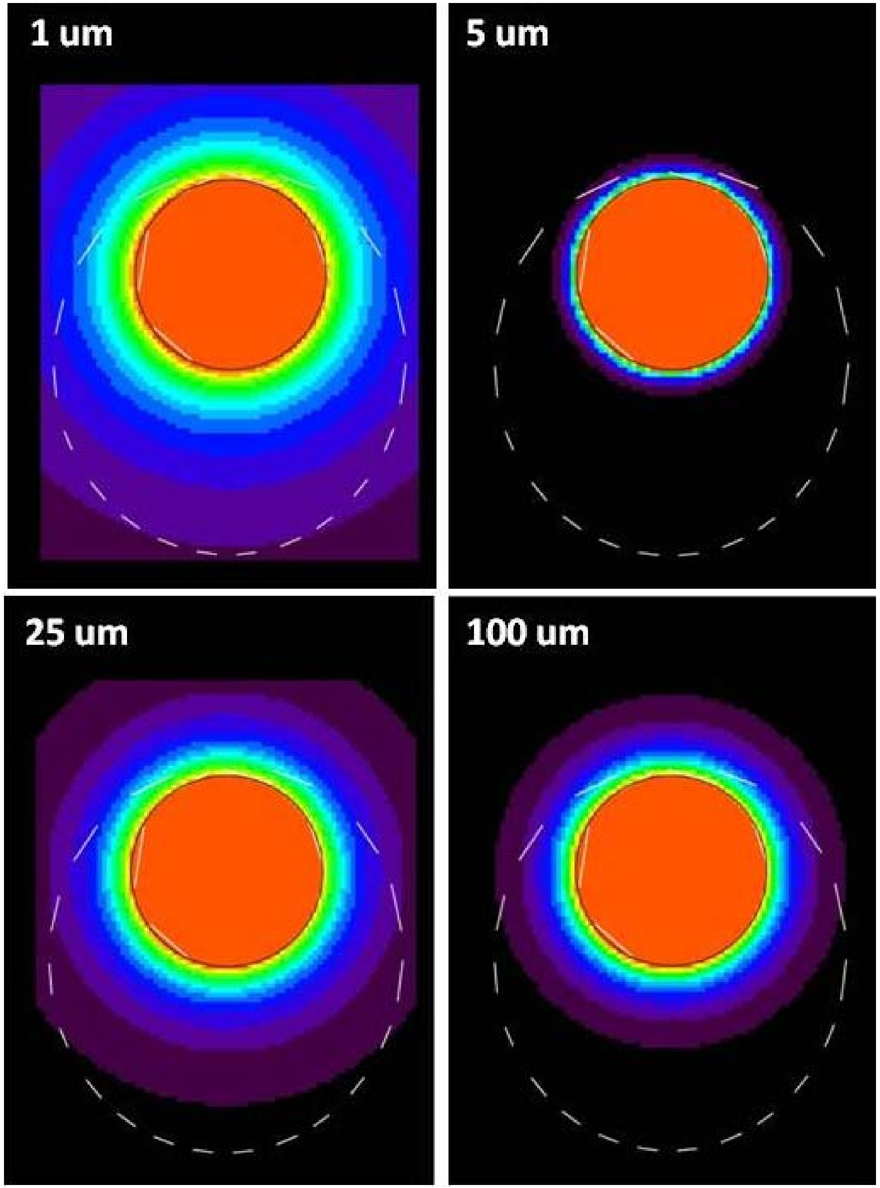


Stiavelli, M. et al. (2008):
http://www.stsci.edu/jwst/science/whitepapers/first_light_study_V.pdf

Serviceable trajectory for a flagship-class EZE mission

- 1x3 AU zero inclination orbit
- start & end at Earth-Moon L1
- 4 year period (non-Keplerian)
- Delta-V 2.12 km/s (low-thrust)

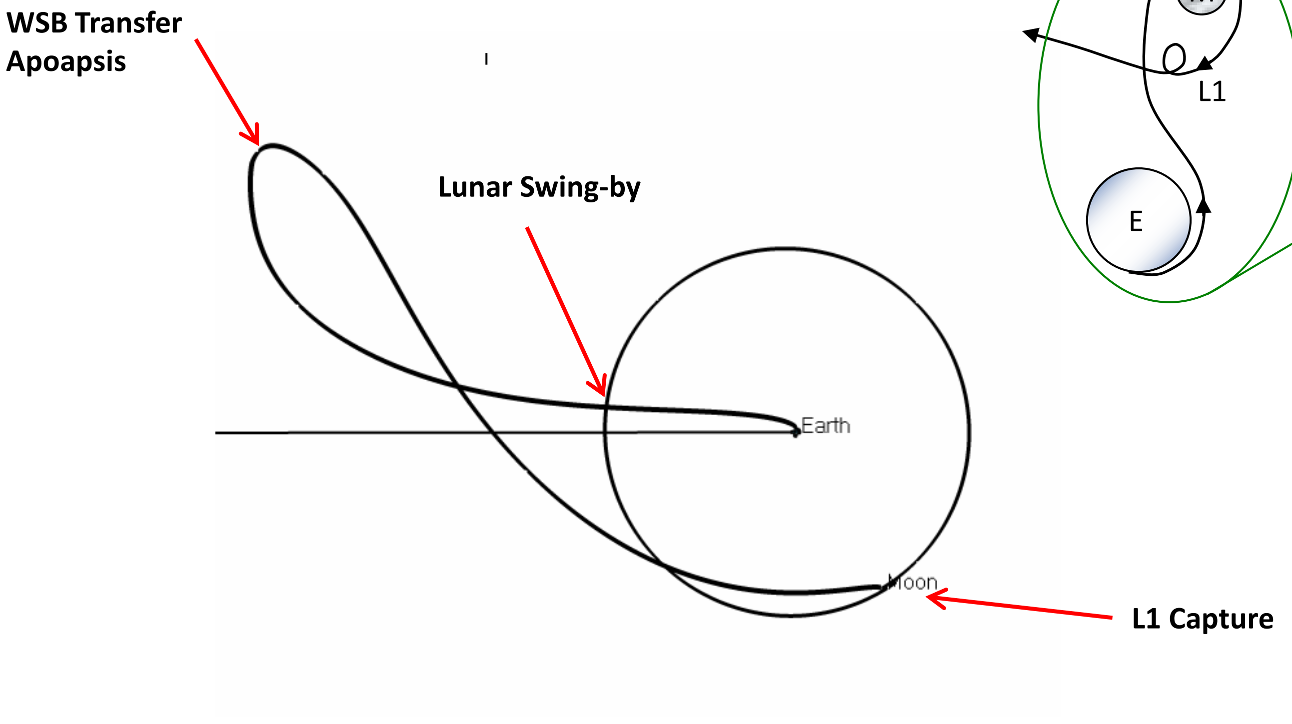


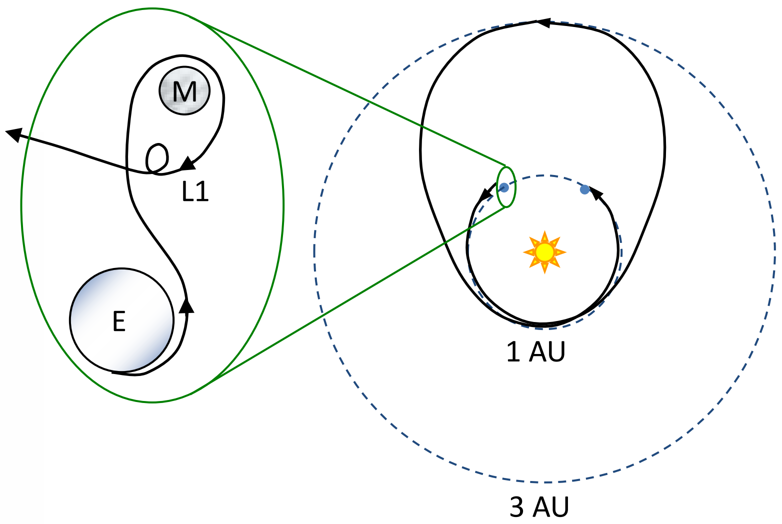


EZE 1x3 AU trajectory shown with dash length equal to 1 month of flight time. Zodiacal background is shown with a linear scale normalized to 1 AU

Earth-Moon L1 capture for servicing feasible

- Weak Stability Boundary (WSB) transfer to Earth-Moon L1
  - ΔV required for WSB transfer and 1 year of station keeping: 180 m/s
  - Transfer time for L1 insertion: 140 – 180 days



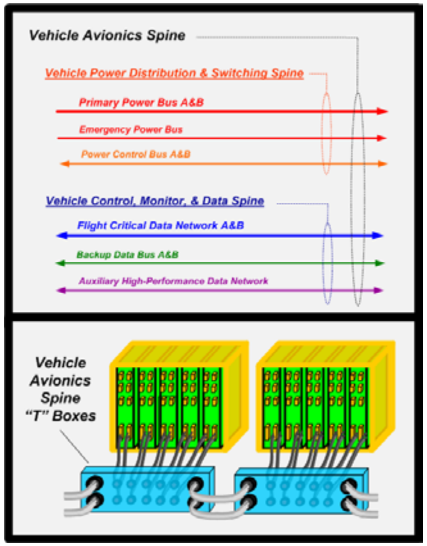


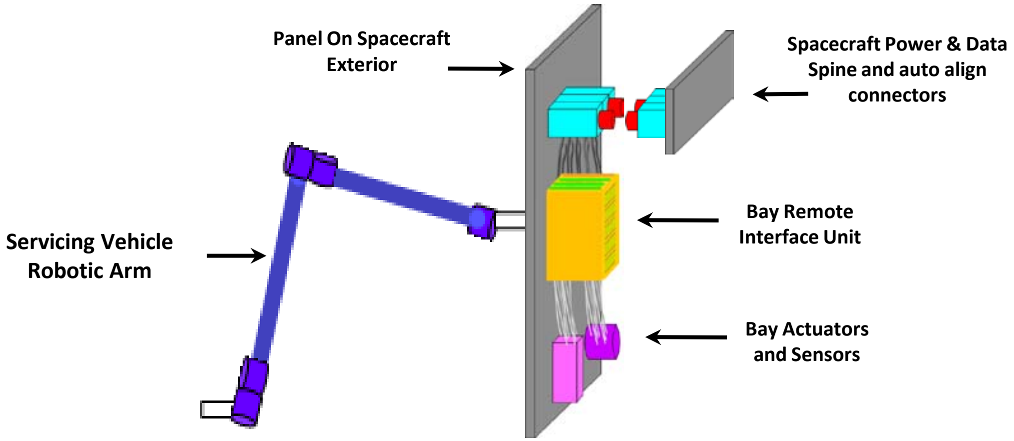
Con-Ops for a servicing-sustained (20 yr) EZE mission

- **Two-element space vehicle design**
- **Science Craft:**
  - Telescope, science instrument module, spacecraft bus, solar array/sunshield
  - Wet mass: 8,400 kg, Delta IV (4050H-26) 56% capability to EML1 used
- **Propulsion Module:**
  - NEXT ion thrusters (20), Xenon propellant (7,400 kg), mini-spacecraft bus
  - Wet mass: 11,200 kg, Delta IV (4050H-26) 74% capability to EML1 used
- **Initial mission sequence:**
  1. Propulsion module launches to EML1
  2. Science Craft launches to EML1 within 11 months
  3. Autonomous rendezvous/dock/commissioning
  4. Transfer to 1x3 AU science orbit (~4 year science mission)
  5. Re-capture into EML1 libration point orbit
  6. First of 4 robotic servicing missions (next chart)
  7. Repeat cycle to achieve 4 science orbits

EZE servicing concept for 20 year mission duration

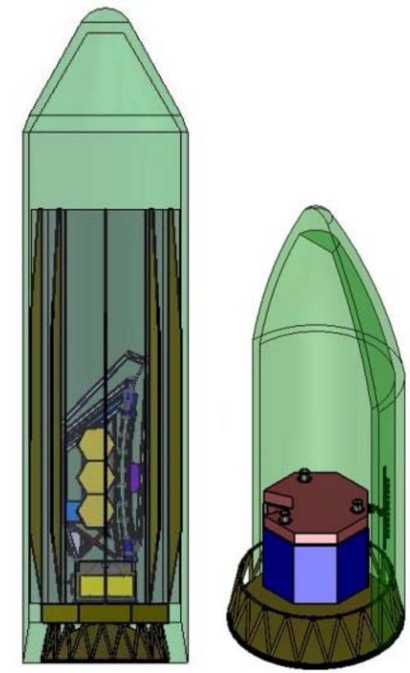
- **Each EML1 servicing mission involves two launches:**
  1. Propulsion module element replaced using same autonomous docking process as in initial space vehicle assembly
  2. Science craft subsystem level robotic servicing:
     - Science instruments
     - Solar array/thermal shield
     - Laser communications subsystem
     - Spacecraft Hydrazine propellant (330 kg) replenished
- Distributed spacecraft architecture to enable replacement of other key subsystems



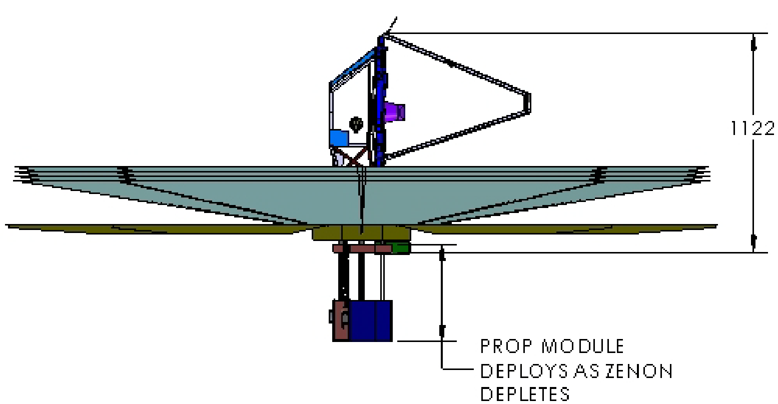


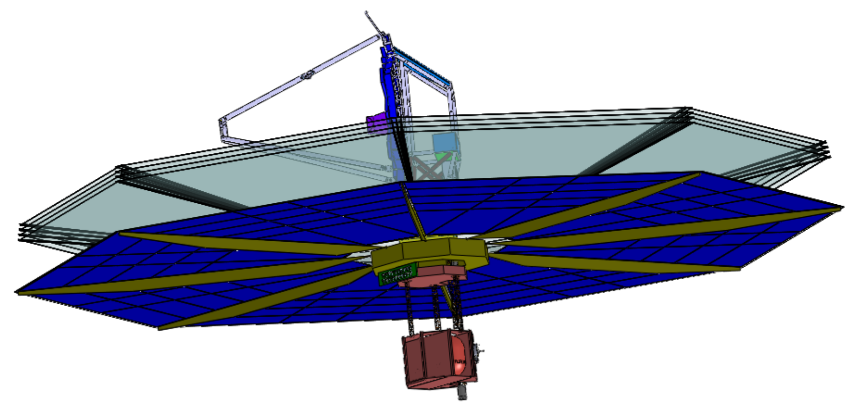
EZE architecture-level feasibility confirmed in MDL analysis

- **Low-thrust flight dynamics solution developed**
  - 1x3 AU, period synced to enable capture into EML1 for servicing
- **Propulsion and power system concept analyzed**
  - Xenon propellant and solar electric power for a specific NEXT thruster
  - CG control approach developed for 7400 kg ion propellant usage
  - Generation, dissipation, and array stowage conservatively addressed
- **Communication solution for 500 Gbit/day at 4 AU max range**
  - Optical communication technology ready and saleable from LLCD
- **Launch requirements met by existing EELV**
  - Delta IV 4050H-26 upgrade configuration, 30% mass margin
  - First-cut solar array stowage solution requires 6 m faring



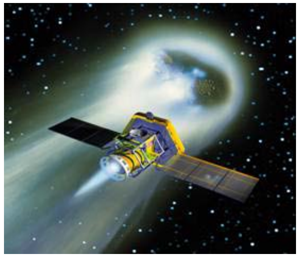
Science Craft **Propulsion Module**





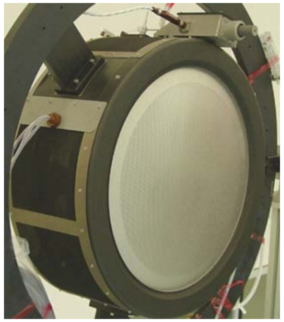
Ion thruster technology is ready to support EZE mission

- NASA has flown ion thrusters for 12 years
  - Deep Space-1: >13 khrs operation in space
  - Dawn: 1000s of hrs operation in space to date

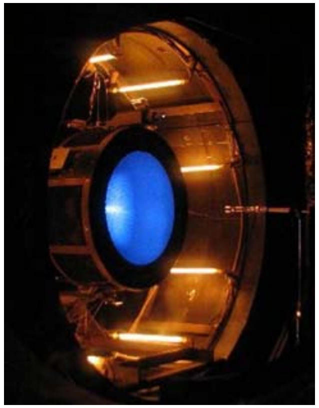

Deep Space-1


Dawn

- NEXT gridded ion thruster baselined for MDL study
  - Efficiency up to 72% spec
  - Input Power spec 0.54 to 6.9 kW. Run as high as 13 kW
  - TRL 6 by end of 2010


NEXT Thruster

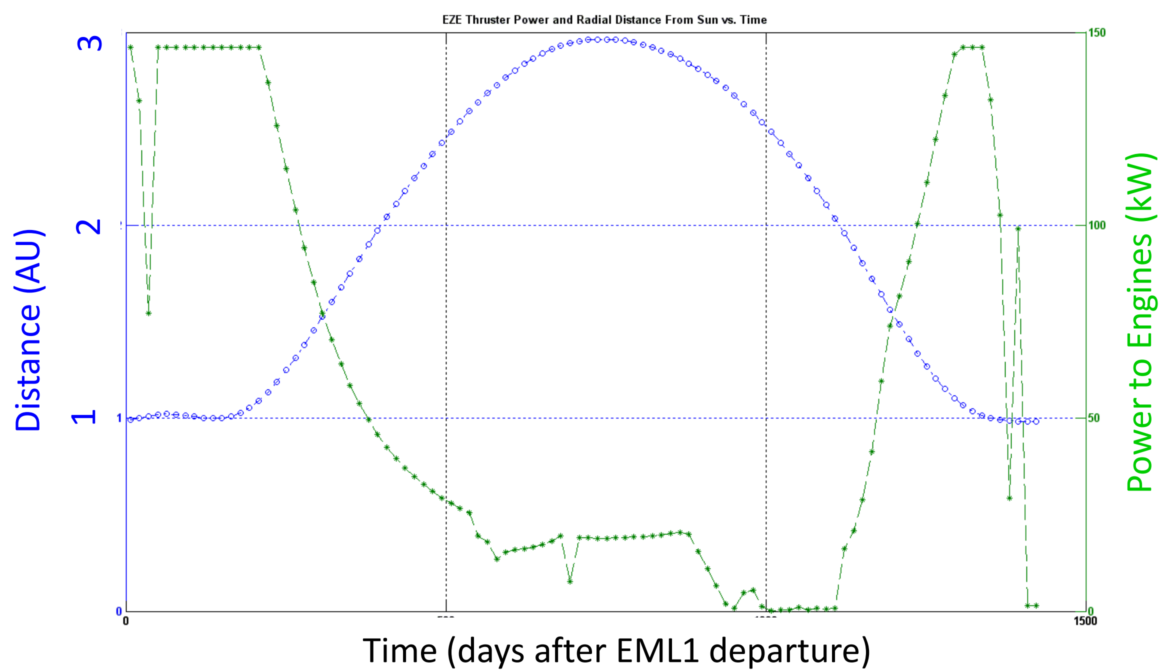
- NEXIS and HiPEP ion thrusters under development since 2003
  - 20-25 kW power each
  - Specific Impulse up to 8000 s (~2X NEXT)
  - Can easily reach TRL 6 by 2020 as priority pull technology


NEXT in thermal vacuum test

Electric propulsion power requirements feasible for EZE

- Assumed 40% efficient multi-junction GaAs cells
  - 28% flown regularly in 2008
  - 43% already demonstrated in lab, increasing ~ 1%/yr
  - 10% EOL (5 year) radiation damage assumed (conservative)
- Areal density 280 W/m^2
  - 900 m^2 accommodated in MDL study configuration
- Bus dissipation (4%) accommodated

EP power (kW) vs heliocentric radius	
150	1.0
80	1.5
50	2.0
30	2.5
25	3.0



Electric propulsion propellant accommodation feasible

- Xenon, 7,400 kg required for each science orbit
  - Propulsion module replaced during each servicing interval
- -35 C storage temperature easily achieved by passive cooling
- Vapor supplied to the engines by electrically heating tanks causing boiling
  - At ~0.2 g/s flow rate, only 20 W heater power needed

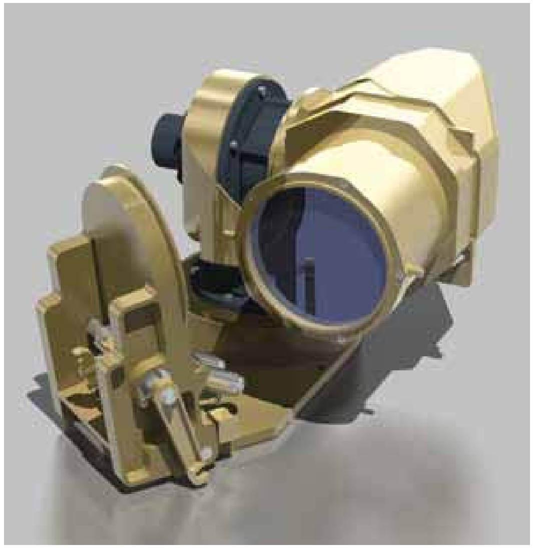
Xenon Storage	Pressure (psi)	Temp.	Density (MT/m^3)	Tank Mass[1] (kg)
Supercritical	1700	20C	2.0	1,050
Passively Cooled	250	-35C	2.4	483

1. System mass including: 2 tanks, MLI, foam insulation, low heat leak mounting hardware

Commercial Cryogenic Tank; rated 250 psi

Science data volume communication feasible for 3 AU orbit

- Optical communications:
  - Sized to transmit 100 mbps in MDL study configuration
  - Requires ~1.4 hours daily to transmit 500 Gbits science data volume
- X-band telemetry, command, and ranging
  - 10 dB link margin at 3 AU (8 kbps)
- S-band wireless data interface between science craft and propulsion module
  - Enables cooperative target rendezvous & dock
  - 125 kbps at 50 km
  - Enables TDRSS compatibility for:
    - launch phase support and critical event coverage during rendezvous & docking
    - 1 kbps for telemetry or command



Lunar Lasercom Demonstration (LLCD)

600 Mbps xmt, 16 Mbps rcv
Launch on LADEE: May 2012

Key challenges for future servicing study

- **Key study areas for EZE are characteristic of those needed by a wide range of missions**
- Space vehicle assembly by autonomous rendezvous & dock at EML1
- Robotic servicing at EML1
  - Hydrazine propellant replenishment (~300 kg)
  - Solar array/thermal shield replacement
  - Science instrument replacement
    - Modularity and opto/mechanical interface concept needed
  - Spacecraft subsystem servicing:
    - Design modularity guidelines to enable contingency replacement of subsystems
- Human servicing at EML1
  - Assumptions:
    - "Robotic servicing" = telerobotics
    - Is astronaut operator proximity necessary to enable real time control?
      - Transmission delay from Earth to EML1 ~ 1.2 seconds
    - Is zero inclination a requirement for telerobotic servicing?
      - Major simplification of EZE possible if answer is "no".
    - Should be able to avoid need for human EVA in baseline

Summary

- **The future of visible/infrared space astronomy lies outside the Zodical cloud**
  - Significant reduction in required telescope aperture possible relative to SEL2
  - Enables path forward for cosmology without Aries-V
- **An Extra-Zodical mission architecture is feasible today**
  - Initial MDL study revealed no show stoppers
  - In-depth MDL study needed to guide priority technology investments
- **A servicing sustained ~20 year EZE mission lifetime is feasible when a telerobotic servicing technology and infrastructure is ready**
  - EML1 service point feasible in context of numerous extra-Zodical aphelion and inclination orbit choices
  - In-depth servicing study needed for development of robotic servicing mission architecture and associated space vehicle design guidelines