Daedalus:

A Low-Flying Spacecraft for the Exploration of the Lower Thermosphere - Ionosphere

A candidate for ESA's 10th Earth Explorer

Introduction

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The study for the development of "Daedalus", a Low-Flying Spacecraft for the exploration of the lower thermosphere - ionosphere:

- was initiated under the ESA-Greece Task Force initiative, at feasibility study level
- it has derived the performance requirements, specifications, preliminary design and development plan for a Low-Flying Spacecraft
- it has been submitted to ESA's Earth Observation Earth Explorer programme and is one of the three candidates for the 10th Earth Explorer
- It is currently undergoing a Phase-0 study for Mission Definition and Needs Identification

Proposing Team

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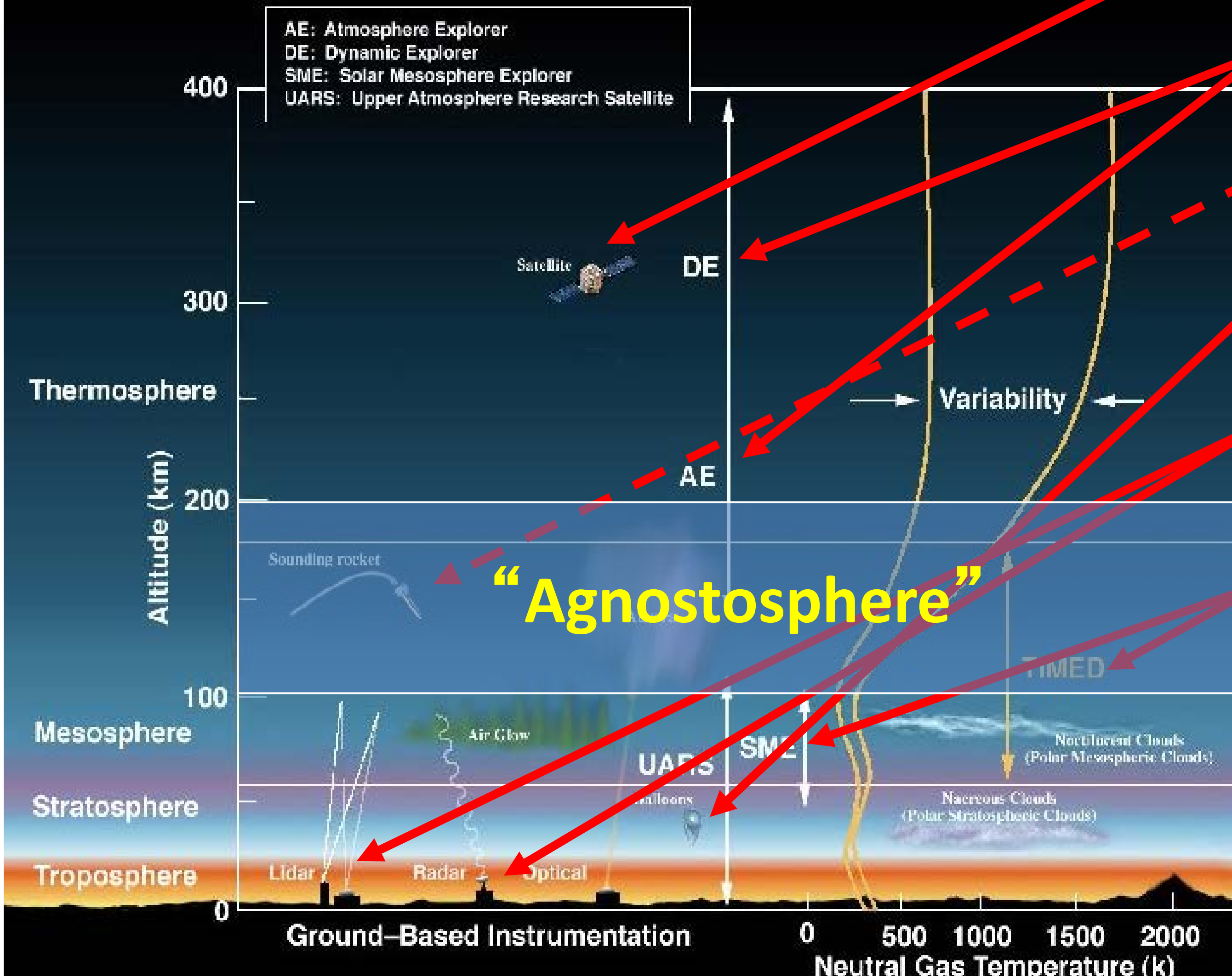
Name	*Affiliation*	*Country*
Sarris, Theodoros	Democritus University of Thrace, lead institution	Greece
Aikio, Anita	Ionospheric Physics Unit, University of Oulu	Finland
Armandillo, Errico	Space Engineering Consultant	Netherlands
Belehaki, Anna	National Observatory of Athens	Greece
Buchert, Stephan	Swedish Institute of Space Physics	Sweden
Clilverd, Mark	British Antarctic Survey	UK
Cully, Christopher	University of Calgary	Canada
Dandouras, Iannis	IRAP, CNRS & Université de Toulouse	France
Halekas, Jasper	University of Iowa	USA
Jaynes, Allison	University of Iowa	USA
Kervalishvili, Guram	GFZ German Research Centre for Geosciences	Germany
Kourtidis, Konstantinos	Democritus University of Thrace	Greece
Lappas, Vaios	ATHENA Research & Innovation Centre	Greece
Malaspina, David	LASP, University of Colorado	USA
Palmroth, Minna	University of Helsinki	Finland
Paschalidis, Nikolaos	Goddard Space Flight Center, NASA	USA
Sample, John	Montana State University	USA
Sandberg, Ingmar	SPARC G.P.	Greece
Wu, Qian	High Altitude Observatory, NCAR	USA

Participants from 9 countries, 17 entities

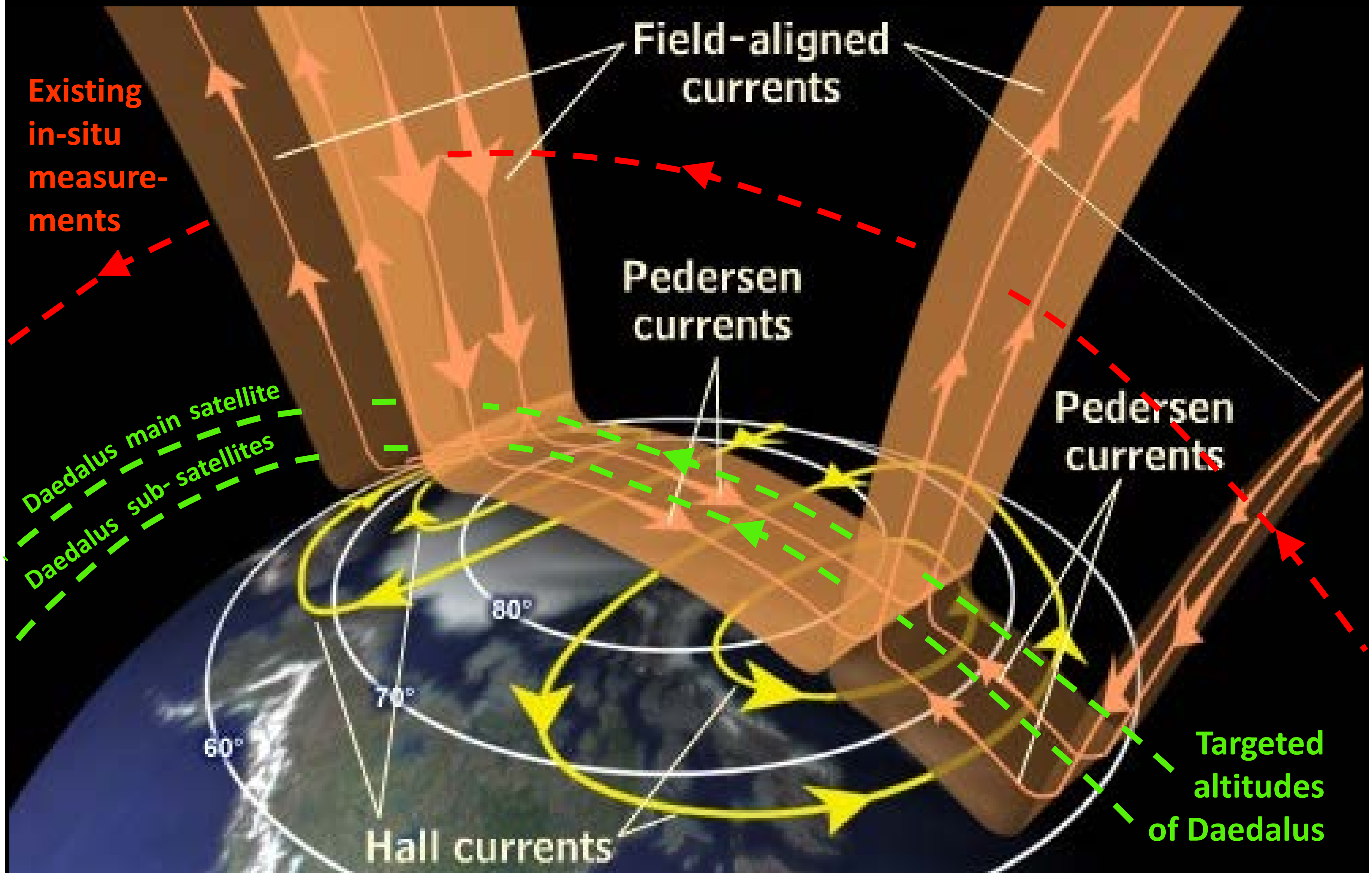
Daedalus Science Objectives

Mesosphere, Lower Thermosphere & Ionosphere (MLTI):
"Terra Incognita"



- Circular Orbits possible down to ~350km
- Elliptic Orbits possible down to ~150 km
- Rockets cross the MLTI for just a few minutes
- Balloons can reach up to ~40 km
- Lidars/Radars can investigate the region only locally
- Remote sensing is the only measurement source
- In-situ measurements are needed for key science issues in the transition region from 100 to 200 km

Daedalus Science Objectives



Daedalus Science Objectives

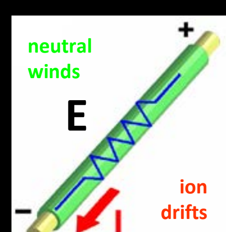
A. Heating processes and energy balance in the MLTI

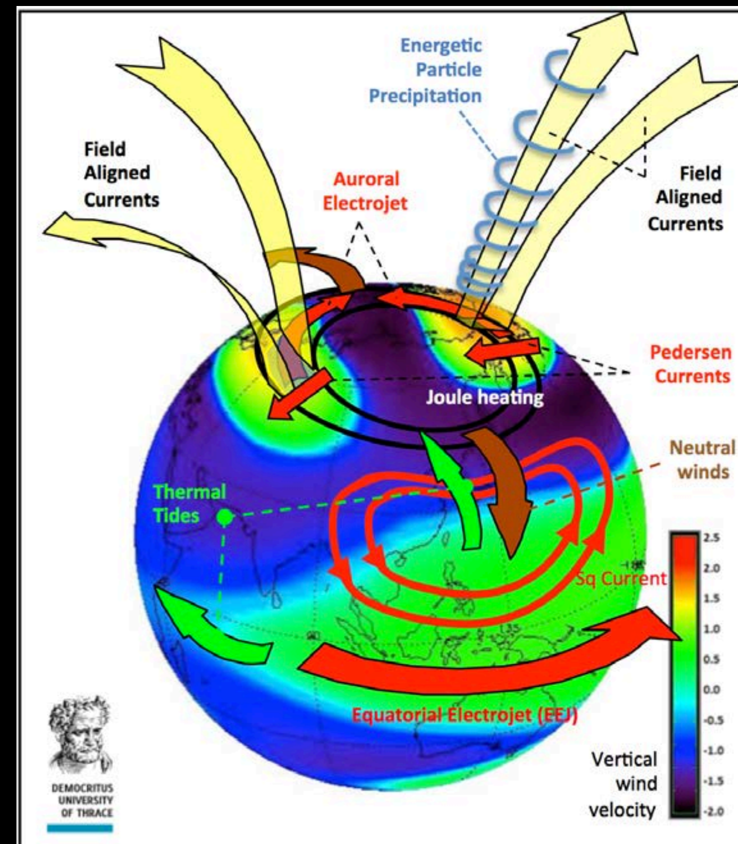
Q1: What is the energy that is deposited into the MLTI via **Joule heating** and **Particle Precipitation** and how exactly does it affect the dynamics and the thermal structure of the MLTI?

Q2: What processes control momentum and energy transport and distribution in the transition region, at 100-200 km altitude range in the high-latitude region?

- **Estimates of Joule (ohmic) heating of the thermosphere require simultaneous measurements of:**

a) Ion drifts
b) Neutral winds
c) Electric field
d) Magnetic field
e) Composition





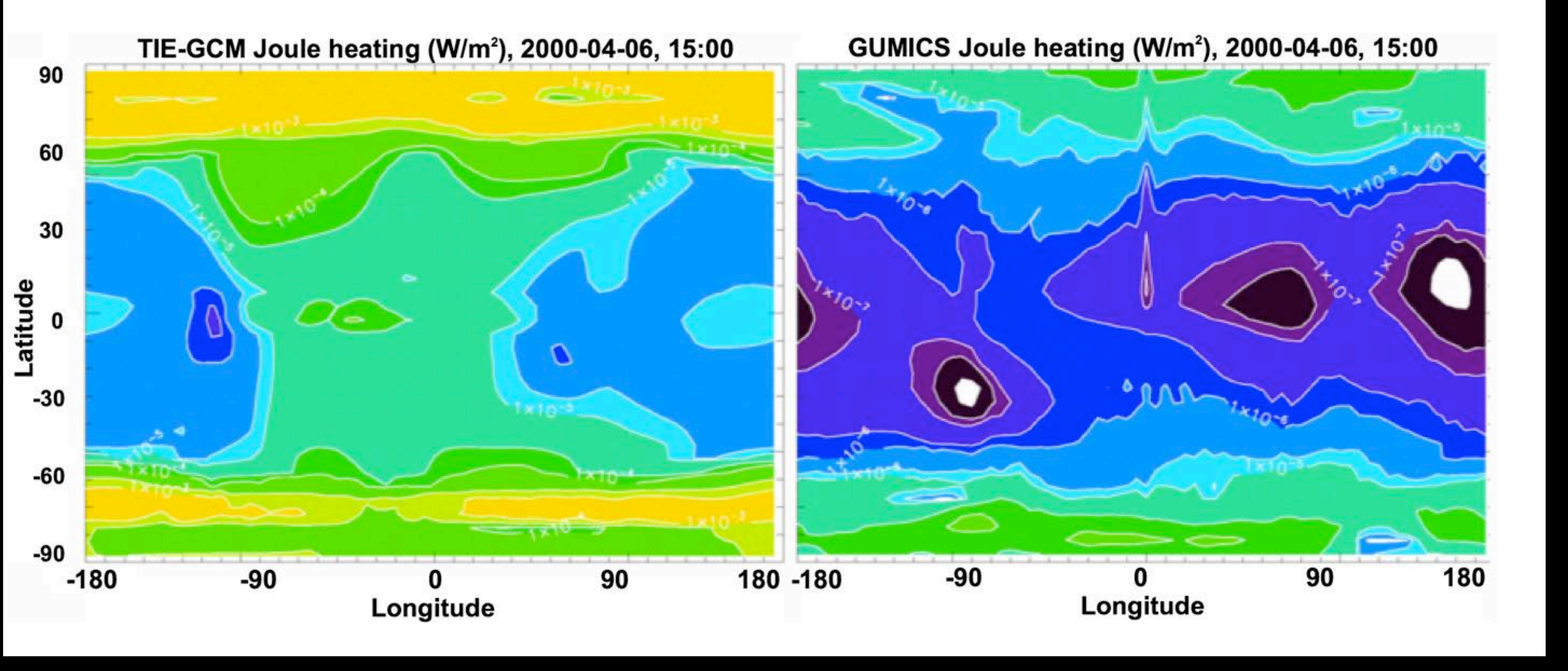
Overview of main processes affecting momentum and energy transport and distribution in the MLTI.

Daedalus Science Objectives

A. Heating processes and energy balance in the MLTI

Justification: Estimates of key heating processes, such as Joule heating, currently vary by a large fraction between models (up to 500% at times and at locations)

Comparison of Joule Heating between models, as a function of latitude and longitude:



Daedalus Science Objectives

A. Heating processes and energy balance in the MLTI

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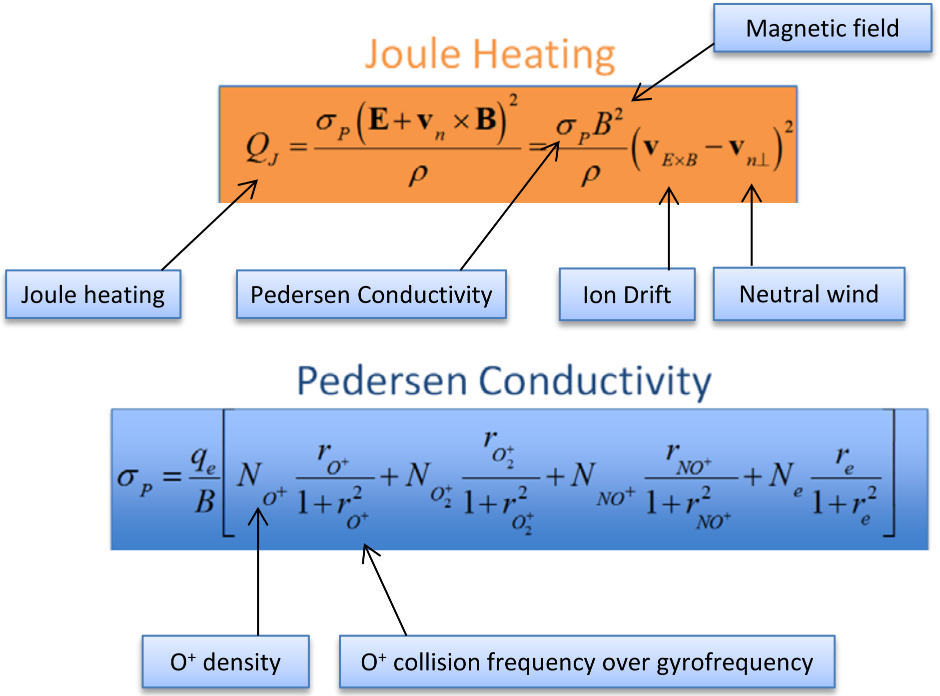
Required parameters and instrumentation for Joule Heating estimates:



$$Q_J = \frac{\sigma_P \left(\mathbf{E} + \mathbf{v}_n \times \mathbf{B}\right)^2}{\rho} = \frac{\sigma_P B^2}{\rho}\left(\mathbf{v}_{E\times B} - \mathbf{v}_{n\perp}\right)^2$$

$$\sigma_P = \frac{q_e}{B}\left[N_{O^+}\frac{r_{O^+}}{1+r_{O^+}^2} + N_{O_2^+}\frac{r_{O_2^+}}{1+r_{O_2^+}^2} + N_{NO^+}\frac{r_{NO^+}}{1+r_{NO^+}^2} + N_e\frac{r_e}{1+r_e^2}\right]$$

Required parameter (instrument):

- neutral density **(ACC)**
- neutral winds **(RWS,CTS)**
- ion drifts **(IDM,RPA)**
- magnetic field **(FGM)**
- electric field **(EFI)**

- ion density **(IMS)**
- ion composition **(IMS)**
- ion temperature **(IMS)**
- e^- temperature **(LMP)**
- neutral composition **(NMS)**

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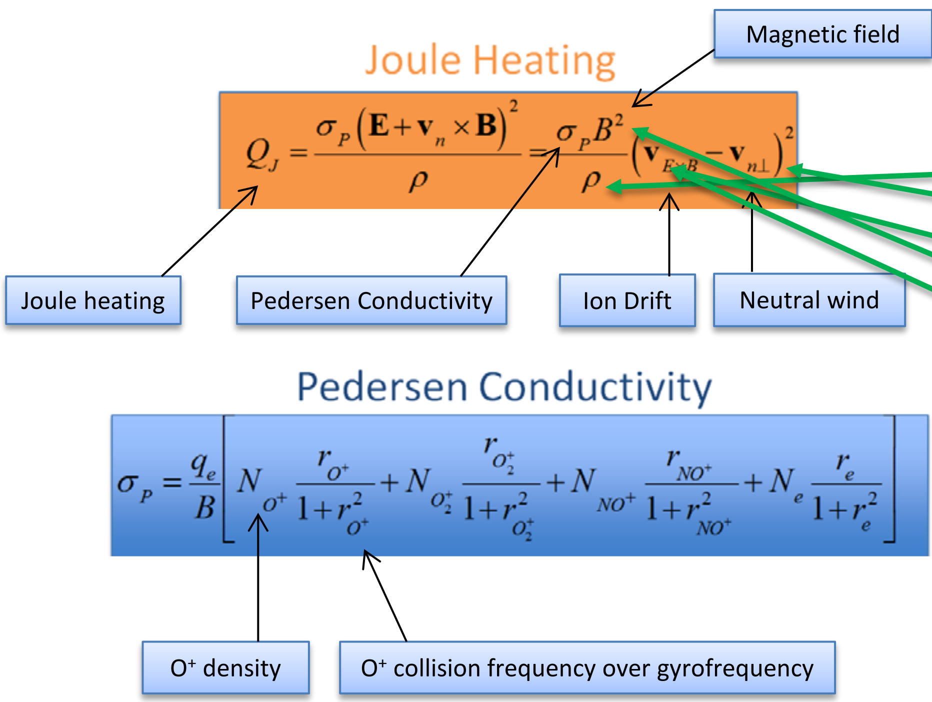

$$Q_J = \frac{\sigma_P (\mathbf{E} + \mathbf{v}_n \times \mathbf{B})^2}{\rho} = \frac{\sigma_P B^2}{\rho} (\mathbf{v}_{E\times B} - \mathbf{v}_{n\perp})^2$$

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Required parameter (instrument):

- neutral density **(ACC)**
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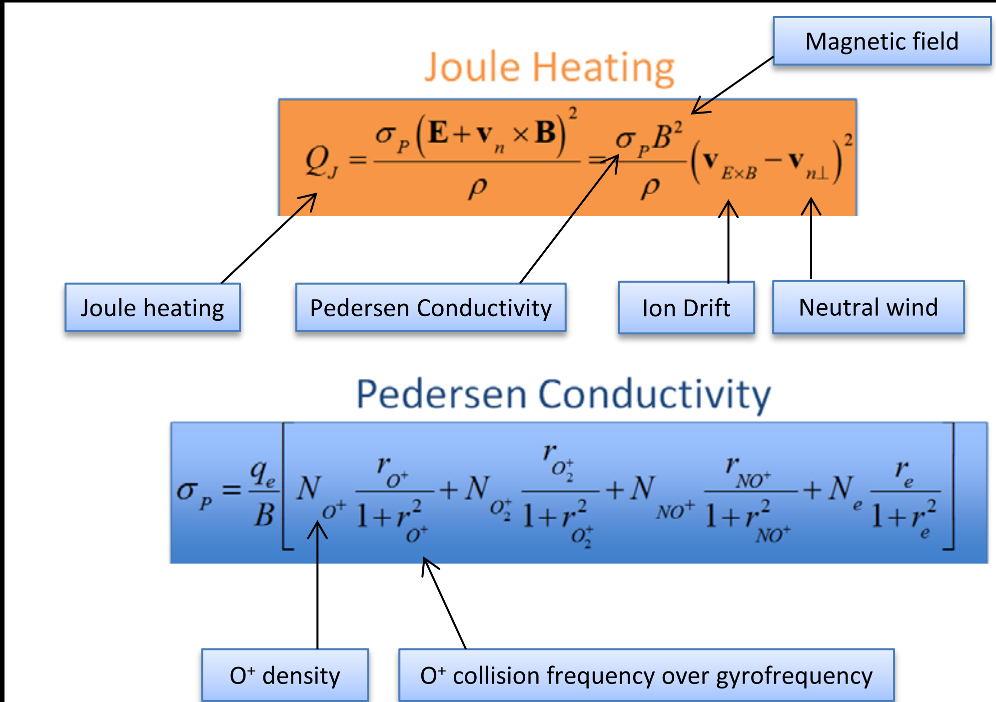


ID	INSTRUMENT	VARIABLES
IDM	Ion Drift Meter	Cross-track ion drifts
RPA	Retarding Potential Analyzer	Along-track Ion Drifts Vertical Ion Drifts Ion Temperature
RWS	Ram Wind Sensor	Along-track neutral winds
CWS	Cross-track Wind Sensor	Cross-track neutral winds
IMS	Ion Mass Spectrometer	Ion density Ion composition
NMS	Neutral Mass Spectrometer	Neutral density Neutral winds Neutral Temperature N_2, O, O_2, NO
ACC	Accelerometer	Cross-track neutral winds Neutral density
EPDS	Energetic Particle Detector Suite	Precipitating e^- Precipitating p^+ Energetic Neutral Atoms
EFI	Electric Field Instrument	Electric Fields
MIP or LP	Mutual Impedance Probe or Langmuir Probe	Electron Temperature
MAG	Magnetometer	Magnetic Fields Currents
GNS	GNSS Receiver	Electron density

Daedalus Science Objectives

A. Heating processes and energy balance in the MLTI

Justification: Estimates of key heating processes, such as Joule heating, currently vary by a large fraction between models (up to 500% at times and at locations)

$$r_i = \frac{\nu_i}{\Omega_i}, \quad r_e = \frac{\nu_e}{\Omega_e}, \quad \Omega_i = \frac{eB}{m_i}, \quad \Omega_e = \frac{eB}{m_e}$$

$$\nu_{O_2^+} = \nu_{O_2^+-O_2} + \nu_{O_2^+-O} + \nu_{O_2^+-N_2}$$

$$\nu_{O^+} = \nu_{O^+-O_2} + \nu_{O^+-O} + \nu_{O^+-N_2}$$

$$\nu_{NO^+} = \nu_{NO^+-O_2} + \nu_{NO^+-O} + \nu_{NO^+-N_2}$$

$$\nu_e = 2.33\times10^{-11} N_{N_2} T_e\left(1-1.21\times10^{-4}T_e\right) + 1.82\times10^{-10} N_{O_2}\sqrt{T_e}\left(1+3.6\times10^{-2}\sqrt{T_e}\right) + 8.9\times10^{-11} N_O\sqrt{T_e}\left(1+5.7\times10^{-4}T_e\right)$$

$$\nu_{O_2^+-O_2} = N_{O_2} 2.59\times10^{-11}\sqrt{\frac{T_i+T_e}{2}}\left[1-0.73\log_{10}\sqrt{\frac{T_i+T_e}{2}}\right]^2$$

$$\nu_{O_2^+-O} = N_O 2.31\times10^{-10}$$

$$\nu_{O_2^+-N_2} = N_{N_2} 4.13\times10^{-10}$$

$$\nu_{O^+-O_2} = N_{O_2} 6.64\times10^{-10}$$

$$\nu_{O^+-O} = N_O\, 3.67\times10^{-11}\sqrt{\frac{T_i+T_e}{2}}\left[1-0.064\log_{10}\sqrt{\frac{T_i+T_e}{2}}\right]^2 f_B$$

$$\nu_{O^+-N_2} = N_{N_2} 6.82\times10^{-10}$$

$$\nu_{NO^+-O_2} = N_{O_2} 4.27\times10^{-10}$$

$$\nu_{NO^+-O} = N_O\, 2.44\times10^{-10}$$

$$\nu_{NO^+-O} = N_{N_2} 2.44\times10^{-10}$$

Pedersen Conductivity

$$\sigma_P = \frac{q_e}{B}\left[N_{O^+}\frac{r_{O^+}}{1+r_{O^+}^2} + N_{O_2^+}\frac{r_{O_2^+}}{1+r_{O_2^+}^2} + N_{NO^+}\frac{r_{NO^+}}{1+r_{NO^+}^2} + N_e\frac{r_e}{1+r_e^2}\right]$$

O^+ density

O^+ collision frequency over gyrofrequency

Required parameter (instrument):

- neutral density **(ACC)**
- neutral winds **(RWS,CTS)**
- ion drifts **(IDM,RPA)**
- magnetic field **(FGM)**
- electric field **(EFI)**

- ion density **(IMS)**
- ion composition **(IMS)**
- ion temperature **(IMS)**
- e^- temperature **(LMP)**
- neutral composition **(NMS)**

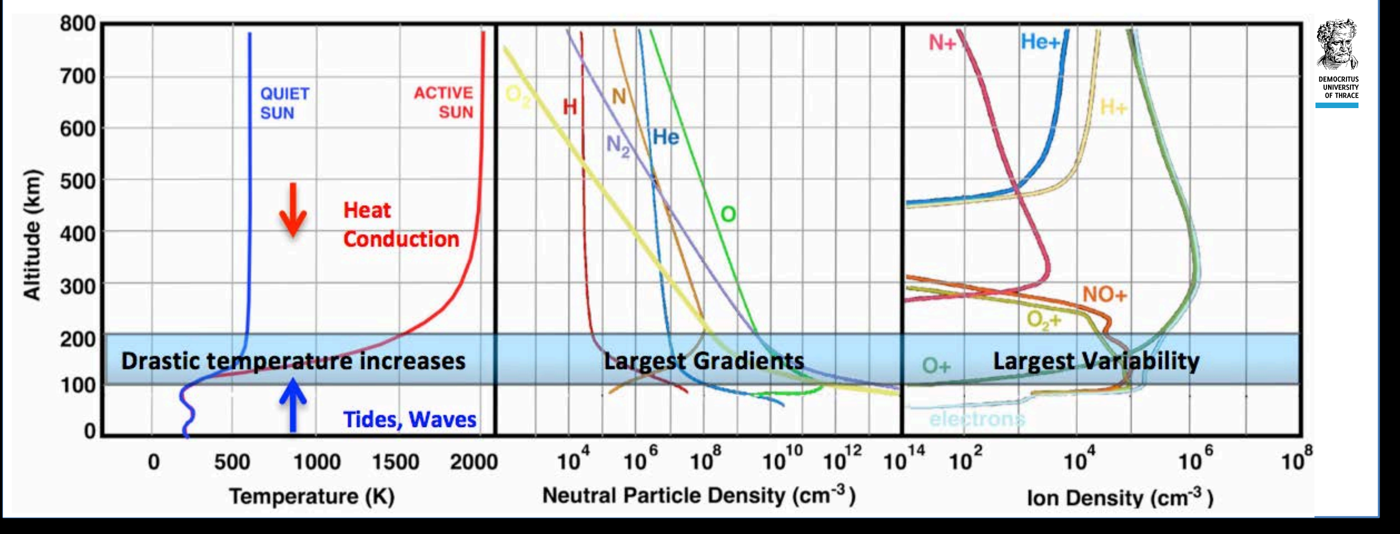
Daedalus Science Objectives

B. Variations in the MLTI temperature & composition structure

Q3: What are the spatial-temporal variations in density, composition and temperature of the neutral atmosphere and ionosphere at altitudes of 100-200 km altitude, with respect to solar activity?

Q4: What is the relative importance of the equatorial dynamo in driving the low latitude ionosphere and how do ions and neutrals couple in the low latitude ionosphere and thermosphere?

Q5: What is the MLTI region's role as a boundary condition to the exosphere above and stratosphere below and how does it affect their energetics and dynamics?



Daedalus Mission Concept

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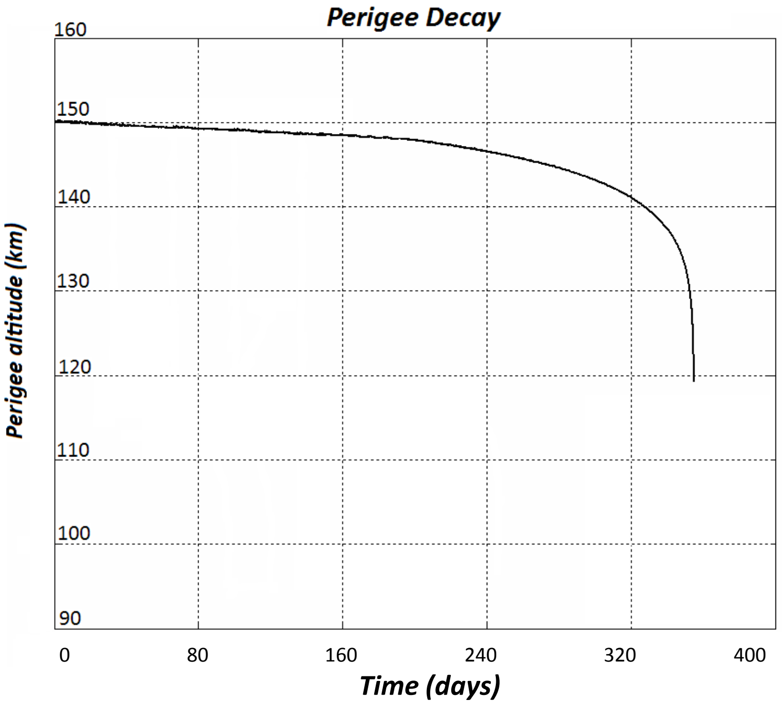
Part A - Measurements in the lower thermosphere down to 150 km:

- **Best realized by a spacecraft in elliptical orbit with perigee 150 km, apogee > 2000 km**



Orbit altitude: 150 x 2000 km, elliptical
Orbit inclination: 85°
Initial argument of periapsis: 90° (northern hemisphere perigee)

Daedalus Mission Concept

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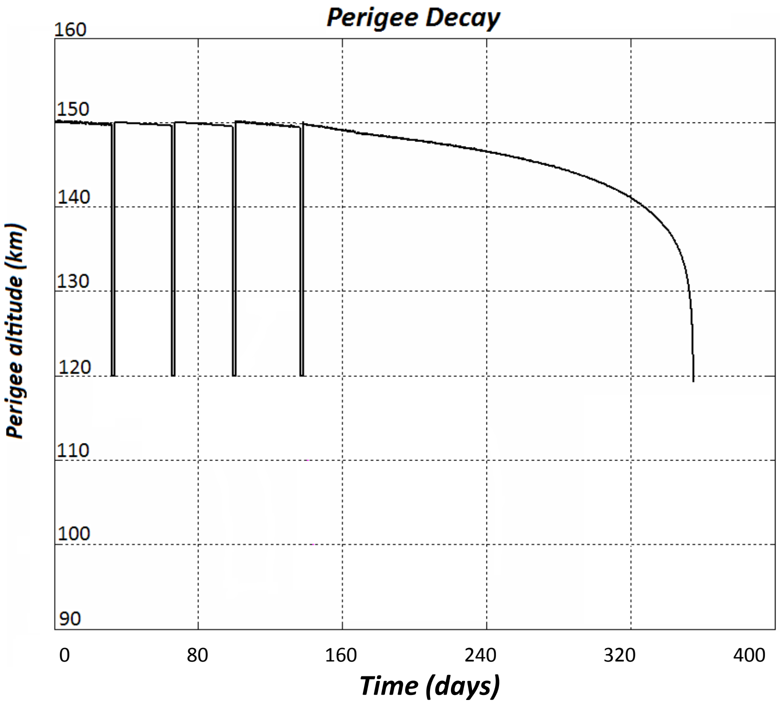
Part B - Measurements through the "Agnostosphere" down to 120 km:

- **Can be accomplished by performing episodic descents to lower altitudes, by use of propulsion**



Orbit altitude: 150 x 2000 km, elliptical

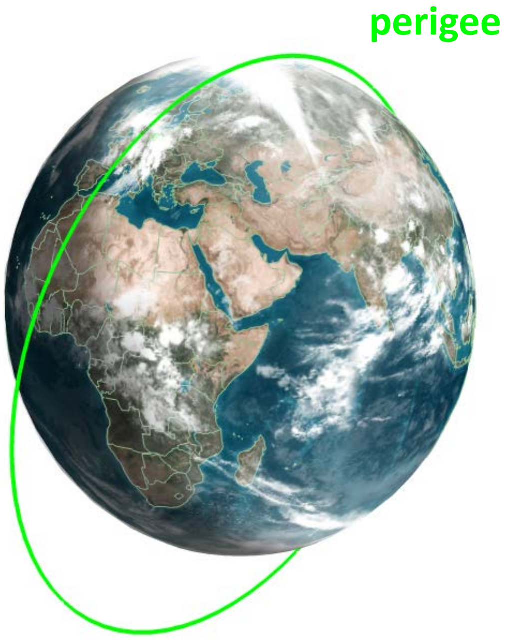
Orbit inclination: 85°

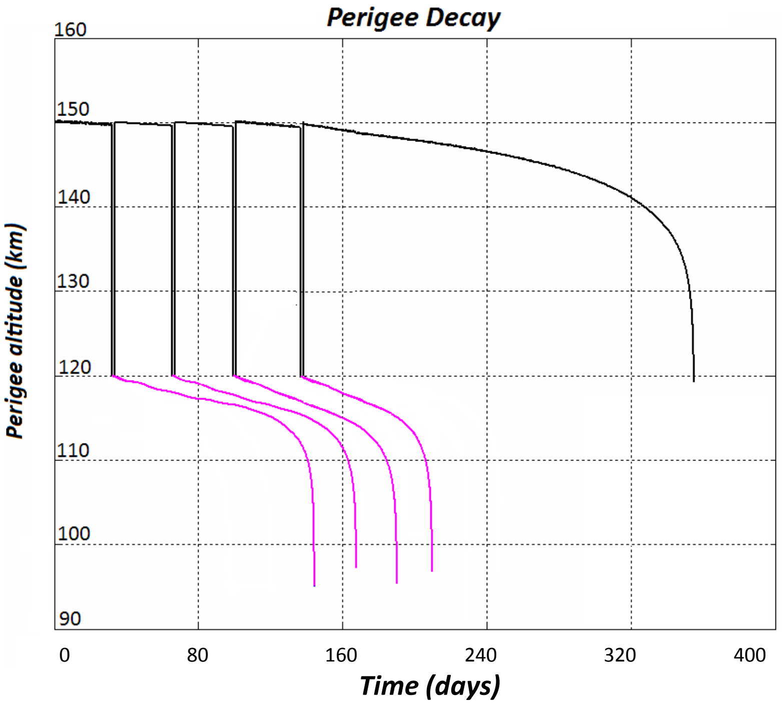
Initial argument of periapsis: 90° (northern hemisphere perigee)

Daedalus Mission Concept

Part C - Simultaneous second-point measurements below 120 km:

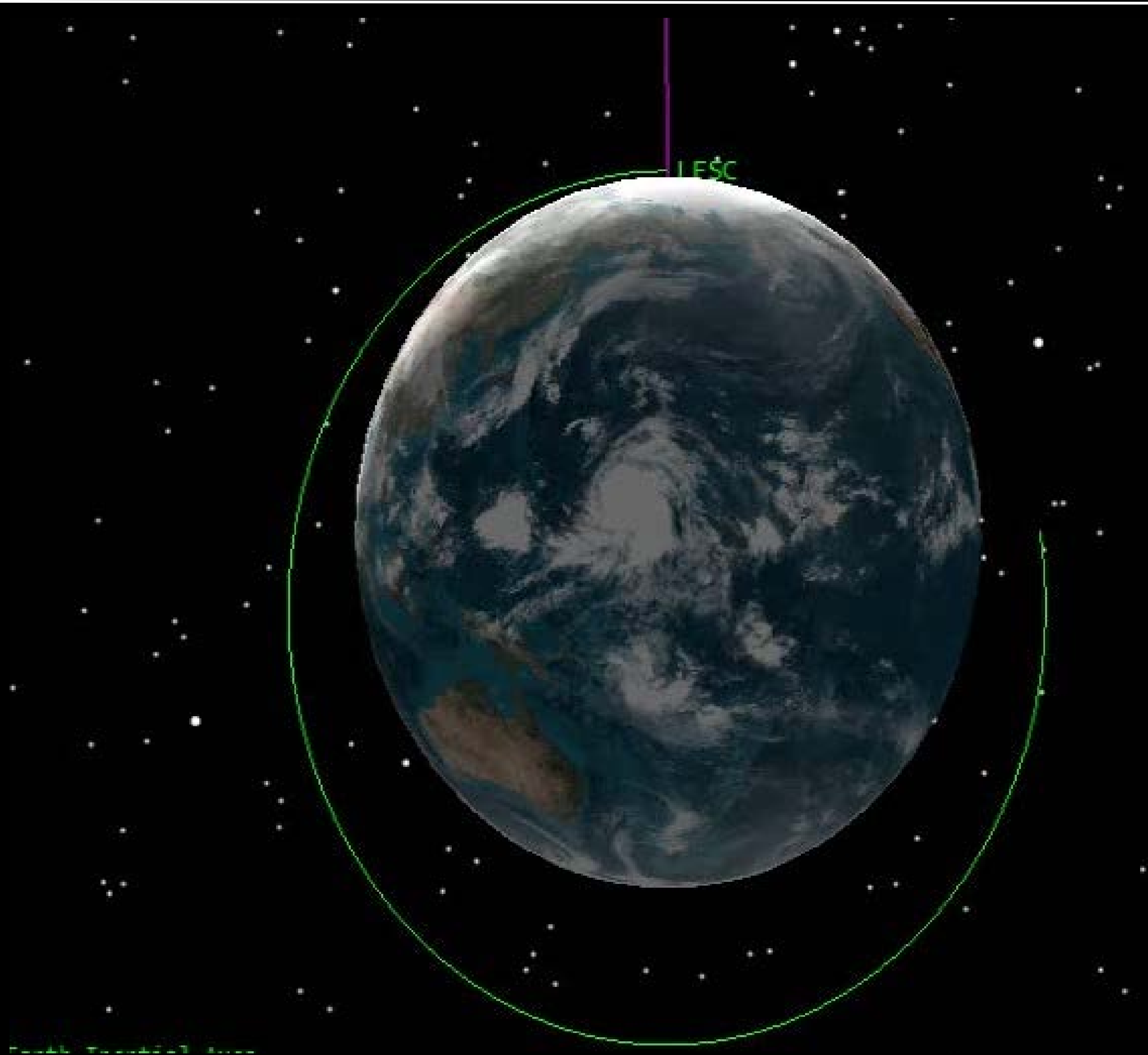
- **Can be accomplished by releasing expendable, miniaturized sub-satellites from the main satellite**



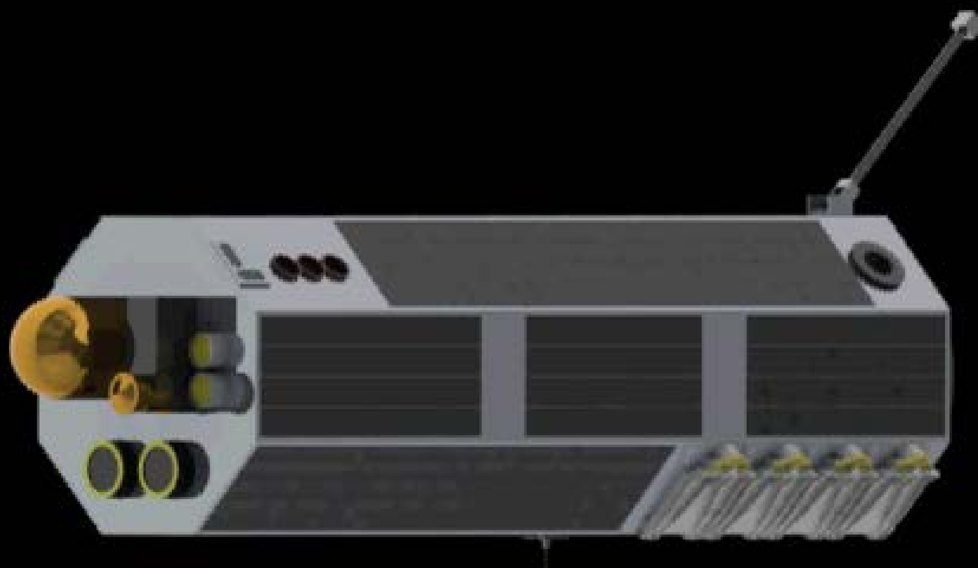


Orbit altitude: 150 x 2000 km, elliptical
Orbit inclination: 85°
Initial argument of periapsis: 90° (northern hemisphere perigee)

Daedalus Orbital Design



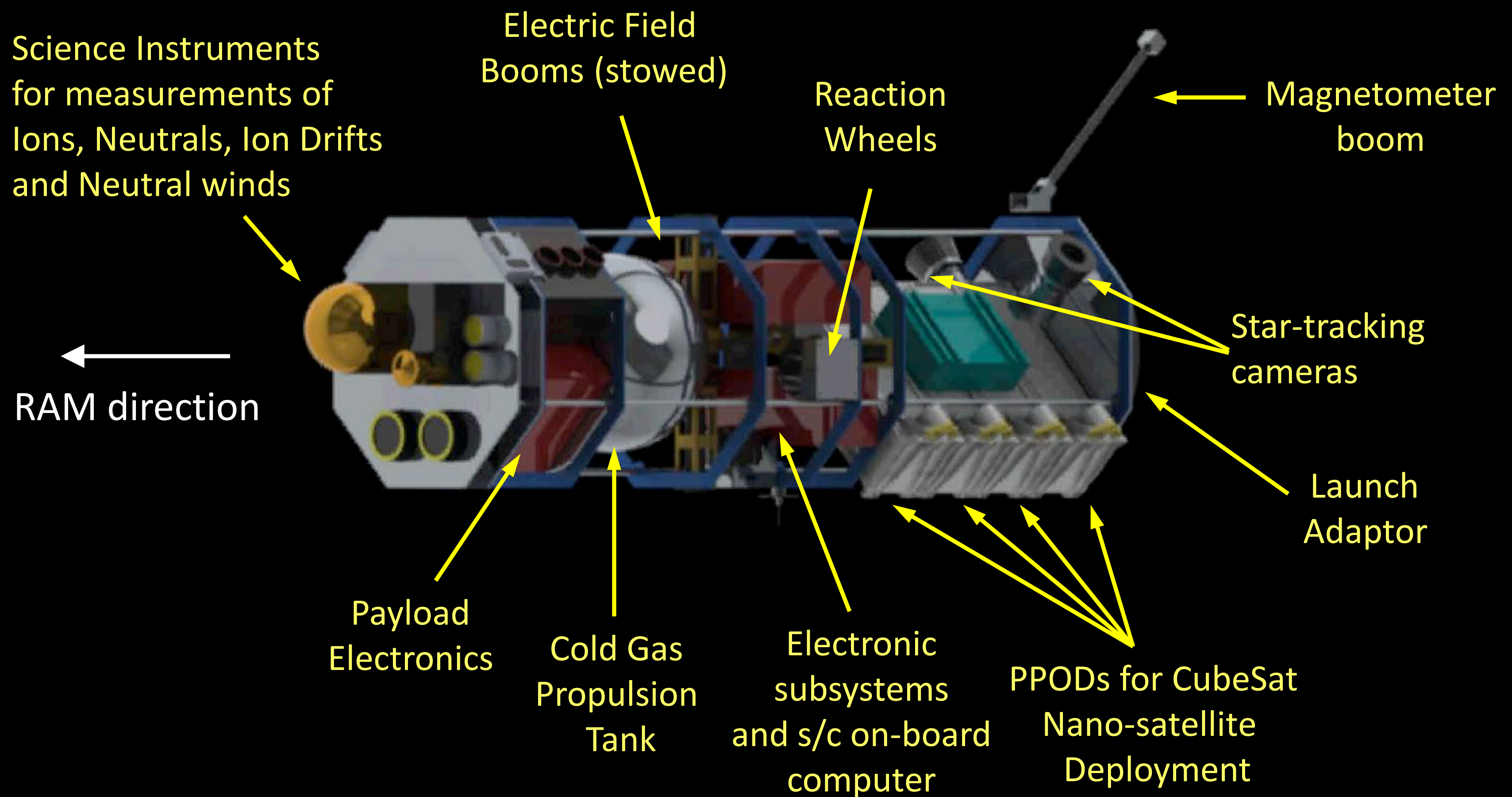
Daedalus Spacecraft Design



Daedalus Spacecraft Design

Daedalus Spacecraft Design

Overview of main s/c subsystems



Daedalus Spacecraft Design

Daedalus with Deployed Electric Field Booms

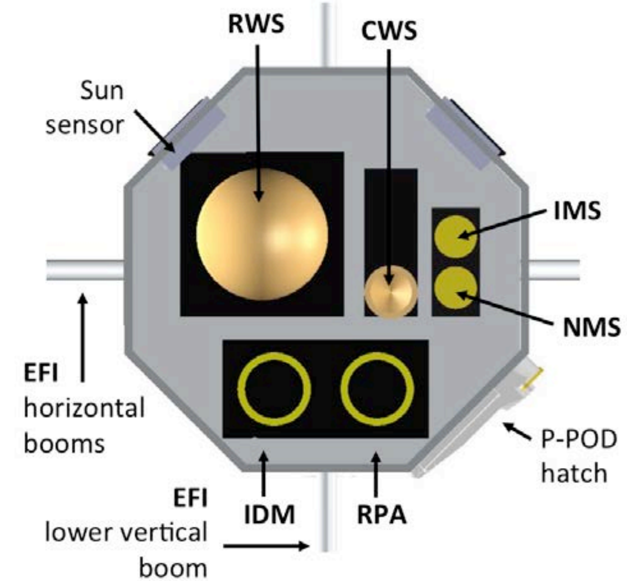
Daedalus Instrumentation

Daedalus Main Satellite Payload

Instrument	*Measurement*
Ion Drift Meter & Retarding Potential Analyzer *[M]*	Ion drifts, ion density
RAM Wind Sensor & Cross-Track Wind Sensor *[M]*	Neutral winds – Diff. pressure
Ion & Neutral Mass Spectrometers *[M&S]*	Ion & Neutral Composition
Accelerometer *[M&S]*	Neutral density
Energetic Particle Detector Suite *[M&S]*	Precipitating particles
Electric Field Instrument *[M&S]*	Electric fields, electron density
Langmuir Probe *[M&S]*	Electron temperature
Magnetometer *[M&S]*	Magnetic fields
GNSS Receiver *[M]*	Total Electron Content

List of Daedalus instruments and measurements

M: Main Satellite, S: Sub-satellite



Daedalus ram direction instrumentation

Daedalus Instrumentation

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Daedalus Main Satellite Payload

Instrument	*Measurement*
Ion Drift Meter & Retarding Potential Analyzer *[M]*	Ion drifts, ion density
RAM Wind Sensor & Cross-Track Wind Sensor *[M]*	Neutral winds – Diff. pressure
Ion & Neutral Mass Spectrometers *[M&S]*	Ion & Neutral Composition
Accelerometer *[M&S]*	Neutral density
Energetic Particle Detector Suite *[M&S]*	Precipitating particles
Electric Field Instrument *[M&S]*	Electric fields, electron density
Langmuir Probe *[M&S]*	Electron temperature
Magnetometer *[M&S]*	Magnetic fields
GNSS Receiver *[M]*	Total Electron Content

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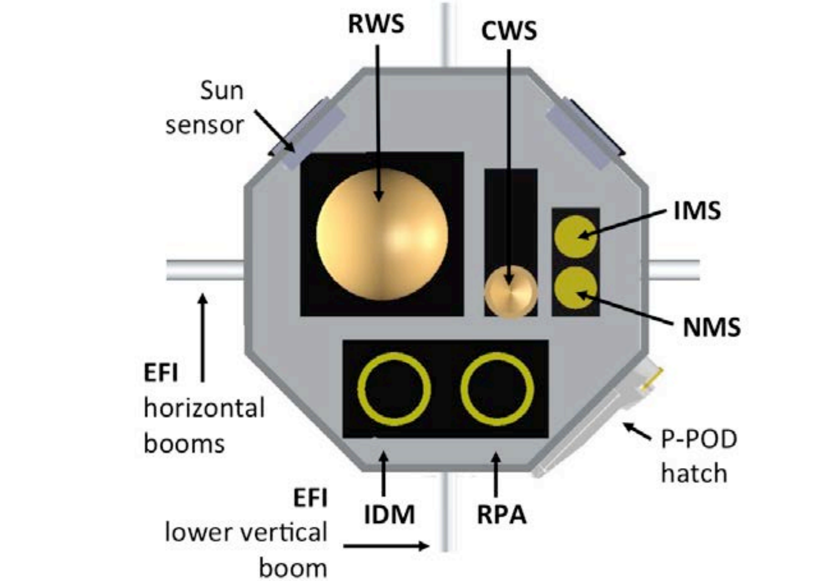
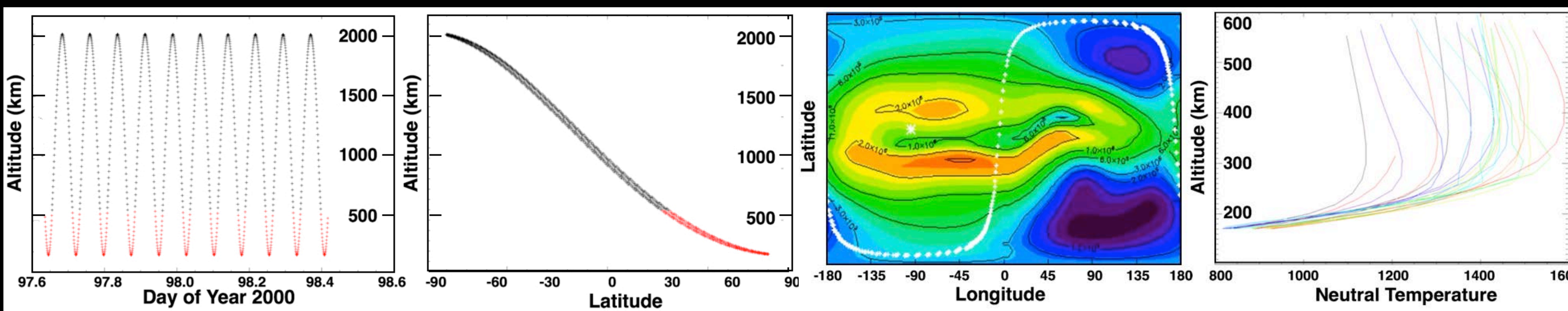


Daedalus ram direction instrumentation

Simulated sampling of the "Ignorosphere" and Joule Heating estimations



Daedalus Instrumentation

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Daedalus Main Satellite Payload

Instrument	*Measurement*
Ion Drift Meter & Retarding Potential Analyzer *[M]*	**Ion drifts, ion density**
RAM Wind Sensor & Cross-Track Wind Sensor *[M]*	**Neutral winds – Diff. pressure**
Ion & Neutral Mass Spectrometers *[M&S]*	**Ion & Neutral Composition**
Accelerometer *[M&S]*	**Neutral density**
Energetic Particle Detector Suite *[M&S]*	**Precipitating particles**
Electric Field Instrument *[M&S]*	**Electric fields, electron density**
Langmuir Probe *[M&S]*	**Electron temperature**
Magnetometer *[M&S]*	**Magnetic fields**
GNSS Receiver *[M]*	**Total Electron Content**

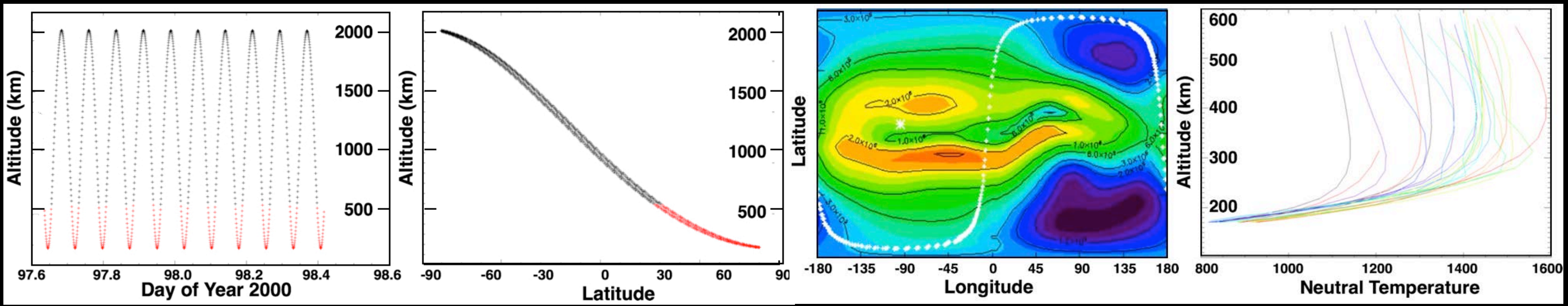
List of Daedalus instruments and measurements

M: Main Satellite, S: Sub-satellite

TRL	*Heritage*	*Required Development*
TRL 6	**DE, DMSP, C/NOFS, Swarm**	**Adjustment of Dynamic Range**
TRL 5-6	**Many; C/NOFS**	**Adjustment of Dynamic Range**
TRL 5-6	**AE, Bepii-Colombo**	**Adjustment of Dynamic Range**
TRL 9	**CHAMP, GRACE, Swarm**	**Identical to heritage missions**
TRL 6	**Many; HEI: VAP/REPT; LEI: rockets**	**Adjustment of Dynamic Range**
TRL 6	**MMS, MAVEN, Parker Solar Probe, DEMETER**	**Many aspects of the electronics stay the same. Heritage boom systems will be used.**
TRL 9	**Roseta/RPC, Swarm**	**Identical to heritage missions**
TRL 9	**Many; Swarm**	**Identical to heritage missions**
TRL 9	**CHAMP, COSMIC, Swarm**	**Identical to heritage missions**

Daedalus instrumentation heritage and required development

Simulated sampling of the "Ignorosphere" and Joule Heating estimations



Next Steps

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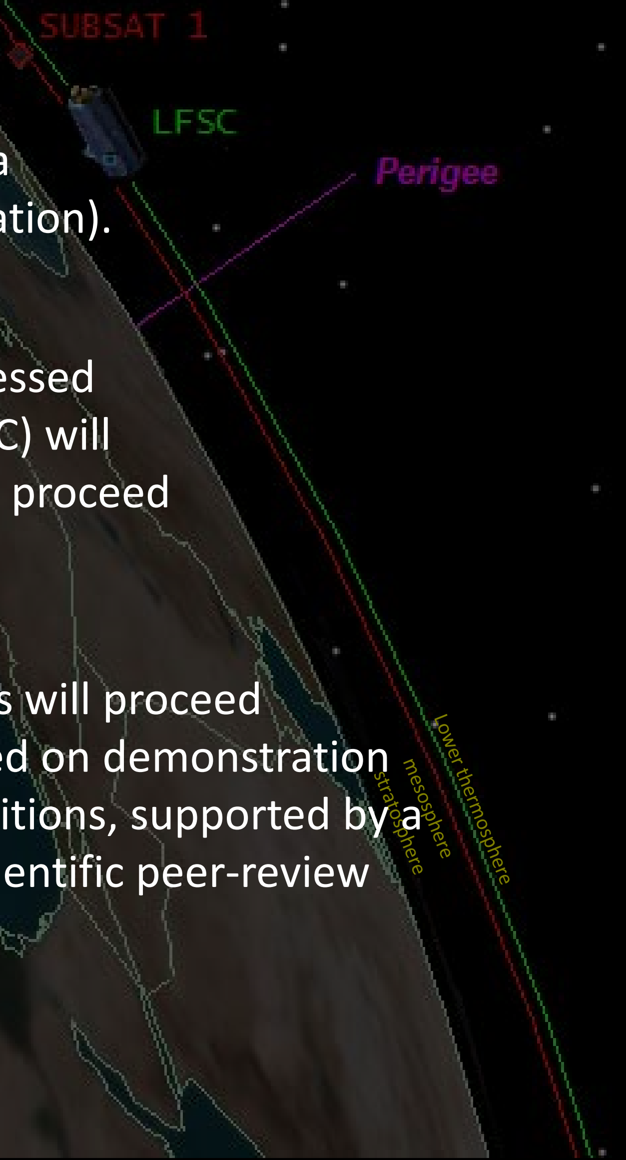
- Daedalus is one of three mission ideas that have been selected as candidates for ESA's 10th Earth Explorer; all three will undergo a Phase-0 study (Mission Analysis/needs identification).

- At the end of Phase-0, each concept will be assessed and the Earth Science Advisory Committee (ESAC) will recommend the two highest ranked concepts to proceed to a Phase-A (Feasibility) study.

- At the end of Phase A, one of the three missions will proceed for full implementation (Phases B/C/D/E1), based on demonstration that the mission respects all the necessary conditions, supported by a public User Consultation Meeting (UCM) and scientific peer-review under the auspices of ESAC.



Traceability Matrix

	Science Questions	Measurement Objectives	Science Results
A. Heating in the MLTI	**Question 1** What is the energy that is deposited into the MLTI via Joule heating and Energetic Particle Precipitation (EPP) and how does it affect the dynamics and thermal structure of the MLTI?	Measure the – neutral winds – ion drifts – neutral and ion temperatures – neutral and ion densities – electric fields – magnetic fields	First systematic, simultaneous measurement of Joule heating and EPP, leading to unambiguous MLTI heating estimates under varying conditions.
A. Heating in the MLTI	**Question 2** What are the spatial-temporal variations in density, composition and temperature at altitudes of 100-200 km, with respect to space weather events	Measure the – winds – drifts – temperatures – densities – particle precipitation	First systematic, simultaneous measurement of key dynamical and energetic parameters in this region leading to quantification of relative factors.
B. Structure of the MLTI	**Question 3** What processes control momentum and energy transport and distribution in the transition region, at 100-200 km altitude in the high-latitude region?	Measure: – O, O_2, N_2, – NO, CO_2 – temperature – O^+, N_2^+, O_2^+, – NO^+	New constituent information by which first principle models may be validated against.
B. Structure of the MLTI	**Question 4** What is the relative importance of the equatorial dynamo in driving the low latitude ionosphere and how do ions-neutrals couple in the low latitude iono-sphere - thermosphere?	Measure: – densities – temperature – electric fields – magnetic fields	Measurements to complement and contextualize recent low-latitude discoveries.
B. Structure of the MLTI	**Question 5** What is the MLTI region's role as a boundary condition to the exosphere above and stratosphere below and how does it affect their energetics and dynamics?	Measure: – densities – temperature – electric fields – magnetic fields – O, O_2, N_2, NO, CO_2 – O^+, N_2^+, O_2^+, NO^+	New measurements that can be used by lower atmosphere models as well as magnetospheric models as boundary conditions.

Questions	Instrument Description	Measurement Requirements	Mission and Spacecraft Requirements
Q1, Q2, Q3, Q4, Q5	**IDM / RPA / RWS / CWS / LP** Ion Drift Meter; Retarding Potential Analyzer; Ram Wind Sensor; Cross-Track Winds; Langmuir Probe	– Measurements below 200 km – Ion drifts – vertical: < 3 m/s – horizontal: < 20 m/s – Along track winds < 20 m/s – Electron density < 300 cm^{-3} – Ion Temperature – Electron Temperature	– High-inclination, dipping orbit – Optical bench for alignment – ±1km altitude registration – RAM direction – Pointing knowl. error < 0.03° – IFOV +/- 45° – Common electronics box – ½ scale height vert. resolution
Q1, Q2, Q3, Q5	**ACC** Accelerometer	– Neutral Density < 20% – Relative density perturb. < 2% – Cross track winds < 20 m/s – Sensitivity: 10^{-7}g, – Dynamic range: 10^{-7}g at 500 km, 10^{-3}g at 120 km	– High-inclination, dipping orbit – Near CoG
Q1, Q4, Q5	**EFI** Electric Field Instrument	– Measurements below 500 km – AC (>10 Hz) – DC electric Fields	– 6 vector booms from s/c: – 4 horizontal booms in X formation in the along-cross-track plane – 2 vertical booms
Q1, Q2, Q5	**EPDS** Energetic Particle Detector Suite	– proton precipitation 30-800 keV – electron precip. 100 eV-800 keV – ENA precipitation 5 keV-200 keV	– Top of spacecraft – Clear FOV
Q1, Q4, Q5	**MAG** Magnetometer	– Currents via magnetic field perturbations	– High-inclination, dipping orbit – May need to be on boom – Cleanliness to 2 nT
Q1, Q3, Q5	**NMS** Neutral Mass Spectrometer	– Neutral composition < 10% – Temperature < 10%	– Ram direction – Outside standoff area – IFOV 5°x10°

Table 5: *Traceability Matrix from Science Questions to Results*

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- End of presentation -