## MOSAIC Concept Study



#### Final report delivered to NASA & NASEM August 7



















#### **MOSAIC**

MARS ORBITERS FOR SURFACE-ATMOSPHERE-IONOSPHERE CONNECTIONS

Mission Concept Study
Planetary Science Decadal Surve

National Aeronautics and Space Administration

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## Mars Orbiters for Surface-Atmosphere-lonosphere **Connections**

Rob Lillis & the MOSAIC team

Presented to the Planetary Science Decadal Survey
2022-2032
Steering Committee 14<sup>th</sup> meeting
May 27, 2021

## **MOSAIC Study Team**



#### Science Team

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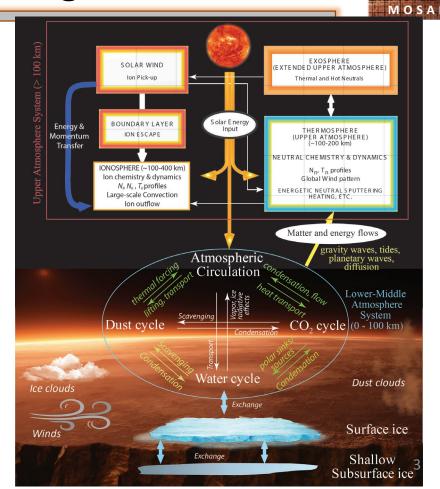
~125 people contributed

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## **MOSAIC Motivating Questions**

- 1. How do volatiles (e.g. H<sub>2</sub>O and CO<sub>2</sub>) move between the subsurface, surface, and atmosphere?
- 2. How does the Martian lower-middle atmosphere respond on meso- and global scales, to the diurnal and seasonal cycles of insolation?
- 3. How does coupling with the lower atmosphere combine with the influence of space weather to control the upper atmospheric system and drive atmospheric escape?

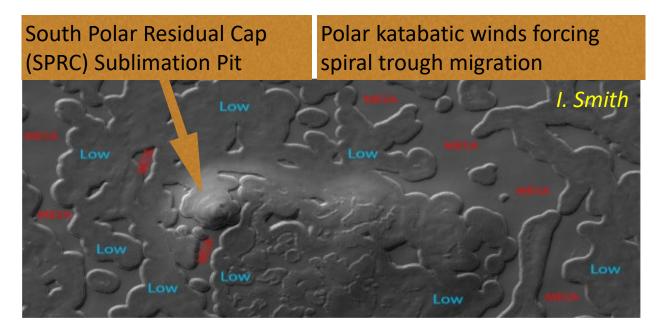


## Ice-Atmosphere interactions



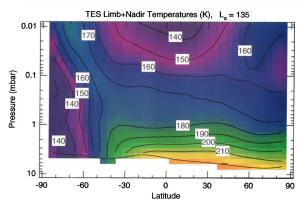
Numerous high latitude processes  $\rightarrow$  surface pressure and distribution of ice on Mars.

- Quantification of their effects is in its relative infancy.
- To adequately characterize surface-atmosphere flux, need simultaneous monitoring of shallow subsurface and surface for changes, and the lower atmosphere for effects.
- SAR and thermal monitoring would detect changes that result from these interactions.



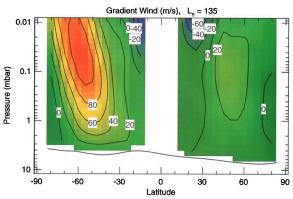
## The Mysteries of Martian Winds





Knowledge of global winds is indirect: estimated from temperature measurements and the thermal wind relationship.





While useful to understand global dynamics, this approach is:

- inappropriate for winds in the tropics.
- far too imprecise for winds in synoptic systems everywhere

Direct measurement of winds are required to move from climatology to true Mars meteorology

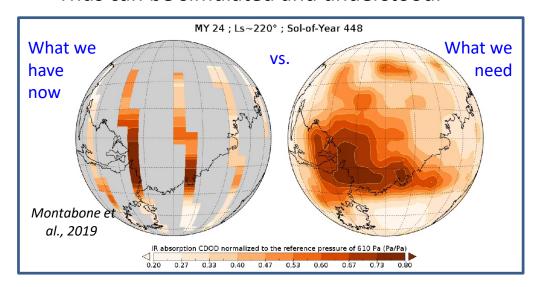
Smith et al. (2001)

## Global Views of Martian weather & climate



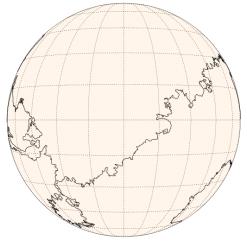
#### **Dust Storm Development and diurnal cycle:**

- Needs to be characterized from a synoptic, near-hemispherical viewpoint
- Thus can be simulated and understood.



Areostationary satellites provide the global perspective necessary to understand the storms

#### What MOSAIC will provide



Column Dust Opacity data from: Montabone et al., JGR, 2020

## Lower/Upper Atmosphere Connections

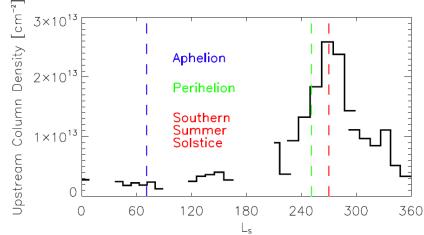


- Measured 10-20x seasonal variability in hydrogen loss to space requires enhanced lower/upper atmosphere interchange. H<sub>2</sub>O transported to high altitudes.
- Mechanism for water transport unknown; multiple competing hypotheses.
- Need simultaneous measurements of the lower & upper atmosphere.

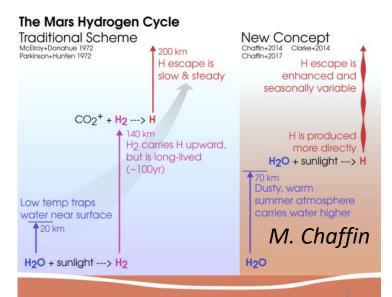
• Once transport mechanism is known, historical H loss (vastly different obliquity) can be

confidently modeled.

**Exospheric hydrogen** 



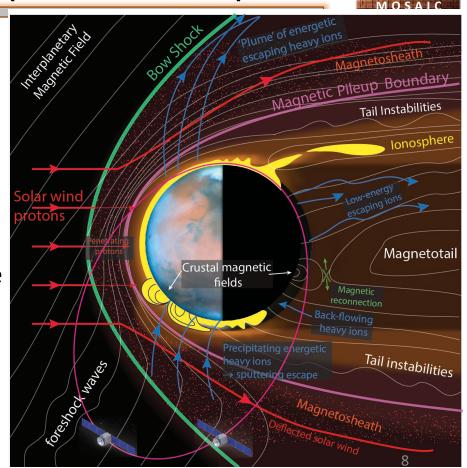
Halekas et al., 2017



## Ionosphere-Magnetosphere & Escape

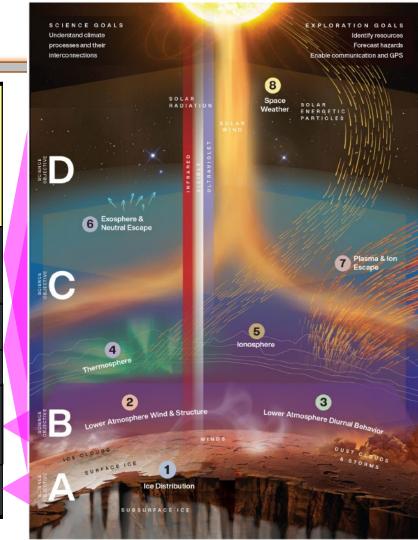
MOSALC

- Crustal magnetic fields create unique "hybrid" magnetosphere.
- Need coordinated multipoint in situ plasma measurements to:
  - Untangle spatial & temporal variability.
  - Measure real-time response to space weather.
  - Unravel chain of cause and effect as sun and solar wind energize ions to escape and precipitate.



## **Science Traceability**

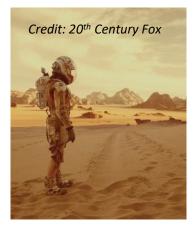
MOSAIC GOALS	Mission Objectives	Inv	estigations:	1. Ice distribution	2. Atmosphere structure	3. Atm. Diurnal behavior	4. Thermosphere	5. Ionosphere	6. Exosphere/neutral esc	7. Plasma /ion escape	8. Space weather
I. Understand Mars's present day	in the upstream throughout the	n sola e magr ere, se	netosphere and eparating spatial					<b>√</b>	<b>√</b>	<b>√</b>	<b>√</b>
climate processes and their	I.C: Correlate variability in the thermosphere,		The space weather environment				✓	✓	✓	<b>√</b>	✓
inter- connections,	ionosphere, an escape rates to		The lower-middle atmosphere.		✓	✓	✓	✓	<b>√</b>	$\checkmark$	
from the sub-surface to the solar wind	atmosphere on	e Mar meso	structure and tian lower-middle o- and global scales, iurnal, and seasonal		<b>√</b>	<b>√</b>					
	I.A: Characteriz between the su atmospheric re	ıbsurf	ace, surface and	✓	✓	✓					



## Preparing for Human Exploration



MOSAIC GOALS	Exploration Objectives	Investigations	1. Ice distribution	2. Atmosphere structure	3. Atm. Diurnal behavior	4. Thermosphere	5. Ionosphere	6. Exosphere/neutral esc	7. Plasma /ion escape	8. Space weather	9. Tech Demonstration
II. Identify hazards,	Characterize potent ice resources to sup	cially extractable water oport ISRU.	✓								
characterize resources,	Allow accurate data weather forecasting			<b>√</b>	✓						
and demonstrate	Characterize neutra mesosphere/therm	ll winds in the osphere for aerobraking.				<b>√</b>					
technologies to enable the Human		rariability to mitigate communication and					✓		✓	<b>√</b>	
Exploration of Mars.	Demonstrate high-le communication bet orbit, and Earth.	oandwidth ween Mars surface, Mars									✓
	Characterize the en penetrating ions (> AU.	vironment of 10 MeV/nuc) at 1.4-1.6								✓	



<u>Relevant to NASA Exploration Goals.</u> knowledge gap-filling activities identified by Precursor Strategy Analysis Group (PSAG):

- Ice depth variation within the first meter (for drinking water & propellant synthesis). Activity D1-5, D1-6.
- 2. Weather forecasting: dust climatology (B1-1), model validation (A2-1), global-scale temperatures, wind, & aerosols (A1-1, A1-2, A1-3).
- 3. Communications & GPS: high-bandwidth comms (A4-2), delay-tolerant networking, Global positioning, and continuous Earth comm with all longitudes.

#### **Goals to Investigations**

**OBJECTIVES** SCIENCE OBJECTIVES

A Characterize volatile cycling

Characterize the structure and

dynamics of the Martian lower-

middle atmosphere on meso- and

global scales, and its geographic,

Conditions in

atmosphere.

The space

environment.

..

weather

the lower-middle

diurnal, and seasonal variability.

D Characterize fields and plasma

Characterize potentially ex-

Characterize the Mars atmo-

spheric state with sufficient spatial

sampling and cadence to allow

accurate data assimilation and

Characterize neutral winds in the

sphere (60 km-130 km) and their

variability with lower atmospheric conditions and solar activity.

Characterize the Mars ionospheric

state and variability sufficiently to determine its likely disruptive

effect on communications and

Characterize the environment of

penetrating ions (>10 MeV/nuc) at 1.38-1.62 AU with season and

Communication (DSOC), and re-

lay communication between Mars surface, Mars orbit, and Earth,

Demonstrate delay-tolerant networking, Deep Space Optical

positioning.

solar cycle.

mesosphere and lower thermo-

weather forecasting.

tractable water ice resources to support in situ resource utilization.

flows in the upstream solar wind

spatial from temporal variability. **EXPOLORATION OBJECTIVES** 

and throughout the magnetosphere and upper ionosphere, separating

variability in the

thermosphere,

ionosphere.

and escape

between the subsurface, surface and atmospheric reservoirs.

## **MOSAIC** Traceability

#### SCIENCE GOALS EXPLORATION GOALS Understand climate Identify resources processes and their Forecast hazards interconnections Enable communication and GPS 8 SOLAR RADIATION ENERGETIC PARTICLES Neutral Escape Plasma & Ion Atmosphere Wind & Structure Lower Atmosphere Diurnal Beha SURFACE ICE Ice Distribution UBSURFACE ICE

#### **Investigations to Instruments**

Table 1-2

	INVESTIGATIONS	MEASUREMENTS	INSTRUMENTS+	FUNCTIONAL REQUIREMENTS
1	Measure the three-dimensional distribution of ice from the surface to 10 m below.	Subsurface ice abundance derived from dielectric constant     Surface thermal inertia     Surface water ice & albedo	P-band SAR & Sounder     Visible imager	<400 km circular near-polar orbit. Hi mass and powe
2	Measure the geographic and altitude distribution of pressure, winds, aerosol concentrations, water vapor, ozone, and temperatures in the Mars lower and middle atmosphere.	Vertical profiles (0-80 km) of: temperature, winds, dust, H2O and CO2 ices, H2O vapor, O3 Surface temperature and pressure	Thermal IR radiometer     Wind LIDAR     Sub-mm sounder	<400 km circular near-polar orbit
3	Measure the complete diumal and geographic behavior of the atmo- sphere and evolution of Martian dust and ice clouds.	Visible and/or UV imagery of clouds/hazes Column opacities/abundances of dust, H2O, ozone, and CO2 ice Temp/pressure profiles 0 - 40 km	Visible imager Near IR spectrometer Thermal IR radiometer Radio occultation	Four Areostational orbits, spaced evenly in longitude
		Vertical profiles (0-80 km) of temperature, dust, H2O and CO2 ices, H2O vapor, spread evenly across 8 local times		Four <400 km circular near-polar orbits, spaced evenly in local time
4	Measure the global 3-D composition, structure, and winds in Mars's thermosphere.	Vertical profiles (90 - 200 km) of: • Horizontal wind velocity • Density and temp. of O, CO, N2, CO2	Wind Doppler inter- ferometer     FUV/MUV spectro- graph	<400 km circular near-polar orbit
5	Measure the global 3-D structure of Mars ionosphere.	Vertical profiles (90-400 km) of: • electron density • electron temperature	Langmuir probe     Radio Occultation	< 400 km circular AND elliptical orbit < 170 km periapse
6	Measure the 3-D density and temperature structure of Mars's hydrogen and oxygen exospheres.	Vertical profiles (200 - 30,000 km) of: • O density and temperature • H density and temperature	FUV/EUV spectro- graph	Circular orbit >10,000 km altitud
7	Measure (from multiple viewpoints) fluxes of light and heavy ions, magnetic field and topology, plasma waves, and electric fields within and between all regions of Mars' hybrid magnetosphere.	Magnetic field Electric field Suprathermal electron pitch angle distributions magnetic topology I on mass, energy, and angular distributions. Thermal electron temperature and density Plasma waves	Fluxgate magne- tometer     Search coil magne- tometer     lon energy/angle/ mass     Electron energy/ angle     Electric fields	2 spacecraft Orbit inclination ~75°, Apoapsis >6000 km, <170 km periapse
8	Measure magnetic field and plasma conditions in the upstream solar wind, and solar extreme ultraviolet irradiance.	Magnetic field     Solar wind density, speed, temp     Solar EUV irradiance     Solar Energetic Particle Flux	Fluxgate Magne- tometer     Ion energy/angle     Electron energy/ angle     Extreme UV monitor     Energetic ion/electron	2 spacecraftCircul orbit >10,000 km altitude
9	formance onboard process	t networking (DTN), high-per- sing, high-bandwidth optical usly available relay communi- ce and Farth via relay.	Electra/Relay antennas     Optical communication     DTN protocols	All

MOSAIC

GOALS

SCIENCE

Mars's

climate processes

and their

from the

connections.

sub-surface

to the solar

**EXPLORATION** 

hazards

es, and demonstrate

characterize resourc-

technologies

to enable the Human

Exploration of Mars.

Understand

present day

KEY MOTIVATING

How do volatiles move

between the subsur-

Martian lower-middle

atmosphere respond

global scales, to the

How does coupling

from the lower atmo-

sphere combine with

the influence of space

SEPs, and solar EUV)

atmospheric system++ and drive atmospheric

How, where, and when

can future astronauts

water ice resources?

With what degree of

accuracy can Martian

How will mesospheric

winds affect aerobrak-

How will space weath-

er effects on the Mars

surface-orbit communi-

particle radiation affect

Can reliable high-band-

ionosphere affect surface-surface and

How will energetic

astronauts in Mars

width Earth-Mars communication be

maintained?

weather be forecast,

for operational pur-

and thermospheric

ing spacecraft?

poses?

access extractable

weather (solar wind,

to control the upper

seasonal cycle of

insolation?

escape?

diumally, on meso- and

face, surface, and

atmosphere?

How does the

QUESTIONS

## Science drives mission architecture

ELLIPTICAL

PLATFORM

AREO

SMALLSAT B

Areo Smallsat B1

Areo Smallsat B 2

Elliptical Orbiter 1

Elliptical Orbiter 2

Electron energy/angle

Fluxgate Magnetometer

Ion energy/angle/mass

Electric Fields

magnetometer

Radio Occultation Langmuir Probe

**NIR Spectrometer** 

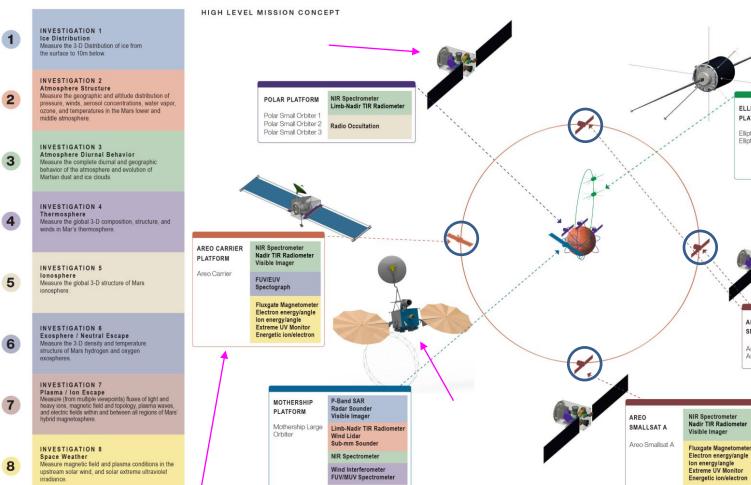
Visible Imager

+ Refer to 3.1, B.1.4, D.1 for detailed

information on instruments

Nadir TIR Radiometer

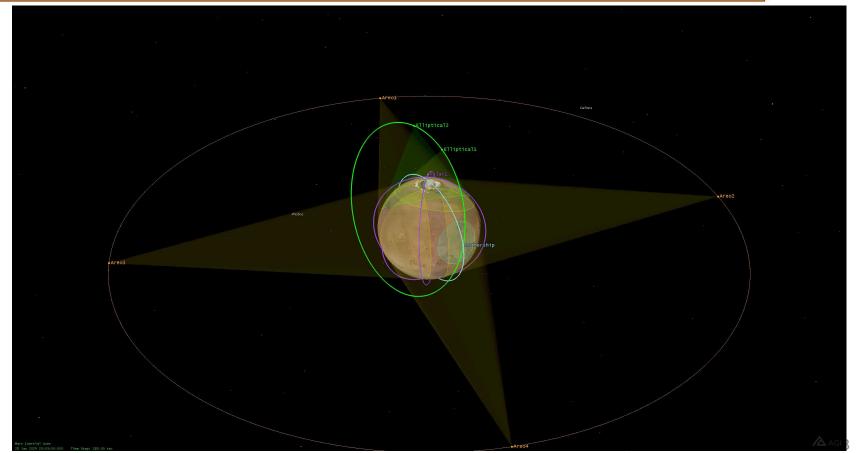
Search coil



Radio Occultation

## MOSAIC constellation movie

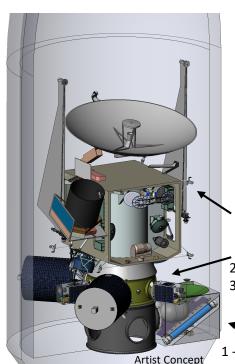




### **MOSAIC** Architecture

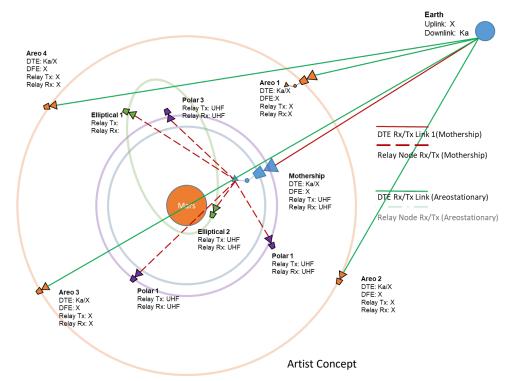


#### MOSAIC By the Numbers



- 10 Spacecraft Elements
- 49 Science Instruments
- 3 Orbital Perspectives
- 1 Launch Vehicle
- 1 Large Orbiter
- 2 Elliptical ESPA-Class S/C
- 3 Polar ESPA-Class S/C
- 1 Areostationary ESPA Class
- 3 Small Areostationary S/C

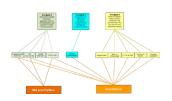
#### **MOSAIC Telecommunications Architecture**



#### MOSAIC cost can spread over 3 Mars launch opportunities

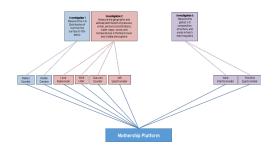


#### Spacecraft delivery via rideshare or propulsive tug element



- 4 Areostationary SSc
- Delivered via rideshare low DV prop capability
- Commercial SSc Builder (target <40M per ssc bus)
- DTE Using Iris and commercial antenna
- Optional: relay capability for future low Mars orbiters





- 4-5 SSc
- Delivered via rideshare very low DV prop capability
- Commercial SSc Builder (target <25M per SSc bus)</li>
- Relay using exisiting relay network including Areo network

Icemapper or another mission

2026

2028

## **MOSAIC Cost & Descopes**



Platforms:			N	1othersh	nip			Polar SmallSa			otical IISats		eostation Satellit		Traditional cost	Newspace cost*	Preserves	Loses
Instrument:  Numbers of each instrument	P-band Radar		Sounder	Doppler Interfer- ometer	FUV/MUV Spectrogr aph	TIR** radiometer Visible Camera NIR Spectr.		Mini TIR radiometer NIR spectrometer	Radio Occultati -includes mothersl	ion sp	phere lasma	EUV/FUV Spectro- graph		Mini TIR radiometer Viz. camera NIR spectr.	FY25 \$M, 50% A-D, 25% E-F (30% A-D, 15% E-F)	FY25 \$M, 50% A-D, 25% E-F (30% A-D, 15% E-F)		
Investigation	1	2	2	4	4	1,2		2, 3	3, 5	5,	, 7	6	8	3				
Baseline (in final report)	1	1	1	1	1	1	1	3	6		2	1	2	4	4,220 (3,719)	4,060 (3,581)	Full MOSAIC Capability	
No Ice Mapping		1	1	1	1	1	1	3	6		2	1	2	4	3,436 (3,034)	3,277 (2,896)	Full top to bottom atmosphere sampling	Exchange of water with subsurface
Descope 1			1			1	1	3	6		2	1	2	4	3,073 (2,722)	2,910 (2,581)	Comprehensive lower atmosphere sampling	Above + Thermosphere + Winds except 10-80 km
Descope Lite			1			1**	1	2	4		1	1	1	3	2,409 (2,212)	1,484 (1,364)	Adequate lower atmosphere sampling	Above + Full diurnal coverage + lon escape short variability + Full space weather coverage
Threshold Plus			1			1**							1	3	1,445 (1,332)	911 (841)	Global/diurnal perspective with winds and ground truth (i.e. side & top views of same atmosphere column)	Above + Boundary layer + Ionosphere + Magnetosphere +Exosphere & neutral escape
Threshold						1 **								3	1,023 (942)	620 (571)	Global/diurnal perspective plus ground truth	Above + Winds + Space Weather
Threshold Class D						1 **								3	561 (514)	376 (344)***	Global/diurnal perspective plus ground truth	Class B reliability

<sup>\*</sup> Low end of triangular distribution from final report.

<sup>\*\*</sup> TIR radiometer could be AMCS (9 kg, 18 W) in higher cost cases or mini-MCS (3.5 kg, 8 W) in lower cost cases.

<sup>\*\*\*</sup> SIMPLEX-style costing results in ~50% lower costs [not a JPL estimate].

## MOSAIC: Sharing the Burden



#### **HEOMD** may fund:

- Ice mapping
- Weather monitoring.
- X-band surface to areostationary relay comm.
- Radiation monitoring



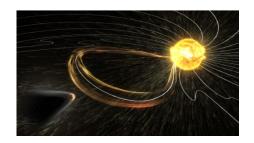
#### STMD may fund:

- Delay-tolerant networking
- High-bandwidth Earth-Mars communications.



#### Heliophysics Division may fund:

- Space weather monitoring
- Magnetosphere measurements (e.g. ESCAPADE is funded by HPD)



NASA SMD divisions & other directorates

#### Other space agencies:

- All copies of one instrument
- All copies of one platform
- Active coordination only required for occultations



European Space Agency







#### Commercial partners:

SpaceX May wish to partner with HEOMD.





## Mars Science: separate treatment?



Mars & Lunar science is in a different category. Much more mature than other planets.

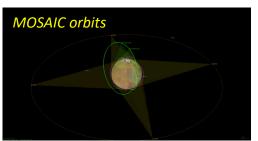
- (mostly) past discovery phase.
- Well into "characterization & understanding" phase. Target for human exploration.
- Arguably should be treated separately from a strategic & funding perspective?

	Flybys	Orbiters	Probes+Landers	Rovers &/or Crew	Aircraft	Networks
Mercury	Few	1				
Venus	Many	4	Few short-lived			
Earth	N/A	hundreds	millions	millions	thousands	many
Moon	Many	43	22	10	N/A	
Mars	Many	16	10	5	1	
Jupiter	4	2	1			
Jupiter moons	Few each					
Saturn	3	1				
Saturn moons	Many		1			
Uranus + moons	1					
Neptune+moons	1					
Pluto & KBOs	1					18

### The Case for MOSAIC



- MOSAIC represents a quantum leap in our understanding of the Mars climate system.
  - Simultaneous observations of climate regions will reveal motion of matter/energy within/between them.
  - 1st time global wind characterization.
  - Help prepare for human exploration.
- Full Constellation has a high price tag, however:
  - Mars orbiter heritage reduces need for reserves.
  - Other missions' simultaneous observations can help.
  - Cost-sharing with HEOMD, STMD, HPD, private sector.
  - Contributions from other agencies (instruments, SC).
  - Threshold mini-constellation (4 SC) fits within Discovery or less, depending on mission class.





MOSAIC in Single 5 m fairing



## Backup:

## Can other missions substitute pieces?



• Existing/planned spacecraft can fulfill aspects of MOSAIC Investigations, but only if measurements are simultaneous.

Mission Status	Missions & Instruments	Investigations:	1. Ice distribution	2. Atmosphere structure	3. Atm. Diurnal behavior	4. Thermosphere	5. Ionosphere	6. Exosphere, neutral escape	7. Plasma & ion escape	8. Space weather
Operational or	Mars Reconnaissance Orbi	ter MCS (2005-								
In	MAVEN Particles & Fields	Package (2013-								
Development	MAVEN IUVS (2013-									
	Trace Gas Orbiter NOMAD	(2016-								
	Emirates Mars Mission EX	I, EMUS, & EMIRS (2021-								
	China Tianwen-1 ion analy	zer & magnetometer (2021-								
	NASA ESCAPADE (2026-	*not confirmed								
	JAXA-ESA MMX MacrOmega, MSA, & IREM (2025-2028)									
Concepts	Ice Mapper									
	COMPASS									

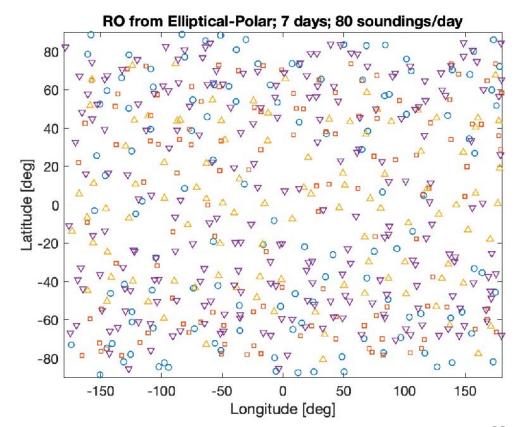
#### Fulfillment:

Baseline						
Adequate						
Partial						
Marginal						
None						

## Radio Occultations probe PBL & Ionosphere



- Occultations provide:
  - Planetary boundary layer pressure/temperature profiles.
  - Ionospheric density profiles.
- Pre-MOSAIC: Singlespacecraft-to-earth occultations extremely limited by cadence and geometry.
- MOSAIC's inter-spacecraft links provide unprecedented remote sensing of the PBL and ionosphere.





## Backup: MOSAIC Descope Option Charts

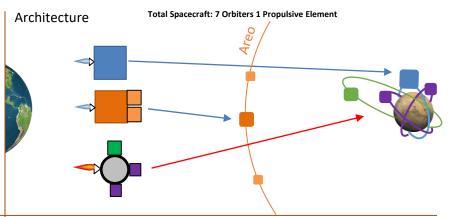
## Descope Lite



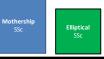
Platforms:	Mothership					Polar Elliptical SmallSats SmallSats			Areostationary Satellites					
Instrument	P-band Radar	Wind LIDAR	Sub-mm Sounder	Interfer-	ph	TIR radiometer Visible Camera NIR Spectr.	У	radiometer NIR	Radio Occulta (include mothers	tion s	sphere Plasma		Weather Package	Mini TIR radiometer Viz. camera NIR spectr.
Investigation	1	2	2	4	4	1,2		2, 3	3, 5		5, 7	6	8	3
Descope Lite			1			1 **	1	2	4		1	1	1	3

Preserves: Adequate lower atmosphere sampling

Loses: Exchange of water with subsurface. Thermosphere Winds except 10-80 km Full diurnal coverage Ion escape short variability Full space weather coverage



#### **Platforms**











Platform	Mothership	Elliptical	Polar	Areo Carrier*	Areo B	Prop. Element
# of Spacecraft	1	1*	2*	1	2	1
# of Instruments	5	6	3	7	3	0
Spacecraft Analogue	Areo Carrier;	No change from report				
Payload Mass (kg)	41	20	4.2	34	4.2	n/a
Data Volume (Gb)	10.8^	0.5	1.4	16.2	0.3	
Spacecraft Wet Mass (kg)	800^	235	92	800	92	~1200
Orbit	300 km x 92.8°	1500 x 6000 km x 75°	300 km x 92.8°	17031 km x 0°	17031 km x 0°	
ΔV Budget (m/s)	7500^	500	250	5000	50	~2000
Telecom. Architecture	DTE; Ka Band	Relay to MS	Relay to MS	DTE; Ka Band	DTE	DTE X-Band

#### Cost/Risk

	Traditional	NewSpace†				
	FY25(\$M),50% A-D cst					
Flight System Total	710	435				
Other Costs	1549	949				
Total w/o LV	2259	1384				
Launch Vehicle	150	100				
Total	2409	1484				

	Traditional	NewSpace1
	FY25(\$M),3	0% A-D cst rs
Flight System Total	710	435
Other Costs	1352	829
Total w/o LV	2062	1264
Launch Vehicle	150	100
Total	2212	1364

	Traditional	NewSpace†
	FY25	(\$M)
Mothership WBS6	133	60
Mothership Payload	53	53
Elliptical 1 WBS6	42	19
Elliptical 1 Payload	29	29
Polar 1 WBS6	32	14
Polar 1 Payload	8	8
Polar 2 WBS6	19	8
Polar 2 Payload	5	5
AreoCarrier WBS6	133	60
AreoCarrier Payload	61	61
AreoB 1 WBS6	32	14
AreoB 1 Payload	30	30
AreoB 2 WBS6	19	8
AreoB 2 Payload	18	18
PropElement 1 WBS6	60	30
PropElement 2WBS6	36	18
Flight System Total	710	435

Cost estimates at CML3, use payload costs from final report, use chemical propellant cruise stage cost estimates from recent similar studies, and estimate the ratio of flight hardware cost to total cost w/o LV from final report numbers (other costs).

† low end of triangular distribution numbers from final report appendix

Note: Assumes a Falcon Heavy reusable similar to Psyche LV 24

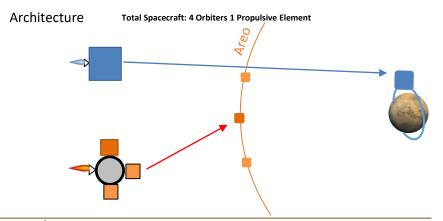
### Threshold Plus



Platforms:			М	othersh	ip			Polar SmallSa			iptical allSats			
	P-band Radar	Wind LIDAR	Sounder	Doppler Interfer- ometer	Spectrogra ph	TIR radiometer Visible Camera NIR Spectr.	У	radiometer NIR	Radio Occulta (include mothers	tion s	sphere Plasma	Spectro-	Weather	Mini TIR radiometer Viz. camera NIR spectr.
Investigation	1	2	2	4	4	1,2		2,3	3, 5		5, 7	6	8	3
Threshold plus wind & space weather			1			1**							1	3

Preserves: Global/diurnal perspective with winds and ground truth (i.e. side & top views of same atmosphere column)

Loses: Above +
Boundary layer
Ionosphere
Magnetosphere
Exosphere & neutral escape



#### **Platforms**









Platform	Mothership	Areo A^	Areo B	Prop. Element
# of Spacecraft	1	1	2	1
# of Instruments	5	6	3	0
Spacecraft Analogue	Areo Carrier;	No change from report	No change from report	
Payload Mass (kg)	41 ^	12	4.2	n/a
Data Volume (Gb)	10.8^	1.53	0.3	
Spacecraft Wet Mass (kg)	800	95^	92	~1200
Orbit	300 km x 92.8°	17031 km x 0°	17031 km x 0°	
ΔV Budget (m/s)	7500	5000	50	~2000
Telecom. Architecture	DTE; Ka Band	DTE	DTE	DTE X-Band

#### Cost/Risk

	Traditional	NewSpace†
	FY25(\$M),	50% A-D est rsv
Flight System Total	407	255
Other Costs	888	556
Total w/o LV	1295	811
Launch Vehicle	150	100
Total	1445	911

	Traditional	NewSpace†
	FY25(\$M),3	0% A-D cst rsv
Flight System Total	407	255
Other Costs	775	486
Total w/o LV	1182	741
Launch Vehicle	150	100
Total	1332	841

	Traditional	NewSpace†
	FY25	(\$M)
Mothership WBS6	133	60
Mothership Payload	53	53
AreoA 1 WBS6	35	15
AreoA 1 Payload	27	27
AreoB 1 WBS6	32	14
AreoB 1 Payload	30	30
AreoB 2 WBS6	19	8
AreoB 2 Payload	18	18
PropElement 1 WBS6	60	30
Flight System Total	407	255

Cost estimates at CML3, use payload costs from final report, use chemical propellant cruise stage cost estimates from recent similar studies, and estimate the ratio of flight hardware cost to total cost w/o LV from final report numbers (other costs).

† low end of triangular distribution numbers from final report appendix

Note: Assumes a Falcon Heavy reusable similar to

Psyche LV

## **Threshold**



Platforms:		Mothership				Polar SmallSa			iptical allSats					
	P-band Radar	Wind LIDAR	Sub-mm Sounder	Interfer-	ph	TIR radiometer Visible Camera NIR Spectr	У	radiometer NIR	(includ	ation les		Spectro-	Weather Package	MiniTIR radiometer Viz. camera NIR spectr.
Investigation	1	2	2	4	4	1,2		2, 3	3, 5		5, 7	6	8	3
Threshold						1**								3

Preserves: Global/diurnal perspective plus ground truth

Loses: Above + Winds Space Weather

# Architecture Total Spacecraft: 4 Orbiters 2 Propulsive Element

#### Platforms



Platform	Mothership	Areo B	Prop. Element
# of Spacecraft	1	3	2
# of Instruments	3	3	0
Spacecraft Analogue	No change from report	No change from report	
Payload Mass (kg)	4.2	4.2	n/a
Data Volume (Gb)	1.4	0.3	
Spacecraft Wet Mass (kg)	92	92	~1200
Orbit	300 km x 92.8°	17031 km x 0°	Platform Specific
ΔV Budget (m/s)	250	50	~2000
Telecom. Architecture	DTE	DTE	DTE X-Band

#### Cost/Risk

	Traditional	NewSpace†
	FY25(\$M),5	0% A-D cst rsv
Flight System Total	290	176
Other Costs	633	384
Total w/o LV	923	560
Launch Vehicle	100	60
Total	1023	620

	Traditional	NewSpace†
	FY25(\$M),3	0% A-D cst rsv
Flight System Total	290	176
Other Costs	552	335
Total w/o LV	842	511
Launch Vehicle	100	60
Total	942	571

	Traditional	NewSpace†
		(\$M)
Polar 1 WBS6	32	14
Polar 1 Payload	8	8
Polar 2 WBS6	19	8
Polar 2 Payload	5	5
AreoB 1 WBS6	32	14
AreoB 1 Payload	30	30
AreoB 2 WBS6	19	8
AreoB 2 Payload	18	18
AreoB 3 WBS6	13	5
AreoB 3 Payload	18	18
PropElement 1 WBS6	60	30
PropElement 2WBS6	36	18
Flight System Total	290	176

Cost estimates at CML3, use payload costs from final report, use chemical propellant cruise stage cost estimates from recent similar studies, and estimate the ratio of flight hardware cost to total cost w/o LV from final report numbers (other costs).

† low end of triangular distribution numbers from final report appendix

Note: Assumes a Falcon 9 reusable

### Threshold Class D



Platforms:	Mothership						Polar SmallSa		iptical allSats	Areostationary Satellites				
	P-band Radar	Wind LIDAR	Sounder	Interfer-	ph	TIR radiometer Visible Camera NIR Spectr.	У	radiometer NIR	Radio Occultatio (includes mothership		sphere Plasma		Weather Package	MiniTIR radiometer Viz. camera NIR spectr.
Investigation	1	2	2	4	4	1,2		2, 3	3, 5		5, 7	6	8	3
Threshold Class D						1**								3

Preserves: Global/diurnal perspective plus ground truth

Loses: Class B reliability

#### Architecture







#### **Platforms**



Platform	Mothership	Areo B
# of Spacecraft	1	3
# of Instruments	3	3
Spacecraft Analogue	No change from report	No change from report
Payload Mass (kg)	4.2	4.2
Data Volume (Gb)	1.4	0.3
Spacecraft Wet Mass (kg)	92	92
Orbit	300 km x 92.8°	17031 km x 0°
ΔV Budget (m/s)	250	50
Telecom. Architecture	DTE	DTE

#### Cost/Risk

	Traditional	NewSpace†
	FY25(\$M),5	0% A-D cst rsv
Flight System Total	170	115
Other Costs	371	251
Total w/o LV	541	366
Rideshare*	20	10
Total	561	376

	Traditional	NewSpace†
	FY25(\$M),3	0% A-D cst rsv
Flight System Total	170	115
Other Costs	324	219
Total w/o LV	494	334
Rideshare*	20	10
Total	514	344

Traditional	NewSpace†				
FY2	5(\$M)				
32	14				
8	8				
32	14				
30	30				
19	8				
18	18				
13	5				
18	18				
	FY2 32 8 32 30 19 18				

Cost estimates at CML3, use payload costs from final report, use chemical propellant cruise stage cost estimates from recent similar studies, and estimate the ratio of flight hardware cost to total cost w/o LV from final report numbers (other costs).

- † low end of triangular distribution numbers from final report appendix
- \* Assumes the spacecraft is deployed at Mars in the final orbit required\_

#### Comments and Observations (Study lead S. Matousek)



- Descope options beyond "Descope 1" from final report cost estimates are at CML3 with larger uncertainty, though largely based on final report design team estimates
- Recommend further study to engage with commercial small spacecraft bus providers to understand cost savings using commercial buses and commercial propulsive tugs (e.g. propulsive ESPA) to support the payloads.
- The descope options (except "descope 1" in the PMCS study report) are all ESPA class or smaller spacecraft form factors. These smallsat platforms could also be accommodated as a rideshare on a Mars-bound rocket.
- If a communications infrastructure was in place prior to placement of the
  constellation the cost savings would be realized in the telecom transceiver for
  direct-to-earth (DTE), reduction of antenna diameter, and reduction or removal of
  any antenna pointing mechanisms. This cost savings is likely small for MOSAIC.

## PI (R. Lillis) Perspective on SIMPLEX costing



- JPL NewSpace cost estimate of \$376M for Threshold Class D is > 2x higher than the existing SIMPLEX missions' \$55M costs would imply.
- If SIMPLEX missions turn out to be viable, then smallsat Mars constellations could be significantly lower cost.

	# small SC	Payload mass	A-E cost
Trailblazer	1	~15 kg	\$55 M
Janus	2	<4 kg	\$55 M
ESCAPADE	2	8 kg	\$55 M
MOSAIC Threshold Class D	4	4.8 kg	\$376 M

<sup>\*</sup>NOTE: Opinion of PI only. Does not reflect the opinion of JPL.



## Backup: MOSAIC Relevance and Rationale

## **MOSAIC Science Impact**



Simultaneous measurements of all "regions" of the climate system will:

- Characterize geographic, diurnal, mesoscale, and seasonal behavior.
- Lead to groundbreaking improvements in our understanding of how climate variables correlate with one another.
  - I.e. uncover how different parts of the climate system "talk" to each other.
- Spur understanding of the physical processes occurring within and between regions.

Charcterizing the effect of $\downarrow$ on $\rightarrow$ :			<b>\</b>	Ice		Lower Atmosphere structure Thermo- sphere			-	lono- sphere			Exosp here		Magn etosp here		Space weather drivers						
MOSAIC will enable, w.r.t. current/planned observations:		ne?	es.				ates									l escape		a				S	
Groundbre	_		alo	ırfa		e e		lens	ပ္သ	e e		so					utra		scap				icle
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Significant	Improven	nent	teri	N St	١,,	pre		2/	ĮŽ,	pre	siti	dyn	den	siti	ics	ıre	ics/	spi	8 0	vina		3	tic
Incremental Improvement		Characterized alone?	Shallow Subsurface	Surface	Temp, pressure	Dust	H2O (g) /condensates	Wind/dynamics	Temp, pressure	Composition	Wind/dynamics	Temp, density	Composition	Dynamics	Structure	Dynamics/Neutral	E, B Fields	Flows & ion escape	Solar wind	IMF	Solar EUV	Energetic Particles	
Ice	Shallow subsurfac	e	В		BPPB First systematic observations of subsurface material propert						/	Areostation observatio											
	surface		1	В		В	В	1	Р											_			
Lower Atmo- sphere	Temp, pre	essure	1	В	1		1	1	В	В	В	Ρ	В	В	Р	В	В	Ρ	Р	1			tema nosph
	Dust		ı	Р	В	I		В	Ρ	В	В	Ρ	В	В	Р	В	В	Ρ	Р	Ш		wii	nd .
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5	Structure		1		Tex				inuo	us			1	1	В		В	В	В				
Exosphere	Neutral E	scape	В	L,				oring		Ľ			В	В	В	В		В	В				
Magnetos	E, B fields		1				ated Iasm			В	В	Ρ	В	В	В	В	В		В				
phere	Flows & id		1	L			men		-	В	В	P	В	В	В	В	В	В					
C	Solar win	d	М				ie so			В	В	Ρ	В	В	В	В	В	В	В				
Space	IMF		М				& IMI			В	В	Ρ	В	В	В	В	В	В	В				
weather	Solar EUV		М	L						1	1	Р	1	1	P	1	В	В	В				
drivers	Energetic Particles		М					Р		В	В	P	В	В	Р								
Current degree of understanding enabled by Mostly We available understood		Vell-		(I)In at le impe	ast	one			(B) Basic understanding but many issues remain						(P) Poor understanding and/or based solely on models.				ls.	di	rect	ctio	



<u>MEPAG.</u> Goal II "Understand the processes and history of climate on Mars":

- A1. Constrain the processes that control the present distributions of dust, water, & carbon dioxide in the lower atmosphere, at daily, seasonal & multi-annual timescales.
- A2. Constrain the processes that control the dynamics & thermal structure of the upper atmosphere & surrounding plasma environment.
- A4. Constrain the processes by which volatiles & dust exchange between surface & atmospheric reservoirs.
- **C3.** Determine present escape rates of key species & constrain the processes that control them.

#### Mars Science Goals, Objectives, Investigations, and Priorities: 2020 Version

Mars Exploration Program Analysis Group (MEPAG)

#### **Prepared by the MEPAG Goals Committee:**

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Representing Goal I: Determine If Mars Ever Supported, or Still Supports, Life
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Representing Goal II: Understand The Processes And History Of Climate On Mars

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**2013-2022 Decadal Survey** calls for a mission like MOSAIC, stating:

"Fundamental advances in our understanding of modern climate would come from a complete determination of the three-dimensional structure of the martian atmosphere from the surface boundary layer to the exosphere. This should be performed globally, ideally by combining wind, surface pressure and accurate temperature measurements from landed and orbital payloads."

## VISION VOYAGES

for Planetary Science in the Decade 2013-2022

Committee on the Planetary Science Decadal Survey

Space Studies Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS Washington, D.C. www.nap.edu



### Concept maturity/relationship to SAGs.

NEX-SAG and ICE-SAG outline the needed measurements in the lower-and middle atmosphere. BUT:

- SAGs didn't account for recent discoveries:
  - Strong relationships between lower/middle atmospheric dynamics and escape from the upper atmosphere.
  - Extreme weather in mesoscale systems.
- This concept is technically immature at present. We need to:
  - Understand the risks and challenges of flying and operating a mothership with several linked daughtercraft in the Mars environment
  - Specify the resolution and sampling frequency needed to understand extreme weather at sub-100 km scales.



<u>Relevant to NASA Exploration Goals.</u> MOSAIC fulfills *seven* high-priority knowledge gap-filling activities identified by PSAG:

- Ice depth variation within the first meter (for drinking water & propellant synthesis). Activity D1-5, D1-6.
- Weather forecasting: dust climatology (B1-1), model validation (A2-1), global-scale T, wind, aerosols (A1-1, A1-2, A1-3).
- Communications: deep space optical comms (A4-2), delay-tolerant networking, and continuous relay-to-Earth from any Mars longitude.



In LEO
Commercial & International partnerships

In Cislunar Space
A leturn to the moon for long-term exploration

On Mars
Research to reform future



## Backup: MOSAIC Investigations

# **Science Investigations**

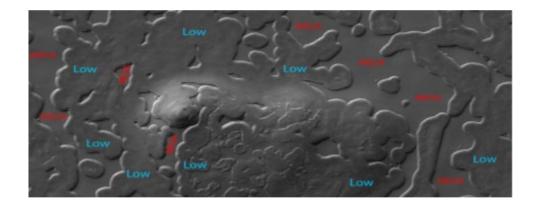
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MO	SAIC

Investigations *	Magguramanta**	In about the contract of the c	Platforms
Investigations *	Measurements**	Instruments	
1. Measure the three-dimensional distribution of ice from the surface to 10 m below.	Subsurface ice abundance derived from dielectric constant. Surface thermal inertia Surface water ice & albedo	P-band radar with VV or HH polarization. Thermal IR imager Visible camera	Mothership
2. Measure the geographic and altitude distribution of pressure, winds, aerosol concentrations, water vapor, ozone, and temperatures in the Mars lower and middle atmosphere.	Vertical profiles (0-80 km) of: temperature, winds, dust, $\rm H_2O$ and $\rm CO_2$ ices, $\rm H_2O$ vapor, $\rm O_3$ . Surface temperature and pressure.	Microwave/sub-mm limb and nadir sounder Thermal infrared spectrometer/radiometer Near-infrared spectrometer LIDAR	Mothership
3. Measure the complete diurnal and geographic behavior of the atmosphere and evolution of Martian dust and ice clouds.	Visible and/or UV imagery of clouds/hazes Column opacities/abundances of dust, $\rm H_2O$ , ozone, and $\rm CO_2$ ice Temp/pressure profiles 0 - 40 km	Visible and/or UV imager NIR spectrometer Thermal infrared spectrometer Radio Occultation	Areo-stationary
	Vertical profiles (0-80 km) of temperature, dust, $\rm H_2O$ and $\rm CO_2$ ices, $\rm H_2O$ vapor.	Thermal infrared spectrometer/radiometer	Polar orbiting smallsats
4. Measure the global 3-D composition, structure, and winds in Mars's thermosphere.	Vertical profiles (90 - 200 km) of: Horizontal wind velocity Density and temp. of 0, CO, N2, CO2	Wind interferometer FUV/MUV Spectrograph	Mothership
5. Measure the global 3-D structure of Mars	Vertical profiles (90-400 km) of	Radio Occultation	All orbiters
ionosphere.	electron density	Langmuir probe	Elliptical
	electron temperature CO2+ density	FUV/MUV Spectrograph	Mothership
6. Measure the 3-D density and temperature structure of Mars's hydrogen and oxygen exospheres.	Vertical profiles (200 - 30,000 km) of: density and temperature H density and temperature	FUV Spectrograph with hydrogen absorption cell.	Areostationary and/or Mothership
7. Measure (from multiple viewpoints) magnetic field and topology and fluxes of light and heavy ions across Mars's bow shock, through magnetosheath, down magnetotail, and into and out of the Martian upper atmosphere and ionosphere.	Magnetic field Suprathermal electron pitch angle distributions → magnetic topology Ion mass, energy, and angular distributions. Thermal electron temperature and density.	Magnetometer Electron analyzer Ion mass analyzer Langmuir probe	Elliptical
8. Measure magnetic field and plasma conditions in the upstream solar wind, and solar extreme ultraviolet irradiance.	Magnetic field Solar wind density, speed, temp. Solar EUV irradiance Solar Energetic Particle Flux	Magnetometer Solar Wind Ion analyzer Solar EUV monitor Solid State Telescope	Long Orbit

# Investigation 1: Ice (subsurface & surface)



Investigations	Measurements	Instruments	Platform
1. Measure the three- dimensional distribution of ice from the surface to 10 m below.	<ul> <li>Subsurface ice abundance derived from dielectric constant.</li> <li>Surface thermal inertia</li> <li>Surface water ice &amp; albedo</li> </ul>	<ul> <li>P-band radar with VV or HH polarization.</li> <li>Thermal IR imager</li> <li>Visible camera</li> </ul>	Near-polar low altitude circular orbit.



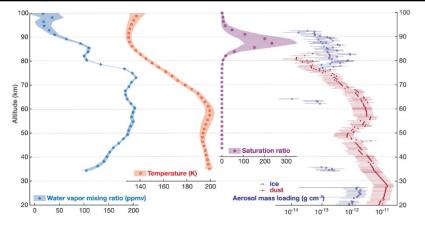
Leads: <u>T. Harrison, C. Stuurman</u>, C. Neish, I. Smith, G. Osinski,, S. Spencer.

Strong overlap with MORIE (next presentation).

## Investigations 2 & 3: lower-middle atmosphere



Investigations	Measurements	Instruments	Platforms
2. Measure the geographic and	Vertical profiles (0-80 km) of:	Microwave/sub-mm limb	Near-polar
altitude distribution of pressure,	temperature, winds, dust, H <sub>2</sub> O	and nadir sounder	low altitude
winds, aerosol concentrations,	and $CO_2$ ices, $H_2O$ vapor, $O_3$ .	Thermal infrared	circular
water vapor, ozone, and	Surface temperature and	spectrometer/radiometer	orbit.
temperatures in the Mars lower	pressure.	NIR spectrometer	
and middle atmosphere.		Wind LIDAR	



Fedorova et al., 2020

Leads: L. Montabone, S. Guzewich

M. Kahre, N. Heavens, M. Smith, A. Spiga, M. Mischna, M. Wolff, A. Kleinboehl, D. Hinson, F. Forget, L. Tamppari, B. Cantor

## Investigations 2 & 3: lower-middle atmosphere



Investigations	Measurements	Instruments	Platforms
2. Measure the geographic and altitude distribution of pressure, winds, aerosol concentrations, water vapor, ozone, and temperatures in the Mars lower and middle atmosphere.	temperature, winds, dust, $H_2O$ and $CO_2$ ices, $H_2O$ vapor, $O_3$ . Surface temperature and pressure.	and nadir sounder Thermal infrared	Near-polar low altitude circular orbit.
3. Measure the <b>complete diurnal</b> and <b>geographic behavior</b> of the atmosphere and evolution of Martian dust and ice clouds.	clouds/hazes Column opacities/abundances of dust, H <sub>2</sub> O, ozone, and CO <sub>2</sub> ice	NIR spectrometer	Areo- stationary
		spectrometer/radiometer	Near-polar low altitude circular @ different

Leads: L. Montabone, S. Guzewich

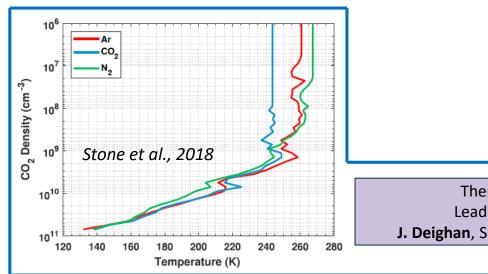
M. Kahre, N. Heavens, M. Smith, A. Spiga, M. Mischna, M. Wolff, A. Kleinboehl, D. Hinson, F. Forget, L. Tamppari, B. Cantor

local times

## Investigations 4 & 5: Thermosphere-Ionosphere



			Charles and the control of the contr
Investigations	Measurements	Instruments	Platforms
		Wind interferometer FUV/MUV	Near-polar low altitude circular
winds in Mars's thermosphere.	-Density and temp. of $O$ , $CO$ , $N_2$ , $CO_2$	0 . 1	orbit.



Thermosphere

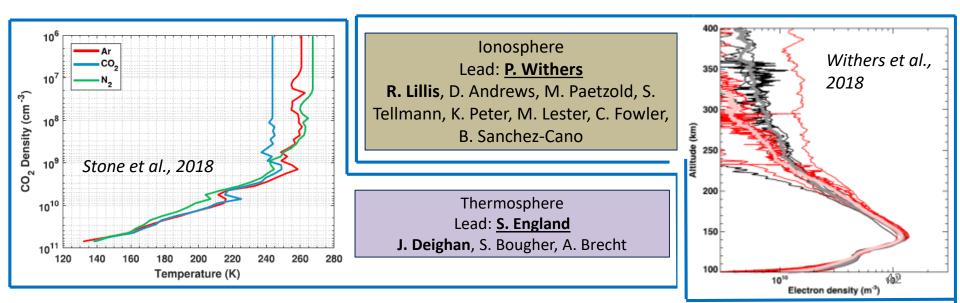
Lead: **S. England** 

J. Deighan, S. Bougher, A. Brecht

## Investigations 4 & 5: Thermosphere-Ionosphere



Investigations	Measurements	Instruments	Platforms
composition, structure, and	-Horizontal wind velocity -Density and temp. of O, CO, N <sub>2</sub> , CO <sub>2</sub>	Spectrograph	Near-polar low altitude circular orbit.
			Elliptical+polar Elliptical orbit

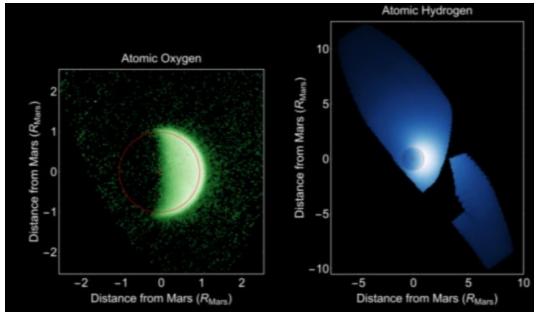


# Investigation 6: exosphere



Investigations	Measurements	Instruments	Platforms
6. Measure the 3-D density and	Vertical profiles (200 - 30,000	FUV Spectrograph.	Areostationary
	km) of:		
hydrogen and oxygen exospheres.			
	H density and temperature		

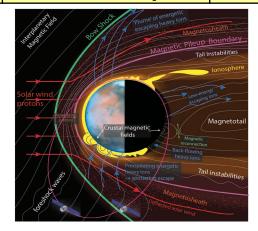
Team members: M. Chaffin, J. Deighan



# Investigations 7&8: Magnetosphere & Escape

			MUSA
Investigations	Measurements	Instruments	Platforms
shock and throughout the magnetosphere, from multiple simultaneous locations.	Suprathermal electron pitch angle distributions → magnetic topology	Electron analyzer Ion mass analyzer Langmuir probe	Elliptical orbit ~150km x ~6000 km
plasma conditions in the upstream	Solar wind density, speed, temp. Solar EUV irradiance	Solar Wind Ion analyzer	Outside Mars' bow shock

Magnetosphere/Escape Lead: <u>S. Curry</u> J. Luhmann, R. Lillis, F. LeBlanc, J. Halekas, D. Brain, X. Fang, J. Espley, H. Opgenoorth, O. Vaisberg



## Connections between science and architectures



### Investigation 1

Measure the 3-D Distribution of ice from the surface to 10m below.

### Investigation 2

Measure the geographic and altitude distribution of pressure, winds, aerosol concentrations, water vapor, ozone, and temperatures in the Mars lower and middle atmosphere.

### Investigation 3

Measure the complete diurnal and geographic behavior of the atmosphere and evolution of Martian dust and ice clouds.

### Investigation 4

Measure the global 3-D composition, structure, and winds in Mar's thermosphere.

### Investigation 5

Measure the global 3-D structure of Mars ionosphere.

### Investigation 6

Measure the 3-D density and temperature structure of Mars hydrogen and oxygen exospheres.

### **Investigation 7**

Measure (from multiple view points) magnetic field and topology and fluxes of light and heavy ions across Mars' bow shock, down magnetotail, and into and out of the Martian upper atmosphere and ionosphere.

### Investigation 8

Measure magnetic field and plasma conditions in the upstream solar wind, and solar extreme ultraviolet irradiance.

Mothership Platform

Areo Platform

Polar Platform

Elliptical Platform



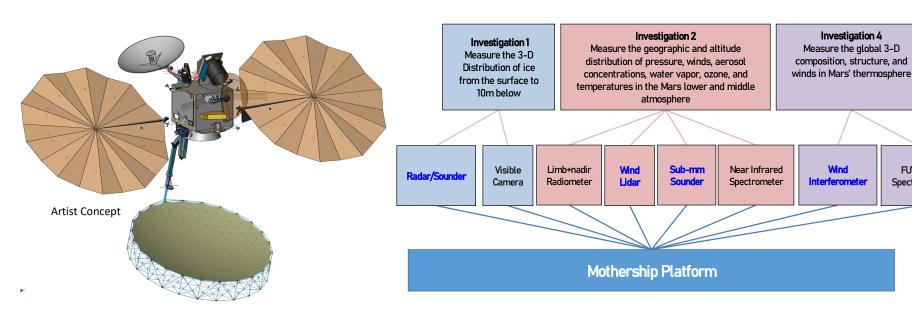
# Backup: MOSAIC Orbital Platforms

# **Mothership Platform**



FUV/MUV

Spectrometer



## Solar Electric Large Orbiter

(1) Orbiter Spacecraft

Wet Mass: 3721 kg

Orbit: 300 km; ~93° (MRO Orbit)

# **Areostationary Platform**





**Areostationary Small Orbiter** 

(1) Orbiter Spacecraft

Wet Mass: 565 kg

Orbit: 17,000 km; Equatorial

#### Investigation 3 Measure the complete diurnal

and geographic behavior of the atmosphere and evolution of Martian dust and ice clouds

### Investigation 6

Measure the 3-D density and temperature structure of Mars hydrogen and oxygen exospheres.

#### Investigation 8

Measure magnetic field and plasma conditions in the upstream solar wind, and solar extreme ultraviolet irradiance.

Nadir IR Radiometer Visible Imager Spectrometer

FUV/EUV Magnetometer Spectrograph

Electron energy/angle

energy/angle

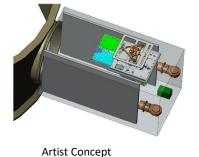
Extreme UV

Monitor

Energetic ion/electron

Mini Areo Platform

Areo Platform



## Mini Areostationary Orbiter

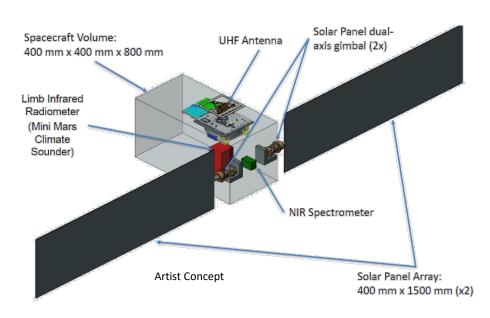
(3) Orbiter Spacecraft

Wet Mass: 93 kg

Orbit: 17,000km; Equatorial

## Polar Platform



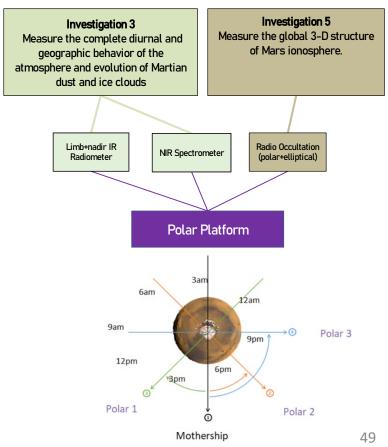


## Polar Small Spacecraft

(3) Orbiter Spacecraft

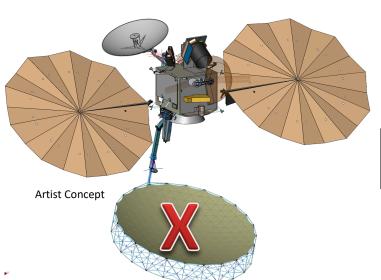
Wet Mass: 93 kg

Orbit: 300 km; ~93° (MRO Orbit)



# "Mini" Mothership Option





# Solar Electric Small Orbiter

(1) Orbiter Spacecraft

Wet Mass:  $\sim$ 3700  $\rightarrow$   $\sim$ 750 kg

Orbit: 300 km; ~93° (MRO Orbit)

# Investigation 1 Measure the 3-D Distribution of ice from the surface to

10m below

.

### Investigation 2

Measure the geographic and altitude distribution of pressure, winds, aerosol concentrations, water vapor, ozone, and temperatures in the Mars lower and middle atmosphere

#### Investigation 4

Measure the global 3-D composition, structure, and winds in Mars' thermosphere



Visible Camera Limb+nadir Radiometer



Near Infrared Spectrometer



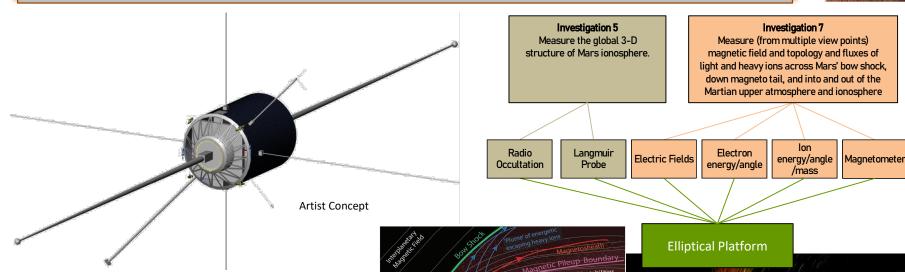
FUV/MUV Spectrometer

### Mothership Platform

- <u>Huge reduction</u> in mass and cost
- **Preserves**: global coverage of atmospheric connections
- Sacrifices: brand-new measurements (ice and wind)

# **Elliptical Platform**



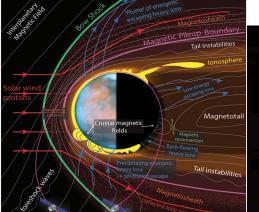


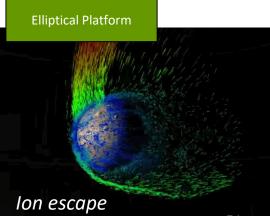
## Elliptical Small Spinning Spacecraft

(2) Orbiter Spacecraft

Wet Mass: 221 kg

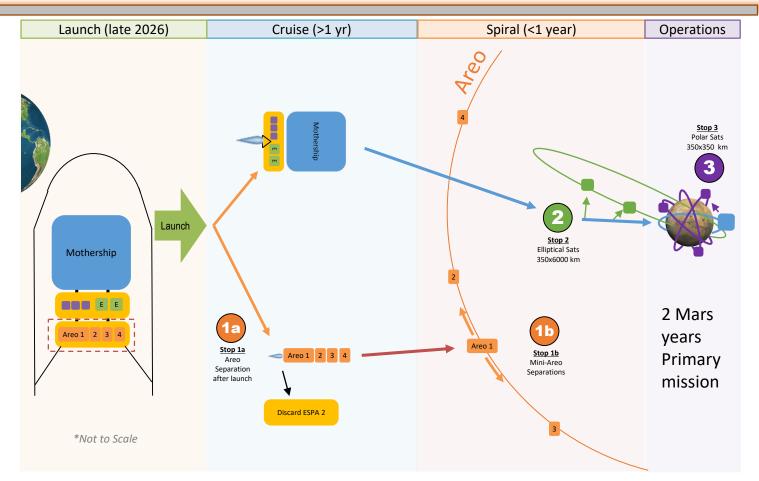
Orbit: 150 x 6000 km; 75°





# Constellation Delivery (Example Option)







# Backup: MOSAIC Synergies with other Mars missions

# Fitting in with the Crowd: TGO



## The ESA Trace Gas Orbiter:

- measures altitude profiles of H<sub>2</sub>O, O<sub>3</sub>, and aerosols but only at 6 AM and 6 PM (via solar occultation), providing a precursor to MOSAIC's much more systematic sub-mm limb sounding.
- conducts traditional nadir mapping of temperature profiles, ice, and aerosols, as MRO MCS has done, but takes ~55 days to cover all local times. MOSAIC will ensure full diurnal, geographic, altitude, and seasonal coverage.
- uses neutrons to derive total water ice abundance in the top ~1 m with 100-200 km resolution, i.e. complementary to the muchhigher resolution, and deeper ice depth profiles from MOSAIC's radar.



## Fitting in with the Crowd: EMM



- Starting in May 2021, the Emirates Mars Mission will make total column abundance/opacity measurements from a 55-hour high circular orbit.
  - no altitude info except crude temperature profiles
- As a single spacecraft, EMM will observe most of the diurnal cycle over most of the planet once every 10 days (inevitable gaps in latitude-local time space), not *continuously* as MOSAIC will.



# Fitting in with the Crowd: MAVEN



Hopefully MAVEN is still operational in the 2028-2034 timeframe. However MAVEN, as a single spacecraft:

- Samples the upstream solar wind for 10s of minutes per 3.7-hour orbit on only ~40% of orbits.
- Has raised its periapsis to ~200 km in September 2020, continuing its remote FUV/MUV measurements of thermosphere density (MOSAIC Investigation 4) but no longer sampling the thermosphere or photochemical ionosphere in situ (needed for MOSAIC Investigation 5).

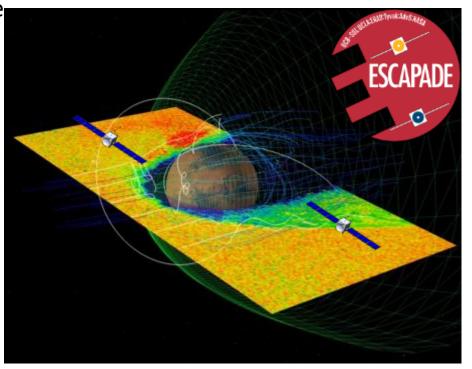


## Fitting in with the Crowd: ESCAPADE



ESCAPADE fulfills some of the science goals of MOSAIC's elliptical orbit satellites. However ESCAPADE:

- Does not measure electric fields, which are <u>the</u> key factor in accelerating plasma throughout the Mars magnetosphere.
- Must pass its PDR & Confirmation Review summer 2021.
- Does not have any budget line item within HPD. Contingent on available funds.

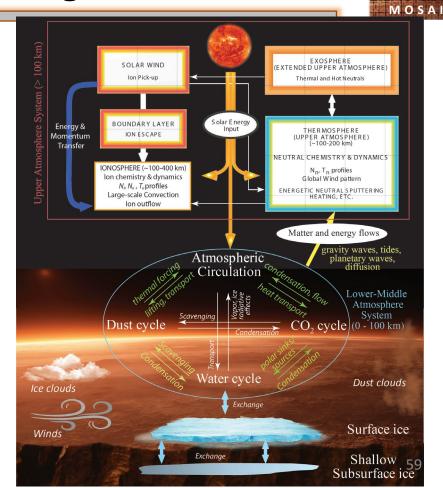




# MOSAIC Science Background

## **MOSAIC Motivating Questions**

- 1. How do volatiles (e.g. H<sub>2</sub>O and CO<sub>2</sub>) move between the subsurface, surface, and atmosphere?
- 2. How does the Martian lower-middle atmosphere respond on meso- and global scales, to the diurnal and seasonal cycles of insolation?
- 3. How does coupling with the lower atmosphere combine with the influence of space weather to control the upper atmospheric system and drive atmospheric escape?





# MOSAIC Concept Study Science Process

## Science Requirements Definition



## For each investigation we defined:

- <u>Measurement</u> requirements: range, accuracy, resolution, coverage, physical parameter vs. observable quantity, baseline vs. threshold.
- *Instruments* that can meet measurement requirements.
- Example below from investigation 2:



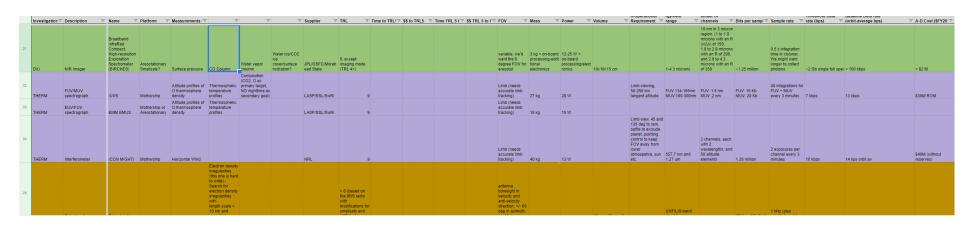
TLDR: we compiled all the MEASUREMENT requirements in 8 spreadsheets

## Instrument Requirements



### For each instrument we defined:

 Description, name, platform, measurements, supplier, TRL, FOV, mass, power, volume, accommodation, resolution, data rate, cost.



TLDR: we compiled lots of INSTRUMENT requirements to guide the JPL concept study team

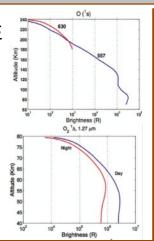
## Quad chart example: NIR, Visible Doppler Interferometer



### Middle-Upper Atmosphere Winds

- Knowledge gap in dynamics especially between homopause and near exobase.
- Winds reveal global-scale dynamics, large-sale waves, provides inputs to models.

MOSAIC Objectives: I.C, II.C



### Resources/accommodations

Platform (order)	M
# platforms	Baseline: 1
Mass	40 kg (for both channels
Power (incl. heat)	20 W ave. (heat est.)
Data Rate	Baseline: 14 kbps (number already accounts for duty
	cycling of 2 images per 3 min)
FOV	3°H x 5°V x 2 channels, 45° and 135° to ram
Limb Pointing (deg)	Contrl: 0.1, Know: 0.05, Jitter., 0.06 over 30s
Keep out zones.	No sun in FOV while on. Baffle scatter below ~50km
Conops.	Always on, 2x30s exp per 3 min

### <u>Measurement Requirements</u>

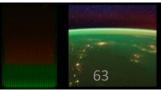
Physical Parameter/	Doppler shift of	Doppler shift of O <sub>2</sub> 1Δ
Observable Quantity	O( <sup>1</sup> S) (557.7 nm)	(1.27 μm)
Altitude range	80-150 km <sup>+</sup>	60-80 km
Altitude resolution	5 km <sup>++</sup>	2.5 km <sup>++</sup>
Precision - f(alt)	10-20 m/s	5-10 m/s
Cadence	3 minutes	3 minutes

<sup>&</sup>lt;sup>+</sup>Daytime only

### TRL story/development required

	THE Story acveropinen
Current TRL	5 Recent flight, 1 channel needs different wavelengths, vastly different radiation, thermal
Heritage	ICON MIGHTI
\$ to TRL 6	? Not too much ?
Time to TRL 6	Months?
Notes:	Thermal control, pointing stability, knowledge are drivers



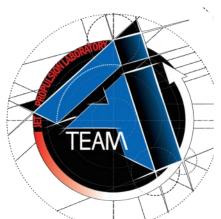


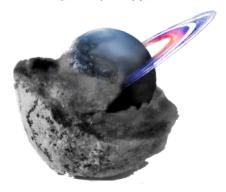
<sup>\*\*</sup>Must be ½ scale height or better

## JPL A-Team & Team-X Studies



- Examined the study trade space and produced the MOSAIC architecture "building blocks" relevant to the trade space.
- Defined technologies would enable parts of the trade space over the Decadal Survey span (e.g. optical comm).
- Looked at 13 potential architectures, quickly narrowed to four
- Team-Xc and Team-X (in their first ever virtual session) produced point designs by early April 2020.



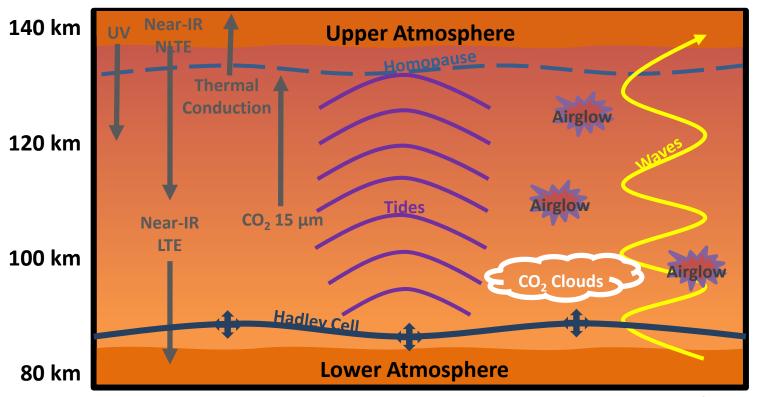




# Backup: MOSAIC Science Slides

# Lower/Upper Atmosphere Connections





A. Brecht

## Need comprehensive Lower-Upper atmosphere monitoring



Dust, H<sub>2</sub>O, and HDO surface monitoring

D/H Map - Ls: 83° (Northern late spring)
(RIRES/VLT Jan/29 and Jan/30 2014

Oympun Name

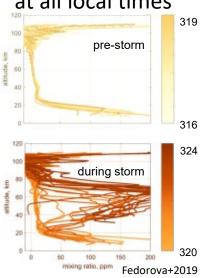
D/H(H, 0) [VSMOW]

L0 55 100

Argyne Caster

180 -150 -120 -50 -60 -30 0

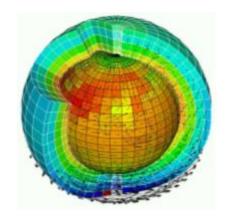
H<sub>2</sub>O profiles to ~100km, at all local times



Vis/IR, Microwave, and submm limb and nadir observations

Villanueva+2013

Waves, Tides, and Winds, revealing dynamics



Wind LIDAR, Wind interferometer,
Tidal analysis of other datasets

Monitoring of H+O escape



FUV spectroscopy, H absorption cell, Ion Mass Analyzer



# Backup: MOSAIC Descope Science matrices

## Case 1: No Ice Radar



2 x Elliptical

**Platforms** 

			· · · · · · · · · · · · · · · · · · ·			- tationis		r tationino		· tationing	
					\/				1	1	
Science & Exploration Goals	Scientific Objectives	Investigations:	1. Ice distribution	2. Atmosphere structure	3. Atm. Diurnal behavior	4. Thermosphere	5. Ionosphere	6. Exosphere, neutral escape	7. Plasma & ion escape	8. Space weather	
I. Understand	LA: Characterize volatile cycling between the subsurface, surface and atmospheric reservoirs.			✓	✓						
Mars's present day climate	<u>L.B.</u> : Characterize the structure and dynamics of the Martian lower-middle atmosphere on meso- and global scales, and its geographic, diurnal, and seasonal variability.			✓	✓						
processes and their inter-	I.C: Correlate variability in the thermosphere,	The lower-middle atmosphere.		✓	✓	✓	✓	✓	✓		
connections, from	ionosphere, and escape rates to:	The space weather environment				✓	✓	✓	✓	✓	
the sub-surface to the solar wind	LD: Characterize fields and plasma flows in the upstream solar wind and throughout the magnetosphere and upper ionosphere, separating spatial from temporal variability.						✓	✓	✓	✓	
II. Identify	II.A: Characterize potentially extractable water ice re	sources to support in situ resource utilization									
characterize resources, and demonstrate technologies to enable the Human Exploration of Mars	<u>II.B:</u> Characterize the Mars atmospheric state with sufficient spatial sampling and cadence to allow accurate data assimilation and weather forecasting.			✓	✓						
	<u>II.C:</u> characterize neutral winds in the mesosphere and lower thermosphere (60 km-130 km) and their variability with lower atmospheric conditions and solar activity.					✓					
	II.D: Characterize the Mars ionospheric state and variability sufficiently to determine its likely disruptive effect on communications and positioning						✓		✓	✓	
	II.E: characterize the environment of penetrating ions (>10 MeV/nuc) at 1.38-1.62 AU.									✓	

Smaller

**Mothership** 

4 x Areo

**Platforms** 

3 x Polar

**Platforms** 

# Case 2: "Descope"



2 x Elliptical

**Platforms** 

					1				1	
Science & Exploration Goals	Scientific Objectives	Investigations:	1. Ice distribution	2. Atmosphere structure	3. Atm. Diurnal behavior	4. Thermosphere	5. Ionosphere	6. Exosphere, neutral escape	7. Plasma & ion escape	8. Space weather
	<u>I.A</u> : Characterize volatile cycling between the subsurface, surface and atmospheric reservoirs.			✓	✓					
day climate	<u>L.B.</u> : Characterize the structure and dynamics of the Martian lower-middle atmosphere on meso- and global scales, and its geographic, diurnal, and seasonal variability.			✓	✓					
		The lower-middle atmosphere.		✓	✓		✓	✓	✓	
connections, from		The space weather environment					✓	✓	✓	✓
the sub-surface to the solar wind	L.D. Characterize fields and plasma flows in the upstream solar wind and throughout the magnetosphere and upper ionosphere, separating spatial from temporal variability.						✓	✓	✓	✓
II. Identify	H.A: Characterize potentially extractable water ice re	esources to support in situ resource utilization								
characterize resources, and demonstrate technologies to enable the Human Exploration of	II.B: Characterize the Mars atmospheric state with sufficient spatial sampling and cadence to allow accurate data assimilation and weather forecasting.			✓	✓					
	ILC: characterize neutral winds in the mesosphere and lower thermosphere (60 km-130 km) and their variability with lower atmospheric conditions and solar activity.									
	II.D: Characterize the Mars ionospheric state and variability sufficiently to determine its likely disruptive effect on communications and positioning						✓		✓	✓
	II.E: characterize the environment of penetrating ions (>10 MeV/nuc) at 1.38-1.62 AU.									✓

Smaller

**Mothership** 

4 x Areo

**Platforms** 

3 x Polar

**Platforms** 

# Case 3: "Descope Lite"



1 x Elliptical

			Mothership		Pl	Platforms		Platforms		ittorms
					1			<b>/</b>	1	1
Science & Exploration Goals	Scientific Objectives	Investigations:	1. Ice distribution	2. Atmosphere structure	3. Atm. Diurnal behavior	4. Thermosphere	5. lonosphere	6. Exosphere, neutral escape	7. Plasma & ion escape	8. Space weather
I. Understand	<u>I.A</u> : Characterize volatile cycling between the subsurface, surface and atmospheric reservoirs.			✓	✓					
day climate	LB: Characterize the structure and dynamics of the Martian lower-middle atmosphere on meso- and global scales, and its geographic, diurnal, and seasonal variability.			✓	✓					
	I.C: Correlate variability in the thermosphere,	The lower-middle atmosphere.		✓	✓		✓	✓	✓	
connections, from		The space weather environment					✓	✓	✓	✓
	<u>L.D.</u> Characterize fields and plasma flows in the upstream solar wind and throughout the magnetosphere and upper ionosphere, separating spatial from temporal variability.						✓	✓	✓	✓
II. Identify	II.A: Characterize potentially extractable water ice r	esources to support in situ resource utilization								
characterize resources, and demonstrate technologies to enable the Human Exploration of Mars	II.B: Characterize the Mars atmospheric state with sufficient spatial sampling and cadence to allow accurate data assimilation and weather forecasting.			✓	✓					
	ILC: characterize neutral winds in the mesosphere and lower thermosphere (60 km-130 km) and their variability with lower atmospheric conditions and solar activity.									
	II.D: Characterize the Mars ionospheric state and variability sufficiently to determine its likely disruptive effect on communications and positioning						✓		✓	✓
	II.E: characterize the environment of penetrating ions (>10 MeV/nuc) at 1.38-1.62 AU.									✓

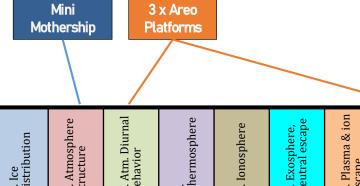
Smaller

3 x Areo

2 x Polar

## Case 4: Threshold

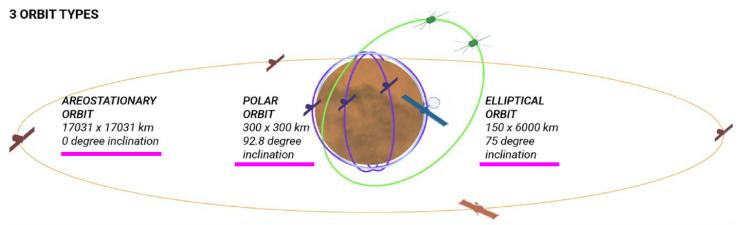




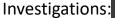
Science & Exploration Goals	Scientific Objectives	Investigations:	1. Ice distribution	2. Atmosphere structure	3. Atm. Diurnal behavior	4. Thermosphere	5. Ionosphere	6. Exosphere, neutral escape	7. Plasma & ion escape	8. Space weather
I. Understand	LA: Characterize volatile cycling between the subsurface, surface and atmospheric reservoirs.			✓	✓					
Mars's present day climate	<b>I.B</b> : Characterize the structure and dynamics of the Martian lower-middle atmosphere on meso- and global scales, and its geographic, diurnal, and seasonal variability.			✓	✓					
processes and their inter-		The lower-middle atmosphere.		✓	✓					
connections, from		The space weather environment								✓
the sub-surface to the solar wind	<u>I.D.</u> Characterize fields and plasma flows in the upstream solar wind and throughout the magnetosphere and upper ionosphere, separating spatial from temporal variability.									✓
II. Identify	H.A: Characterize potentially extractable water ice re	sources to support in situ resource utilization								
hazards, characterize resources, and	II.B: Characterize the Mars atmospheric state with su accurate data assimilation and weather forecasting.	fficient spatial sampling and cadence to allow		✓	✓					
demonstrate technologies to enable the Human Exploration of Mars	<u>II.C:</u> characterize neutral winds in the mesosphere and lower thermosphere (60 km-130 km) and their variability with lower atmospheric conditions and solar activity.									
	II.D: Characterize the Mars ionospheric state and variability sufficiently to determine its likely disruptive effect on communications and positioning									✓
	II.E: characterize the environment of penetrating ions (>10 MeV/nuc) at 1.38-1.62 AU.									✓

## The MOSAIC Constellation





### **5 PLATFORMS**





### 10 SPACECRAFT

