Advancing Planetary Climate Science with the Planetary Cloud Aerosols Research Facility (PCARF)

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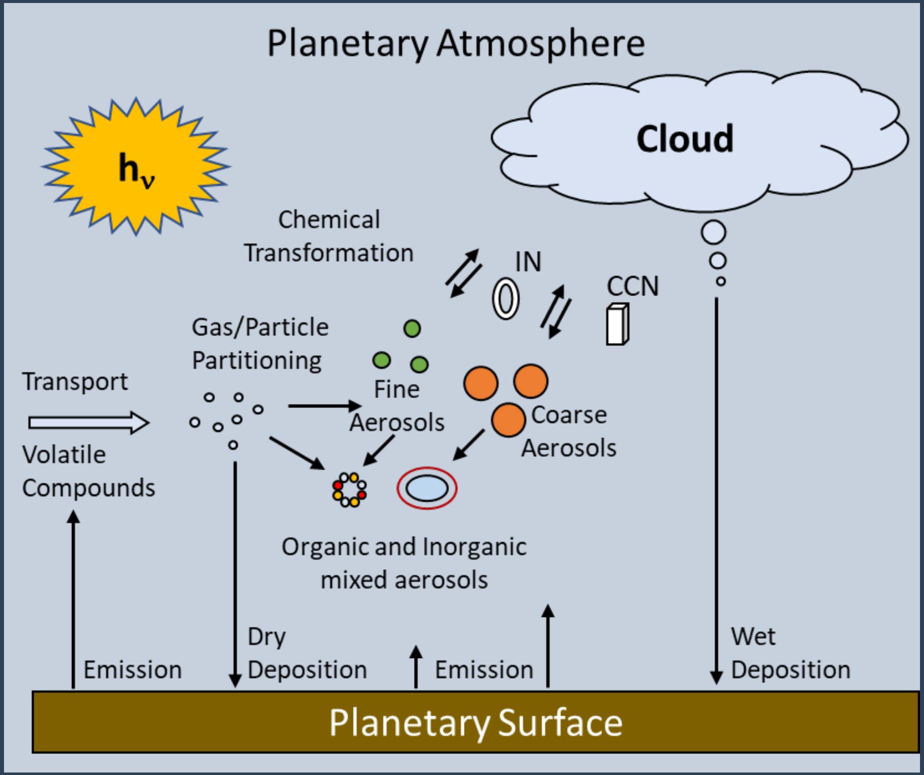
Motivation

The goal of creating the Planetary Cloud Aerosols Research Facility (PCARF) is to *enable scientific experimental investigation of aerosol processes, particularly how planetary atmospheric aerosols form clouds and evolve within our solar system and on exoplanets*.

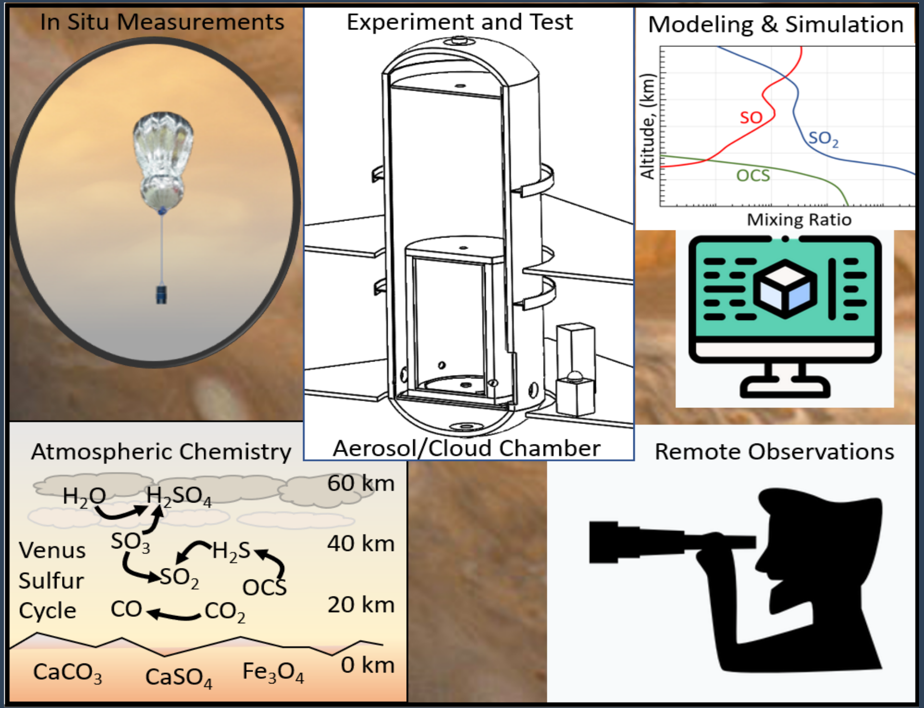


Numerous processes are involved in forming clouds

Project Goals

This physical-experiment-focused facility will complement, confirm and corroborate current and future research into planetary aerosols conducted through:

- Remote observations
- In situ measurements
- Computational modeling
- Experimental chemistry



Project Objective 1

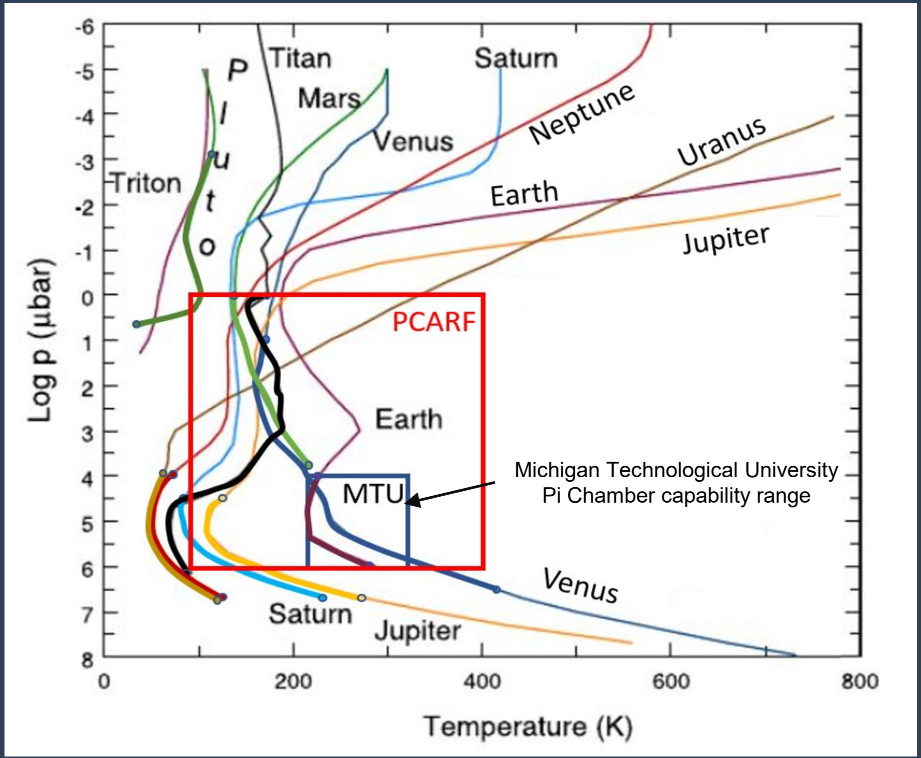
Create a facility to simulate the atmospheric conditions on a wide variety of planets/moons.

Chamber operates over

Temperature range: -180° to +125°C,

Pressure range: 1 µbar to 1 bar

Ambient gases: N_2, CO_2, and He/H_2.

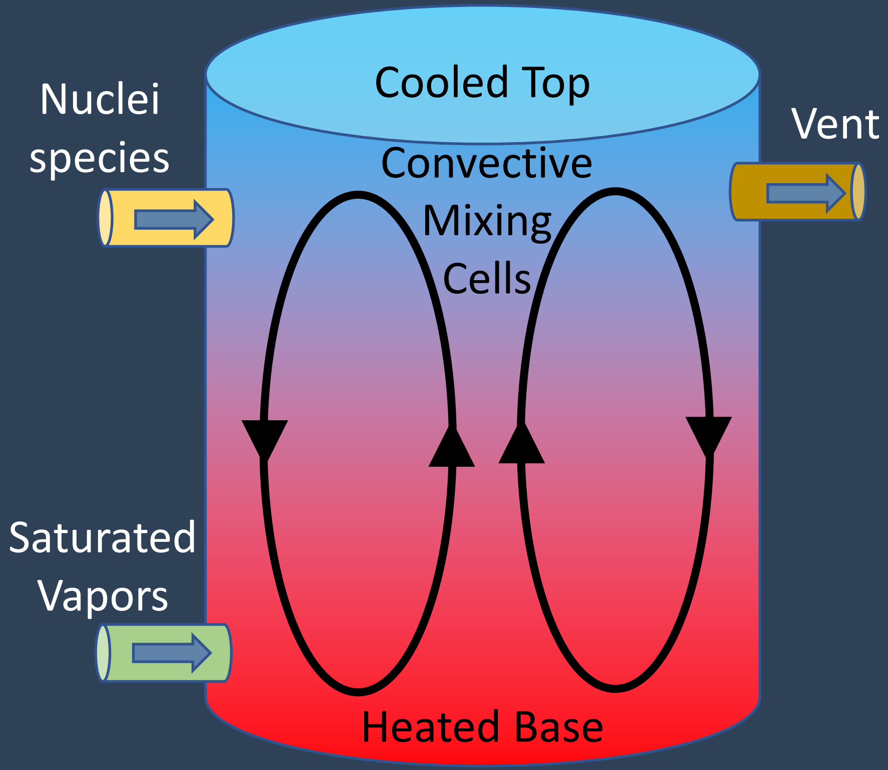


The regions where clouds/haze are found are highlighted by a thick line segment along the temperature-pressure profiles. PCARF could clearly enable cloud research on many planets.

Project Objective 2

Demonstrate clouds like those found in other planetary atmospheres can be created in the facility.

Replicate the physical processes of aerosol formation and evolution through turbulent convective mixing of saturated volatiles and nuclei species.

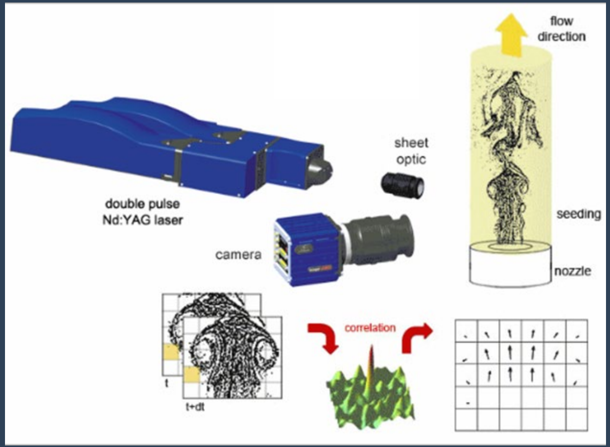


Project Objective 3

Demonstrate that the instrumentation acquired for this facility will provide aerosol property data that includes:

- aerosol size distribution
- number density
- optical properties
- chemical composition
- particle velocity and trajectories during formation and evolution.

Scanning Mobility Particle Size Spectrometer

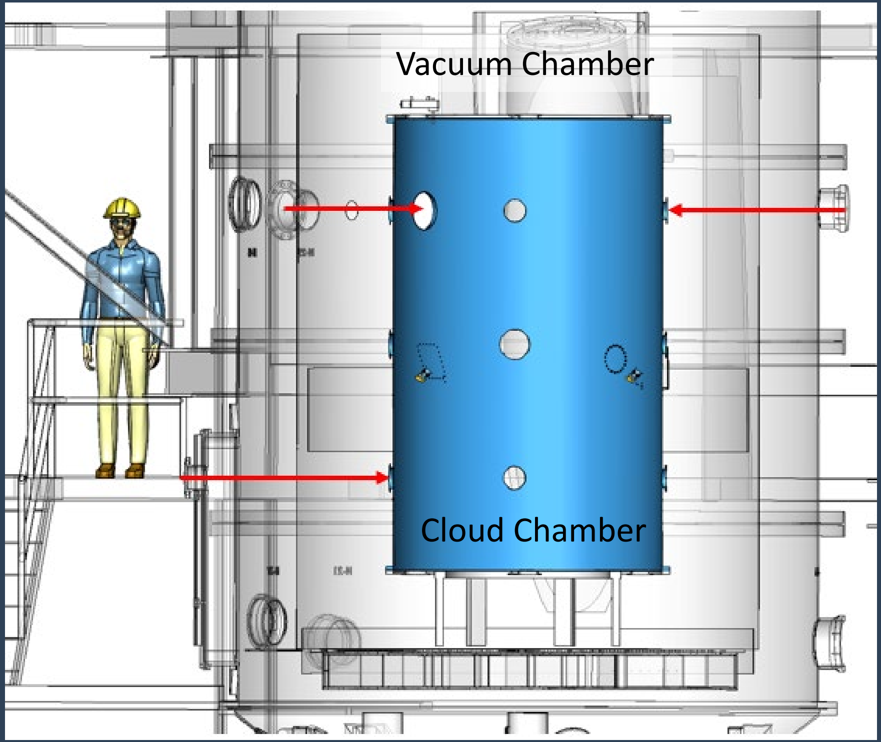


Particle Image Velocimetry

Planetary Cloud Chamber Specifications

Dimensional
6 ft. internal diameter by 10 ft. height
5 ports on top and bottom plates: 6” diam
14 ports on the lateral wall (10 ports at 6” ID, 2 ports at 8” ID, and 2 ports at 10” ID)

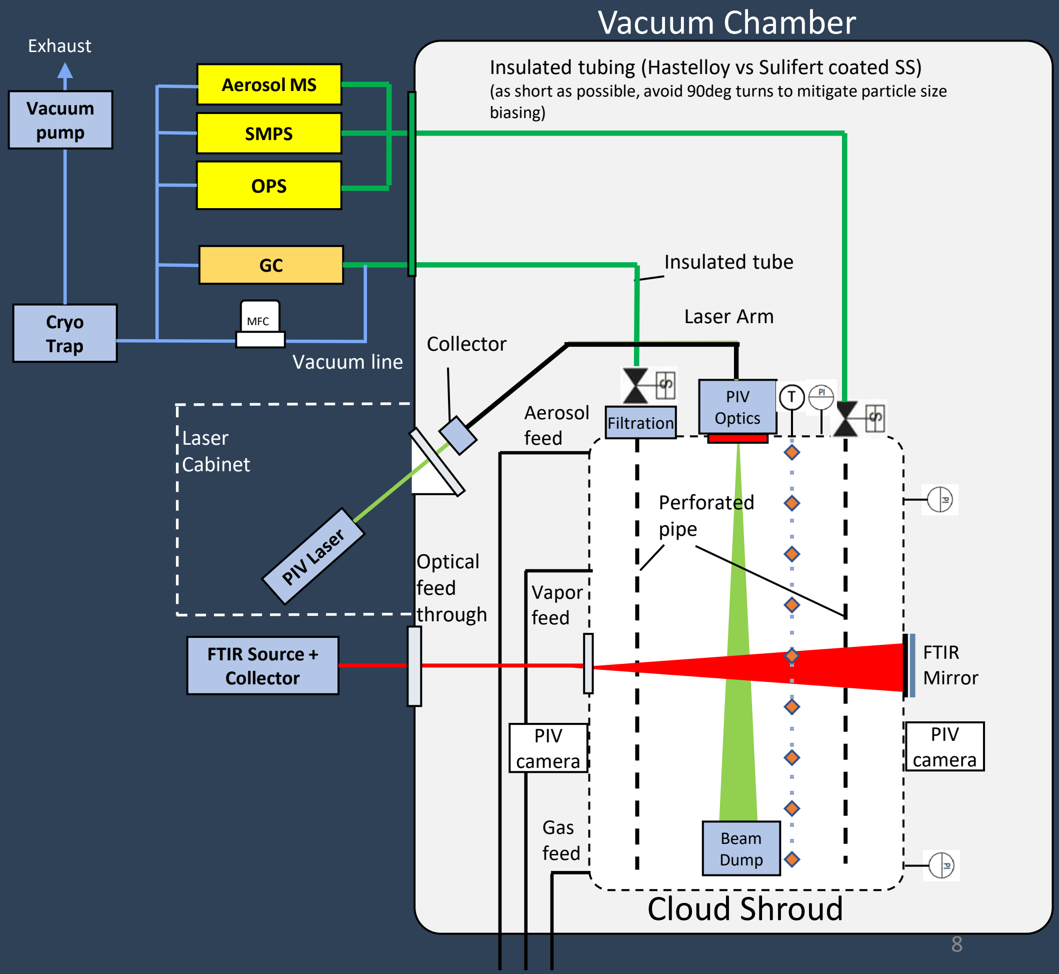
Operational
Temperature range: -180°C to +125°C
Pressure range: 1 µbar to 1 bar
Max differential pressure: 1 psig
Max temperature gradient: 50°C
Ambient gases: N_2, CO_2, and He/H_2.



Systems Layout

Instrumentation available to researchers

- Measure chamber temperature and pressure
- Aerosol size distribution, mass density, number density
- Particle velocity and trajectory
- Chemical composition
- Rate of aerosol particle growth and evaporation



PCARF Instrumentation

– to quantify the chemical composition and microphysical property of planetary atmospheres

PCARF will be equipped with a suite of instruments to quantify the following observables:

1. Aerosol size distribution
2. Aerosol number density
3. Aerosol optical properties
4. Aerosol chemical composition
5. Particle velocity and trajectories during cloud formation and evolution
6. Number density and optical properties of trace gases

Instrument	Observable	Technique	Source, Status
Optical Particle Spectrometer (OPS) for size > 1 µm	1, 2	in situ	COTS, PO
Scanning Mobility Particle Sizer (SMPS) for size < 1 µm	1, 2	in situ	COTS, delivered
Gas and Aerosol Separator Mass Spectrometer (GAMS)	2, 4	in situ	JPL, to I&T
Particle Image Velocimetry (PIV)	5	remote sensing	COTS, delivered
Fourier Transform Spectrometer for the Infrared (FTIR)	1, 2, 3, 4, 6	remote sensing	COTS, PO

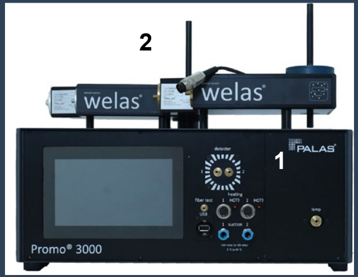
Optical Particle Spectrometer (OPS)

– to quantify size distribution and number density of large aerosols

Characteristics

- A COTS system (vendor: Palas GmbH)
- Sensor inlet samples in a broad range of atmospheric conditions
  - P: 0.2-10.0 bar; T: -130 to +120 ºC
- Uses a corrosion-resistant sensor made from Hastelloy
- Provides aerosol sizing and counting
  - sizing: 0.3 to 100 µm, up to 4 measuring ranges
    - 0.3 – 10, 0.3 – 17, 0.6 – 40, and 2.0 – 100 µm
    - up to 128 size channels per measuring range
  - concentration range: 1 to 10^6 particle/cm^3
  - When aerosol concentration 2.0 x 10^5 particle/cm^3 or higher, measure the aerosol concentration on a 1 second basis

OPS consists of two subsystems
1) system control unit (Promo 3000)
2) aerosol sensor (Welas 2100 HP)



Scanning Mobility Particle Sizer (SMPS)

– to quantify size distribution and number density of small aerosols

Characteristics

- COTS system (vendor: TSI Inc)
- Requires aerosol samples at SMPS inlet operating conditions
  - P: 700-1250 mbar; T: 10 to 40°C
- Provides aerosol size and count
  - 10 nm to 1 μm
  - 128 size channels in measuring range
  - Size resolution < 3% at 100 nm
- Three subsystems conduct a 4-step measurement sequence
  - Large particle removal > 1μm
  - Charge conditioning
  - Particle sizing
  - Aerosol concentration measurement

SMPS consists of three subsystems
1) electrostatic classifier (EC)
2) differential mobility analyzer (DMA)
3) condensation particle counter (CPC)

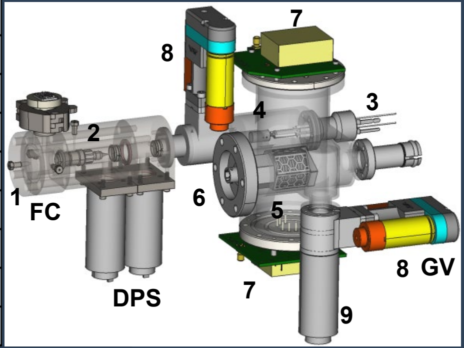
Gas and Aerosol separator Mass Spectrometer (GAMS)

– to quantify chemical composition of planetary atmosphere

Characteristics

- conduct a wide range of in-situ measurements in sulfuric acid aerosol environment
  - P: 0.01 to 60 bar; T: -40 to +80 ºC
- provides speciation and quantification of trace gases and aerosols
  - measures species within mass range of 1-150 amu or Dalton
  - achieves precision of 20% within 0.5-hour for any species with concentration 50 ppb
  - measures aerosol size smaller than 10 micron
- Advanced Aerosol Inlet (AAI) module separate aerosols from trace gases, then direct them to Quadrupole Ion Trap Mass Spectrometer (QITMS) module

GAMS system consists of two subsystems: AAI and QITMS	
AAI	1) variable aperture MEMS piezo valve with gas feeding cell (FC)
	2) aerosol separator (AS) with differentially pumped system (DPS)
	3) custom vaporizer with feed-through power and thermocouple
	4) 3D-printed QIT-MS sensor vacuum chamber
	5) QIT-MS sensor
QITMS	6) SAES Z200 ion/getter pump
	7) QIT-MS support electronics, now using ground support equipment
	8) motorized Gate Valve (GV)
	9) Creare miniature turbo/drag pump



Fourier Transform Infrared Spectrometer (FTIR)

– to quantify chemical composition and microphysical property of trace gases and aerosols

FTIR spectrometer uses white mirror cells for long path length observations of trace gas concentrations, particle composition, size, and shape. Path length is adjustable from ~12 to ~150 m.

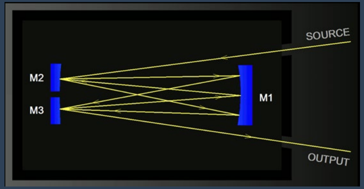
Characteristics

- Nicolet iG50 or iS50 Standard Mid-IR Spectrometer (KBr Beamsplitter + MCT detector)
  - Spectral coverage: 600-7800 cm^{-1}, 16.67-1.28 μm
  - Spectral resolution: 0.5 cm^{-1} (iG50) or 0.09 cm^{-1} (iS50)
- measure absorption spectra of trace gases, e.g.,
  - CO, CO_2, NH_3, CH_4, H_2O, D_2O (Fleury *et al.*, ApJ, 2019, 2020, 2023)
- measure absorption spectra of aerosols, e.g.,
  - H_2SO_4/H_2O droplets (Wagner *et al.*, Atmos. Chem. Phys., 2006)

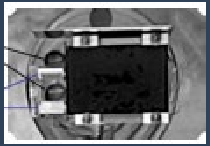
FTIR system, all parts are COTS
1) Nicolet iG50 Standard Mid-IR Spectrometer
2) Nicolet iG50 External Detector Module with Elliptical Mirror
3) Liquid N_2 Cooled MCT-A Detector with CdTe window
4) Polaris High Stability, Long Lifetime Mid-IR Source
5) White cell and transfer optics
6) Linear actuator for applications in vacuum & cryogenic Environ. (Phytron Inc.)

Nicolet™ iG50 FTIR Spectrometer

White cell in AIDA chamber at KIT



M2 & M3
gold coated mirrors



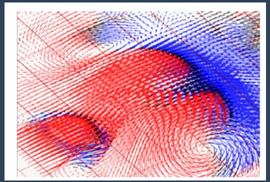
M1
field mirror

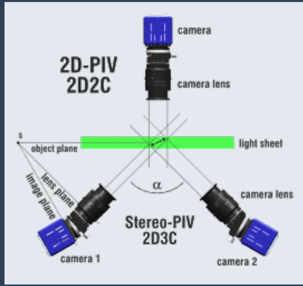
Particle Image Velocimetry (PIV)

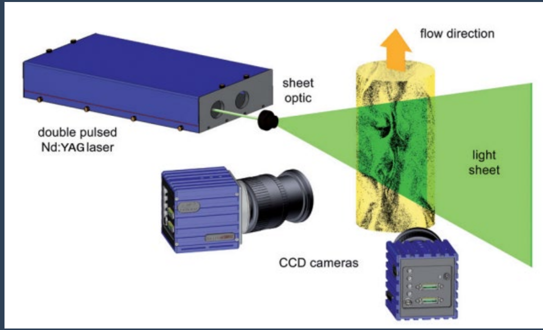
– to capture large scale and small-scale analyze particle motion

Characteristics

- COTS system (vendor: LaVision Inc.)
- 2D, 3 velocity component PIV light sheet with two cameras
- Directly track condensation particle 0.5-micron diameter and larger
- 2-lens configurations: large-scale flow 500x500 mm FOV; or detailed local features 50x50 mm FOV
- 15 Hz laser pulse rate
- Laser install outside vacuum chamber with optical pass through and arm to direct laser
- Camera operate remotely with focus adjustment in environmental enclosure



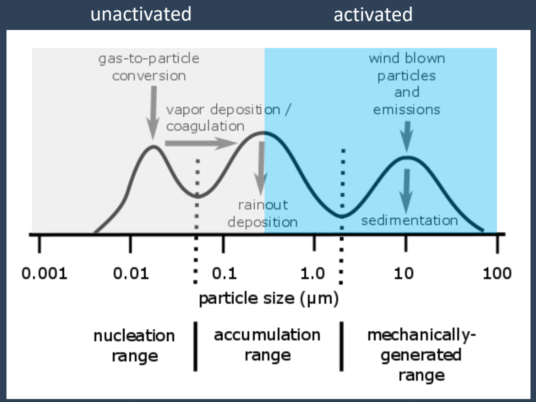




Chemical Feed System (CFS)

- Establishes target environmental conditions inside chamber:
  - Provides desired atmospheric composition
  - Manages pressure and temperature control
  - Aerosol generation and feed
  - Provides gas/particle analysis for measurements and feedback control
- Multiple flow stream architecture:
  - **Atmospheric gas stream** (controls atmospheric composition (incl. T, p) inside PCARF)
  - **Condensable saturated vapors**
  - **Cloud condensation nuclei** or ice nuclei species
  - Feed systems will be independently controlled for injecting respective constituents in the chamber for aerosol formation.

Chemical Feed System: Schematic Layout

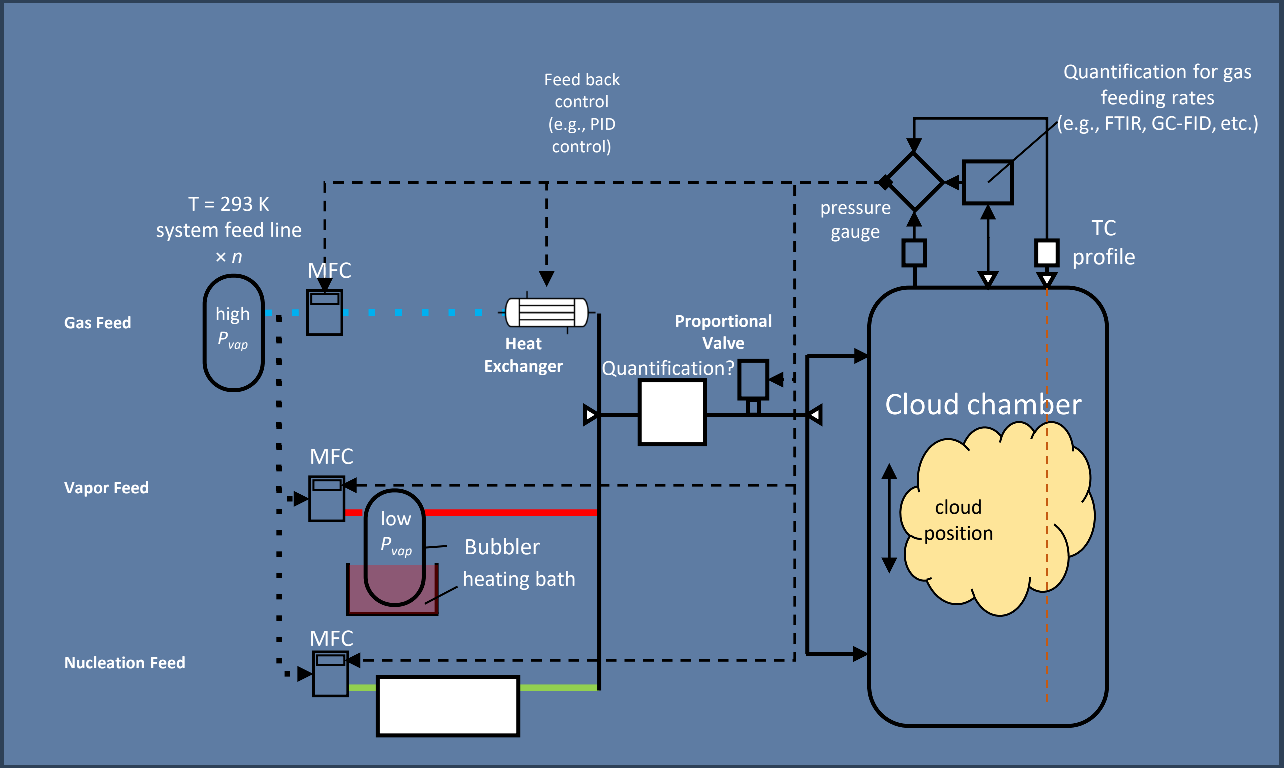


Gas Feed system (gas-phase only)

H_2O
SO_2
CH_4
CO
CO_2
AHs
NH_3
etc.

Nucleation Feed system (condensed phase)

H_2O (liquid)
$H_2SO_4 + H_2O$
PAHs
SiO_2
TiO_2
Al_2O_3
$MgSiO_4$
etc.



Acknowledgements

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Backup Materials

Atmospheric Compositions

- Chemical feed system capable of supplying **N_2, CO_2, or He/H_2 mixtures** to replicate planetary atmospheres at p,T
- Most systems determined by 3 major constituents

Earth		Venus		Mars		Titan		Jupiter		Saturn		Uranus		Neptune	
N_2	78.1 %	CO_2	96.5 %	CO_2	95.3 %	N_2	95 %	H_2	86.4 %	H_2	88 %	H_2	~82.5 %	H_2	~80 %
O_2	20.9 %	N_2	3.5 %	N_2	2.7 %	CH_4	4.92 %	He	13.6 %	He	12 %	He	15.2 %	He	19.0 %
Ar	0.93 %	SO_2	150 *ppm*	Ar	1.6 %	H_2	0.98 %	CH_4	0.18 %	CH_4	0.47 %	CH_4	2.3 %	CH_4	1 – 2 %
CO_2	0.04 %	Ar	70 *ppm*	O_2	0.13 %	CO	0.05 %	NH_3	0.061 %	NH_3	0.016 %	HD	148 *ppm*	HD	192 *ppm*
Ne	18.2 *ppm*	H_2O	20 *ppm*	CO	0.07 %	Ar	0.04 %	H_2O	520 *ppm*	HD	110 *ppm*	CH_3D	8.3 *ppm*	CH_3D	12 *ppm*
He	5.2 *ppm*	CO	17 *ppm*	H_2O	0.03 %	C_2H_6	0.01 %	H_2S	67 *ppm*	$^{13}CH_4$	51 *ppm*	H_2S	0.8 *ppm*	H_2S	3 *ppm*
CH_4	1.5 *ppm*	He	17 *ppm*	Ne	2.5 *ppm*	Kr	1.1 *ppm*	HD	45 *ppm*	C_2H_6	7.0 *ppm*			C_2H_6	1.5 *ppm*
Kr	1.1 *ppm*	Ne	7 *ppm*	Kr	0.3 *ppm*	Xe	0.9 *ppm*	$^{13}CH_4$	19 *ppm*	PH_3	4.5 *ppm*				
Xe	0.9 *ppm*			Xe	0.08 *ppm*			C_2H_6	5.8 *ppm*	CH_3D	0.3 *ppm*				
H_2	0.5 *ppm*			O_3	0.03 *ppm*			PH_3	1.1 *ppm*	C_2H2	0.3 *ppm*				
								CH_3D	0.2 *ppm*						
								C_2H2	0.1 *ppm*						

Atmospheric Compositions: CFS Strategy

Environment	Major Constituent	Minor Constituent	Traces
Earth	**N2** (78.1%)	**O2** (20.9%)	**Ar, CO2** (0.93%, 0.04%)
Venus	**CO2** (96.5%)	**N2** (3.5 %)	**SO2** (0.01 %)
Mars	**CO2** (95.3 %)	**N2, Ar** (2.7 %, 1.6 %)	**O2, CO2** (0.13%, 0.07%)
Titan	**N2** (94.2%)	**CH4** (5.65%)	**H2** (0.099%)
Jupiter	**H2** (86%)	**He** (13.6%)	**CH4** (0.2%)
Saturn	**H2** (96.3%)	**He** (3.25%)	**CH4** (0.45%)
Uranus	**H2** (85 %)	**He** (15%)	**CH4** (1%)
Neptune	**H2** (85 %)	**He** (15%)	**CH4** (1%)

Tradeoff between installing dedicated lines for each gas (continuous operation) or limited number of ports/lines which require switching over of gas (modular operation)

Rapid switch-over of atmosphere not necessary
System with 4 independent gas streams most sensible solution, provides atmospheric composition with major constituents >1% + separate stream for trace gases

Continuous Operation:
7 Ports

1	**CO2**
2	**N2**
3	**Ar**
4	**CH4**
5	**O2**
6	**H2**
7	**He**

Modular Operation:
3 Ports

1	**CO2**	**N2**	**N2**	**H2**
2	**N2**	**O2**	**CH4**	**He**
3	**(Ar)**	**(Ar)**		**CH4**
	Mars, Venus	Earth	Titan	GG, IG

Atmospheric Composition - CFS Example: Venus

System with 4 independent gas streams allows to mix major constituents (>0.1%) for Venus and other planetary atmospheres.

Alternative: Airgas provides custom gas mixtures for trace gases, which can be introduced using one of the gas streams

Gas Mixing 1

Gas	Percent Volume
Carbon Dioxide (CO_2)	**96.5**
Nitrogen (N_2)	**3.5**
Sulfur Dioxide (SO_2)	**150 ppm**
Argon (Ar)	**70 ppm**
Carbon Monoxide (CO)	**17 ppm**
Helium (He)	**17 ppm**
Neon (Ne)	**7 ppm**
Water Vapor (H_2O)	**20 ppm**

Gas Mixing 2

Gas	Percent Volume
Carbon Dioxide (CO_2)	**96.5**
Nitrogen (N_2)	**3.5**
Sulfur Dioxide (SO_2)	**150 ppm**
Argon (Ar)	**70 ppm**
Carbon Monoxide (CO)	**17 ppm**
Helium (He)	**17 ppm**
Neon (Ne)	**7 ppm**
Water Vapor (H_2O)	**20 ppm**

Gas Mixing 3

Gas	Percent Volume
Carbon Dioxide (CO_2)	**96.5**
Nitrogen (N_2)	**3.5**
Sulfur Dioxide (SO_2)	**150 ppm**
Argon (Ar)	**70 ppm**
Carbon Monoxide (CO)	**17 ppm**
Helium (He)	**17 ppm**
Neon (Ne)	**7 ppm**
Water Vapor (H_2O)	**20 ppm**

- Individual gas stream
- Gas mix (pre-mixed by supplier)

Solar System Planetary Cloud Compositions

Planet	Chemical Composition	Source
Earth	Ice and liquid water (**H_2O**)	Ramanathan, V. L. R. D., Cess, R. D., Harrison, E. F., Minnis, P., Barkstrom, B. R., Ahmad, E., & Hartmann, D. (1989). Cloud-radiative forcing and climate: Results from the Earth Radiation Budget Experiment. Science, 243(4887), 57-63.
Venus	Sulfuric Acid (**H_2SO_4**)	Titov, D. V., Ignatiev, N. I., McGouldrick, K., Wilquet, V., & Wilson, C. F. (2018). Clouds and hazes of Venus. Space Science Reviews, 214, 1-61.
Mars	Water ice (**H_2O**) and carbon dioxide ice (**CO_2**)	Read, P. L., Lewis, S. R., & Mulholland, D. P. (2015). The physics of Martian weather and climate: a review. Reports on Progress in Physics, 78(12), 125901.
Jupiter	Ammonia ice (NH_3), ammonium hydrosulfide solid (NH_4SH), water ammonia aqueous solution (H_2O-NH_3)	Atreya, S. K., Wong, M. H., Owen, T. C., Mahaffy, P. R., Niemann, H. B., De Pater, I., ... & Encrenaz, T. (1999). A comparison of the atmospheres of Jupiter and Saturn: deep atmospheric composition, cloud structure, vertical mixing, and origin. Planetary and Space Science, 47(10-11), 1243-1262.
Saturn	Ammonia ice (NH_3), ammonium hydrosulfide solid (NH_4SH), ice water (H_2O), water ammonia aqueous solution (H_2O-NH_3)	
Titan	Methane (CH_4)	Griffith, C. A., Penteado, P., Rodriguez, S., Le Mouélic, S., Baines, K. H., Buratti, B., ... & Sotin, C. (2009). Characterization of clouds in Titan's tropical atmosphere. The Astrophysical Journal, 702(2), L105.
Uranus & Neptune	Methane ice (CH_4), hydrogen sulfide ice (H_2S), ammonia ice (NH_3), ammonium hydrosulfide ice (NH_4SH), ice water (H_2O)	Mousis, O., Atkinson, D. H., Cavalié, T., Fletcher, L. N., Amato, M. J., Aslam, S., ... & Villanueva, G. L. (2018). Scientific rationale for Uranus and Neptune in situ explorations. Planetary and Space Science, 155, 12-40.

Solar System Prevalent Aerosols

Planet	Chemical Composition	Source
Earth	**Sea salt**, dust, sulfates, organic carbon, black carbon (soot), nitrates, volcanic ash, biological particles.	"Aerosol–Cloud–Climate Interactions" by K. S. Carslaw, et al. (2013), "Atmospheric Chemistry and Physics" by J. H. Seinfeld and S. N. Pandis (2016), "Cloud and Aerosol Effects on Climate" by B. Stevens and G. Feingold (2009) "The Role of Aerosols in Cloud Formation and Climate" by M. O. Andreae and D. Rosenfeld (2008)
Venus	**Sulfuric acid droplets**, sulfur dioxide, sulfur particles, water vapor, chlorine compounds, unknown UV absorbers	"Venus II: Geology, Geophysics, Atmosphere, and Solar Wind Environment" edited by S. W. Bougher, D. M. Hunten, and R. J. Phillips (1997) "The Atmosphere and Climate of Venus" by D. Crisp (1986) "Sulfur Chemistry in the Venus Clouds and Upper Atmosphere" by F. M. Flasar and A. H. Stamnes (1982) "The Clouds and Hazes of Venus" by L. Esposito et al. (1983) NASA Planetary Atmospheres Program Reports
Mars	**Dust**, water ice, carbon dioxide ice.	"The Atmosphere of Mars" by R. T. Clancy, M. J. Wolff, and P. B. James (1996) "The Climate of Mars" by H. H. Kieffer, B. M. Jakosky, and C. W. Snyder (1992) "Mars Atmospheric Dust Properties and Seasonal Variability" by M. D. Smith (2004)
Jupiter	Ammonia ice, water ice, ammonium hydrosulfide ice.	"The Clouds of Jupiter" by D. A. Gierasch and C. M. Goody (1968) "Jupiter's Atmospheric Composition and Cloud Structure" by G. S. Orton, B. M. Fisher, and L. D. Roth (1998) "Dynamics and Chemistry of Jupiter's Atmosphere" by A. P. Ingersoll, T. E. Dowling, and P. J. Gierasch (2004)
Saturn	Ammonia ice, water ice, ammonium hydrosulfide ice	"The Clouds of Saturn" by R. G. Prinn and B. Fegley Jr. (1981) "Saturn's Atmospheric Composition and Cloud Structure" by L. N. Fletcher, P. G. J. Irwin, and G. S. Orton (2007) "Saturn's Dynamic Atmosphere" by K. H. Baines, A. A. Simon-Miller, and T. W. Momary (2009)
Titan	Methane ice, ethane ice, complex organic aerosols (tholins)	"Photochemistry and Clouds in Titan's Atmosphere" by C. P. McKay, J. B. Pollack, and R. Courtin (1989) "Organic Haze on Titan" by M. G. Tomasko, L. R. Doose, and P. H. Smith (2008) "Titan's Methane Clouds and Their Seasonal Variability" by S. Rodríguez, C. A. Griffith, and R. H. Brown (2009)
Uranus & Neptune	Methane ice, hydrogen sulfide ice, ammonia ice.	"Uranus' and Neptune's Deep Atmospheres: Properties and Processes" by L. N. Fletcher, P. G. J. Irwin, and G. S. Orton (2014) "Clouds and Hazes in Uranus and Neptune's Atmospheres" by K. H. Baines, M. E. Hofstadter, and G. S. Orton (1999) "Aerosols and Clouds in Uranus and Neptune's Atmospheres" by R. Hueso and A. Sánchez-Lavega (2001)