MIMI : Investigation of the interaction of Titan's exosphere with Saturn's magnetosphere and first observations of Saturn

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Titan Huygens Conference, ESTEC, April 2004

ABSTRACT

The Magnetospheric Imaging Investigation (MIMI) is a neutral and charged energetic particle detection system on the Cassini Orbiter spacecraft, designed to perform both global imaging and in-situ measurements to study the overall configuration and dynamics of Saturn's magnetosphere, and its interactions with the solar wind, Saturn's atmosphere, Titan, and the icy satellites.

Titan's nitrogen-rich atmosphere is subject to direct magnetospheric interaction, due to its lack of a significant magnetic field. Energetic ions from Saturn's magnetosphere can undergo charge exchange collisions with neutral atoms from Titan's exosphere, being transformed to energetic neutral atoms (ENAs). The energy of the incident ions is almost entirely transferred to the charge exchange produced ENAs, which then propagate along nearly rectilinear ballistic trajectories. Thus the ENAs can be used like photons, in order to form an image of the energetic ion distribution and its interaction with the upper neutral atmosphere. The Ion and Neutral Camera (INCA), a magnetospheric imaging ENA camera which is part of MIMI, will perform remote sensing of this interaction by imaging the charge-exchange neutrals. During the Jupiter flyby INCA demonstrated the power of this technique by discovering and imaging a fast and hot magnetospheric neutral wind, originating from interactions with atoms from Io volcanic gases.

The parent ion population will be also directly measured by MIMI, along the Cassini trajectory, by using the CHEMS and LEMMS ion sensors. This will provide additional information for characterizing the plasma environment in the vicinity of Titan, for measuring the composition of the suprathermal ions, and for extracting the quantitative information from the ENA images, which contain an admixture of information on energetic ions and cold neutral distributions.

The Saturn observation sequences for MIMI begun in January 2004, and will culminate in orbit injection on July 1, 2004. The MIMI sensors, INCA CHEMS and LEMMS, observed substantial activity in the interplanetary space through January and February, including numerous increases most likely originating from particle streams in the vicinity of the Saturnian bow shock . Strong modulation of intensity is observed during spacecraft rolls, suggesting anisotropic pitch angle distributions down to the lowest observed ion energies (~3 to 10 keV). When the INCA sensor was switched to its energetic neutral atom (ENA) operating mode on February 21, at $\sim 10^3$ R_S (0.43AU), a weak signal was observed in the pixels pointing in the direction of Saturn, denoting the presence of Saturn's magnetosphere. Thus the source strength at ~30 R_S should be > 10^3 times stronger. As Cassini approaches Saturn, the full range of MIMI measurements will be used to address boundaries, spectra, composition, magnetosphere dynamics, and possible satellite micro signatures during the first orbit.

OVERVIEW

- ENA (Energetic Neutral Atoms) production principle
- The MIMI investigation
- ENA production in the Titan / Saturn system
  - Titan exosphere modelling : H > 1600 km
  - ENA production: image and spectra simulations
- Titan exosphere modelling :
  atmosphere and lower exosphere (0 - 1900 km)
- MIMI performance and first results:
  - Jupiter flyby
- First Saturn observations by MIMI
- Implications and Conclusions

ENA (Energetic Neutral Atoms) production principle

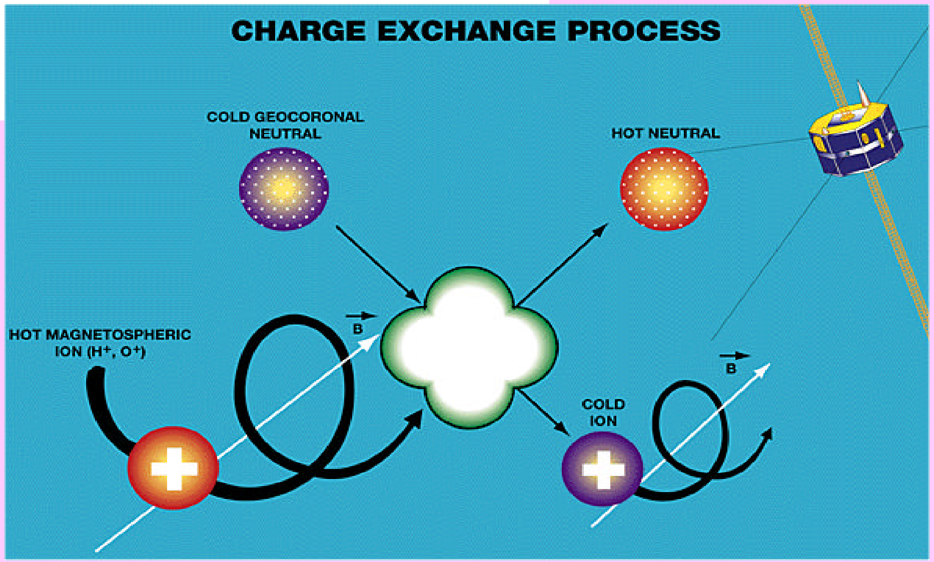
$$j_{ENA}(E) = \Sigma_k \, \sigma_{ik}(E) \int j_i(E) \, n_k(l) \, dl$$

$j_{ENA}(E)$: Energetic Neutral Atoms (ENA) Flux

$j_i(E)$: Ion Flux (i species)

$n_k(l)$: Exospheric Density (k species)

$\sigma_{ik}(E)$: Charge Exchange Cross-Section between Ions i and Exospheric Atoms k



MIMI

(Magnetospheric Imaging Instrument) onboard

Cassini

P.I. : S.M. Krimigis, APL/JHU

- **INCA**

(Ion and Neutral Camera)

~3 *keV - 3 MeV ions and neutrals*

- **CHEMS**

(Charge-Energy-Mass Spectrometer)

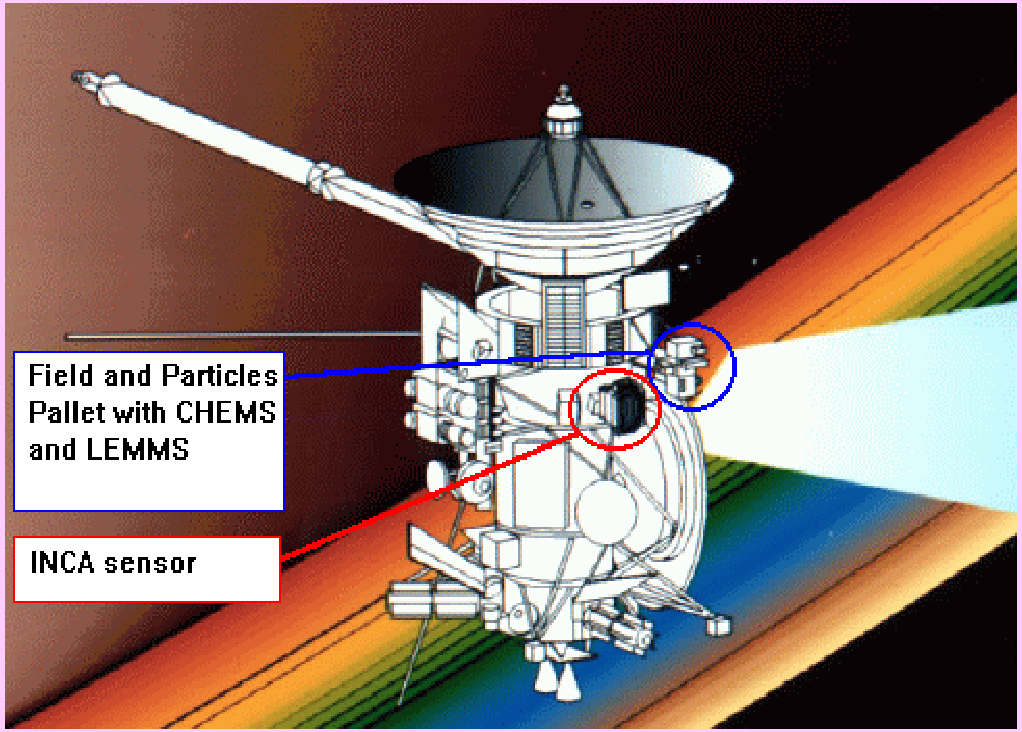
3 - 220 keV ions

- **LEMMS**

(Low Energy Magnetospheric Measurement System)

30 keV - 160 MeV ions

15 keV - 5 MeV electrons



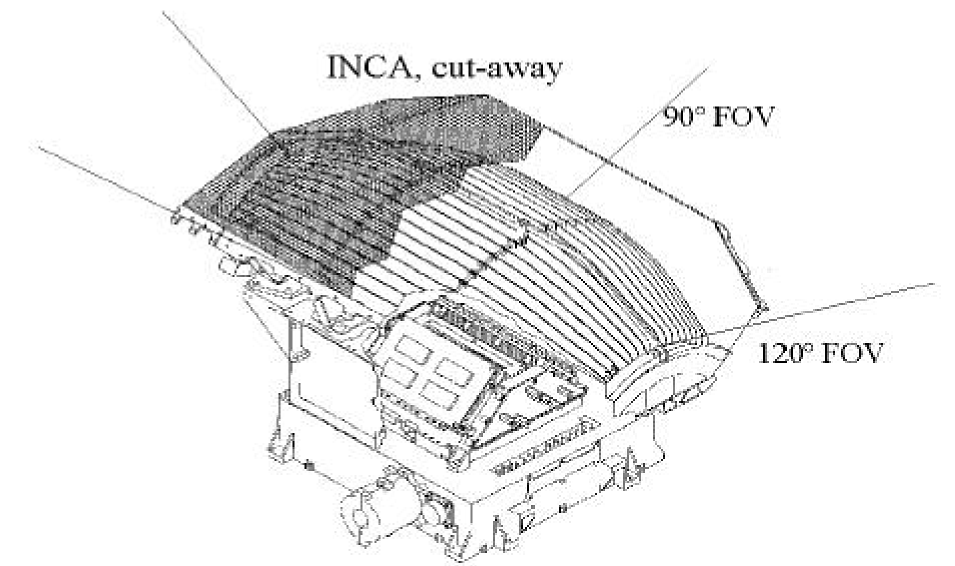
INCA

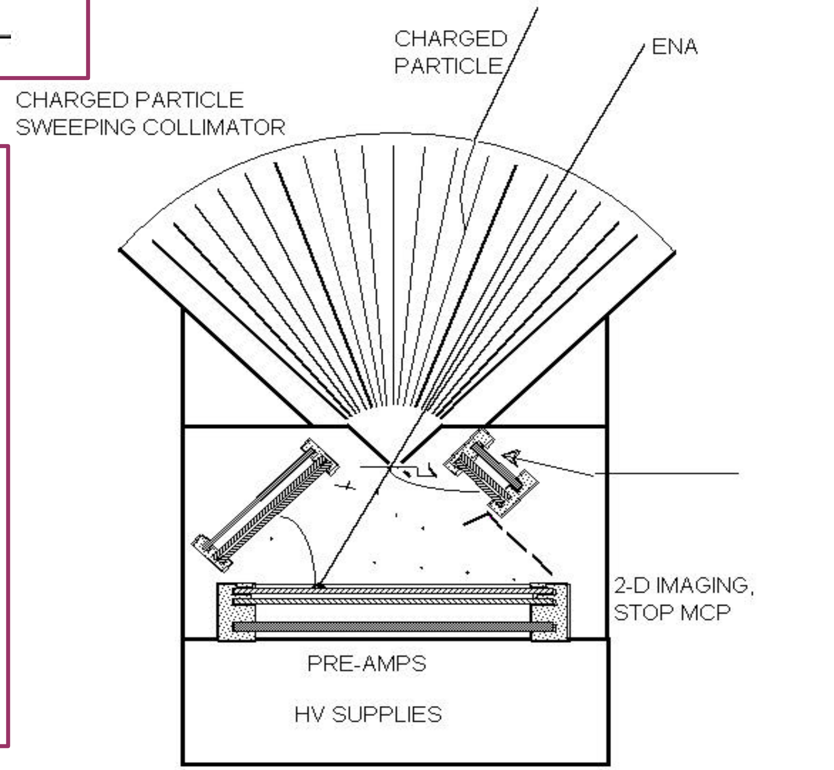
(Ion and Neutral Camera)

Instrument Scientist :
D. G. Mitchell, APL/JHU

INCA Sensor Characteristics

Energetic neutral atoms or ions, chosen by command:	
Energy range	<7 keV - 3 MeV/nuc.
Velocity resolution	50 km/sec (1ns TOF)
Mass Resolution	H, O, Heavies
Field Of View	120° x 90°
Angular coverage	0.76π sr (3π, if spinning)
Angular resolution	~8° x 4°, E_H > 50 keV
(scattering in foils at low E)	>8° x >8°, E_H ~ 20 keV
Time resolution	6 sec., PHA events
	85 sec, low resolution
	6 min., high resolution
	23 min., full sky
G x ε (cm^2-sr)	~2.4 for O, ~0.6 for H
G x ε for 4° x 4° pixel (O)	.007, tapered at edges
Dynamic range	~10^7





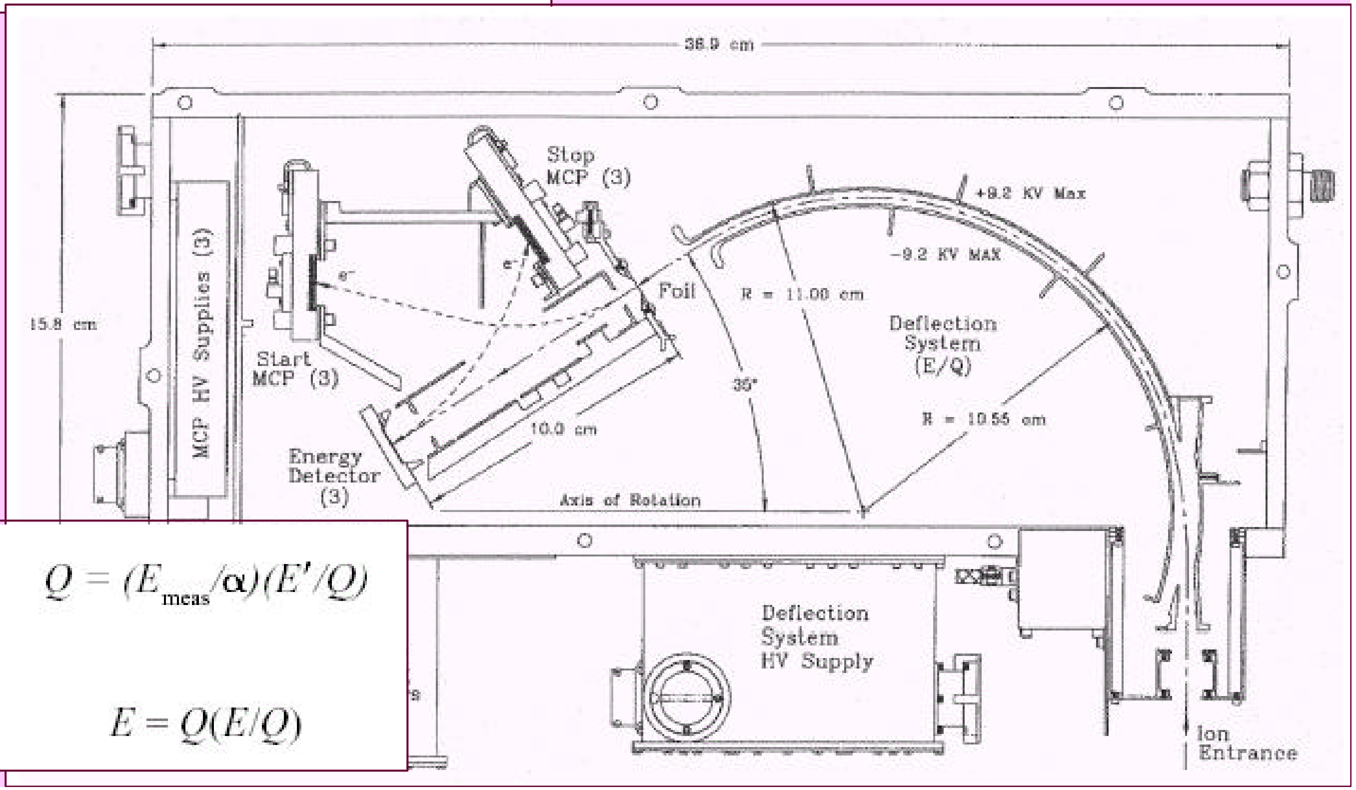
CHEMS

(**Ch**arge **E**nergy **M**ass **S**pectrometer)

Instrument Scientist :
D.C. Hamilton, Univ. Maryland

Capabilities of the CHEMS instrument

Energy per charge range	3-220 keV/e
Ion Species	H–Fe
Mass per charge range	1–80 amu/e
Resolution (FWHM)	
Energy per charge, $\Delta(E/Q)/(E/Q)$	0.03
Mass per charge, $\Delta(M/Q)/(M/Q)$	0.08, He^{++} at 100 keV/e
	0.07, O^{+} at 100 keV
Mass, $\Delta M/M$	0.15, He^{++} at 100 keV/e
	0.5, O^{+} at 100 keV
Geometrical factor	0.05 cm^2-sr
Field of view (FWHM)	4.0° by 159°
Dynamic range	10^{10}



$$M/Q = 2(\tau/d)^2(E'/Q) \qquad Q = (E_{meas}/\alpha)(E'/Q)$$

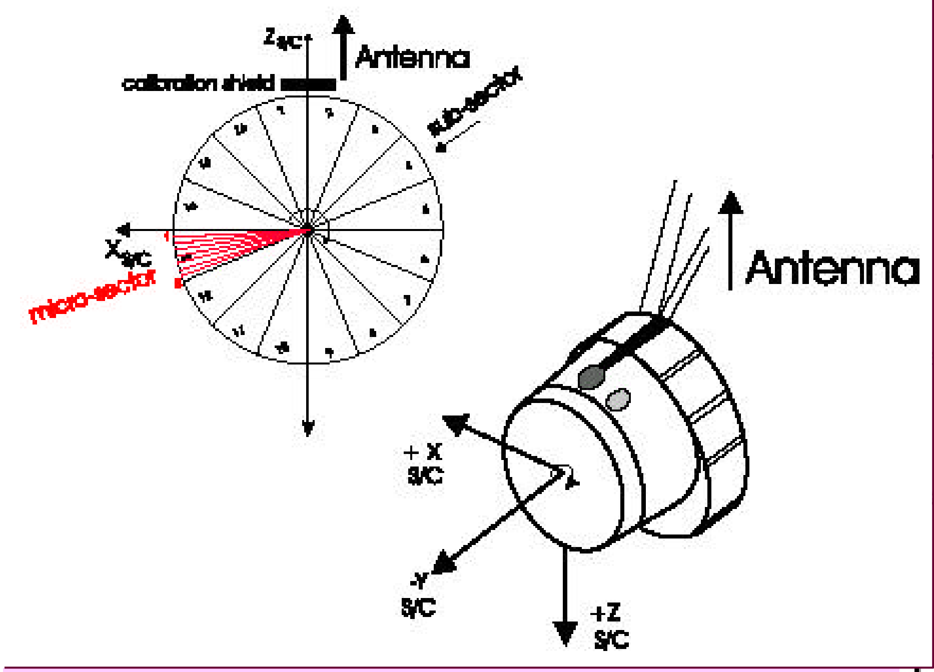
$$M = 2(\tau/d)^2(E_{meas}/\alpha) \qquad E = Q(E/Q)$$

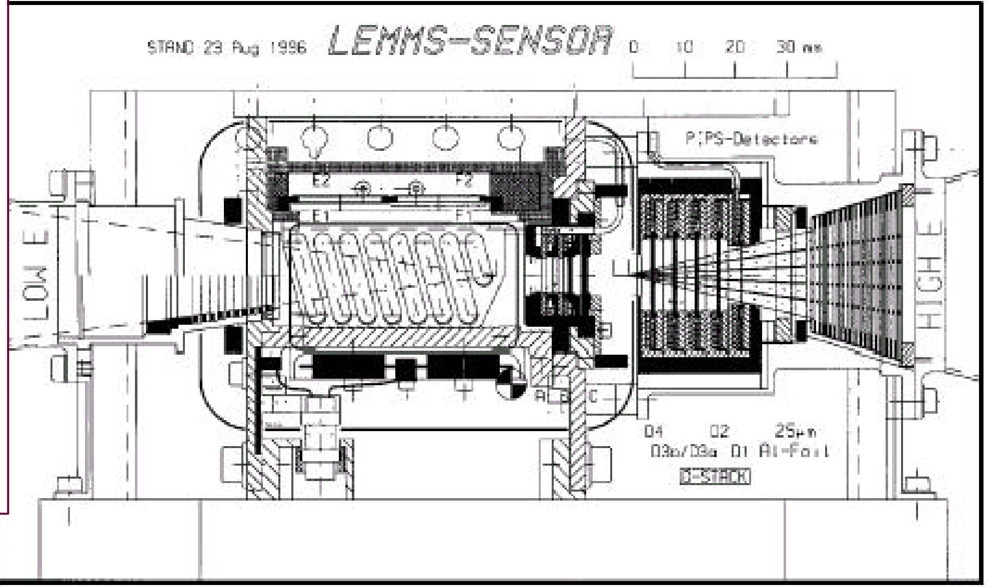
LEMMS

(<u>L</u>ow <u>E</u>nergy <u>M</u>agnetospheric <u>M</u>easurement <u>S</u>ystem)

Energy range	<u>normal counters:</u> ions: 0.030–160 MeV electrons: 0.015–5.0 MeV <u>priority counters:</u> ions: 0.030–0.036 & 0.036–0.053 MeV electrons: 0.015–0.028 & 0.028–0.043 MeV

Instrument Scientist :
S. Livi, MPAe, now at APL/JHU





Titan’s exosphere interaction with Saturn’s magnetosphere

• Titan’s orbit places it, most of the time, within Saturn’s magnetosphere.

• Titan's nitrogen-rich atmosphere is subject to direct magnetospheric interaction, due to its lack of a significant magnetic field.

• Energetic ions in the magnetosphere occasionally will undergo a charge exchange collision with cold neutral atoms from the upper Titan atmosphere, giving rise to the production of energetic neutral atoms.

• The coexistence of energetic ions and cold tenuous gas in the Saturn/Titan system makes this system particularly suitable for magnetospheric imaging via energetic neutral atoms.

Titan Exosphere Model (H > 1600 km)

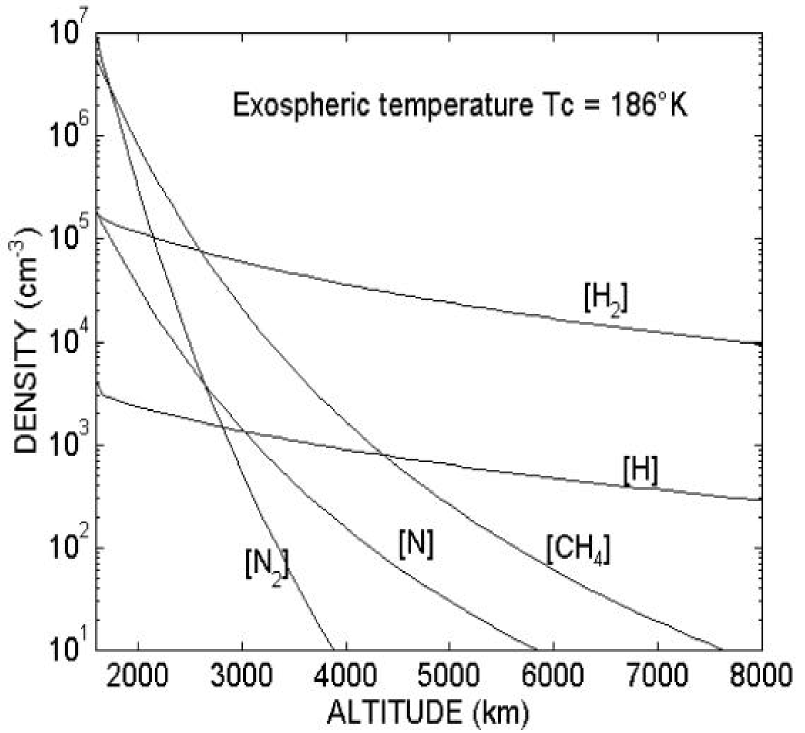
Hypotheses :

- *Chamberlain* [1963] formalism
- Spherical symmetry
- Neutral particles whose orbits are controlled only by gravity
- Ballistic and escape orbits
- Knowledge of the exobase altitude, or critical level h_C, temperature T_C and densities N_C
- Maxwellian distribution at the exobase, for each species
- Altitude profile of the distribution function determined by using the Liouville equation. The density altitude profile is then :

$$N(r) = N_C\, e^{-(\lambda_C - \lambda)}\, \zeta(\lambda)$$

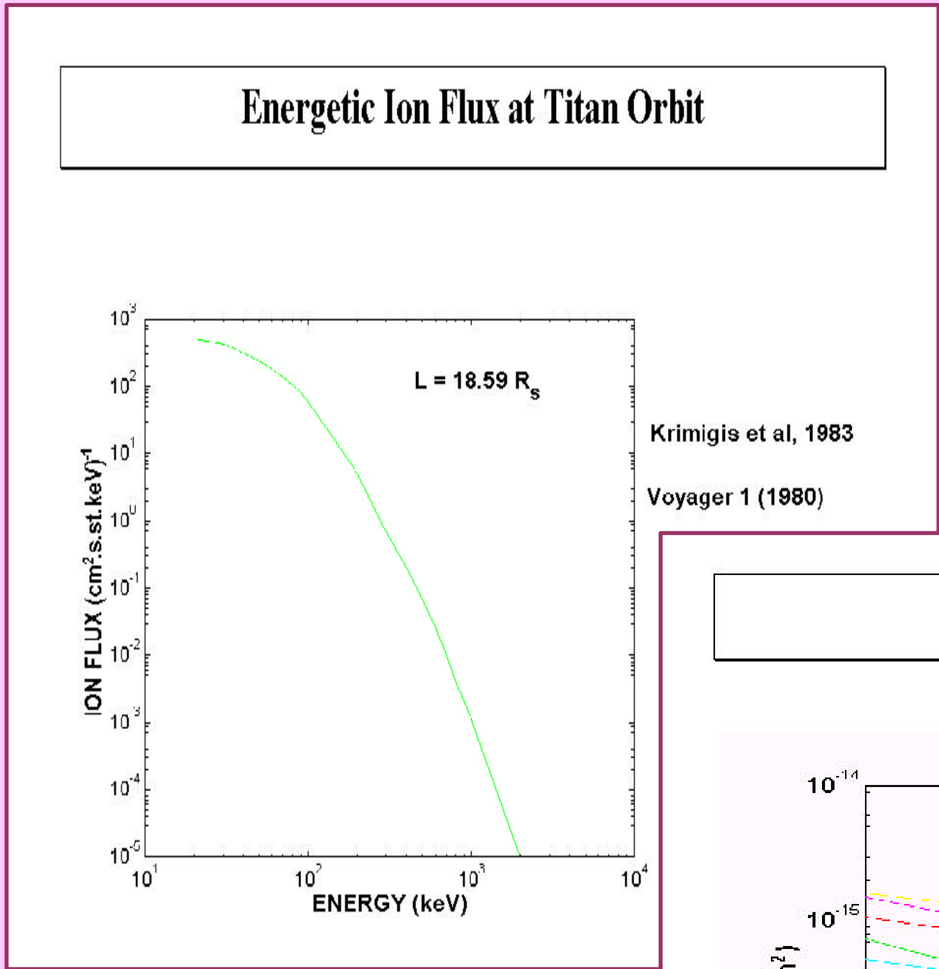
$\zeta(\lambda)$: partition function, $\lambda = G\,M\,\mathrm{M} / k\,T_C\,r$

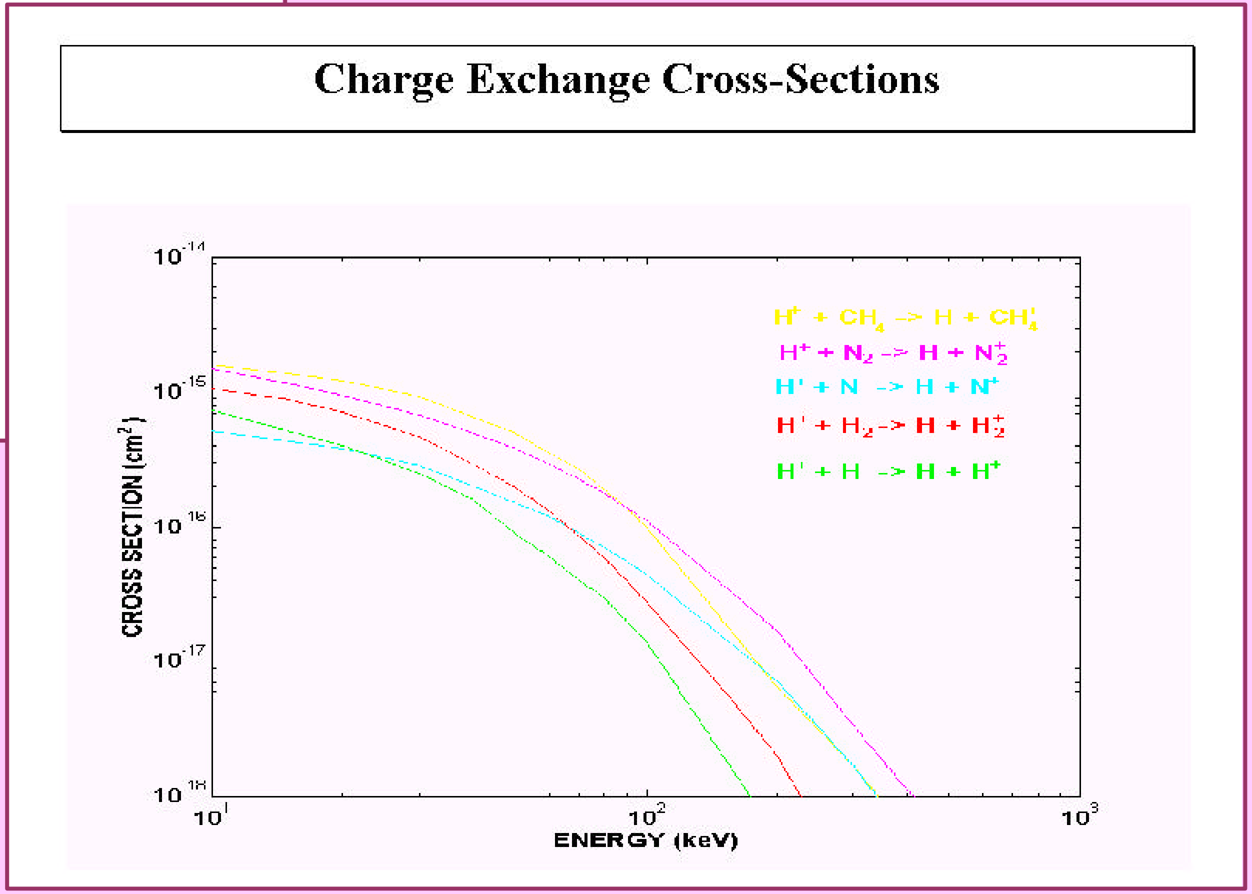
- Species considered : CH_4, N_2, N, H_2, H
- Boundary conditions : densities given at h_C = 1600 km by the *Keller et al* [1992] model, T_C = 186 K



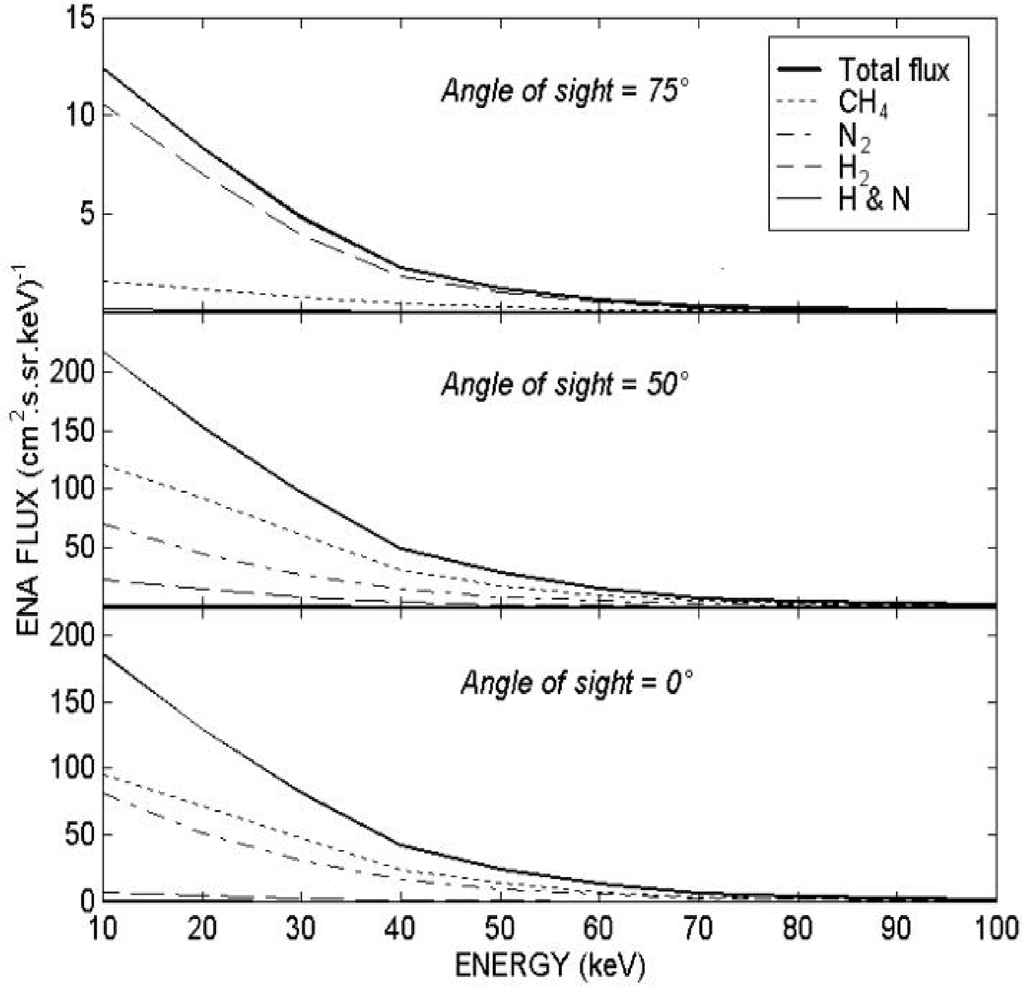
Amsif, *Dandouras*, *Roelof*, *JGR*, 1997

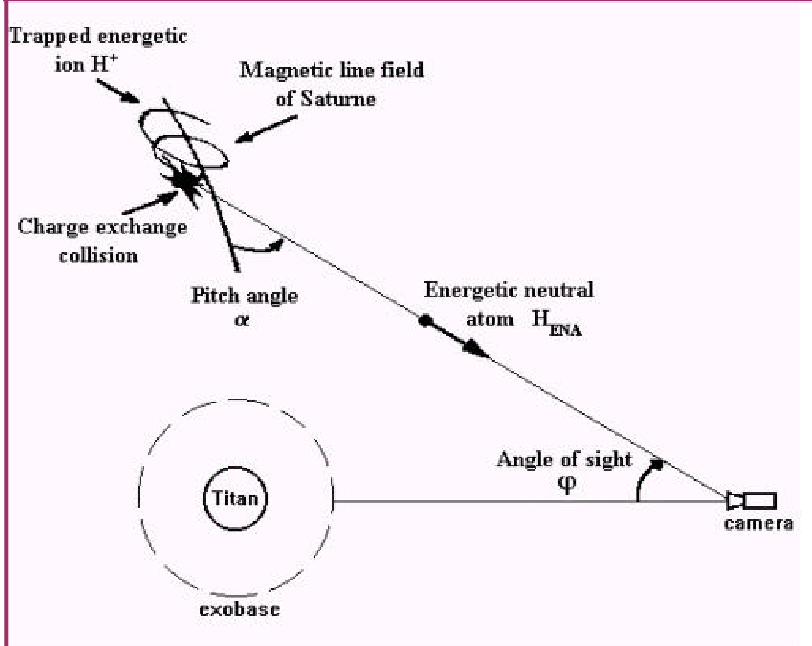
Titan ENA Production Model : input





Titan ENA Production 2D Model: Results



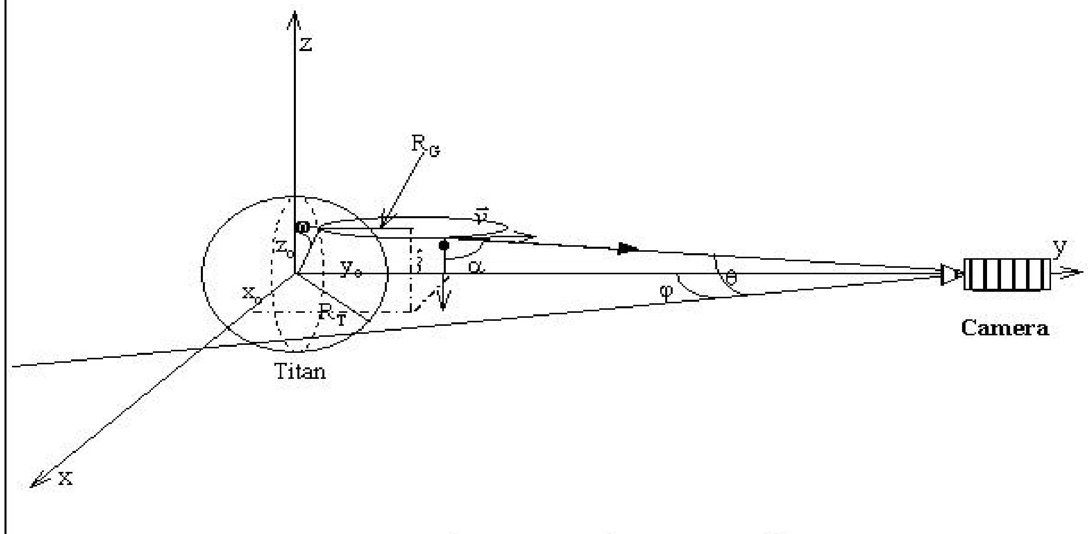


Contribution to the ENA flux of each exospheric species:

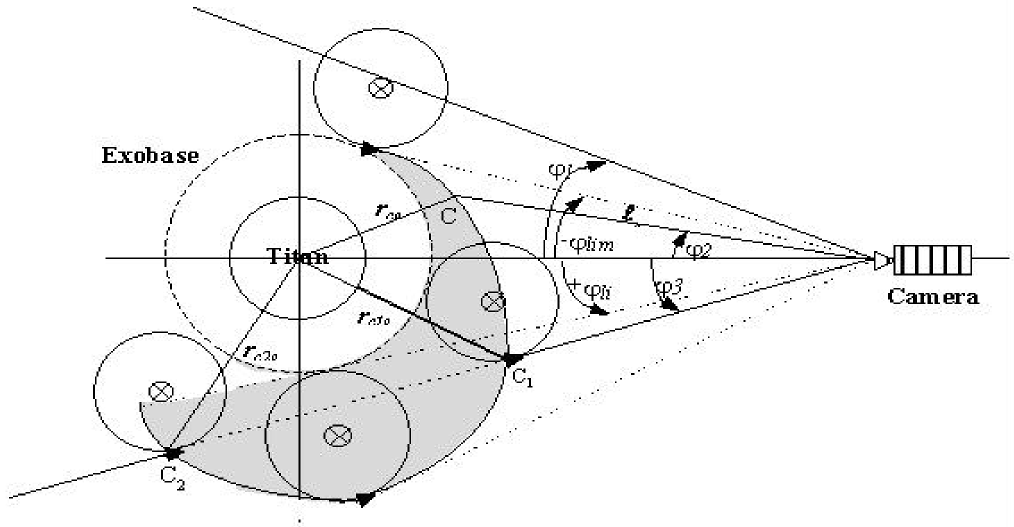
Titan ENA spectra at 3000 km

Amsif, Dandouras, Roelof, JGR, 1997

Titan ENA Production 3D Model

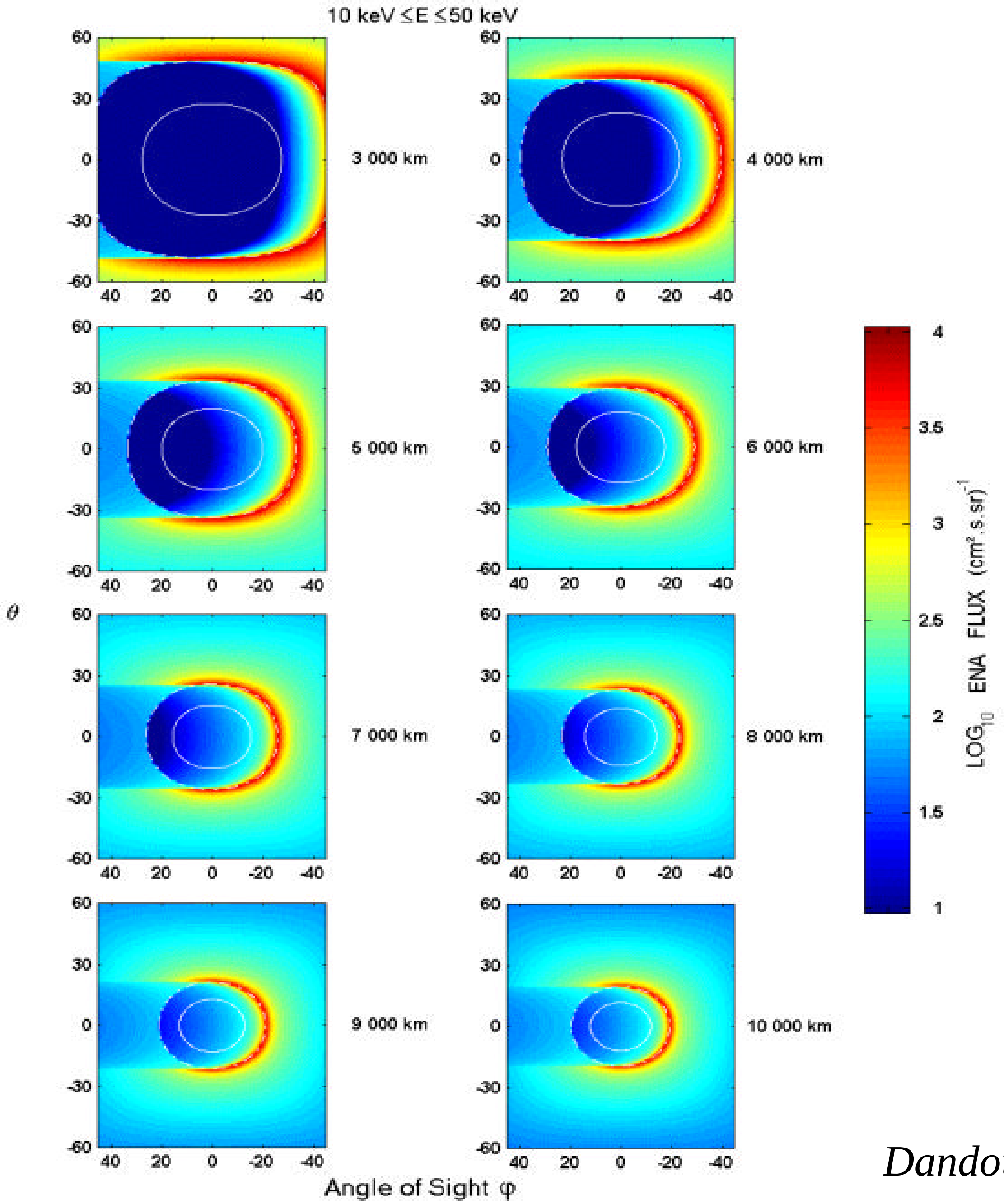


3D Perspective of ENA Production and Detection



Ion Gyroradius Shadow Effect

Titan ENA Production 3D Model : Results

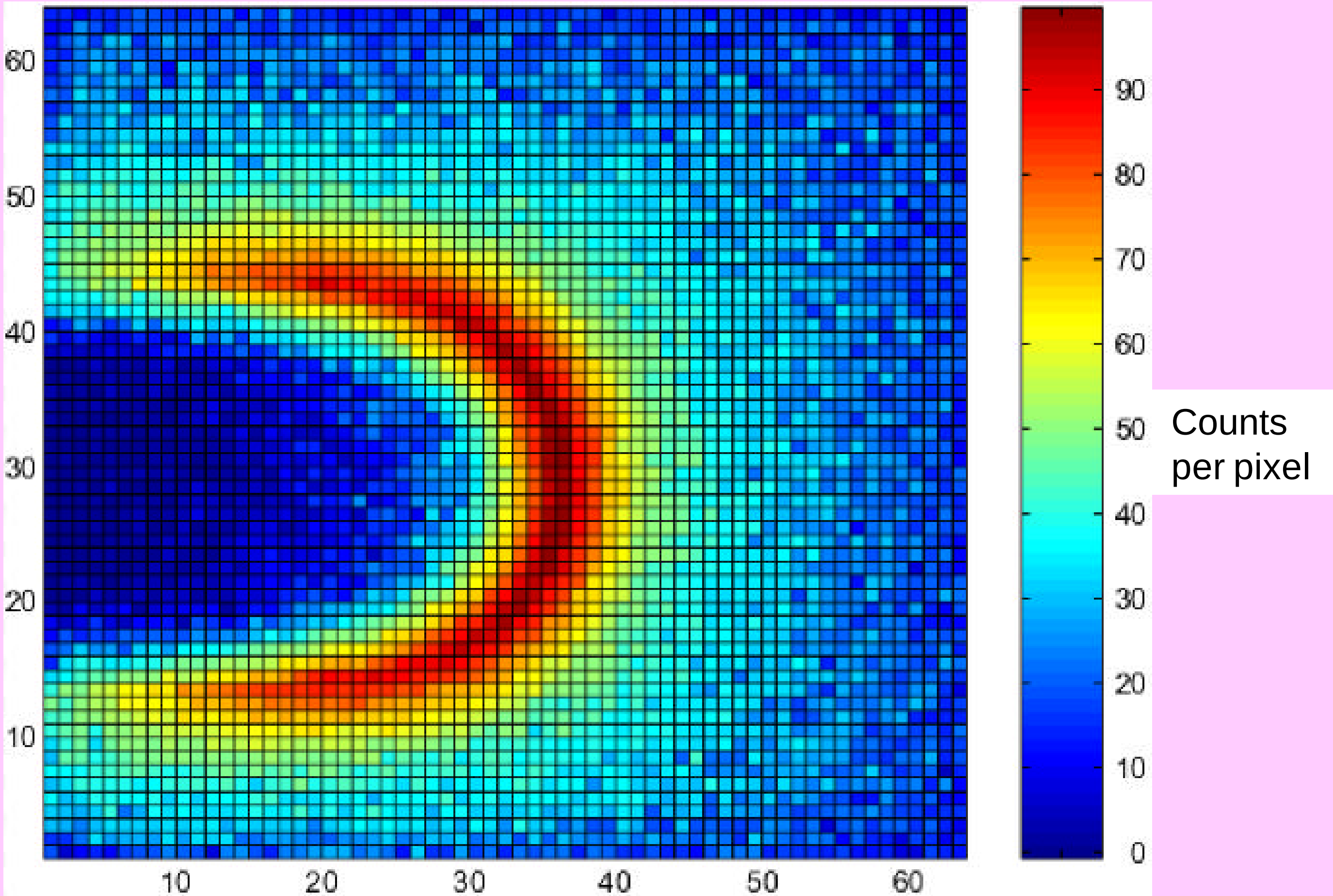


Simulated INCA images of the interaction of Titan's exosphere with Saturn's magnetosphere:

ENA flux
for different altitudes

Dandouras and Amsif, Planet. Sp. Sci., 1999

Titan ENA Production Model :
INCA Performance Simulation



H = 6000 km 10 keV < E < 50 keV t_{expo} = 5.75 minutes

Counting statistics Noise + C-foil straggling Monte Carlo Simulation

Titan Exosphere Numerical Modelling : Atmosphere and lower exosphere (0 - 1900 km)

- Radiative transfer – 1D model, then 3D
- Vertical turbulent diffusion
- Molecular / ambipolar diffusion
- Complete chemical reactions set : ~ 1000 reactions, 111 components
- Electron transport
- Neutral + Ion chemistry
- Photochemistry
- Dayside and Nightside case
- Adaptation of an atmospheric circulation model
- A lot of patience...

Toublanc et al., 1995

Lebonnois et al., 1999, 2000, 2001

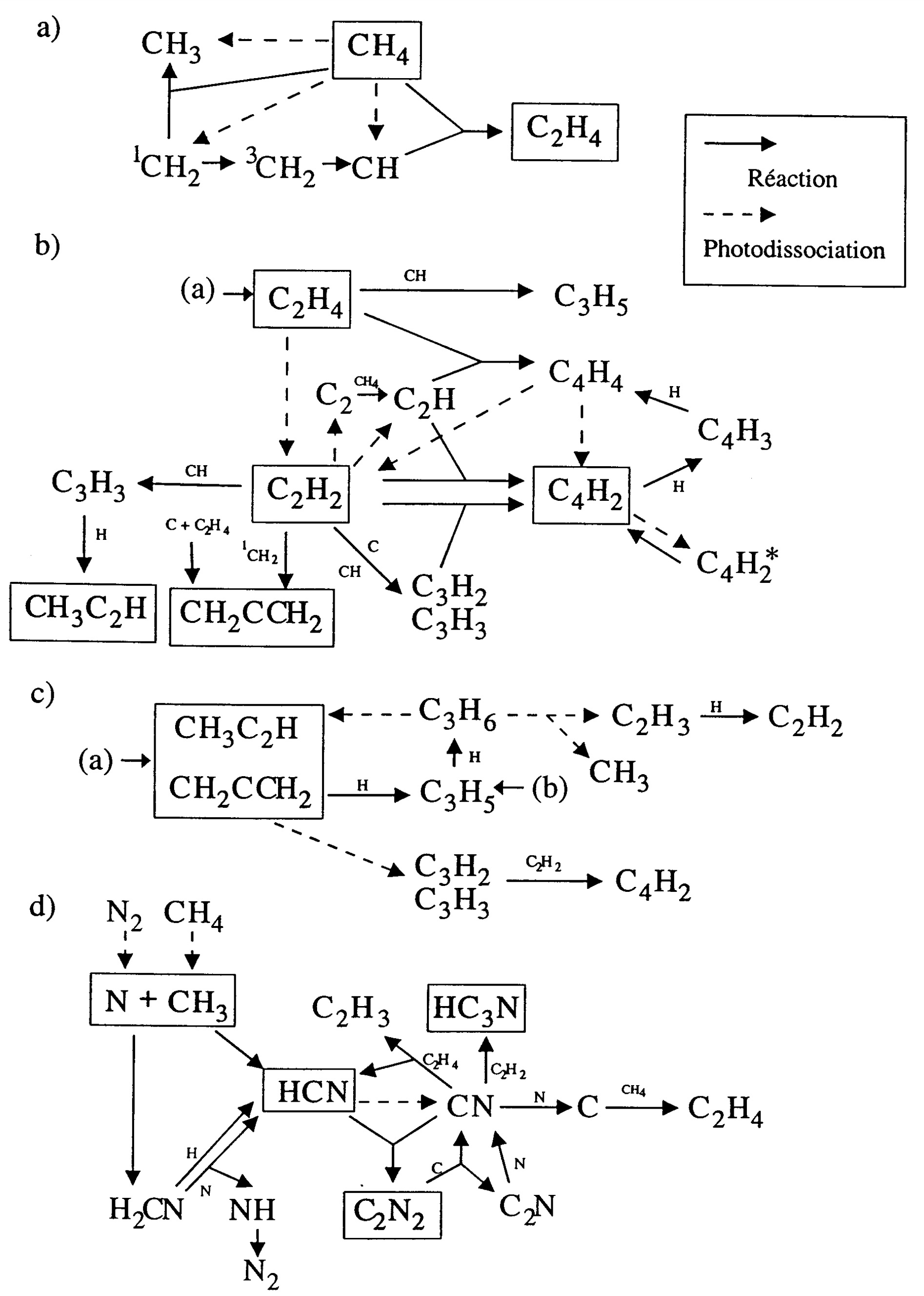
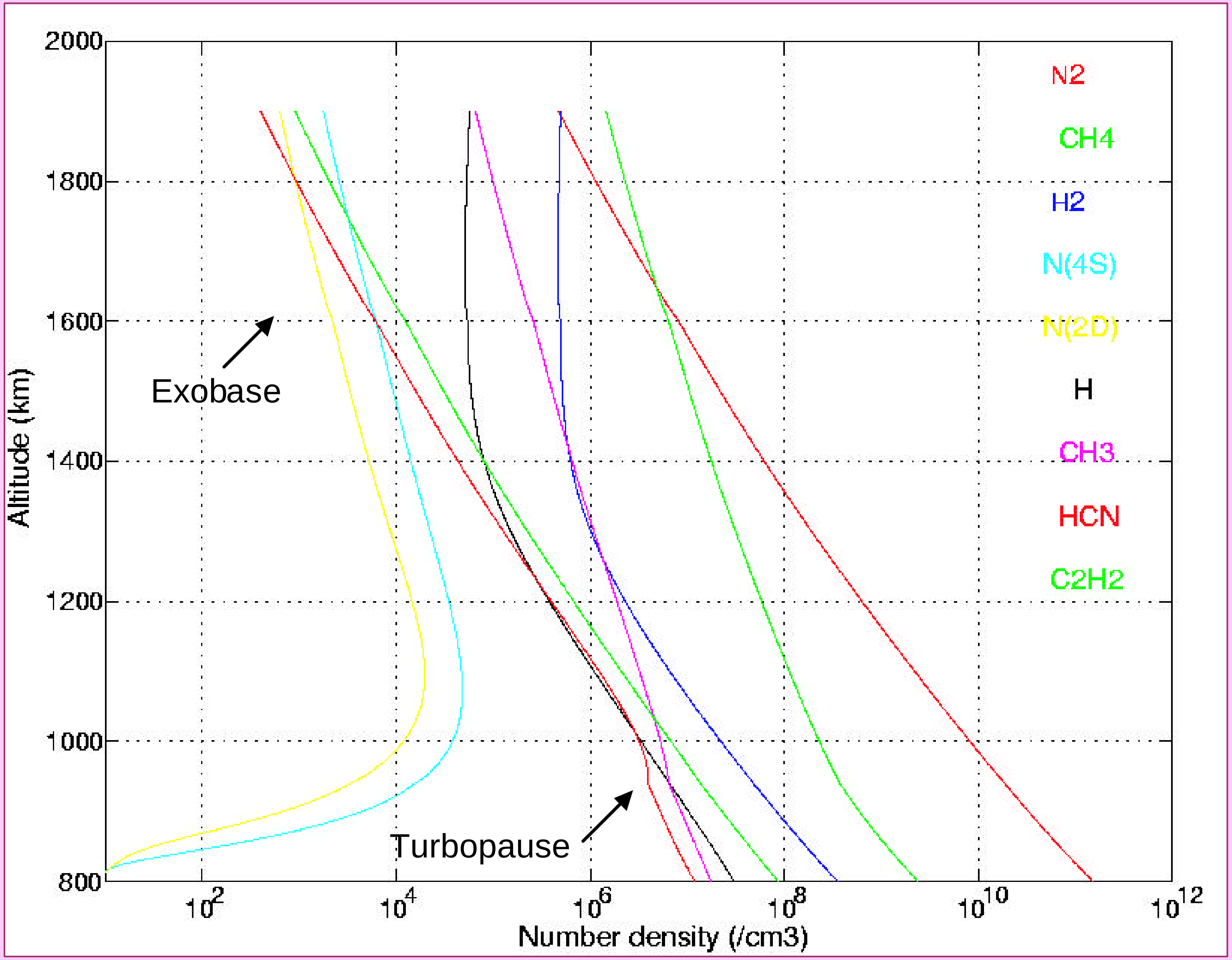
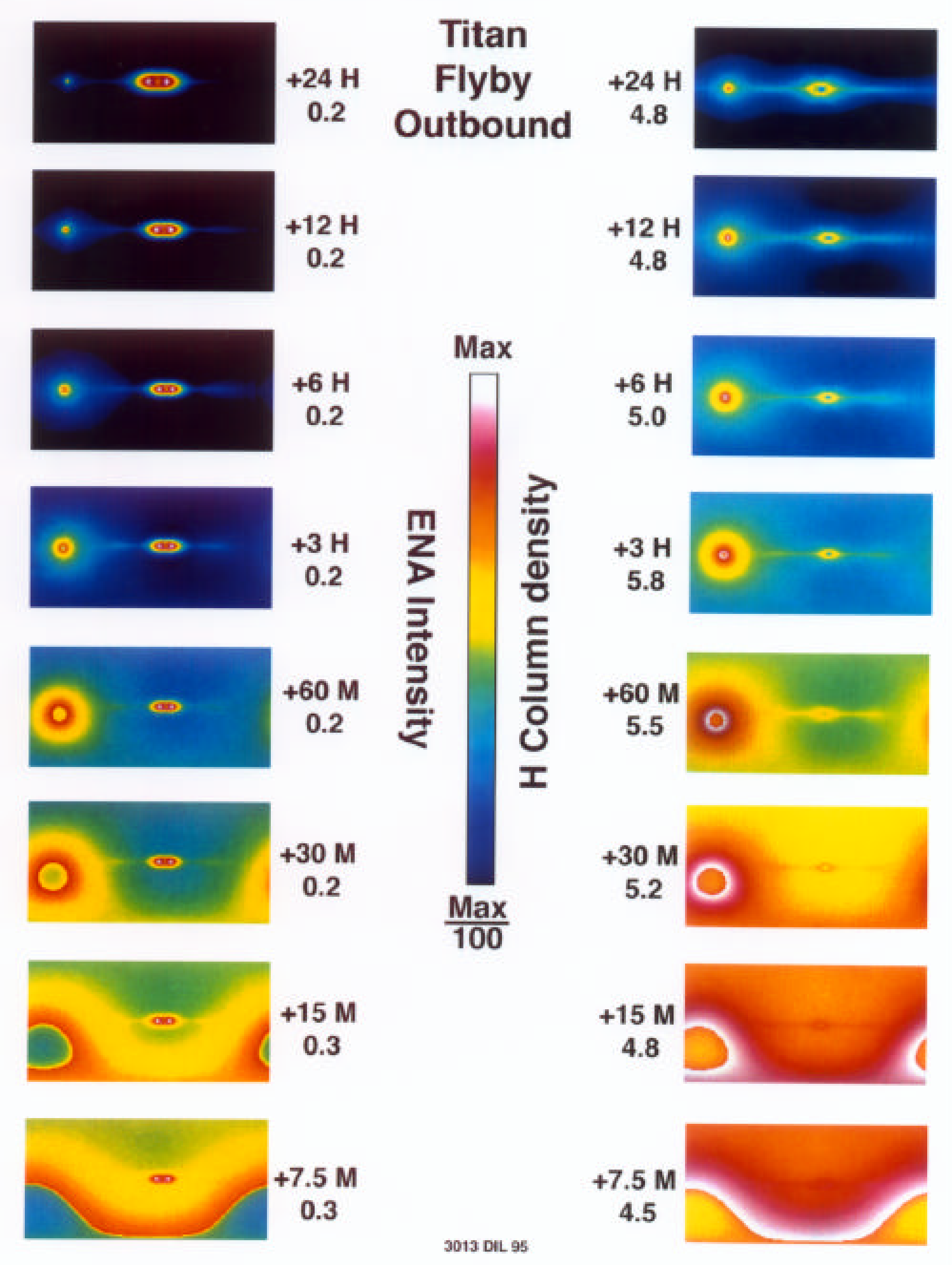


Figure 4.1 – *Schémas réactionnels pour la thermosphère de Titan (z > 600 km).*

Titan atmosphere and lower exosphere model :
Density profile at the equator for H = 800 to 1900 km





Simulation of a complete Titan flyby: outbound

Mercator projections of the entire sky. Bold numbers are times relative to closest approach (M= minutes, H= hours).

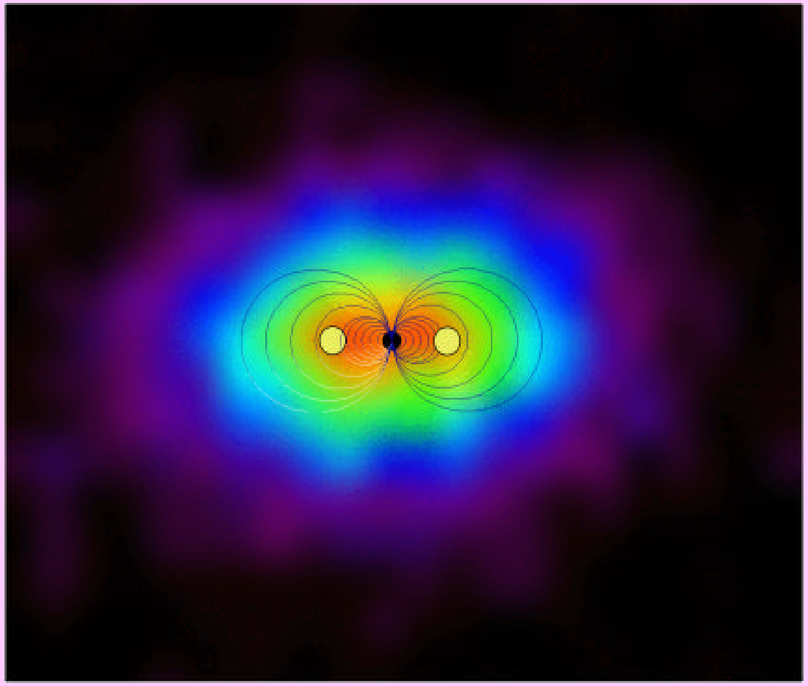
Logarithmic colour bar (factor of 100) normalised to brightest pixel in each panel. Multiply dimensionless column densities by 1.2×10^{13} cm^{-2}.

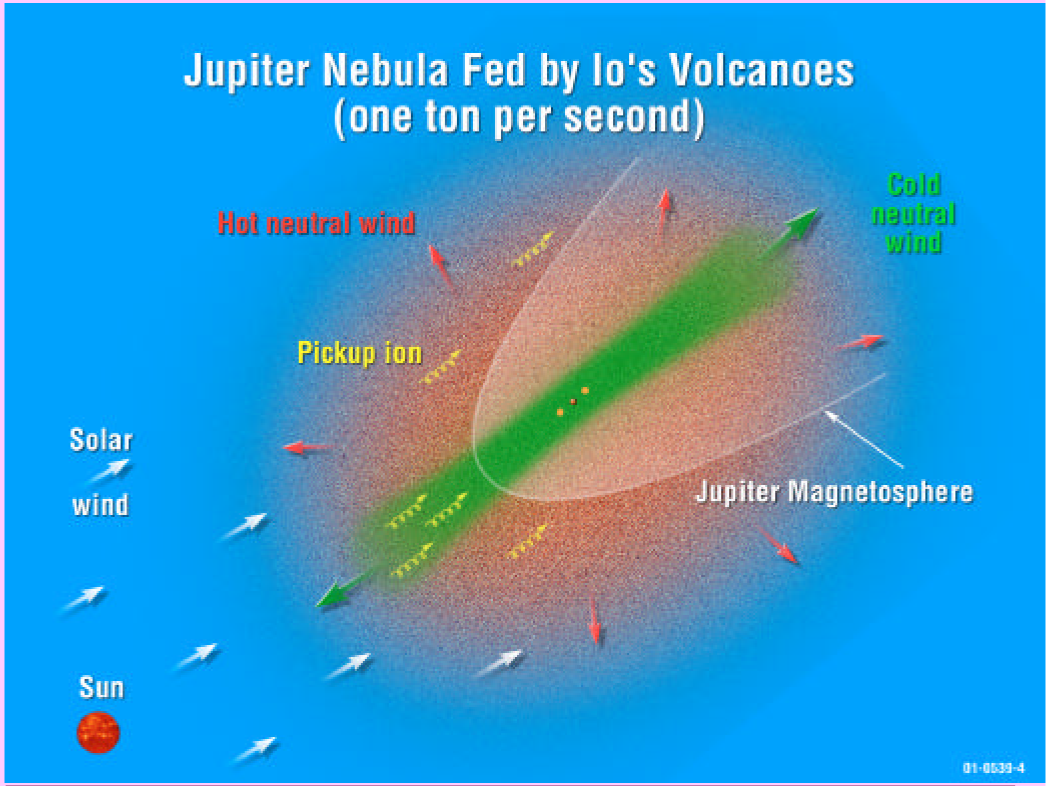
Distant Saturn magnetosphere (brightest points are ring current at L3) is comparable in ENA brightness to Titan exosphere, while Titan hydrogen torus (idealised) is much weaker. Note ENA image of Titan exosphere is distinct from Saturn magnetosphere.

Roelof and Williams, 1990

MIMI performance and first results

Cassini Jupiter Flyby





Jupiter Image : 4-5 Jan. 2001
Superposed on the MIMI image:
Jupiter disk (black circle)
Magnetic field lines
Io torus (yellow circles)

Discovery of a magnetospheric neutral wind extending more than 0.5 AU from Jupiter:

- Hot quasi-isotropic component
- Cold component :

neutrals escaping from Io's plasma torus, following charge exchange and having a corotation speed of ~75 km s^{-1}, confined close to the equatorial plane

Krimigis et al., Nature, 2002

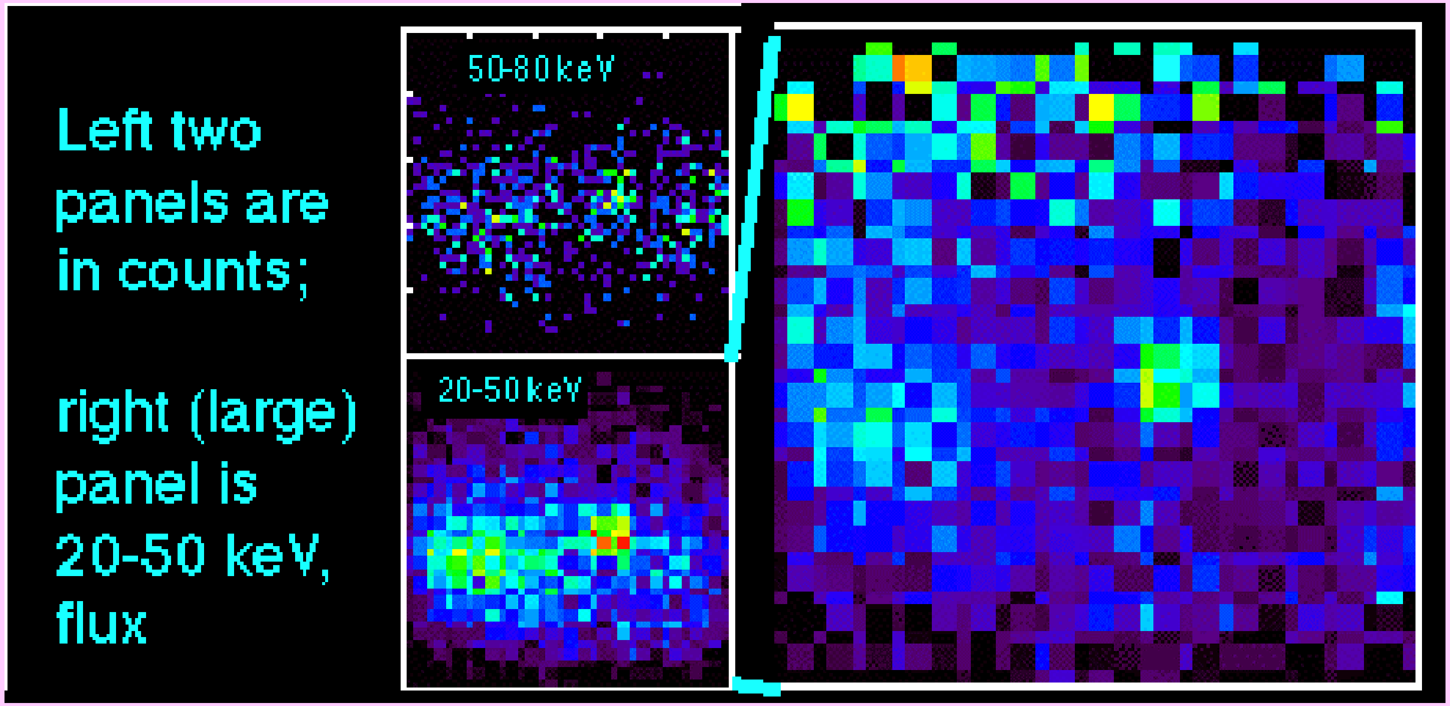
First Saturn observations by MIMI

• The Saturn observation sequences for MIMI begun in January 2004, and will culminate in orbit injection on July 1, 2004.

• The MIMI sensors, INCA CHEMS and LEMMS, observed **substantial activity in the interplanetary space**, including numerous increases **most likely originating from particle streams in the vicinity of the Saturnian bow shock** .

• **Strong modulation of ion intensity** is observed during spacecraft rolls, **suggesting anisotropic pitch angle distributions** down to the lowest observed energies (~3 to 10 keV).

First ENA emissions from Saturn seen by INCA



• INCA collimator plates (ENA mode) were first switched-on on 20 February 2004, to start searching for ENA emission from Saturn.

• The above figure is from a **two-day integration** of INCA data.

• The signal is very weak, but the images are taken **at about 1000 R_S** out, or about 0.43 AU. Much of the ENA data **during tour** will be taken at 10 - 30 R_S, so the signal should be **1000 to 10,000 time stronger** (~1 minute integration), assuming no change in the source strength .

• **Signal modulation** was subsequently observed (magnetospheric dynamics).

• As Cassini approaches Saturn, the full range of MIMI measurements will be used to address **boundaries**, **spectra**, **composition**, **magnetosphere dynamics**, and **possible satellite micro signatures** during the first orbit.

• In the vicinity of Titan the **parent ion population will be also directly measured** by MIMI, along the Cassini trajectory, by using the **CHEMS** and **LEMMS** ion sensors. This will complement the lower-energy plasma measurements by **CAPS**.

• This will provide additional information for characterising the plasma environment and measuring the composition of the suprathermal ions, and for extracting the quantitative information from the ENA images, which contain an admixture of information on energetic ions and cold neutral distributions.

• **UVIS** observations of the neutral Titan torus and **INMS** in-situ measurements of the neutrals will be of paramount importance in order to invert the ENA images, and separate the energetic ion and the neutrals contributions to ENA production.

Implications and Conclusions

- The coexistence of energetic ions and cold tenuous gas in the Saturn / Titan system makes this system particularly suitable for magnetospheric imaging via energetic neutral atoms.
- MIMI has the capability of measuring the charged particle populations and the energetic neutral atoms.
- ENA fluxes and spectra are very sensitive to the exospheric composition and density profile, providing thus a diagnostic tool that will allow to constrain these parameters.
- CH_4 and N_2 are the main contributors to the ENA fluxes from the inner exosphere, although these species are less abundant than H and H_2.
- Limb brightening effects in the ENA images, above the Titan exobase.
- First ENA images acquired from the Saturnian magnetosphere, and first charged particles detected, most likely originating from the vicinity of the Saturnian bow shock.
- Looking forward to an exciting mission…