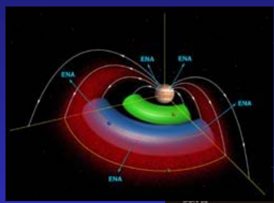
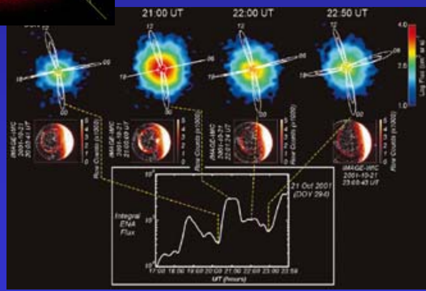
Energetic Neutral Atom - *ENA* - Imaging
Application to Planetary Research

Joachim Woch, MPAE



- Goal
- Principle
- Methods
- Instrumental Techniques
- Application - Results



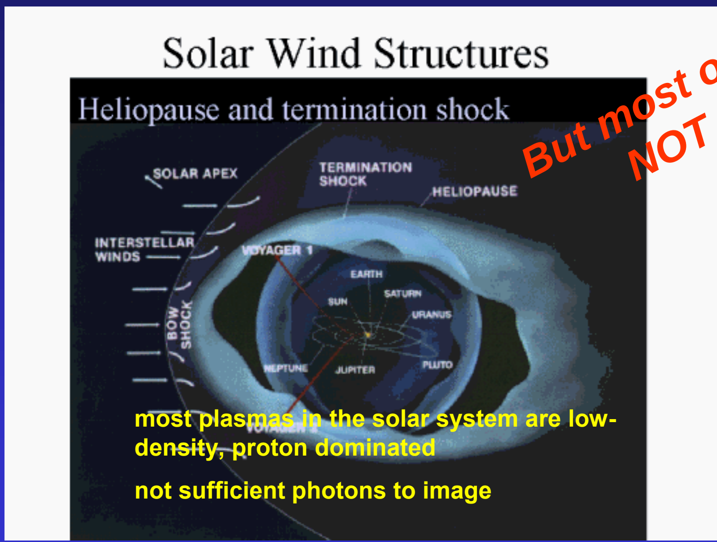
ENA Imaging – What For ?

GOAL: Making plasma processes visible by monitoring the evolution of space plasma processes on a global scale

Sometimes nature is friendly!

view on plasma processes in a high-density, collisional, light emitting environment

ENA Imaging – What For ?
'Imaging' of Plasma Processes

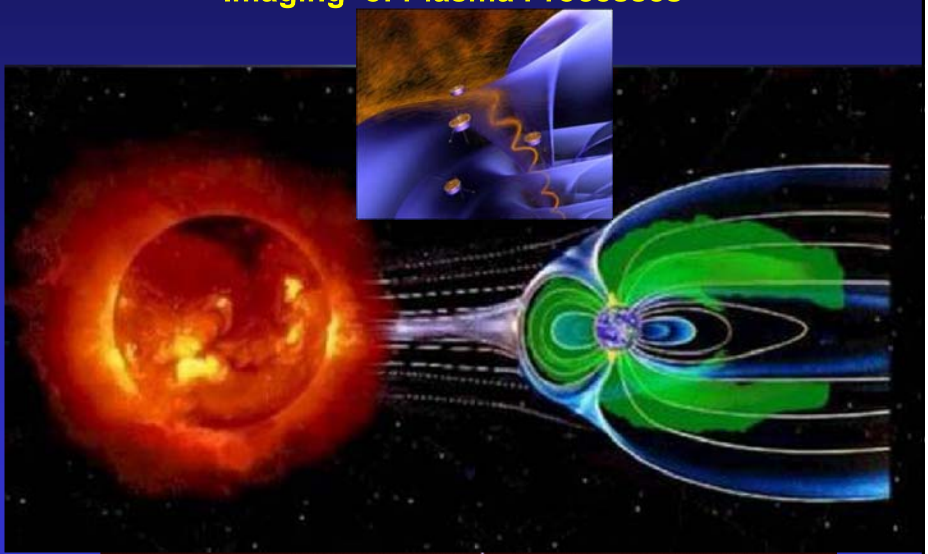


But most often NOT !

most plasmas in the solar system are low-density, proton dominated

not sufficient photons to image

ENA Imaging – What For ?
'Imaging' of Plasma Processes



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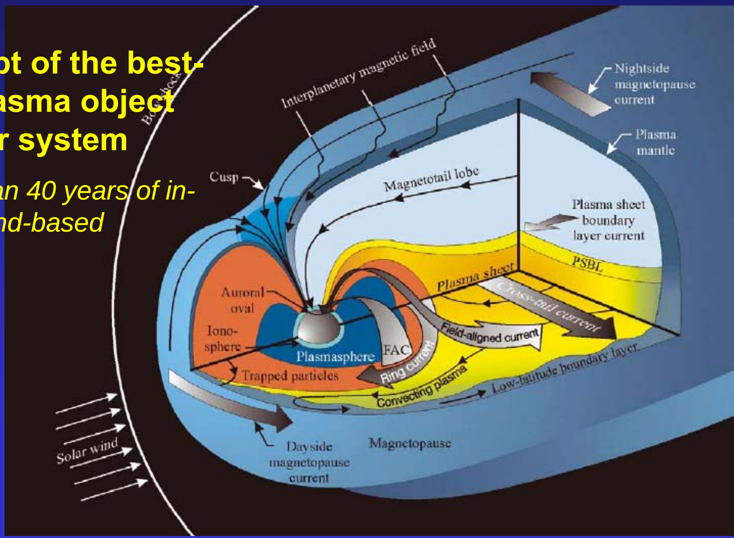
Studying Space Plasma Objects / Processes
The traditional way

our concept of the best-studied plasma object in the solar system

after more than 40 years of in-situ and ground-based observations



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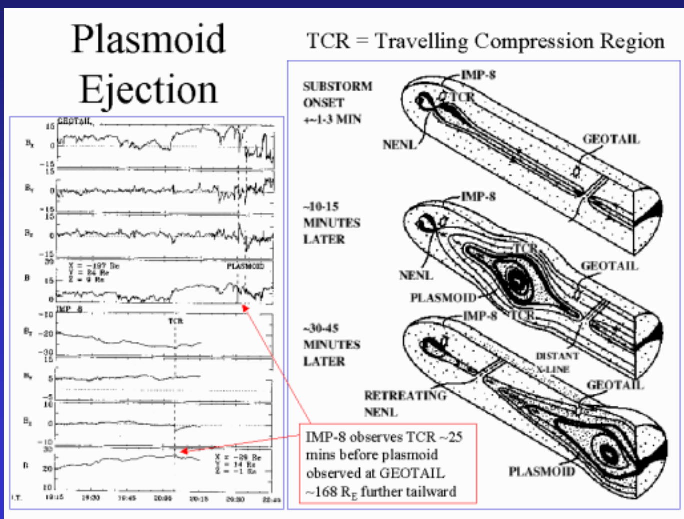
‘Imaging’ of Plasma Processes – The Reality
Single Point Observations of Magnetospheric Tail Processes



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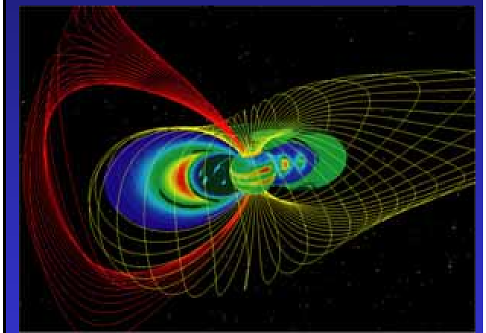
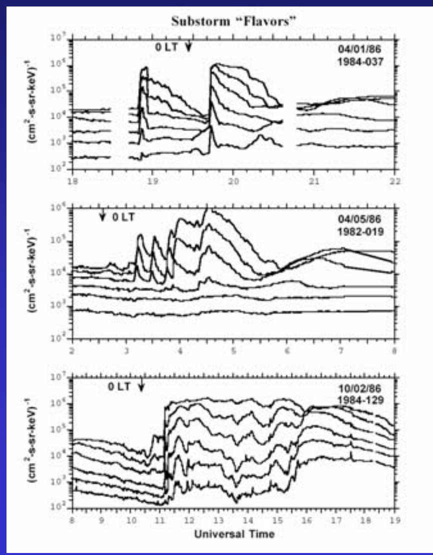
'Imaging' of Plasma Processes – The Reality

Multiple point observations of ring current injections





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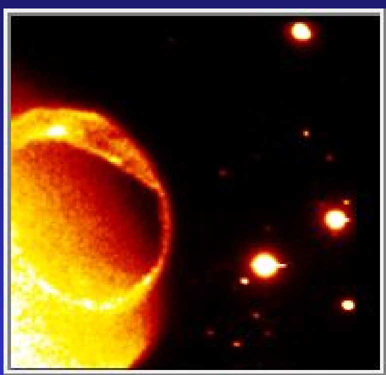
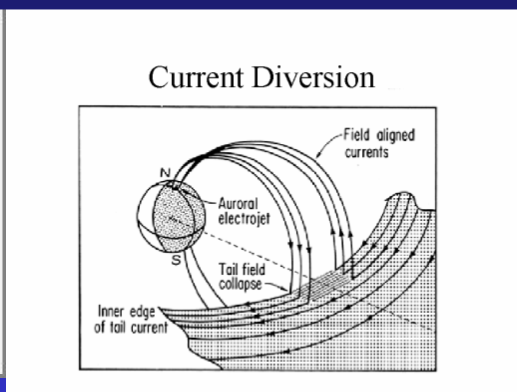
'Imaging' of Plasma Processes – The Reality

atmosphere and its aurorae as screen of magnetospheric processes





Studying Space Plasma Objects
The Traditional Way

we are using

- in-situ observations, mostly single-point
- ground-based observation
- remote-sensing of auroral displays

to study a huge, highly complex, dynamical system

in this way:

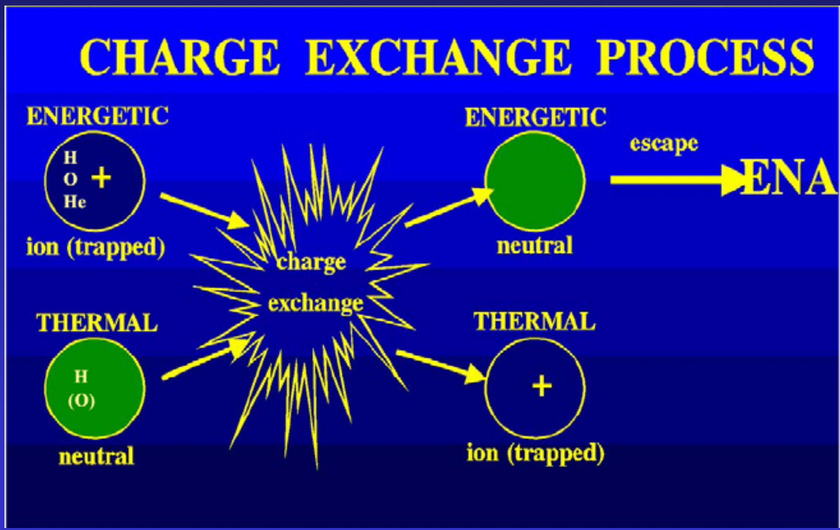
a global continuous monitoring of the evolution of the system is not easy to achieve

Energetic Neutral Atom – ENA – Imaging

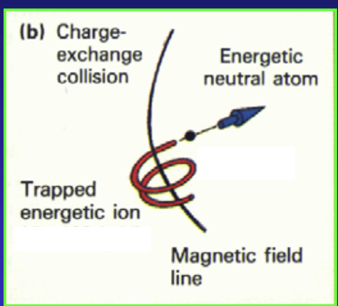
First of all: **Do not take serious**

‚Energetic' means anything above a neutral at rest

ENA Imaging – The Principle



ENA Imaging – The Principle



The co-existence of an energetic charged particle population (solar wind, magnetospheric plasma) and a planetary neutral gas leads to interaction, e.g., through charge-exchange:

A^+(energetic) + P(cold) $\Rightarrow$ A(energetic) + P^+(cold)

Little exchange of momentum → conserve velocity
ENA are not influenced by E- and B-fields; they travel on straight ballistic path like a photon
Directional detection of ENAs yields a global image of the interaction and allows to deduce properties of the source populations.

ENA production mechanism in space plasmas

- **Charge - exchange reaction with atmospheric / exospheric gases**
- Sputtering of planetary atmospheres
- Backscattering from the planetary atmospheres (ENA albedo)
- Sputtering from planetary surfaces
- Ion neutralization / sputtering on dust particles
- Recombination (CMI)

ENA Imaging – The Principle
In Other Words ...

Energetic ions in a planetary magnetosphere (environment) interact with cold neutral atom populations through charge exchange collisions to produce energetic neutral atoms:

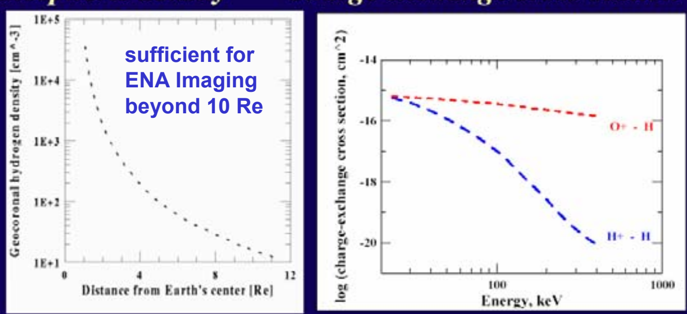
The charge exchange collision involves little exchange of momentum, so that an ENA moves off from the collision point on a ballistic trajectory, with initial velocity equal to that of the parent ion immediately before the collision. The ENAs can be sensed remotely since they are no longer confined by the magnetic field as the parent ions were.

→ ions' velocity distribution is preserved in the ENA distribution
→ composition is preserved
→ Thus, the ENA imaging technique enables quantitative, global-scale measurements of energetic ion populations from a remote observing point.

ENA Imaging – Interpretating the Image
A Mayor Challenge

ENA flux ~

*exospheric density * Charge exchange cross-section * ΔR*



** ION FLUX ??*

ENA Imaging – Interpretating the Image *A Mayor Challenge*

The main challenge facing ENA image science is to retrieve the underlying parent ion distribution from the ENA images.
The directional ENA flux (J_{ena}) at a point in space represents an integral along the chosen line-of-sight of the product of the hot ion flux toward the observation point ($j_{ion}(\mathbf{r},\mathbf{v}, t)$), the cold neutral density ($n_{neutral}(\mathbf{r},t)$), and the charge exchange cross section. That is,

$$j_{ENA} \cong \int_0^\infty dr \times j_{Ion}(\vec{r},\vec{v},t) \times n_{Neutral}(\vec{r}) \times \sigma_{CE}(|\vec{v}|)$$

where **r** is the location along the line-of-sight at which the charge exchange interaction occurs, **v** is the ion vector velocity at the instant of the interaction, and t is time. Ion distributions are obtained by relating the remotely observed differential directional ENA flux (j_{ENA}) to the path integrated source intensity, and mapping this to the equatorial plane under the assumptions of gyrotropy and conservation of the first adiabatic invariant. This inversion problem is not well constrained from a single observation point.

ENA Imaging – Interpretating the Image *in other words ...*

Interpretation of images is difficult and severely model-dependent

For a magnetospheric ENA image the emission regions are optically thin. Therefore, the image is a 2-D projection of the 3-D emission structure in the magnetosphere. Interpretation of the image requires constraining the position of the emissions along the line-of-sight by the known physics of the magnetosphere (e.g. Liouville‘s theorem constraining the particle phase space density distribution along the magnetic line of force).

Analogous to medical x-ray imaging (3-D optically thin body collapsed into a 2-D plane). Interpretation only possible based on prior understanding of anatomy

Way-Out (in future): multipoint imaging constrains models and parameter space; optical thin nature becomes distinct advantage

allows tomographic reconstruction (CAT) of spatial distributions of plasmas

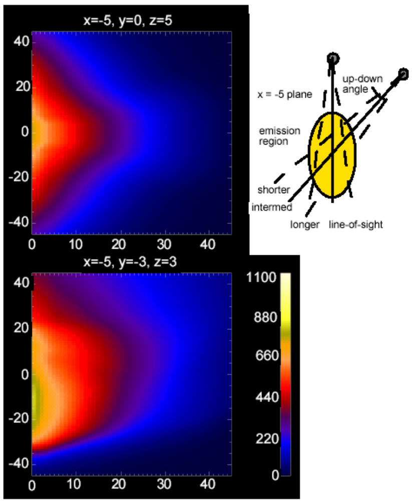


Figure 1. The same model magnetotail viewed from two locations. The combination of the two images shows that the asymmetry is caused by the viewing geometry, as illustrated in the sketch to the right.

A simulated magnetotail viewed from two different positions

ENA Imaging – How to do it ?
Measurement Techniques

it's tough !

ENAs are tenuous and have to be measured against a \`foreground´ of charged particles and UV photons

⟶ imposes difficulties even when doing \`White Light Imaging´

ENAs are not influenced by em-fields

⟶ How to do spectral analysis ?

ENA Imaging Instruments The Recipe

step 1: prevent ions and electrons to enter the instrument

→ electric and magnetic collimator deflection systems

step 2: reduce UV and EUV

→ foils, gratings

step 3: convert neutral particle into ion

→ ionizing foils, grazing incidence on surfaces

step 4: perform spectral, mass analysis

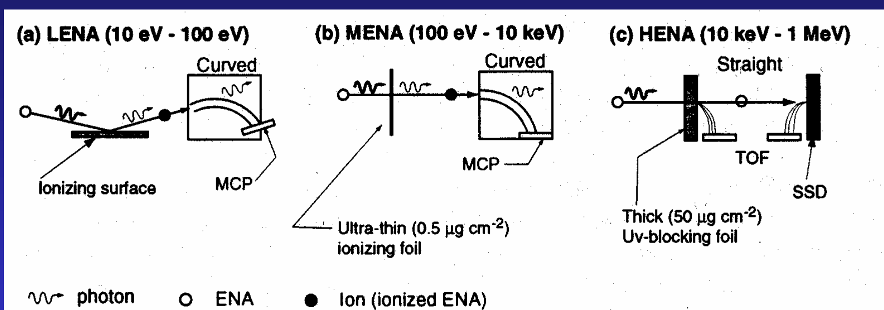
→ E and/or B fields, TOF system, E-PHA

step 5: perform imaging

→ direction-sensitive detection (MCP, SSD)

conserve velocity and directional information
and *combine it with a high geometric factor* !

ENA Imaging Instruments The Principle



step 2: reduce UV and EUV → foils, photon absorbing surfaces

step 3: convert neutral particle into ion → ionizing foils, grazing incidence on surfaces

step 4: perform spectral, mass analysis → E + B fields, TOF system, SSD

step 5: perform imaging → direction-sensitive detection (MCP, SSD)

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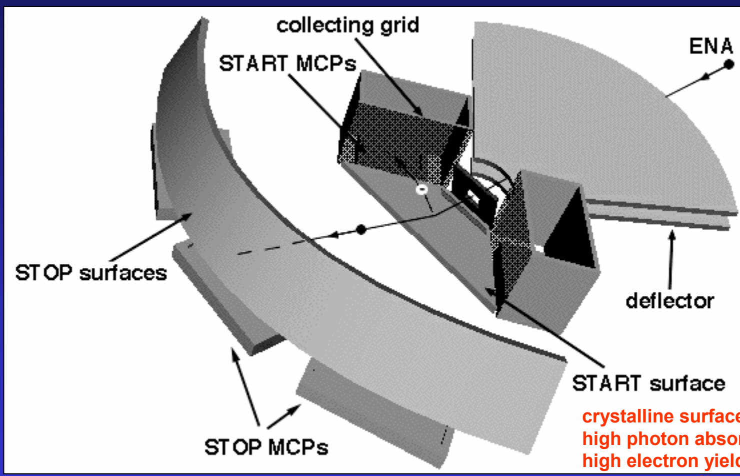
Schematics of a real ENA Instrument

ASPERA for MEX and VEX



crystalline surface with high photon absorption, high electron yield, high conversion efficiency with which neutrals loose or capture electrons e.g. tungsten

energy range several 10 eV to 10 keV
can distinguish H from O
moderate imaging capabilities

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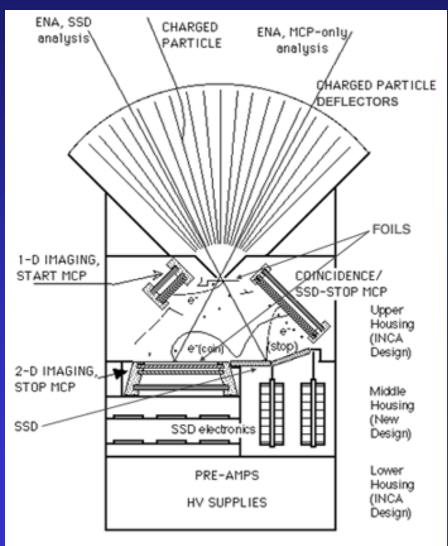
Schematics of a real ENA Instrument

INCA/Cassini and HENA/Image



velocity, trajectory, energy, and mass of ENAs in the 10-500 keV energy range

The HENA sensor consists of alternately charged deflection plates mounted in a fan configuration in front of the entrance slit; three microchannel plate (MCP) detectors; a solid-state detector (SSD); two carbon-silicon-polyimide foils, one at the entrance slit, the other placed just in front of the back MCP; and a series of wires and electrodes to steer secondary electrons ejected from the foils (or the SSD) to the MCPs.

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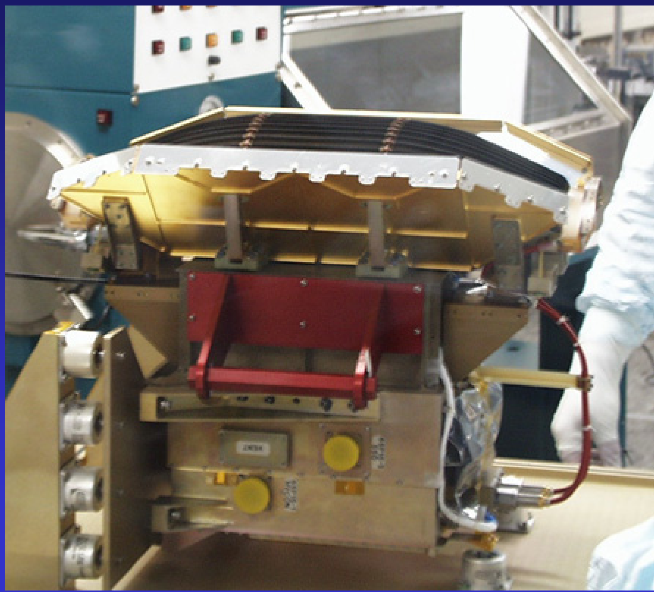
INCA/Cassini and HENA/Image



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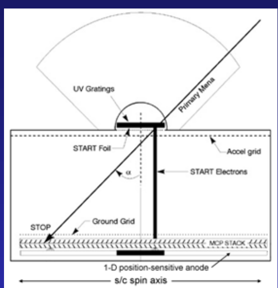
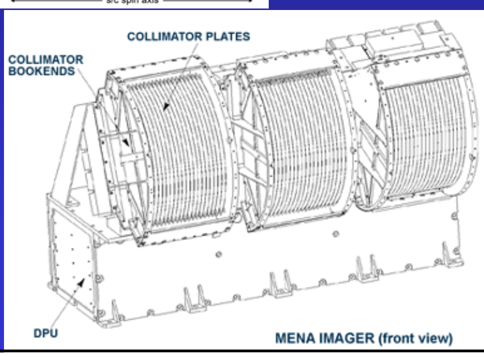
Schematics of a real ENA Instrument

MENA/Image

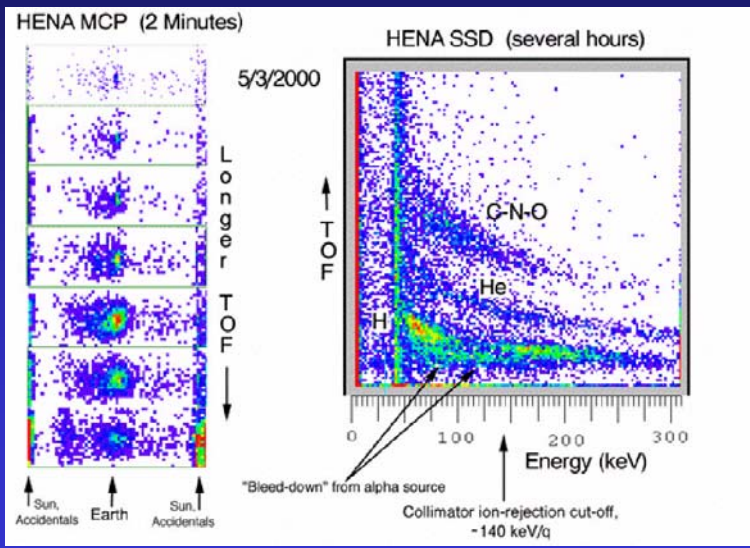


IMAGE's Medium Energy Neutral Atom (MENA) imager is a slit-type imager designed to detect energetic neutral hydrogen and oxygen atoms with energies ranging from 1 to 30 keV. The instrument determines the time of flight and incidence angle of the incoming ENAs; from these it calculates their trajectory and velocity and generates images of the magnetospheric regions from which they are emitted. The imager consists of three identical sensor heads mounted on a data processing unit (DPU).

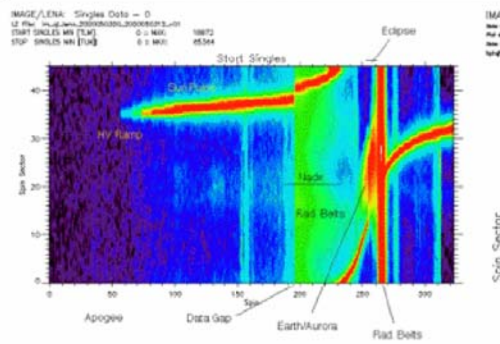


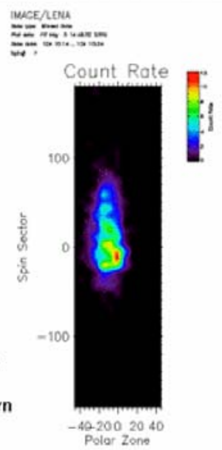
velocity, trajectory, (and mass H from O) of ENAs in the 1-10 keV energy range

ENA Raw Data
HENA / IMAGE



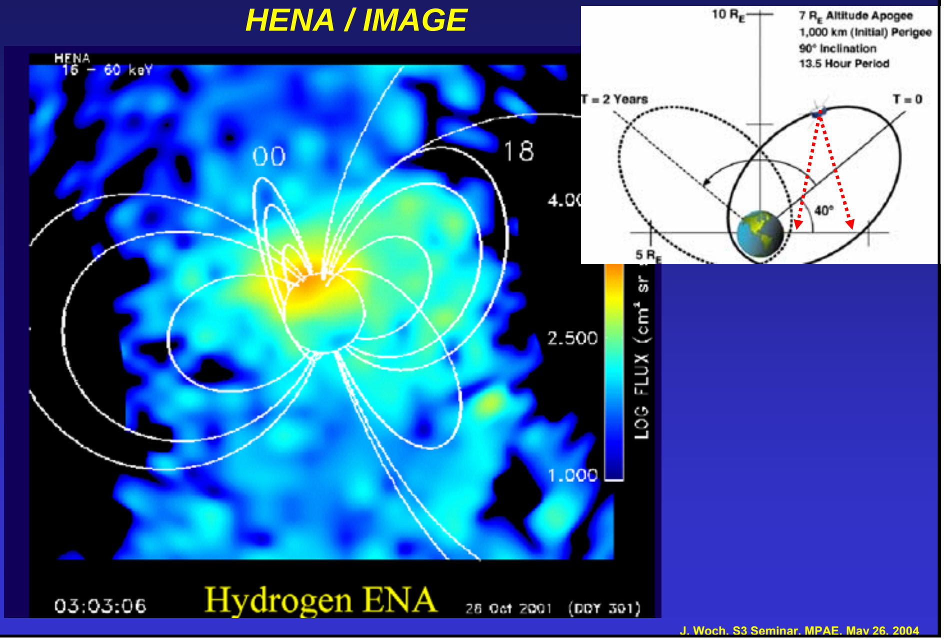
ENA Raw Data
LENA / IMAGE



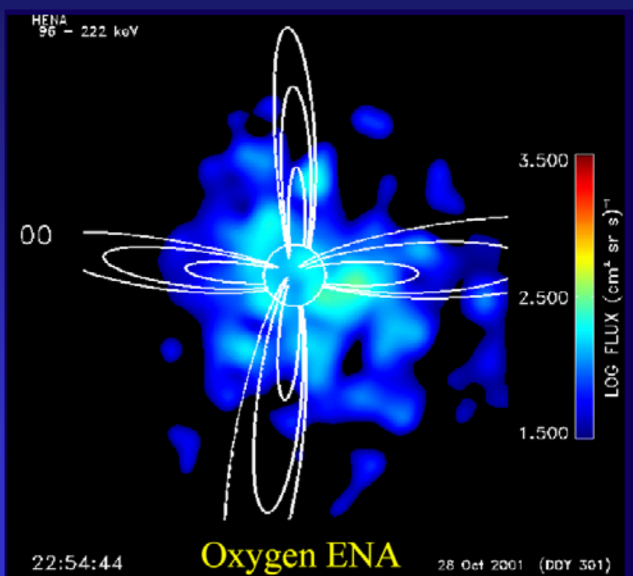


The Low Energy Neutral Atom imager is turned on in this pass on 2000/05/03. A strong signal from the Earth direction is seen during the Eclipse pass over the southern polar cap near perigee. Considerable additional work needs to be done to make this identification definitive.

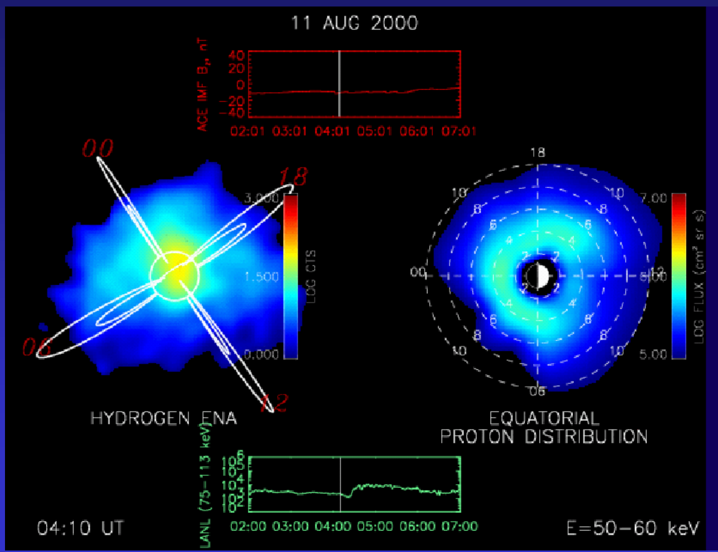
ENA Processed Images
HENA / IMAGE



ENA Processed Images
HENA / IMAGE



ENA Signal Deconvolution
Storm recovery phase



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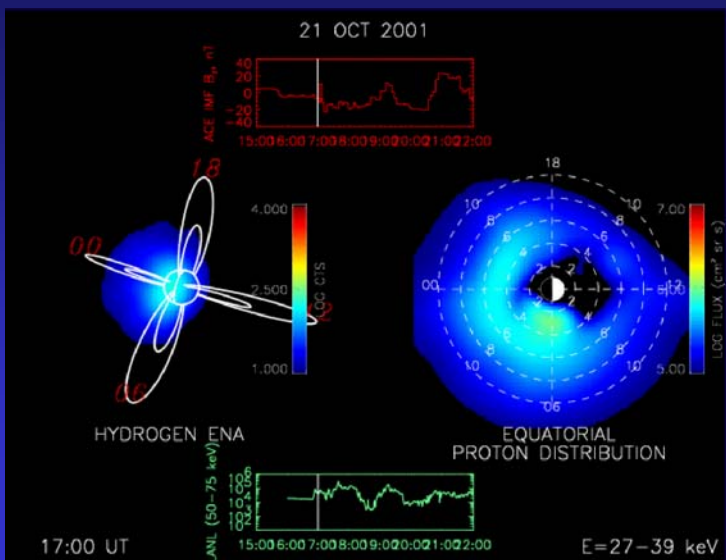
ENA Signal Deconvolution
Substorm Injection



J. Woch. S3 Seminar. MPAE. May 26. 2004

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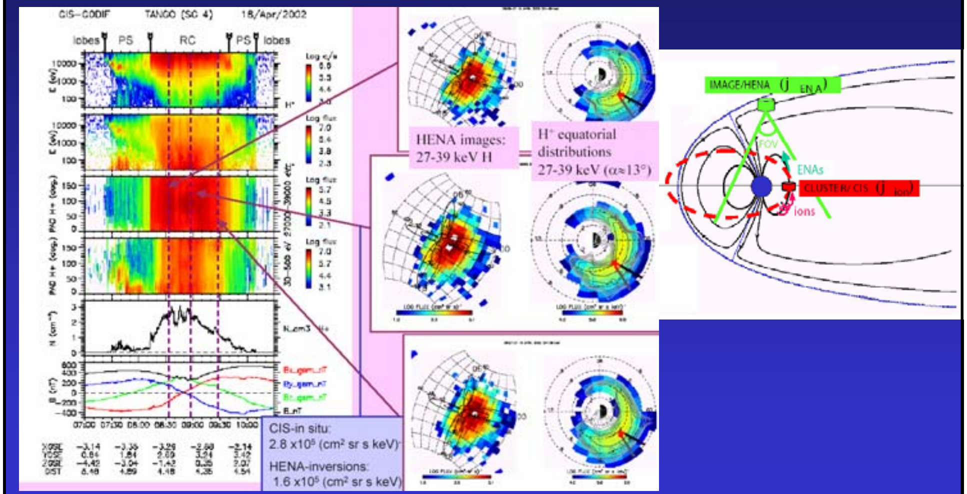
ENA Image Inversions
Validation in Earth's Magnetosphere



J. Woch, S3 Seminar, MPAE, May 26, 2004

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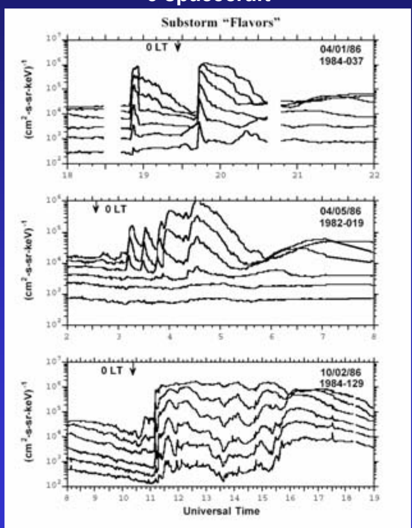
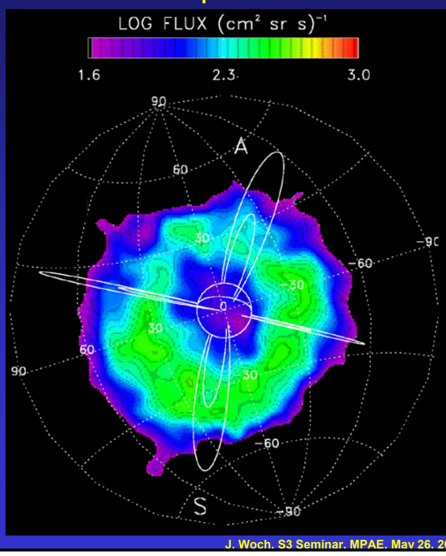
Observing *Substorm Particle Injections into the RC*

the traditional way
3 spacecraft



the ENA way
1 spacecraft



J. Woch, S3 Seminar, MPAE, May 26, 2004

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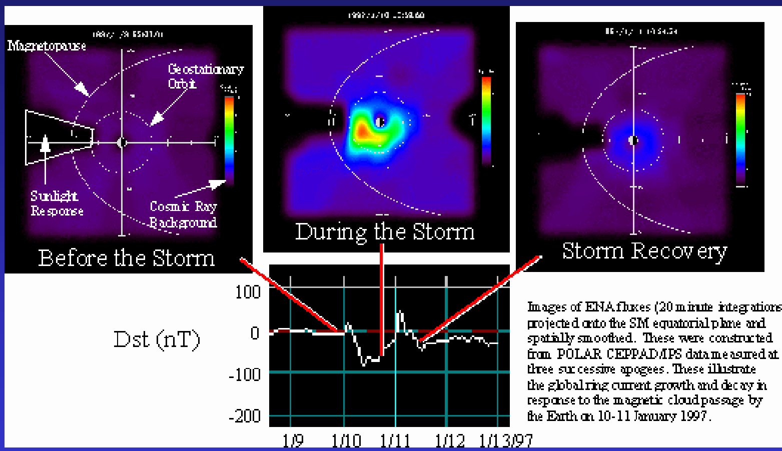
Observing Substorm Particle Injections into the RC
Temporal monitoring with ENA Imaging



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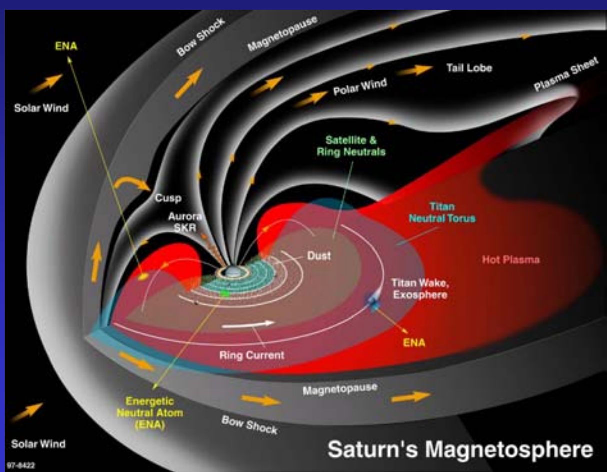
ENA Imaging of other planet's magnetospheres
It's on its way – INCA/Cassini is arriving at Saturn

imaging the magnetospheric plasma

its interaction with

- **the solar wind**
- **the planet's atmosphere**
- **the moon Titan**
- **the dust rings**



ENA Imaging – Further Application

Measuring Neutral Exospheres and Tori

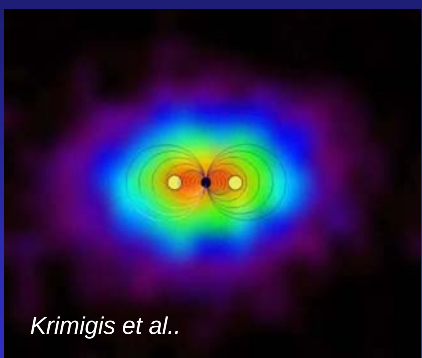
$$j_{ENA} \cong \int_0^\infty dr \times j_{Ion}(\vec{r}, \vec{v}, t) \times n_{Neutral}(\vec{r}) \times \sigma_{CE}(|\vec{v}|)$$

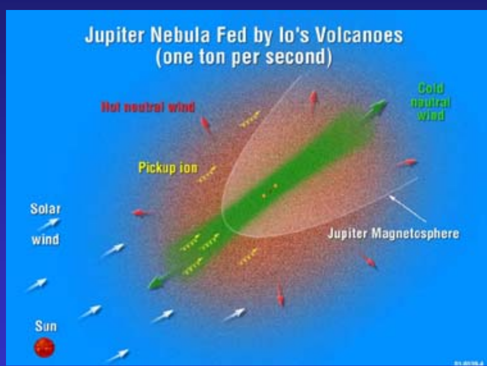
measured — derived — known — known

$$j_{ENA} \cong \int_0^\infty dr \times j_{Ion}(\vec{r}, \vec{v}, t) \times n_{Neutral}(\vec{r}) \times \sigma_{CE}(|\vec{v}|)$$

ENA Images of a neutral gas nebula surrounding Jupiter

from INCA/Cassini during the Jupiter flyby

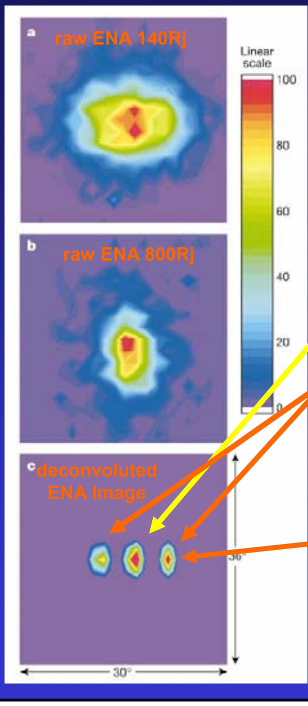




Discovery of a magnetospheric neutral wind extending more than 0.5 AU from Jupiter:
- **Hot quasi-isotropic component**
- **Cold component :**

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

INCA-ENA Images – *Evidence for a Europa Torus*

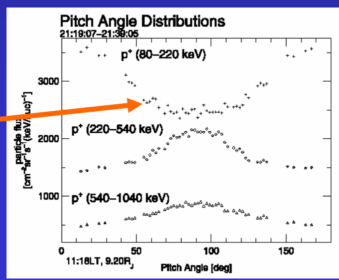


50–80 keV ENA images of Jupiter's magnetosphere, revealed two distinct emission regions:

the upper atmosphere of Jupiter

a torus of emission residing just outside the orbit of Jupiter's satellite Europa ***n ~ 40 cm-3***

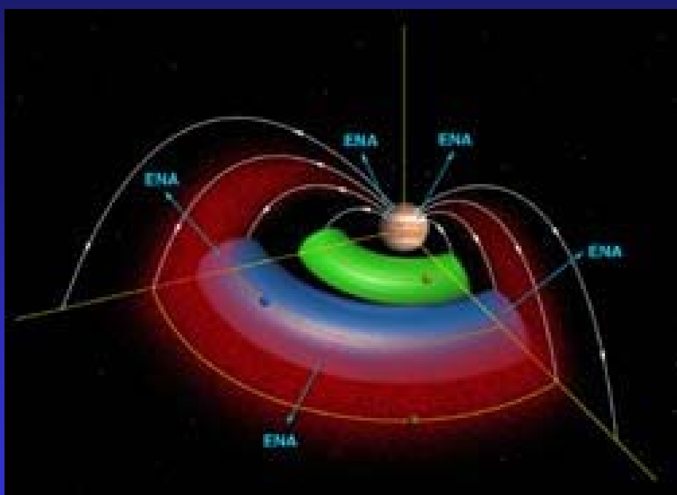
confirmed by in-situ observation in the Europa torus



Mauk et al.

Lagg et al.

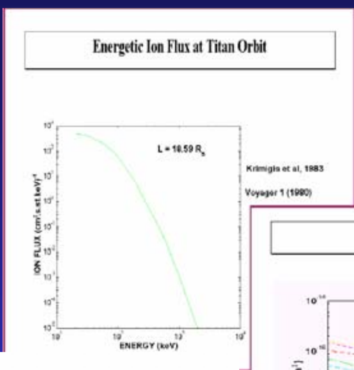
The Io and Europa Gas Torus

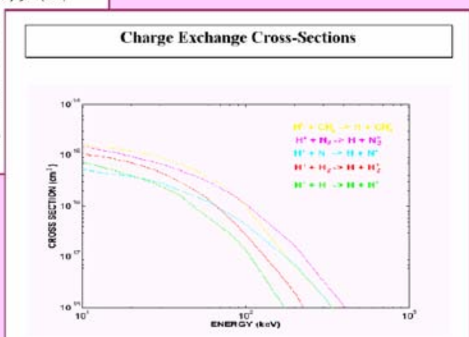


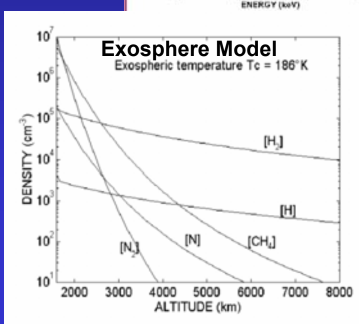
Titan's exosphere interaction with Saturn's magnetosphere

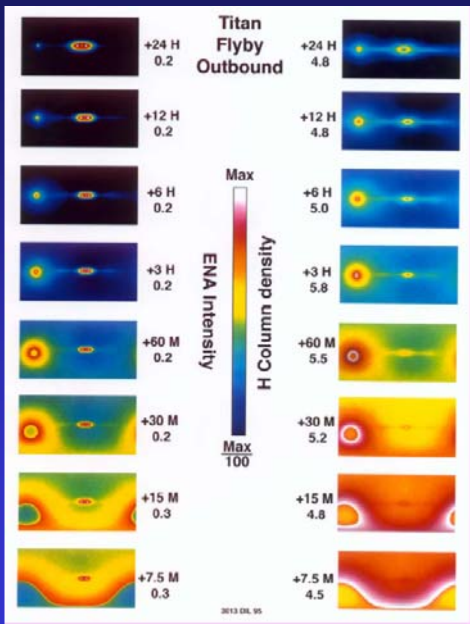
- Titan's orbit places it, most of the time, within Saturn's magnetosphere.
- Titan's nitrogen-rich atmosphere is subject to direct magnetospheric interaction, due to its lack of a significant magnetic field.
- Energetic ions in the magnetosphere occasionally will undergo a charge exchange collision 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 ENA Production Model : input









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}.

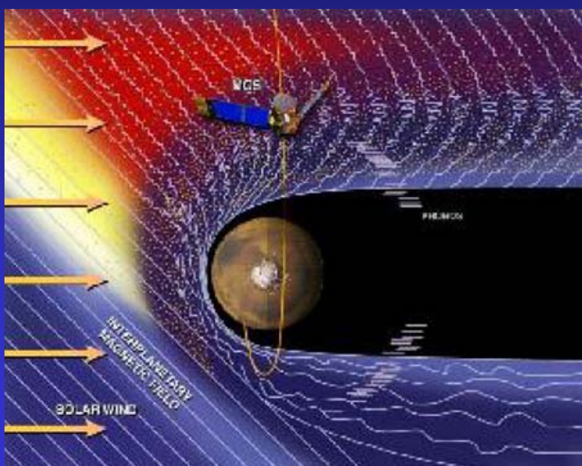
Distant Saturn magnetosphere (brightest points are ring current at L3) is comparable in ENA brightness to Titan exosphere, while Titan hydrogen torus (idealised) is much weaker. Note ENA image of Titan exosphere is distinct from Saturn magnetosphere.

Roelof and Williams, 1990

ENA Imaging at Mars

A Case of non-magnetic solar wind – planet interaction

MarsExpress since 01/2004



ENA Imaging at Mars
Atmospheric Escape at Mars

Absence of planetary magnetic field leads to important differences between Mars' and Earth's atmospheric escape and energy deposition processes

upper atmosphere at Mars not protected by magnetic field

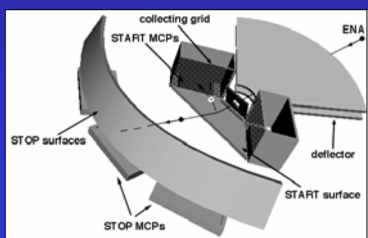
direct interaction of shocked solar wind with exosphere

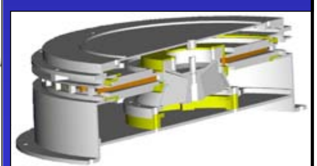
massive erosion through ionisation and tailward convection; sputtering

ASPERA-3 on MarsExpress
Imaging plasma and energetic neutral atoms near Mars

Objective: To measure solar wind scavenging : The slow "invisible" escape of volatiles (atmosphere, hydrosphere) from Mars.

Question: Is the solar wind erosion the prime reason for the present lack of water on Mars?





Solar wind scavenging of the martian atmosphere

Planetary wind = Outflow of atmosphere and ionosphere (cometary interaction)

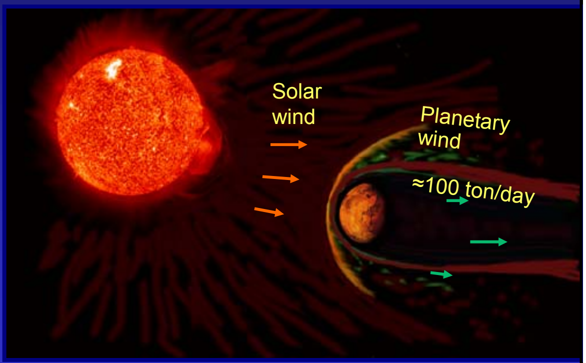
ASPERA will do global imaging and *in-situ* measurements of:

Inflow — solar wind

Outflow — planetary wind

using:

Energetic neutral atom cameras and plasma (ion+electron) spectrometers



Note: Mars (and Venus) are planets lacking a strong intrinsic magnetic field (umbrella) => dehydration.

ENA AT MARS
IMAGING OF PLANETARY OXYGEN

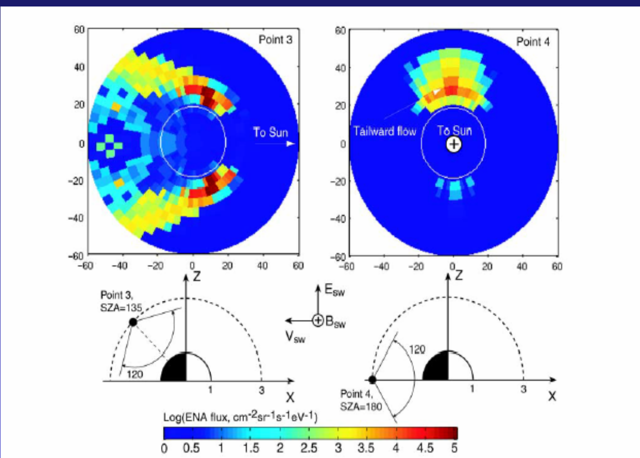


Figure 5. ENA images for vantage points with different solar zenith angles (SZA). The energy range: 0.1–1.65 keV. The position of the vantage points are shown in the inserts as well as electrical and magnetic field vectors. All points are in the *OXZ* plane.

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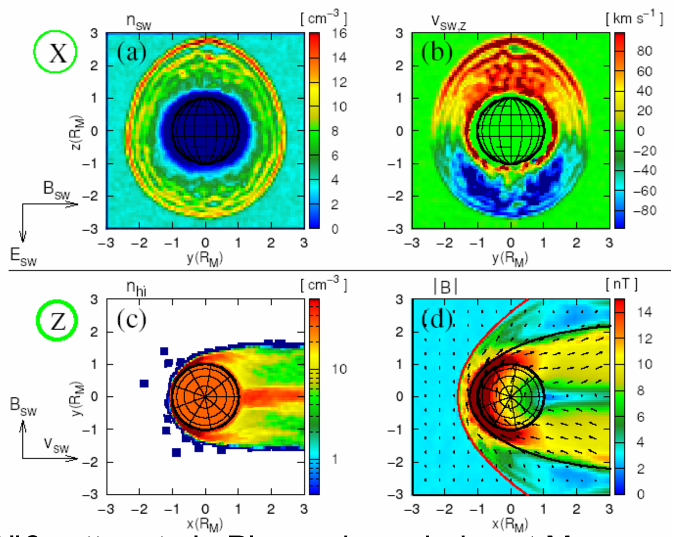
ENA AT MARS

IMAGING OF PLASMA BOUNDARIES



Bößwetter et al.: Plasma boundaries at Mars

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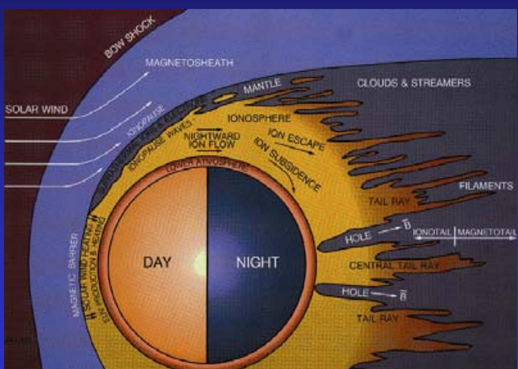
ENA Imaging at Venus

Atmospheric Escape at Venus

VenusExpress: Launch 2005



The Ionosphere of Venus: A complex structure of plasma clouds, rays, and holes formed by the interaction with the solar wind

Absence of planetary magnetic field leads to important differences between Venus' and Earth's atmospheric escape and energy deposition processes

upper atmosphere at Venus not protected by magnetic field

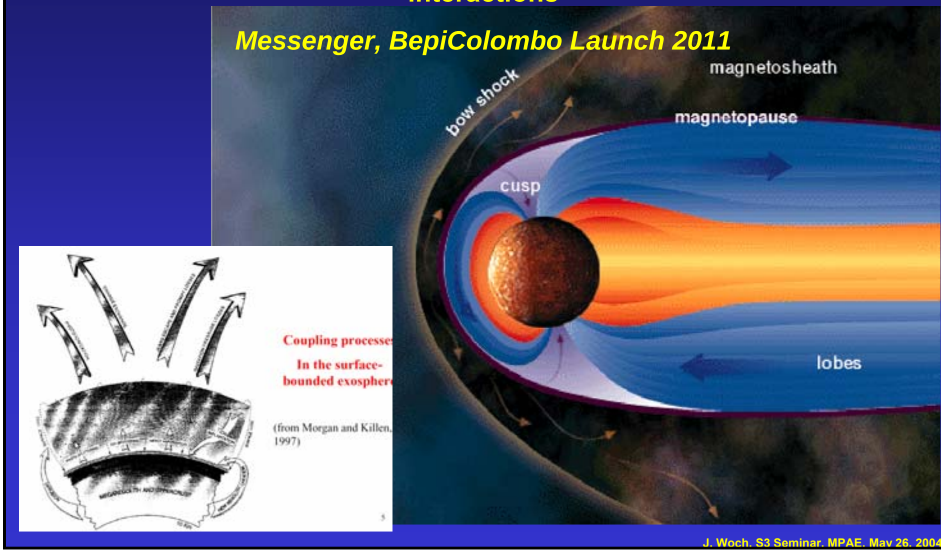
direct interaction of shocked solar wind with exosphere

massive erosion through ionisation and tailward convection; sputtering; em-processes with topside ionosphere

Large similarities Venus / Mars

ENA Imaging at Mercury's Magnetosphere

A case of direct solar wind magnetosphere - exosphere - surface interactions



ENA Imaging – Further Application

Detecting Neutral Particle Populations
Direct Measurements of the LISM

Our solar system moves through the surrounding **Local Inter Stellar Medium (LISM)**
It consists of a mixture of **charged particles**, with embedded magnetic fields, and a **neutral component**, mainly uncharged **hydrogen and helium atoms**. As the interstellar plasma and the solar wind, cannot penetrate each other because of their embedded magnetic fields, a boundary layer, the **Heliopause**, is formed, The Heliopause is assumed to exist at a solar distance of about 100 AU. The **Heliopause prevents the interstellar plasma from entering into the solar system**. Therefore, little is known about the details of the LISM, and the knowledge so far is mainly based on remote sensing techniques. However, the **neutral component of the LISM, not shielded by the magnetic fields can penetrate into the inner solar system and is available for in-situ observation**.

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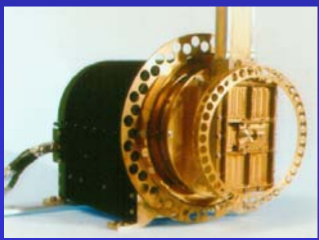
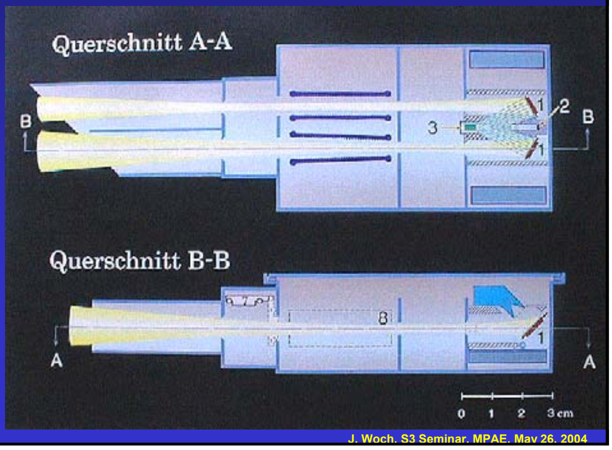
ENA Imaging – Further Application

Direct Measurements of the LISM with GAS on Ulysses

pin-hole camera for neutral helium and ultraviolet photon measurements Channel Electron Multipliers (CEM) are used to amplify and count secondary ions or electrons produced by neutral particle impact on a lithium fluoride surface. The latter is periodically refreshed via a heated filament.

sensor detects neutral helium at energies above 30 eV





J. Woch, S3 Seminar, MPAE, May 26, 2004

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ENA Imaging – Further Application

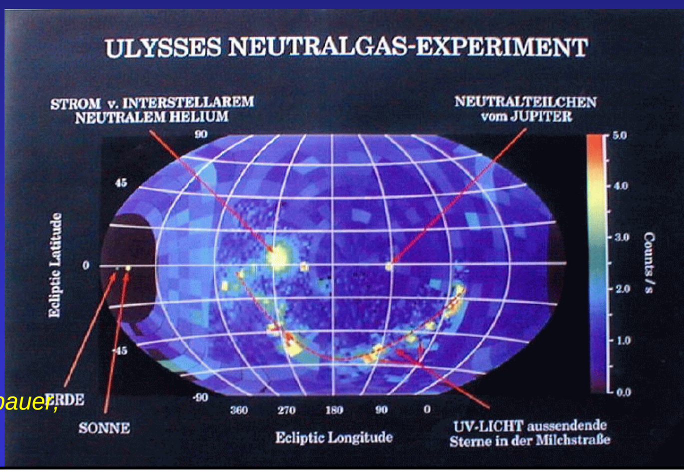
A Neutral Particle Sky Map from GAS on Ulysses

With a mathematical model simulating the motion of the particles, their loss processes and their interaction with the instrument, the characteristic parameters of the interstellar helium can be calculated from the locally observed angular intensity distributions.

Velocity:
25.3 ± 0.4 km/s

Temperature:
7000 ± 600K

M. Witte, H. Rosenbauer, MPAE



Conclusion

Energetic Neutral Atom Imaging has considerable potential for:

- **monitoring space plasma objects and the temporal evolution of plasma processes on global scales and thus contribute significantly to our understanding *(planetary magnetospheres and their interaction with the solar wind)***
- **detecting and/or characterizing planetary neutral gas environments *(planetary exospheres, satellite torii, exosphere – magnetosphere interactions)***