Pickup ions in the outer solar system

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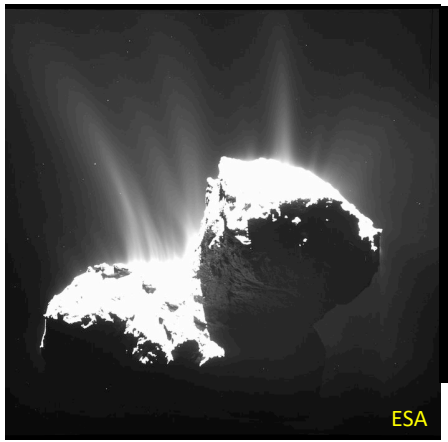
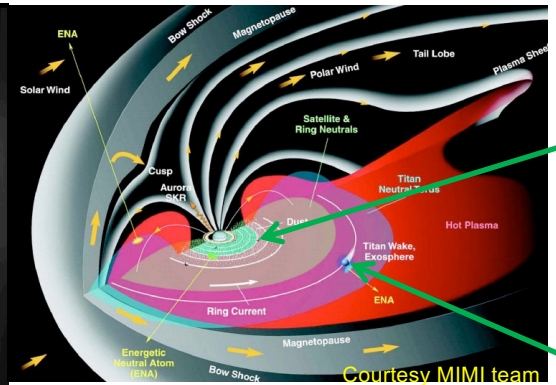
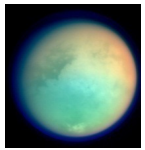
With thanks to

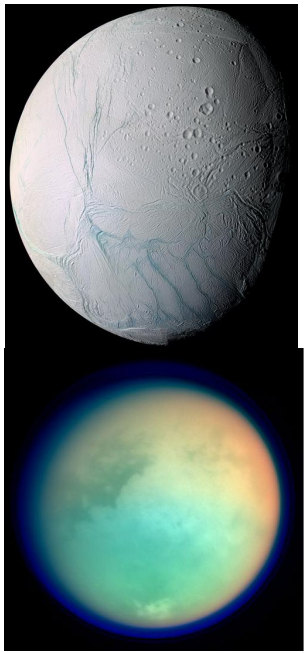
Rosetta RPC team

Cassini CAPS team





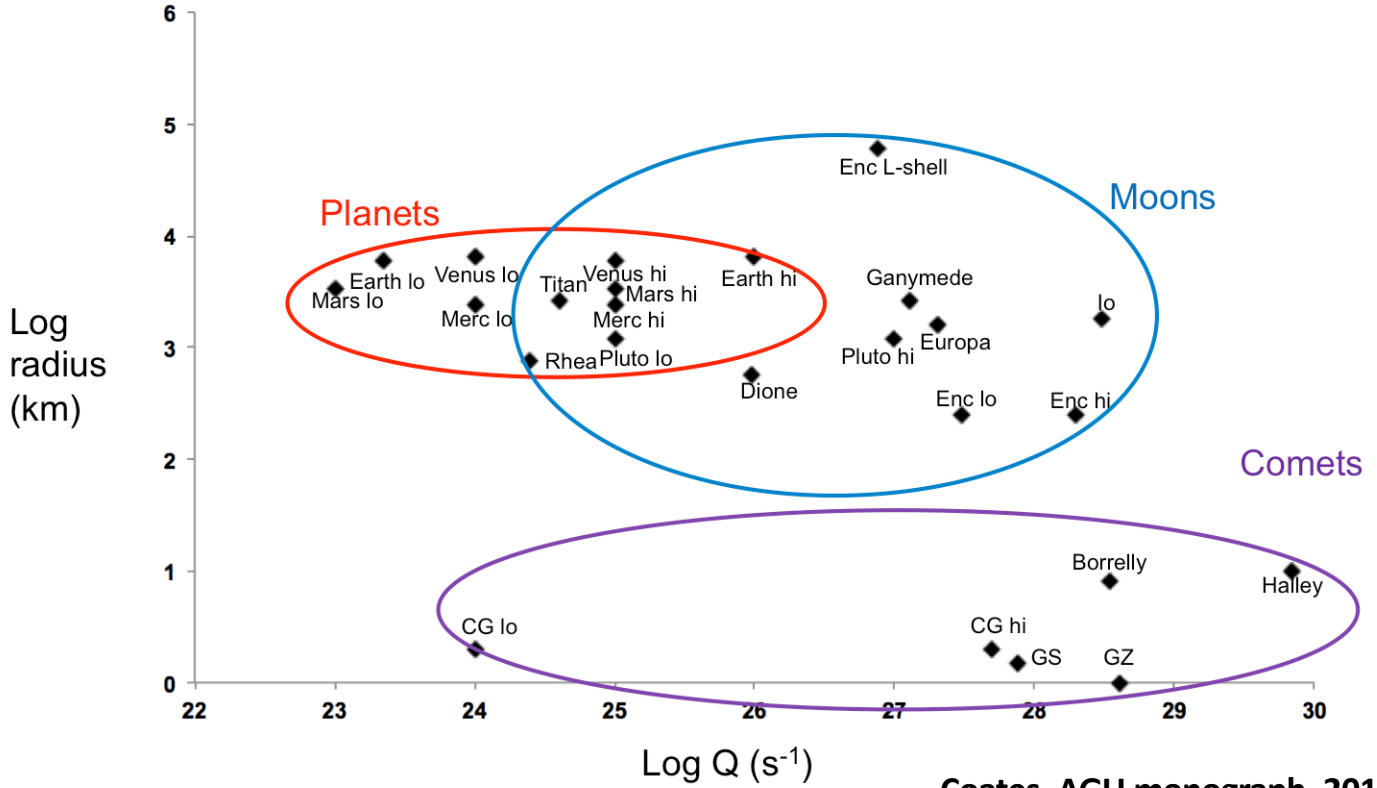




What are pickup ions?

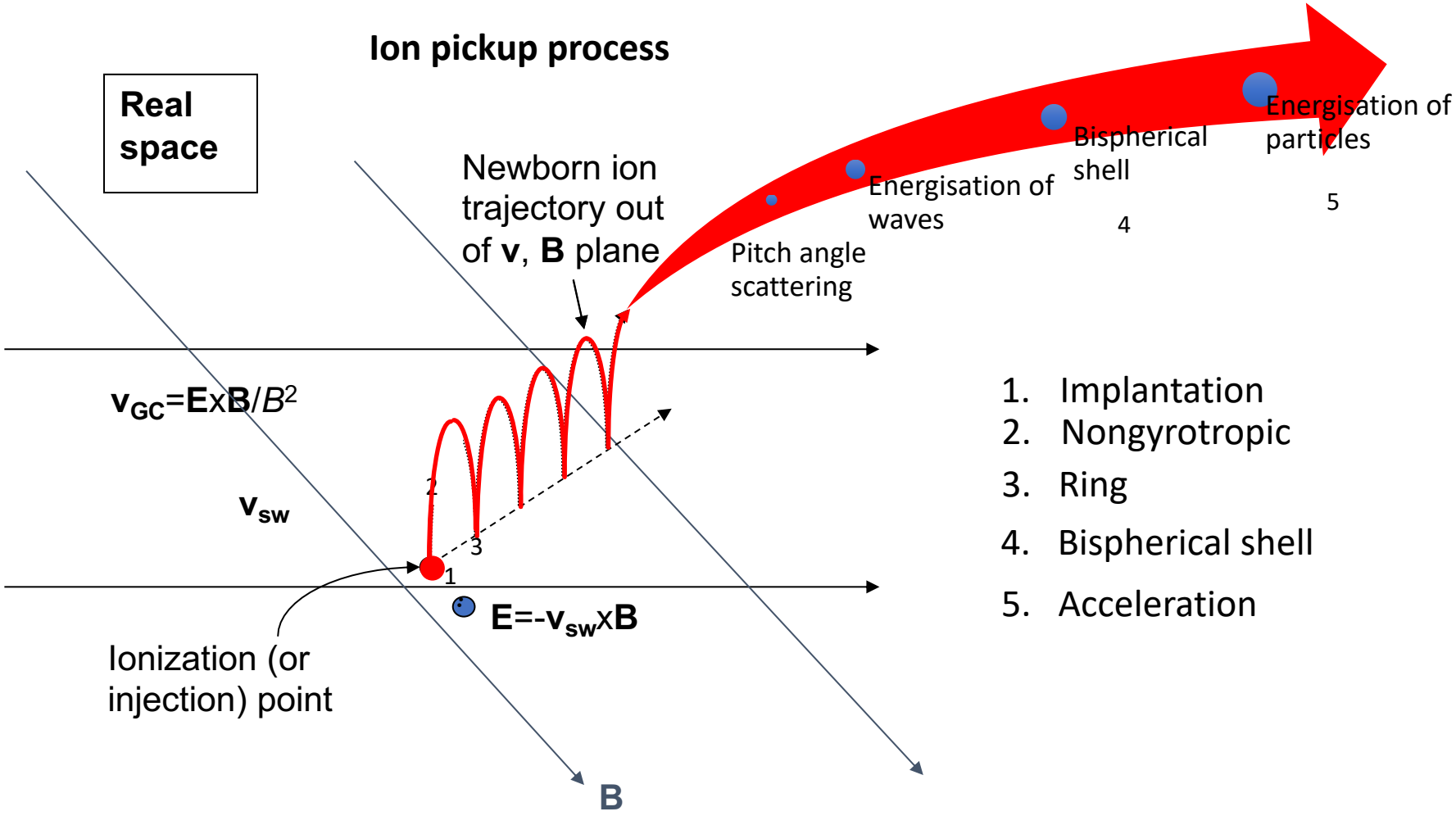
- Result of interaction of flowing plasma with neutral particles
- Neutrals become ionized, by sunlight, impact or charge exchange
- They interact with the flowing plasma and are ‘picked up’

Summary of loss rates (neutrals, ions) for solar system objects



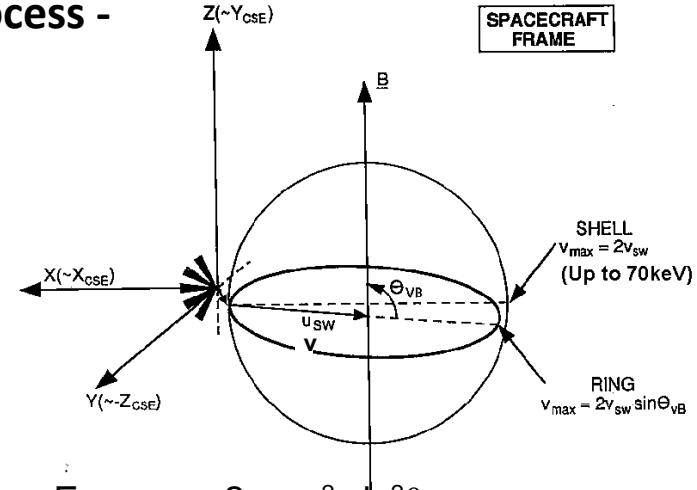
Coates, AGU monograph, 2016

Ion pickup process



1. Implantation
2. Nongyrotropic
3. Ring
4. Bispherical shell
5. Acceleration

Ion pickup process - velocity space



$E_{max,\ ring} = 2mv_{sw}^2 \sin^2\theta_{vB}$

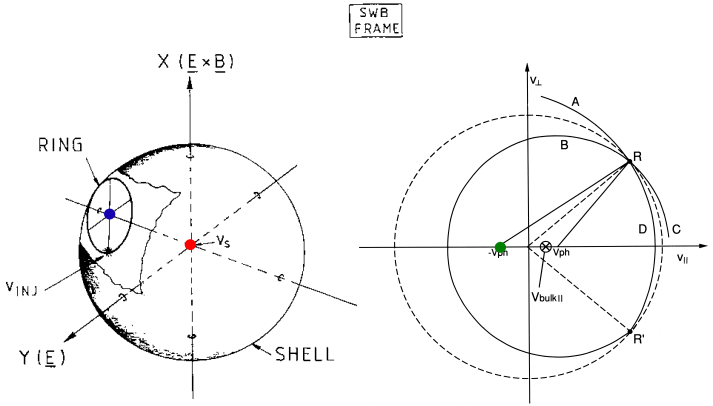
$= 4m_{amu}\ E_{sw}\sin^2\theta_{vB}$

$E_{max,\ shell} = 4m_{amu}E_{sw}$

(e.g. Up to ~70keV for a water group ion in the solar wind)

(Coates et al 1989, 1993)

Reflection e.g. at Moon, up to $9m_{amu}E_{sw}$ possible (Coates, IAC proc 2012)



Solar wind, field aligned (SWB) frame:

$\mathbf{v_{ring}} = (0,0,v_{||})$, $v_{||} = \mathbf{v.B}/B$

$\mathbf{v_{shell}} = (0,0,0)$

Bispherical distribution seen - centred on upstream, downstream propagating waves, at +/- v_{wave} following Galeev & Sagdeev, 1988)

Bulk velocity now $(0,0,v_{bulk||})$

(Coates et al 1990)

Stages in ion pickup process

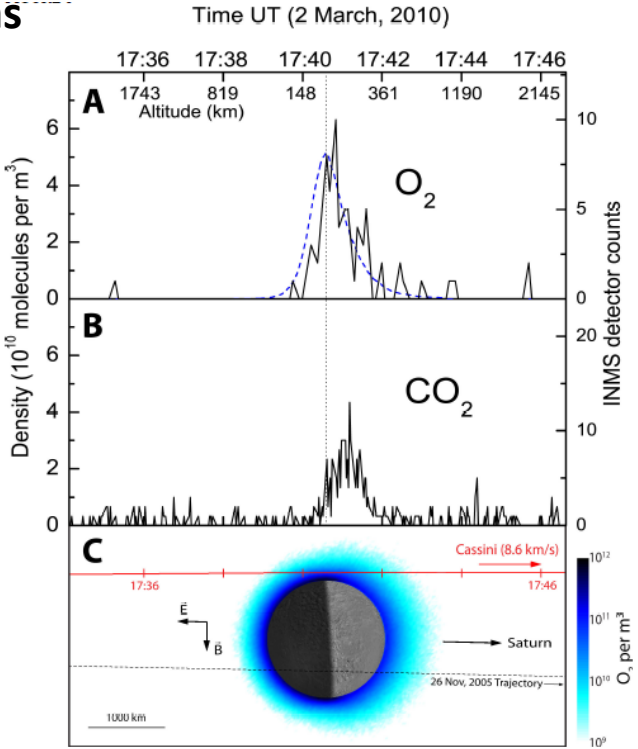
Stage in process	Timescale	Seen at
1. Implantation	<< gyroperiod (f_{ci})	C
2. Nongyrotropic ring	<gyroperiod	C, Me, Mo, R, D
3. Ring	~gyroperiod	C, Ma, Mo, V, Io, E, T, I, R, D
4. (Bispherical) shell	~10 gyroperiods	C, Io?, E?, I?
5. Acceleration, shell filling	~100 gyroperiods	C
6. Maxwellian	?	?

Adapted from Coates, AGU Geoph. Mon. 222, 2016

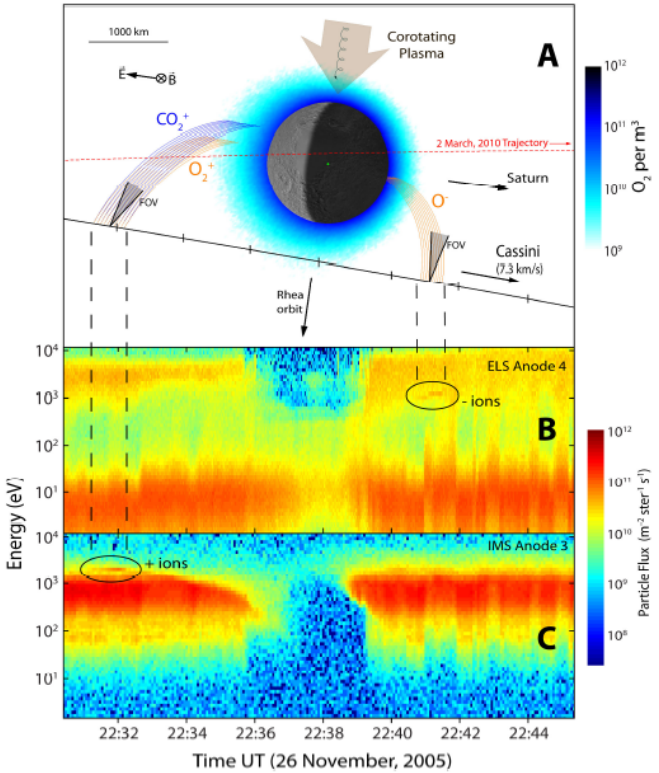
C=Comets, Me=Mercury, Ma=Mars, Mo=Moon, V=Venus, Io=Io, E=Enceladus, T=Titan, R=Rhea, D=Dione, I=Interstellar

Stage 1: implanted ions

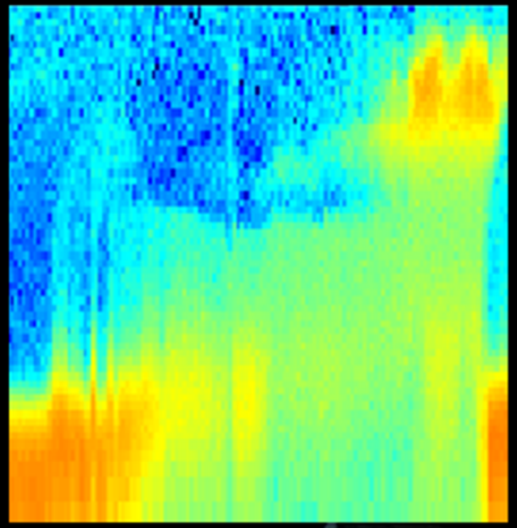
Rhea's O_2 and CO_2 atmosphere – from INMS and CAPS
Teolis et al., Science, Dec 2010

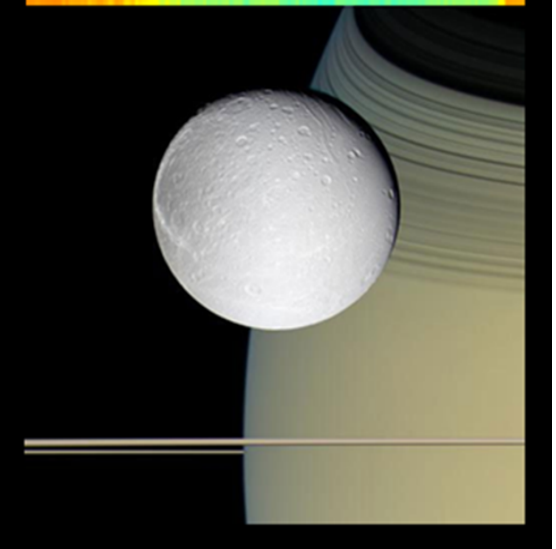


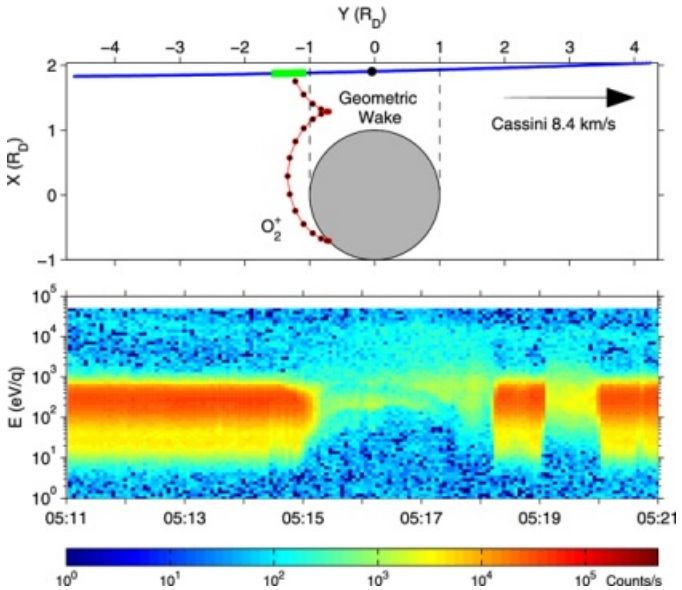
In-situ neutral atmosphere measurements (INMS)



Negative and positive ions picked up from atmosphere pinpoint near-surface source (CAP







Stage 1: implanted ions

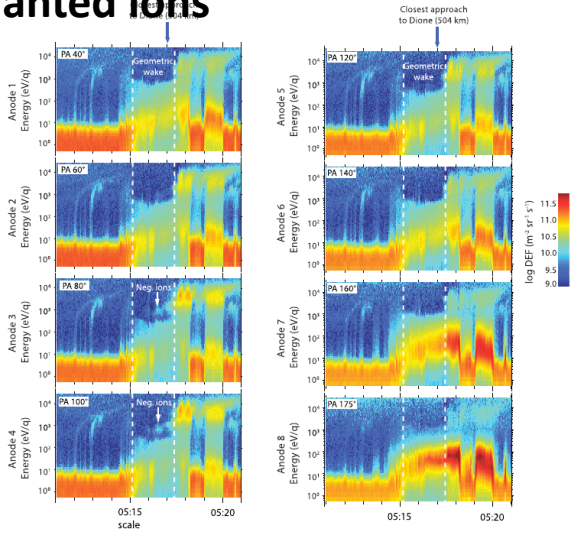
Dione's oxygen exosphere

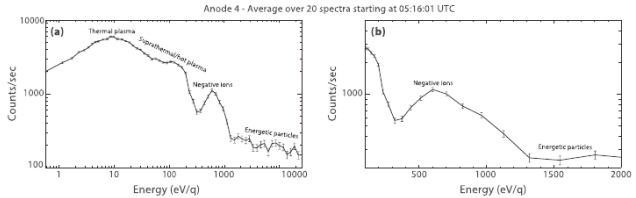
Tokar et al., Geophys Res Lett., Feb 2012

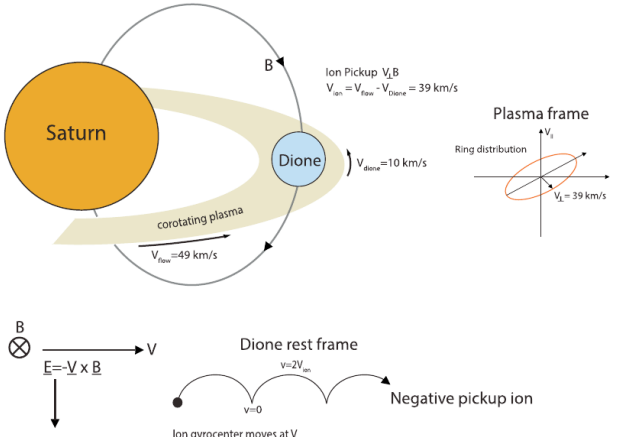
Icy Dione is within Saturn's trapped radiation belts –oxygen forms and is recycled via the surface

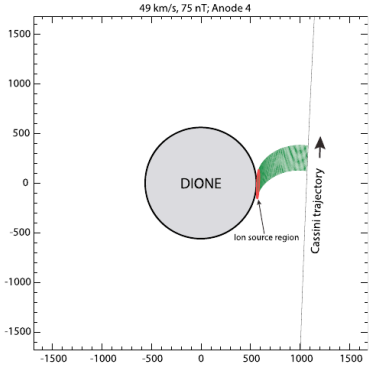
Process occurs at Dione, Rhea and Saturn's main rings, also at Ganymede, Europa and Callisto in Jupiter's - targets for ESA's proposed JUICE (JUpiter ICy moons Explorer) mission for launch in 2022

Stage 1: implanted ions



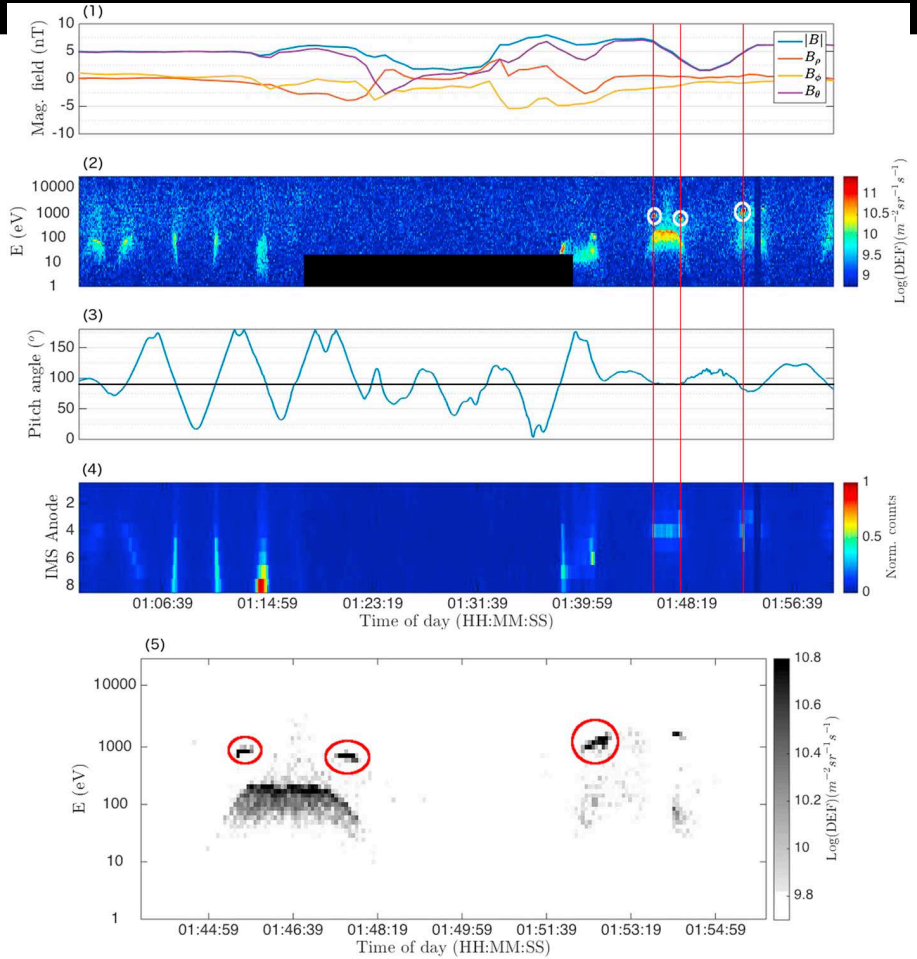






Negative pickup ions from Dione Nordheim et al., 2020

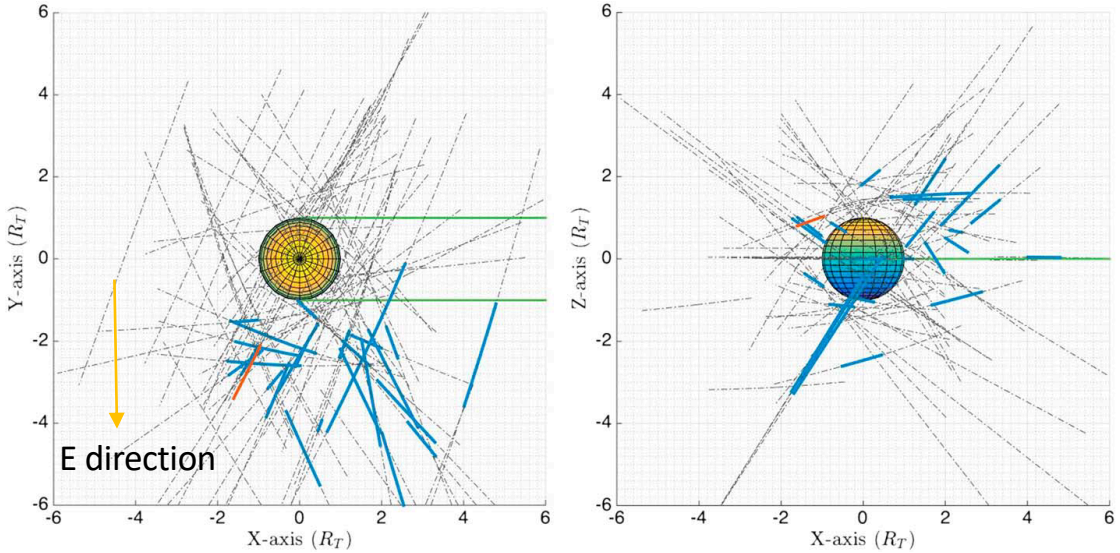
Stage 1: implanted ions



Pickup ions near Titan

Regoli et al., JGR 2016

Stage 1: implanted ions

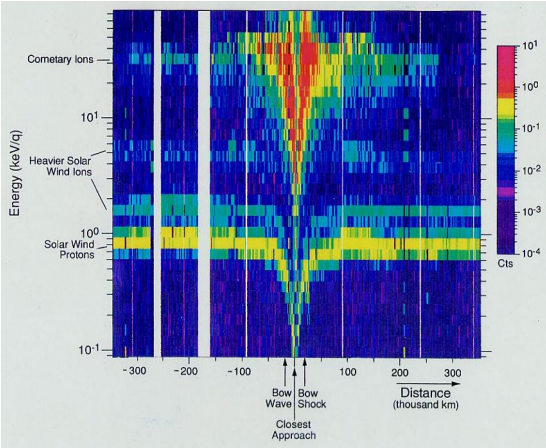


Pickup ions near Titan

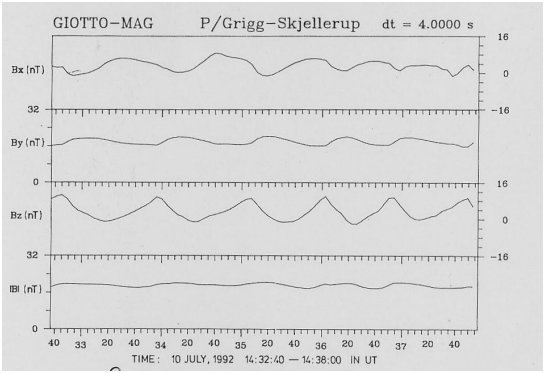
Regoli et al., JGR 2016

Loss rate due to pickup 3.3 x 10^{23} ions s^{-1}.
c.f. (4.2, 0.96, 2.3) 10^{24} ions s-1 from the ionosphere (Coates et al., 2013)

Stage 2: nongyrotropic distribution



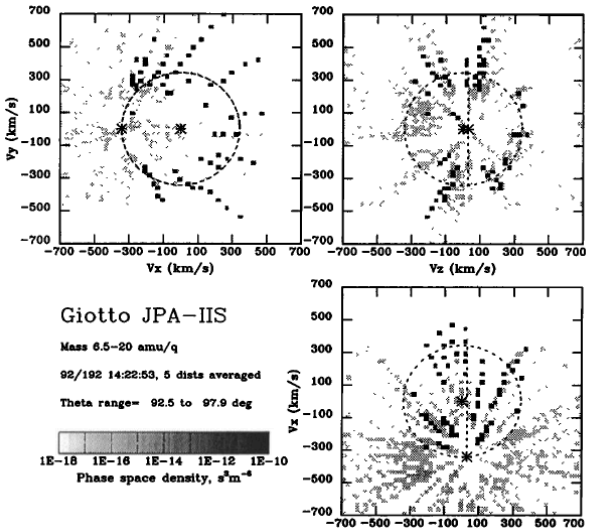
Grigg-Skjellerup (Johnstone et al 93, Coates et al 93)

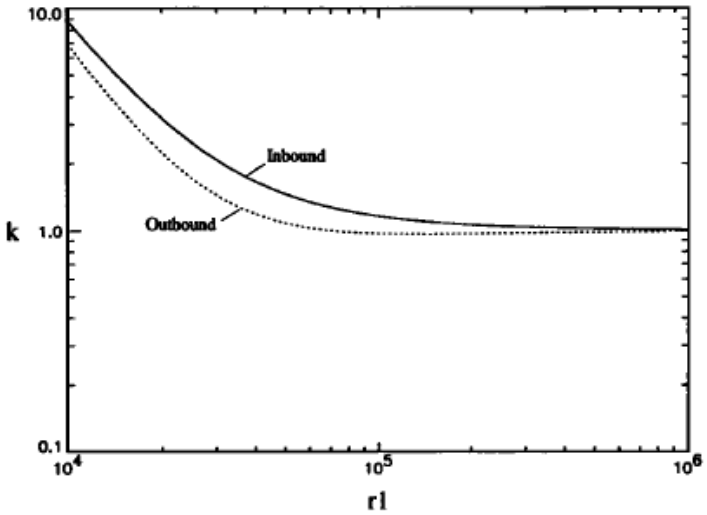


Wave period 61.4s, water group gyrofrequency as $\alpha \sim 90°$ (Neubauer et al, 1992)

Stage 2: nongyrotropic distribution

Water group ion nongyrotropy near GS

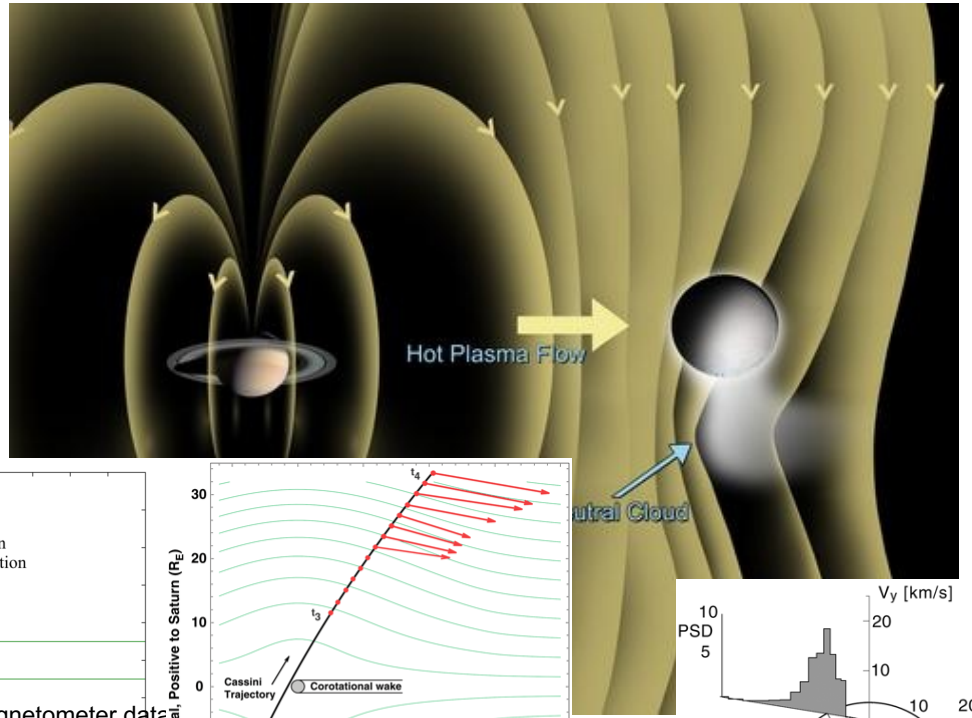


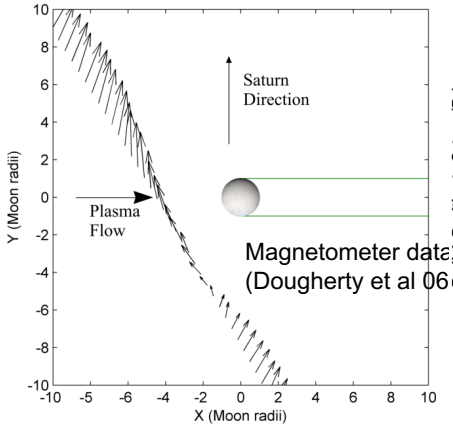


Coates et al 1993

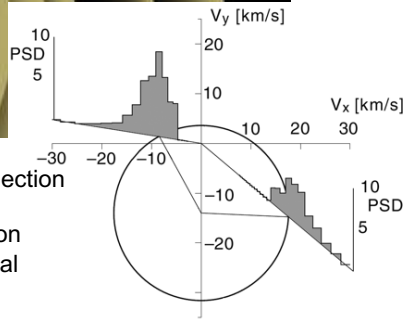
Stage 3: ring distribution

Enceladus atmosphere





Magnetometer data (Dougherty et al 06

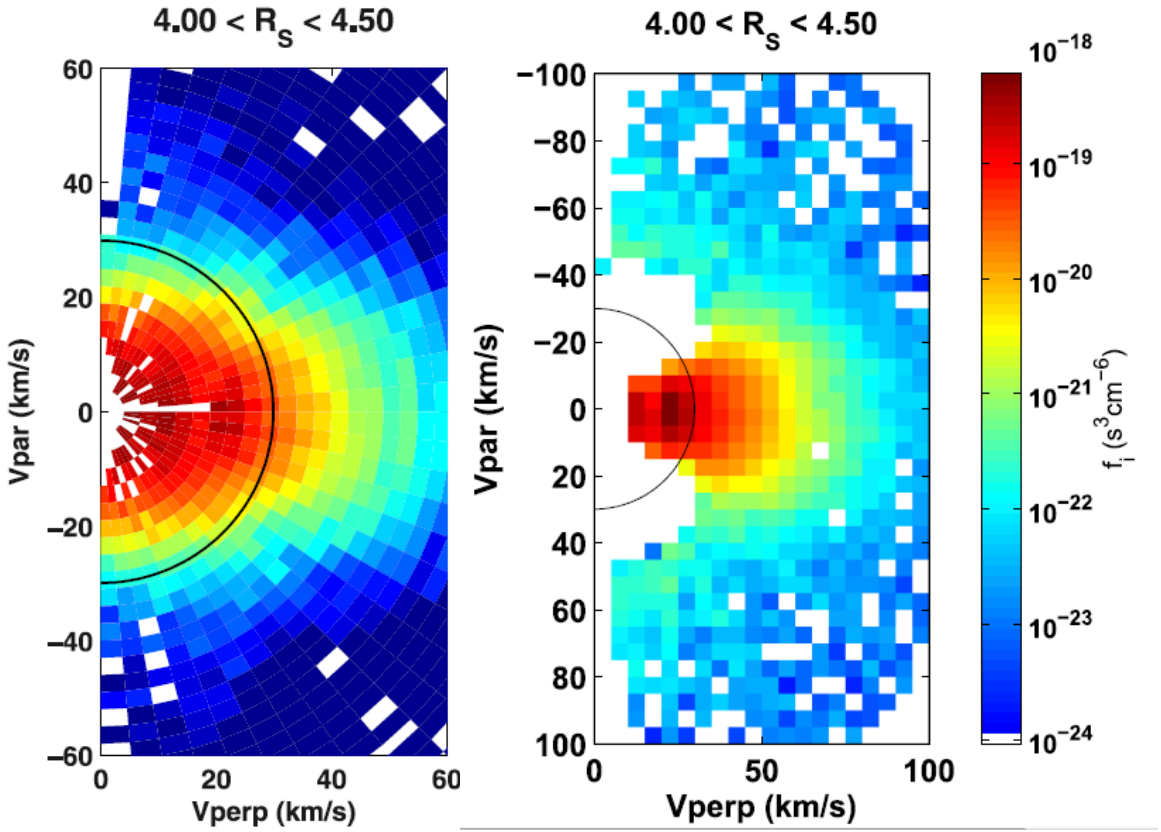


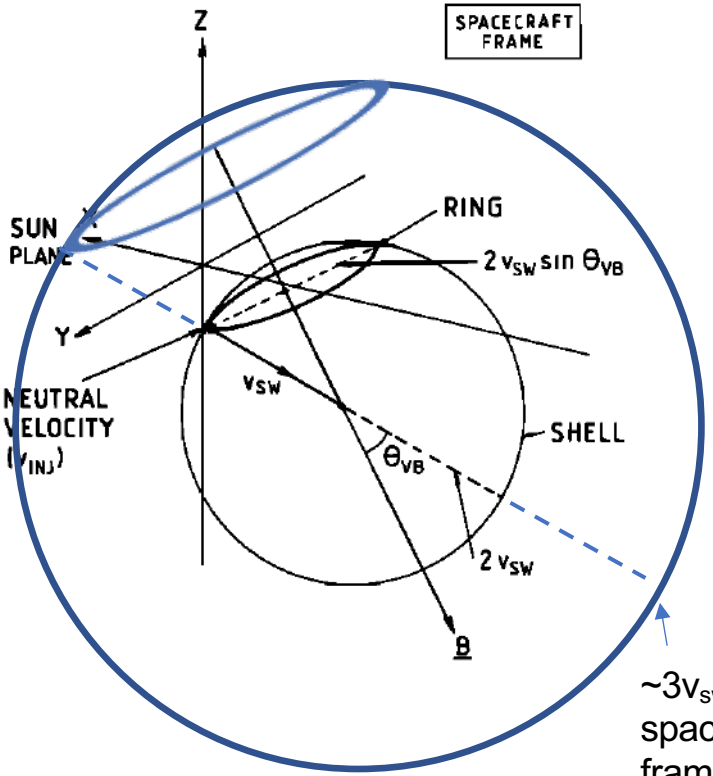
Flow deflection and ring distribution Tokar et al 2006

Stage 3: ring distribution

Water group ions near Enceladus,Tokar et al, GRL 2008

Inner magnetosphere dominated by water group ions from abundant neutrals, Young et al 2005





~3v_{sw} in spacecraft frame

Velocity space sketch for classical pickup and 'self-pickup' (Saito et al., 2010)
Pickup ions from reflected neutralss

Injection point of pickup ions at $-\mathbf{v_{sw}}$

Classical pickup:

$E_{max,\ ring} = 4m_{amu} E_{sw} \sin^2 \theta_{vB}$

$E_{max,\ shell} = 4m_{amu} E_{sw}$

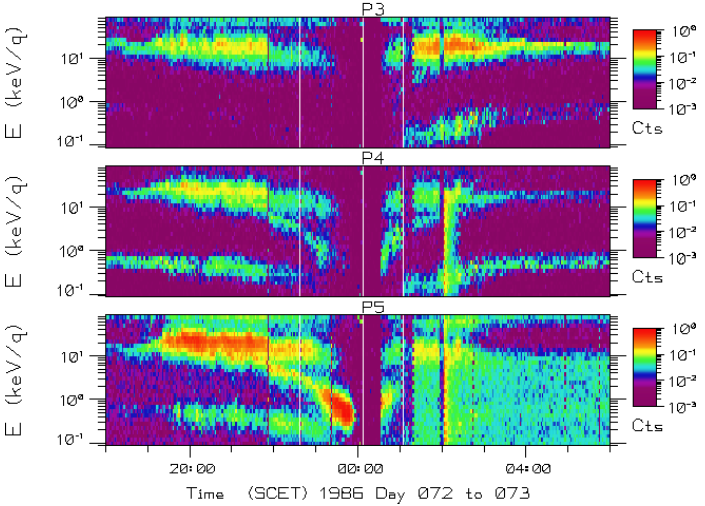
Self pickup:

$E_{max,\ ring} = 9m_{amu} E_{sw} \sin^2 \theta_{vB}$

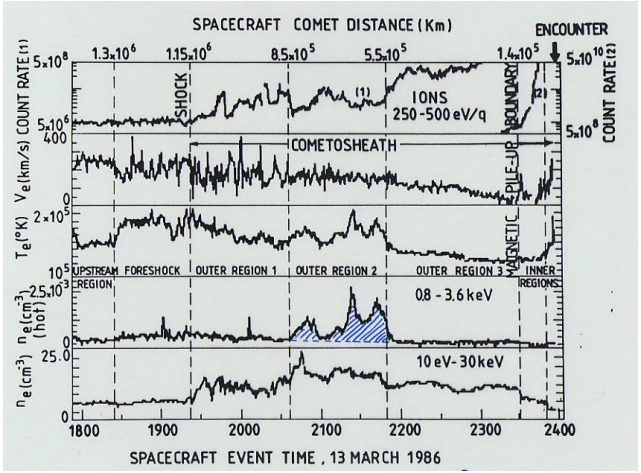
$E_{max,\ shell} = 9m_{amu} E_{sw}$

Coates, 2017, adapted from Coates et al., 1989

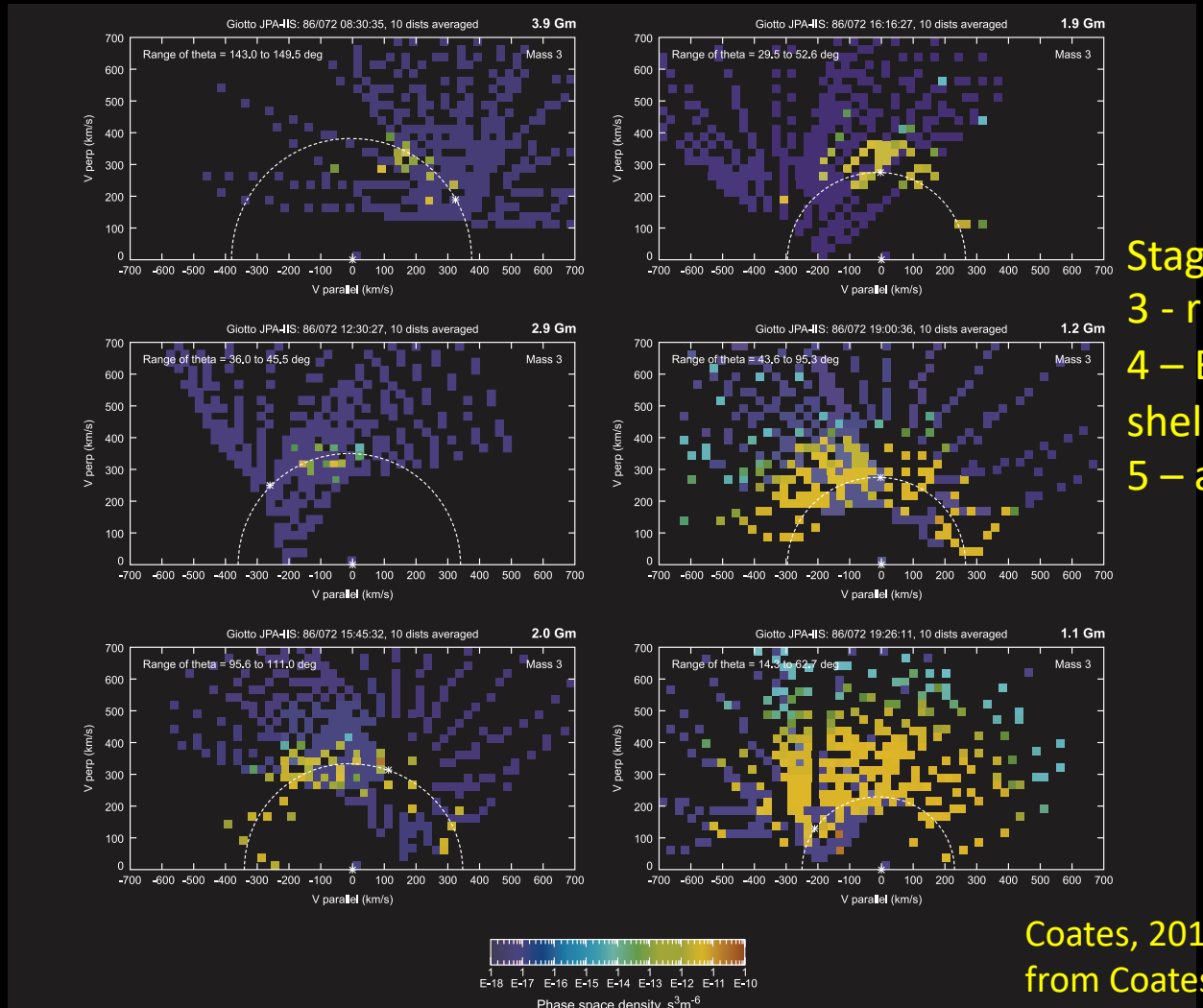
Stage 3 - rings,
Stage 4 – Bispherical shells,
Stage 5 – acceleration – comet Halley



Halley (Johnstone et al, 86)



Expected and new boundaries
(e.g. Reme et al, 86)



Stages
3 - rings
4 – Bispherical shells
5 – acceleration

Coates, 2016 (adapted from Coates et al., 1989)

Summary and conclusions

Plasma and magnetic field measurements show importance of pickup ions

Pickup process has different stages at moons, in magnetospheres and at weak, medium and strong comets

Key source for outer planet magnetospheres

Probes of composition, indications of escape, plasma dynamics

Expect similar signatures from JUICE at Europa, Callisto & Ganymede