Saturn's ring current observed during Cassini's Grand Finale mission

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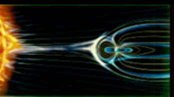

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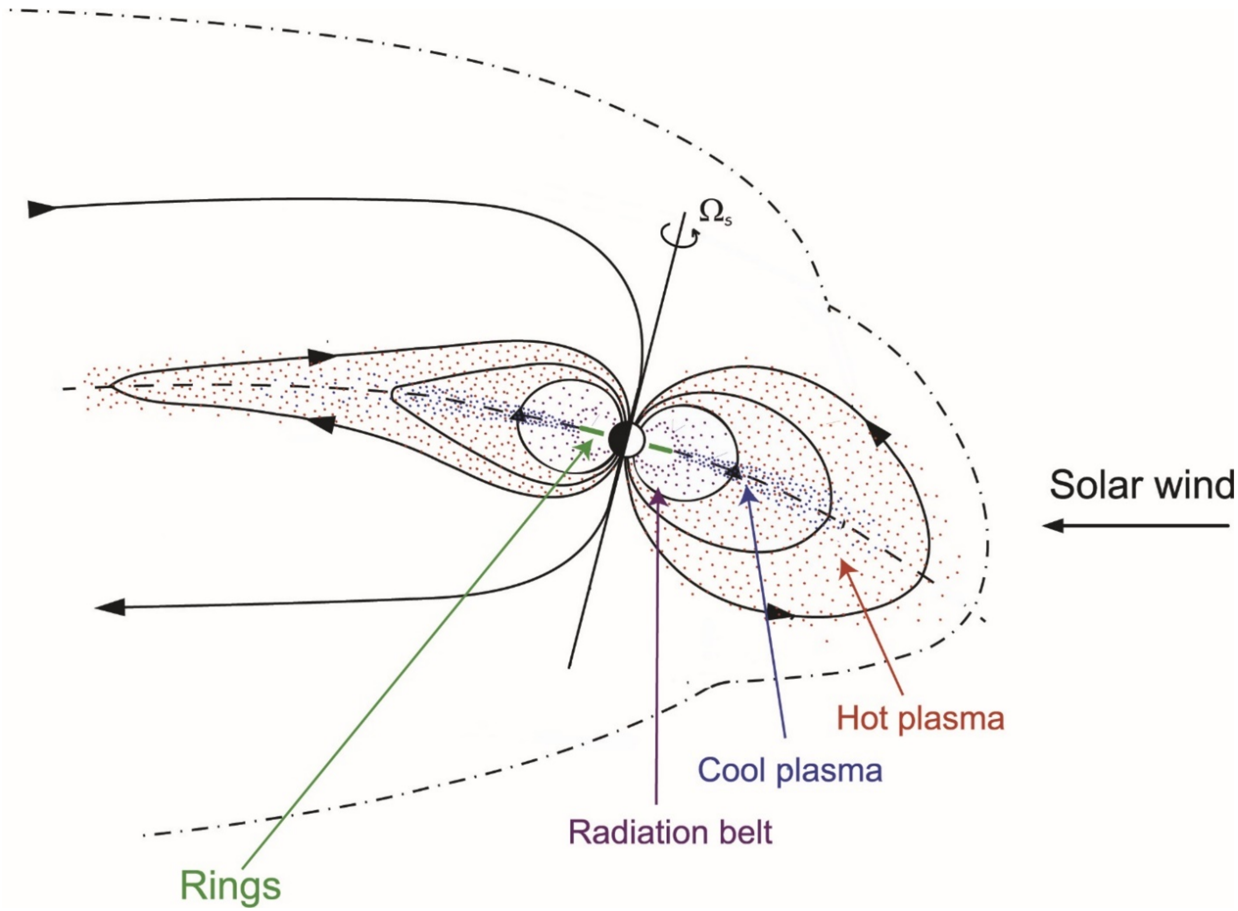
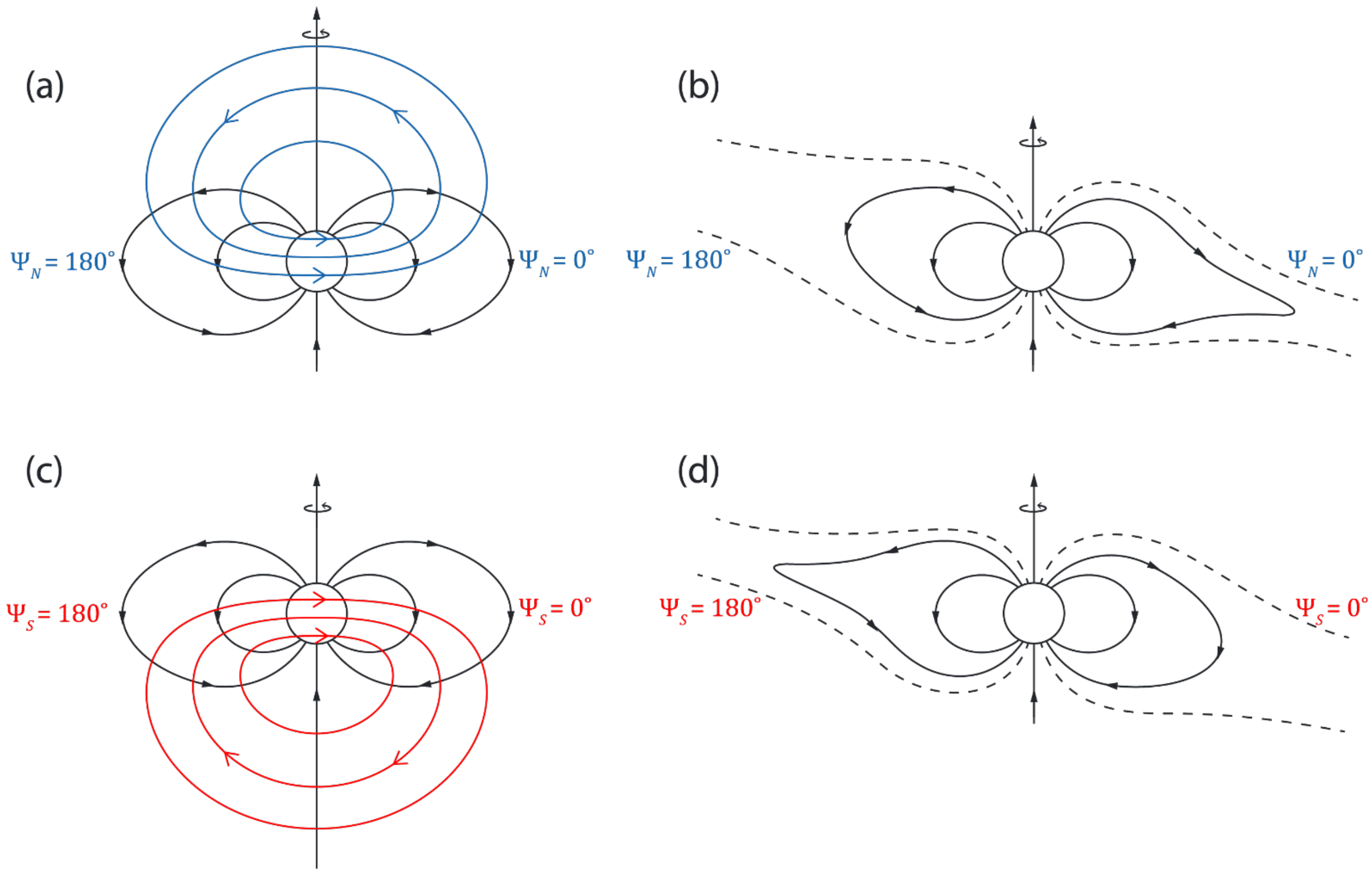
INTRODUCTION



Saturn's magnetosphere is driven by fast rotation, a strong planetary magnetic field and mass-loading from the moon Enceladus. Centrifugal forces confines the magnetospheric plasma towards the equatorial plane, resulting in the formation of a magnetodisc and an azimuthally flowing ring current. Saturn's magnetosphere is bent into a bowl shape by the solar wind.

Ref: Dungey, 1961; Vasyliunas, 1981, 1983; Gombosi et al., 2009; Ness et al., 1981, 1982; Sittler et al., 1983; Krimigis et al., 1983; Cowely et al., 2004; Arridge et al. 2008; Carbary et al., 2018; Carbary, 2019; Young et al., 2005; Mauk et al., 2009 ;Thomsen et al., 2013; Thomsen et al, 2019

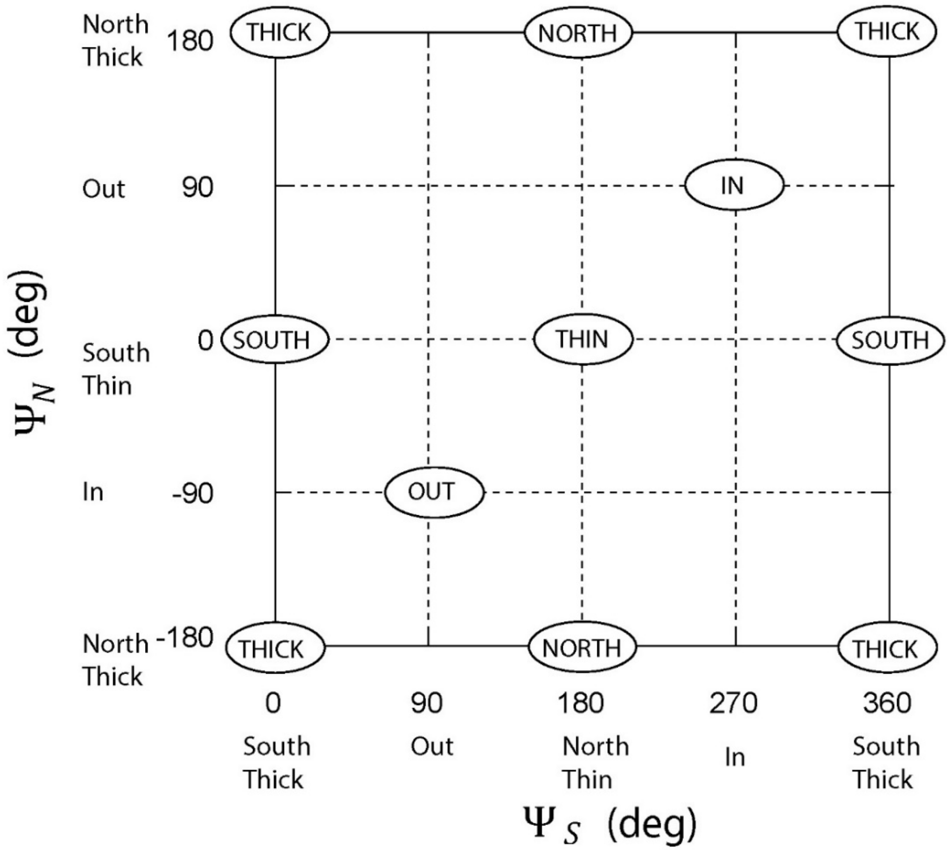
Planetary Period Oscillations (PPOs)



PPOs have been observed throughout Saturn's magnetosphere. There are two PPO systems, one in each hemisphere (Panels a and c). With increasing time each perturbation rotates around the planetary axis at the corresponding PPO period. Panels (b) and (d) shows the vector sum of the perturbation field loops and the background magnetic field, demonstrating how the PPOs modulate Saturn's magnetosphere, including the magnetotail and magnetodisc.

Ref. Andrews et al., 2010, 2011; Arridge et al., 2011; Bader et al., 2018, 2019; Badman et al., 2012; Bradley et al., 2018; Carbary et al., 2011, Carbary 2017; Clarke et al., 2010a, 2010b; Cowley and Provan, 2017; Espinosa & Dougherty, 2000; Gurnett et al., 2009b, 2011; Jackman et al., 2016; Lamy, 2011, 2017; Lamy et al., 2013; Nichols et al., 2010a, 2010b; Provan et al., 2012; Ramer et al. 2017; Southwood and Kivelson, 2007; Thomsen et al., 2017.

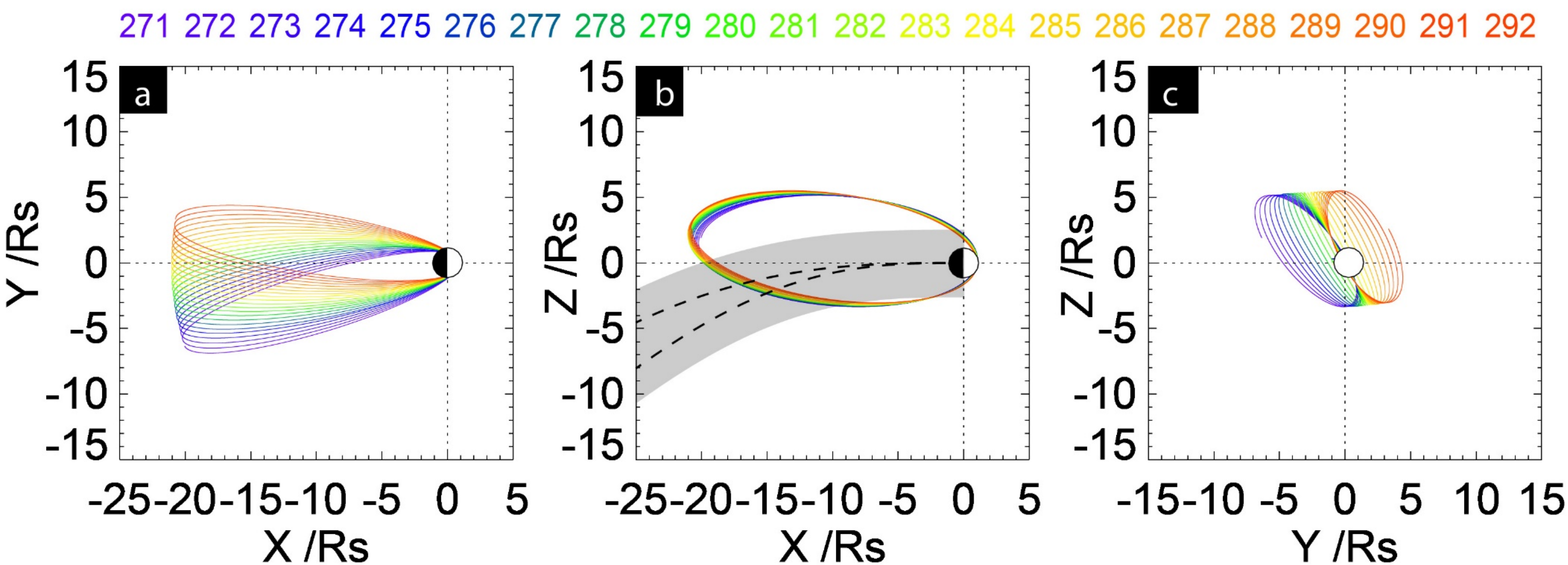
PPO modulation of the tail current sheet



Schematic illustration showing the effect of the PPOs on the tail current sheet. Circles indicate the joint phases at which the two systems act in concert to modulate the thickness and the position of the current sheet. When the N and S PPOs are in-phase we expect maximum north-south oscillations of the current sheet. Conversely, when they are in antiphase, we expect maximum thickening and thinning of the current sheet.

Ref. Jackman et al.,2011, 2015

Method. The Proximal Revs during Cassini's Grand Finale



We employ data from Cassini's final 22 full proximal Revs, 271-292. The trajectories are colour coded by Rev numbers. The Revs are highly inclined with a period of ~ 7 days. Cassini passes through Saturn's nightside ring current and plasma sheet.

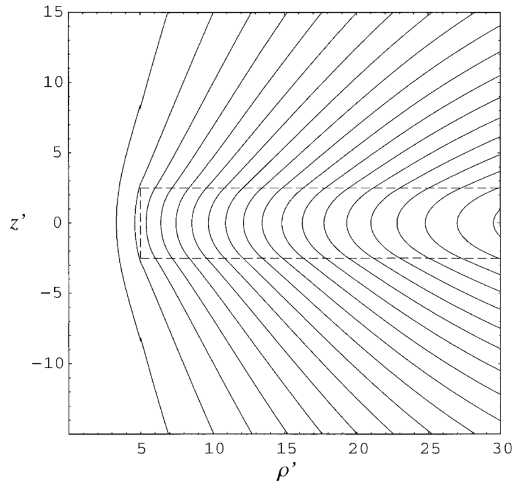
In Panel b we also show the 'Arridge bowl model' for the center of the current sheet, plotted twice for hinging distances of 20 Rs and 30 Rs.

Ref. Arridge et al., 2008

Method. Ring current modelling

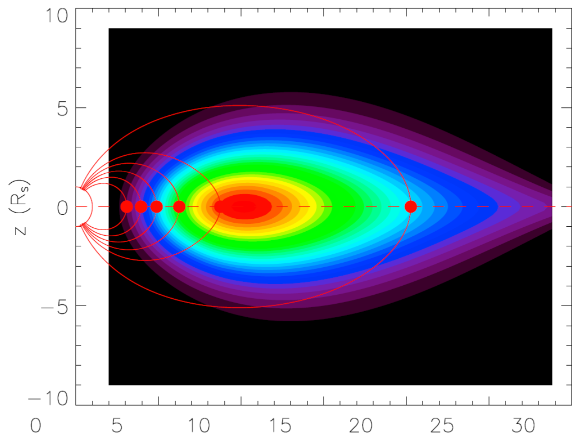
(1)

Use the CAN ring current model, where the ring current is modelled as a cylindrically symmetrical disc. The inner and outer radii of the disc, its thickness and current density is varied to determine the best-fit ring current model.



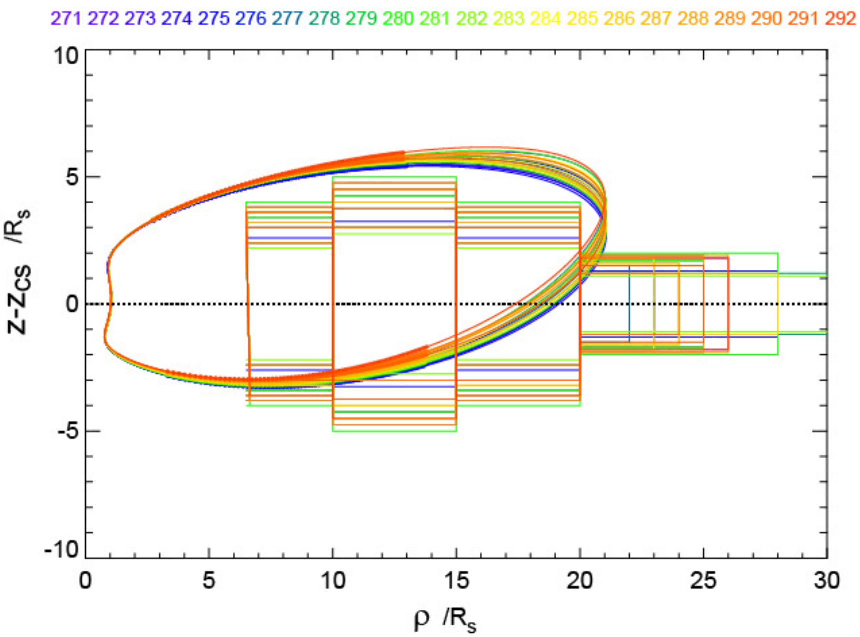
(2)

We use four CAN current discs to approximate the teardrop shaped ring empirically determined by Carbary , 2019



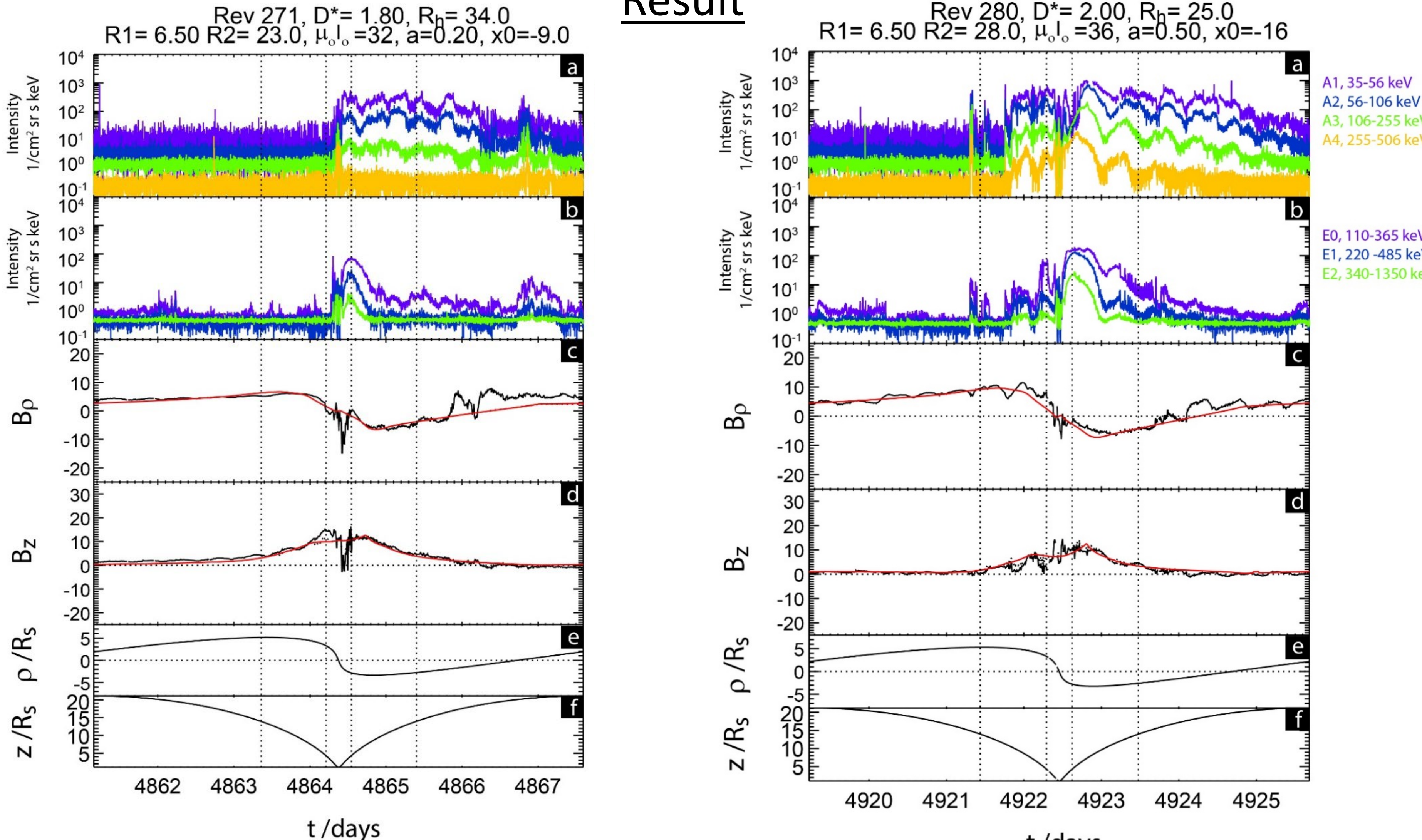
(3)

We fit the model to magnetic field observations from the Proximal Revs. We select data within radial distances of 4.25 and 14 Rs. In this way we include the ring current magnetic field signatures, while excluding signatures associated with the tail plasma sheet and the intra D-ring currents observed close to periapsis.



Ref. Connerney et al., 1981, 1983; Edwards et al., 2001, Carbary et al., 2019, Provan et al., 2019

Result



Example plots for Revs 271 and 280. The top two panels shows LEMMS ion and electron intensity. Panels (c) and (d) shows the Bρ and Bz residual magnetic field (cylindrical coordinates). Overplotted in red are the best-fit ring current models. Inbound, Rev 271 is characterised by quiet solar wind conditions. Rev 280 occurs during a solar wind compression when the two PPO oscillations are close to antiphase - resulting in a magnetospheric storm.

Overview over Ring Current Parameters

The 21 Proximal Revs are colour coded according to solar wind (sw) and magnetospheric conditions

Blue - solar wind rarefaction.
Green -solar wind compression and 'minor' magnetospheric response.
Red - solar wind compression and 'major' magnetospheric response.

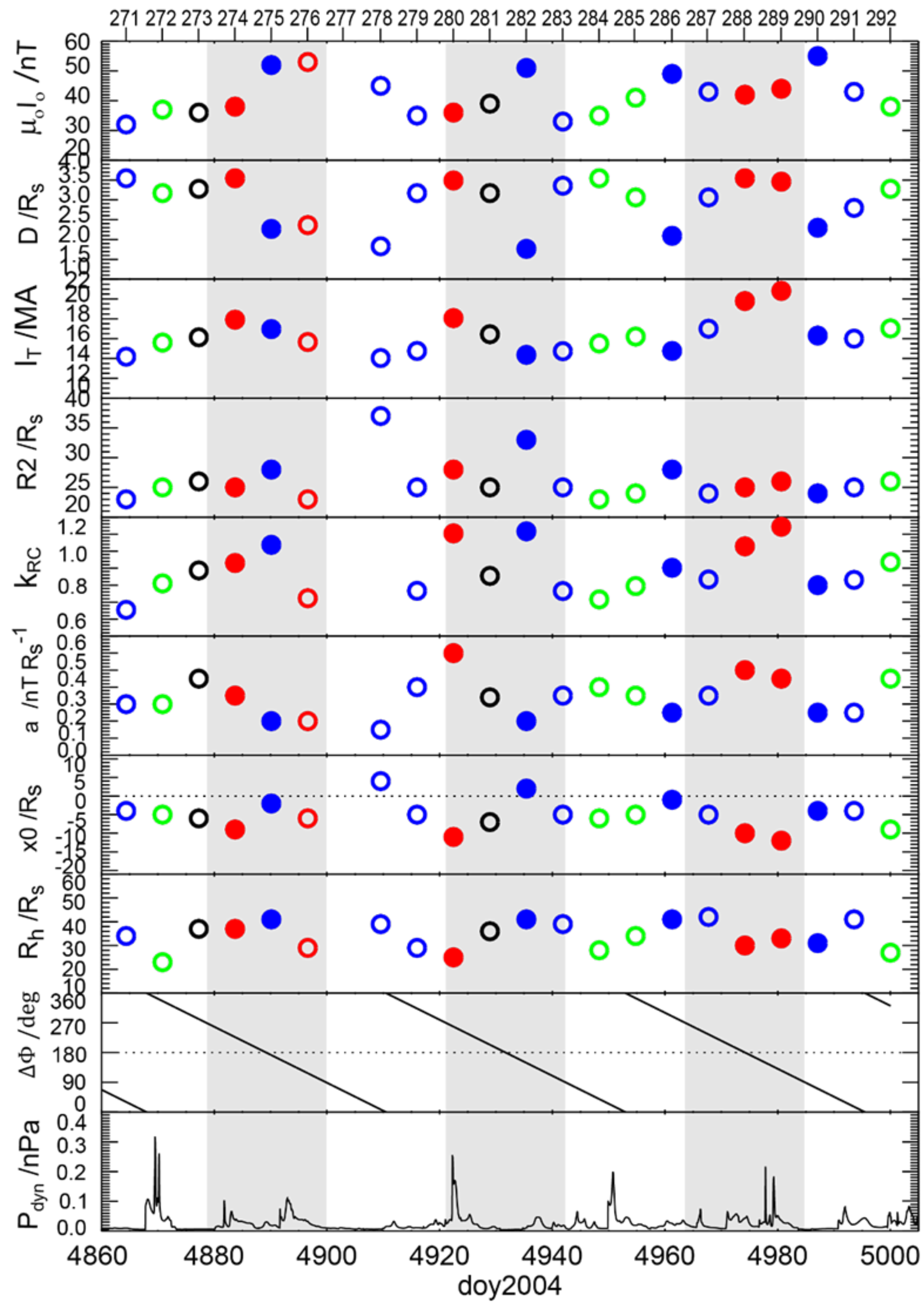
Closed circle means sw conditions persisted both pre- and post- periapsis.

Open circle means sw conditions only observed pre- or post- periapsis .

The grey bars represent times when the two PPO oscillations are in anti-phase.

Magnetospheric storms occur when the PPOs are ~antiphase and the current sheet is thinned (Bradley et al., 2020)

Ref. Bradley et al., 2020



Overview over Ring Current Parameters

$\mu_0 I_0$ – describing the magnitude of the current density in the ring current

D – mean thickness of the current sheet

I_T – total current flowing in the ring current

R2 – radius of outer edge of ring current

k_{RC} – ratio of the magnetic moment of the ring current to the magnetic moment of the planetary dipole.

a – gradient of the magnetopause and magnetotail divergence free fringing fields.

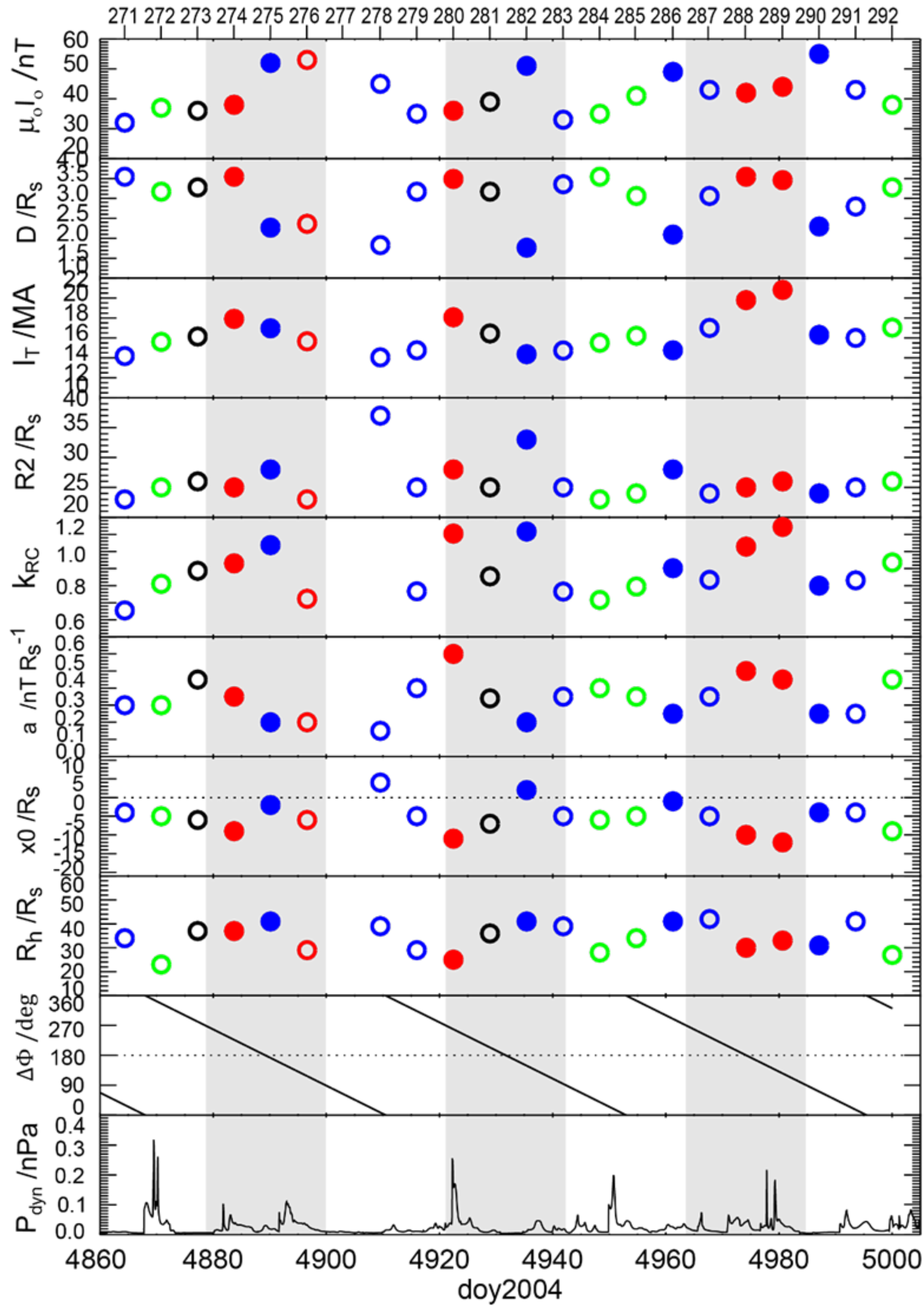
x0 – distance in the x direction where the magnetopause and magnetotail fields are equal but opposite.

R_h – hinging distance of the Arridge et al. (2008) current sheet bowl.

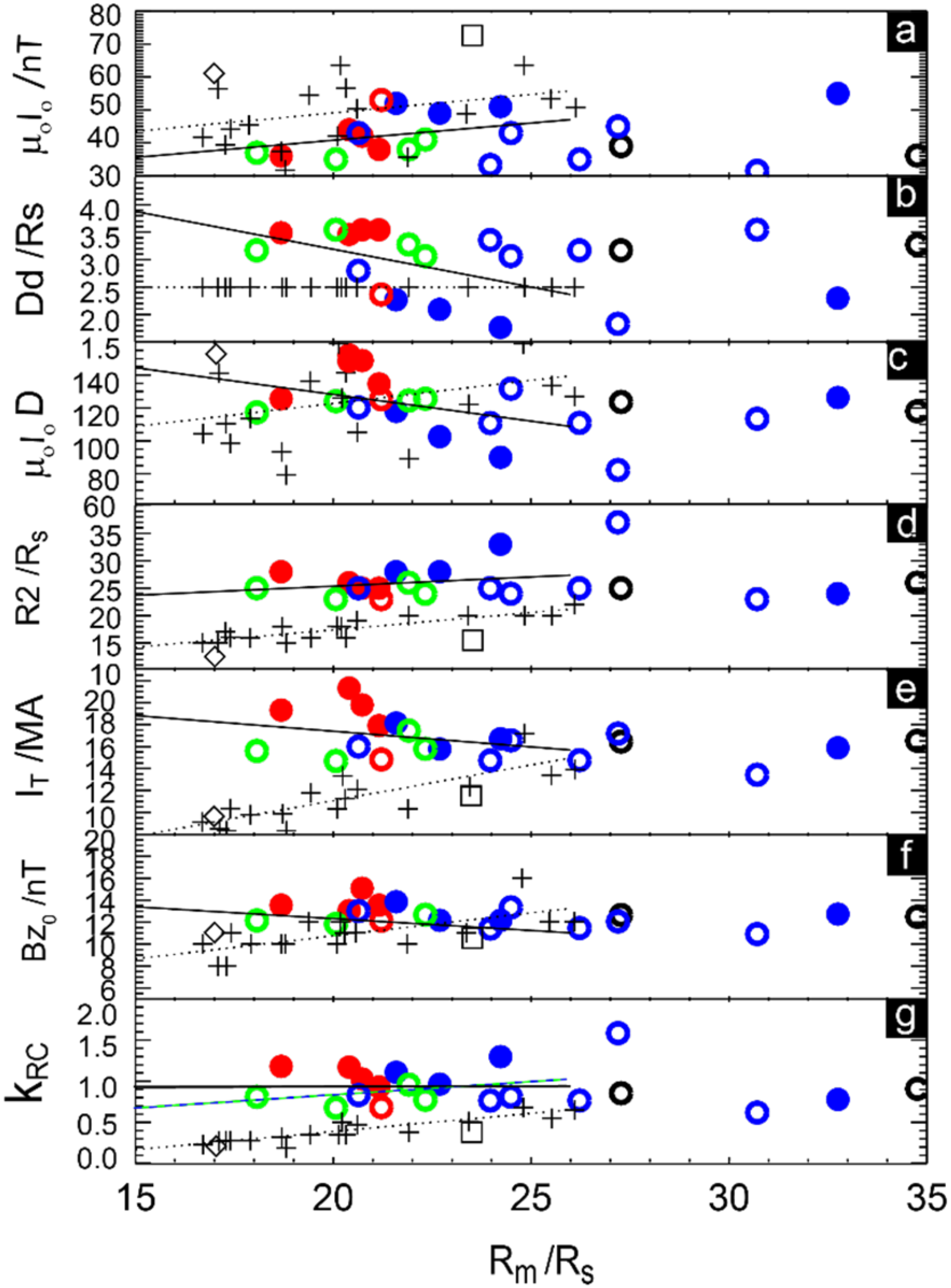
$\Delta\Phi$ – PPO beat phase

P_{DYN} – solar wind dynamic pressure propagated to Saturn (Tao et al., 2005)

Ref. Tao et al., 2005



Ring current parameters plotted versus magnetopause standoff distance.



We determine the position of the magnetopause boundary from the solar wind dynamic pressure.

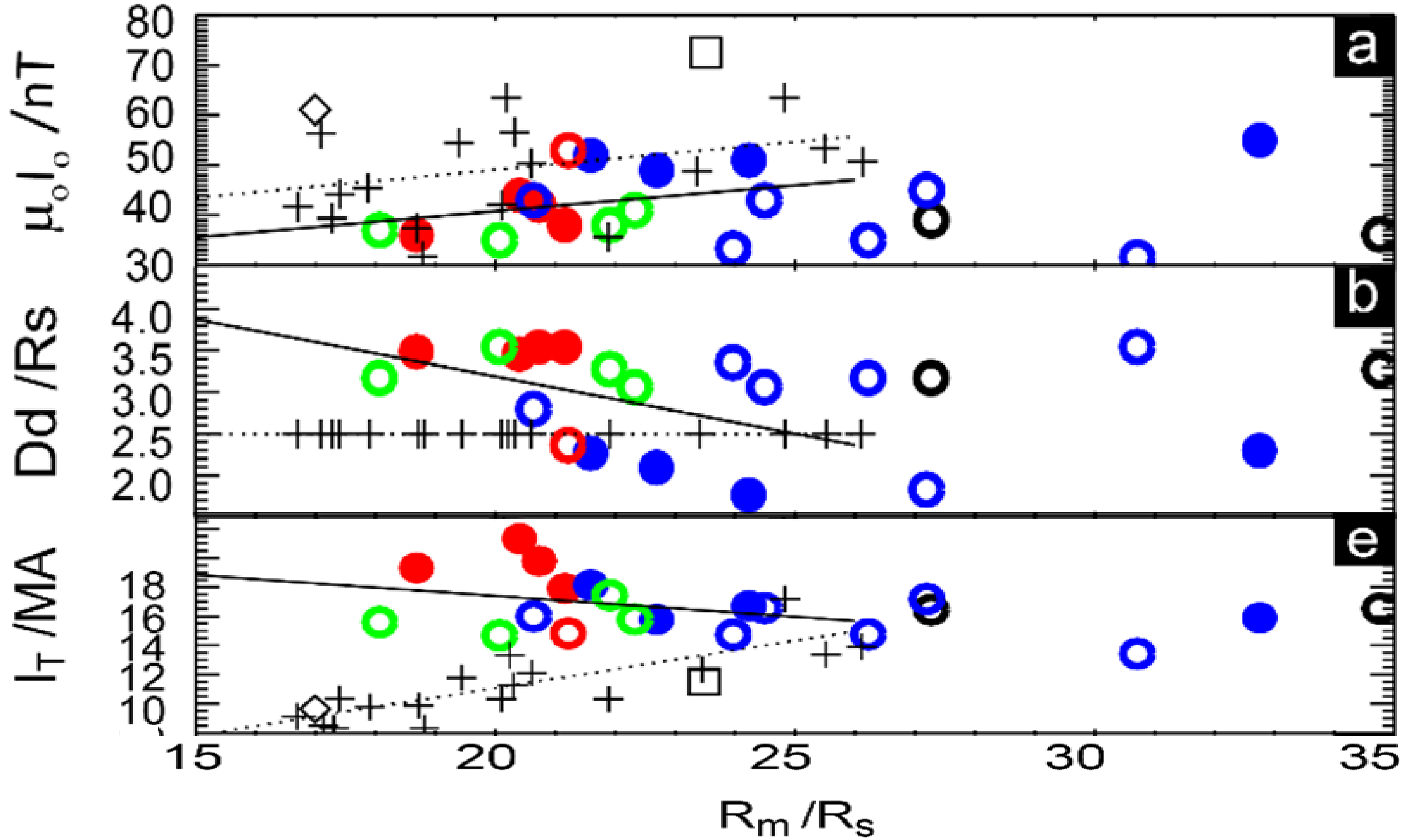
$$R_M = a_1 P_{DYN}^{-a_2}$$

The fitted nightside ring current parameters are shown as a function of magnetopause stand off distance (coloured circles).

The results from the dayside ring current observations from Bunce et al. 2007 (black crosses) are also shown. As well as previous results from Pioneer-11 (diamond) and Voyager-1 (square) spacecraft.

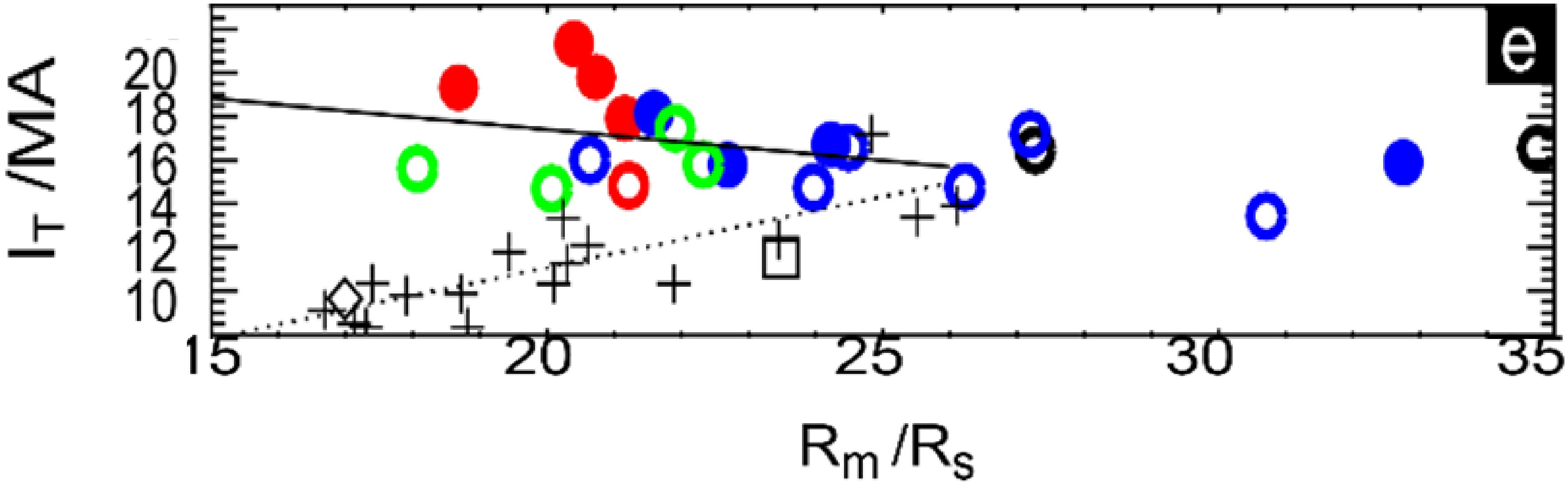
Ref. Bunce et al., 2007 Arridge et al., 2008

Non-storms intervals



During solar wind rarefactions (blue circles) the thickness of the ring current is reduced, but the current density increases, such that the total current is similar to other "non-storm" revs (green circles) - indicative of cool plasma in the current sheet.

Magnetospheric storms - Partial ring current



During solar wind rarefactions when the magnetosphere is expanded and the magnetopause distance is ~25 Rs , the total current of the dayside (black crosses) and the nightside (circles) ring current is approximately equal - **the ring current closes essentially wholly around the planet.**

During solar wind compressions when the magnetopause distance is reduced, the total current is larger on the nightside than on the dayside. The largest currents are observed during magnetospheric storms (red circles) - the nightside ring current does not wholly close via the dayside ring current/magnetodisc region, indicative of a '**partial ring current' on the nightside populate by hot plasma** injected into the ring current during magentotail reconnection. This partial current must close via the magnetopause or planetary ionosphere.

Summary

- Saturn’s ring current is influenced by both external and internal drivers, as is Saturn’s magnetosphere as a whole. The external driver is the solar wind and the internal drivers are the planetary period oscillations.

- **During solar wind rarefactions** the thickness of the ring current is reduced, but the current density increases such that the total current is similar to other non-storm revs - indicative of cool plasma in the current sheet.

- **During solar wind compressions** the total current is larger on the nightside than on the dayside. This is indicative of a partial nightside ring current populated by hot plasma injected from the magnetotail. The current must close via the magnetopause or planetary ionosphere.