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Signatures of field-aligned currents in Saturn's nightside magnetosphere

D. L. Talboys,[1] C. S. Arridge,[2,3] E. J. Bunce,[1] A. J. Coates,[2,3] S. W. H. Cowley,[1]
M. K. Dougherty,[4] and K. K. Khurana[5]

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[1] We report first results of a survey of near-simultaneous and near-conjugate magnetic field perturbations observed over Saturn's northern and southern nightside auroral regions on ~40 periapsis passes of the Cassini spacecraft during 2008. Structured azimuthal fields that are generally anti-symmetric north and south were observed at auroral latitudes on all passes, indicative of the signatures of field-aligned currents associated with magnetosphere-ionosphere coupling. Two basic field patterns are discerned. One is associated exclusively with 'lagging' fields on high-latitude field lines in both hemispheres, while the other includes a transition from 'lagging' to 'leading' fields with decreasing latitude in both hemispheres. The principal field-aligned currents are found to span the region of the open-closed field line boundary and the outer magnetosphere/ring current, with the region of upward current, potentially associated with ionospheric auroral emissions, usually being located on closed field lines just equatorward of the boundary.
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1. Introduction

[2] Initial observations of the signatures of field-aligned currents associated with magnetosphere-ionosphere coupling at Saturn were obtained during the first season of highly-inclined orbits of the Cassini spacecraft that took place from mid-2006 to mid-2007. Study of the data from Rev 37 by *Bunce et al.* [2008b] showed that a major layer of upward-directed field-aligned current flows in the boundary between open and closed field lines near noon, associated with 'lagging' field signatures on southern hemisphere open field lines that are reduced on adjacent closed field lines. The mapped position of this current in the ionosphere was found to be co-located with the dayside UV oval observed near-simultaneously with the Hubble Space Telescope. These observations were thus generally supportive of earlier theoretical modeling that associated the main auroral oval with the boundary of open and closed field lines [*Cowley et al.*, 2004]. We note, however, that *Stallard et al.* [2008] have also reported the presence of weaker IR auroral emissions at lower latitudes that may be related to plasma corotation breakdown deeper inside the magnetosphere. Study of the data from all the Cassini passes during the first high-latitude mission phase by *Talboys et al.* [2009] confirmed the findings of *Bunce et al.* [2008b], but also showed on pre-noon orbits that penetrated deeper inside the magnetosphere in the southern hemisphere that the upward field-aligned current layer often extends into a region of 'leading' fields in the outer magnetosphere, suggestive of plasma super-corotation, which then relaxes in the inner ring current region via a layer of downward-directed field-aligned currents. ('Lagging' and 'leading' fields refer to field lines that are either swept back or swept forward out of meridian planes relative to the sense of planetary rotation. Given the sense of Saturn's planetary field, a 'lagging' field means negative azimuthal field in the northern hemisphere and positive azimuthal field in the southern hemisphere, and vice-versa for 'leading' fields.) *Talboys et al.* [2009] also examined field-aligned current signatures in the northern hemisphere pre-dusk sector. It was shown in these cases that the azimuthal field signatures on open field lines were much reduced in magnitude, possibly due to northern winter conditions and reduced conductivities, while a layer of strongly 'lagging' fields then appears on outer closed field lines, associated with downward-directed currents at highest latitudes together with an adjacent layer of upward currents at lower latitudes.

[3] Following an interval of near-equatorial orbits from mid-2007 to the end of that year, the Cassini orbit was again tilted strongly out of the equatorial plane such that over the course of 2008 it undertook a sequence of ~40 near-polar orbits with apoapsis at ~20–30 R_S in the noon sector and periapsis at ~2.5–4.5 R_S in the midnight sector. These orbits have allowed the first observations to be made of field-aligned current signatures in Saturn's nightside magnetosphere, at radial distances of 3–8 R_S. Furthermore, the northern and southern hemisphere passes are typically separated by only ~2–3 h in local time, and by 6–9 h in UT, such that these data also provide the first near-simultaneous observations of near-conjugate northern and southern field-aligned current signatures at Saturn. Here we provide an overview of these data, exemplifying the typical field signatures observed.

2. Spacecraft Orbit and Data Coverage

[4] The trajectory of Cassini during Rev 74 is shown in Figure 1, which we present as an exemplar from mid-2008

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[1] Department of Physics and Astronomy, University of Leicester, Leicester, UK.
[2] Mullard Space Science Laboratory, University College London, Dorking, UK.
[3] Centre for Planetary Sciences, University College London, London, UK.
[4] Blackett Laboratory, Imperial College, London, UK.
[5] Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA.

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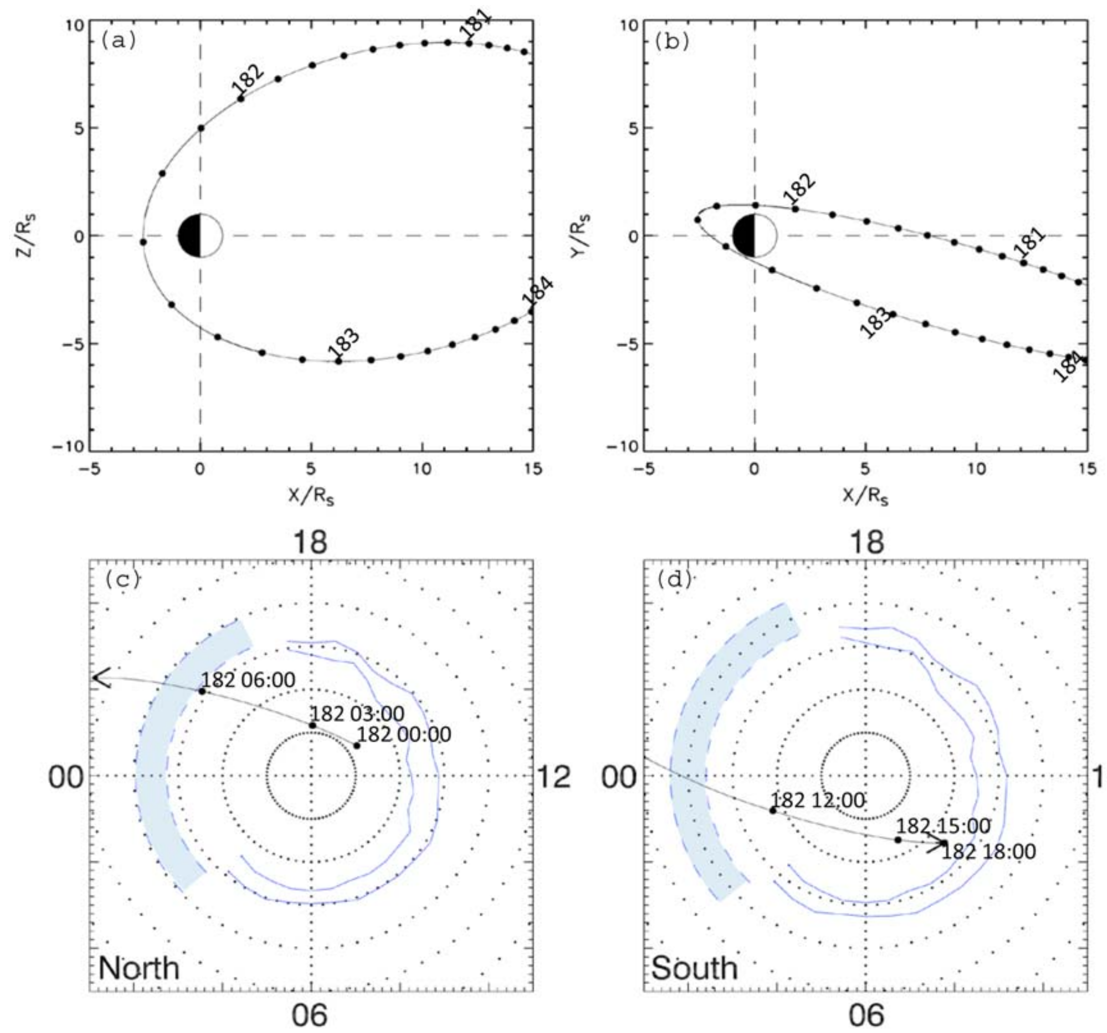

Figure 1. Trajectory of Cassini on days 180–183 of 2008 (Rev 74) showing projections onto (a) the noon-midnight X-Z plane, (b) the X-Y equatorial plane, (c) along field lines into the northern ionosphere, and (d) along field lines into the southern ionosphere.

of the spacecraft's orbit during the interval of interest (the data from which will also be shown in Figure 2). The trajectory is shown in a coordinate system in which the Z axis is aligned with Saturn's rotation axis and the X-Z plane contains the Sun, showing projections onto the noon-midnight X-Z plane (Figure 1a) and the equatorial X-Y plane (Figure 1b). The trajectory is shown by a solid line marked with dots at 3 hourly intervals, labeled with the day of year number (DOY) at the start of each day. It can be seen that Cassini was in a near-polar orbit in a pre-noon to pre-midnight meridian, such that it passed over the northern auroral oval region inbound in the pre-midnight sector, and over the southern auroral region outbound in the midnight and post-midnight sector, following a near-periapsis crossing of the equatorial plane at a local time of ~23 h at a radial distance of ~3 R$_S$.

[5] The expected passes across the auroral region can be seen in Figures 1c and 1d. We have projected the spacecraft footprint along model magnetic field lines into the northern and southern ionospheres for the intervals when Cassini was located north and south of the equatorial plane, respectively. The projection employed a magnetic model consisting of the 'Cassini Saturn Orbit Insertion (SOI)' internal field model of *Dougherty et al.* [2005] and a typical ring current model derived by *Bunce et al.* [2008a], as used for similar purposes by *Bunce et al.* [2008b] and *Talboys et al.* [2009]. The mapped trajectories are shown by solid lines with dots and labels at 3 hourly intervals as in Figures 1a and 1b, which are projected onto a polar grid with dotted circles shown every 5° of colatitude to 25° from the pole, viewed 'onto' the northern hemisphere in Figure 1c and 'through' the planet in the southern hemisphere in Figure 1d. Noon is to the right in these plots, dawn at the bottom, and dusk at the top. The blue lines in Figure 1d show the median poleward and equatorward boundaries of the UV oval located near ~14° and ~16° co-latitude respectively (which we note have an appreciable standard deviation of ~3° reflecting the variable morphology of the aurora), determined from a statistical study of southern hemisphere HST images by *Badman et al.* [2006]. These data are restricted mainly to the dayside due to limited HST coverage of nightside emissions. However, HST images obtained near southern summer solstice conditions indicate nightside emissions centered at larger co-latitudes of ~20°, indicated

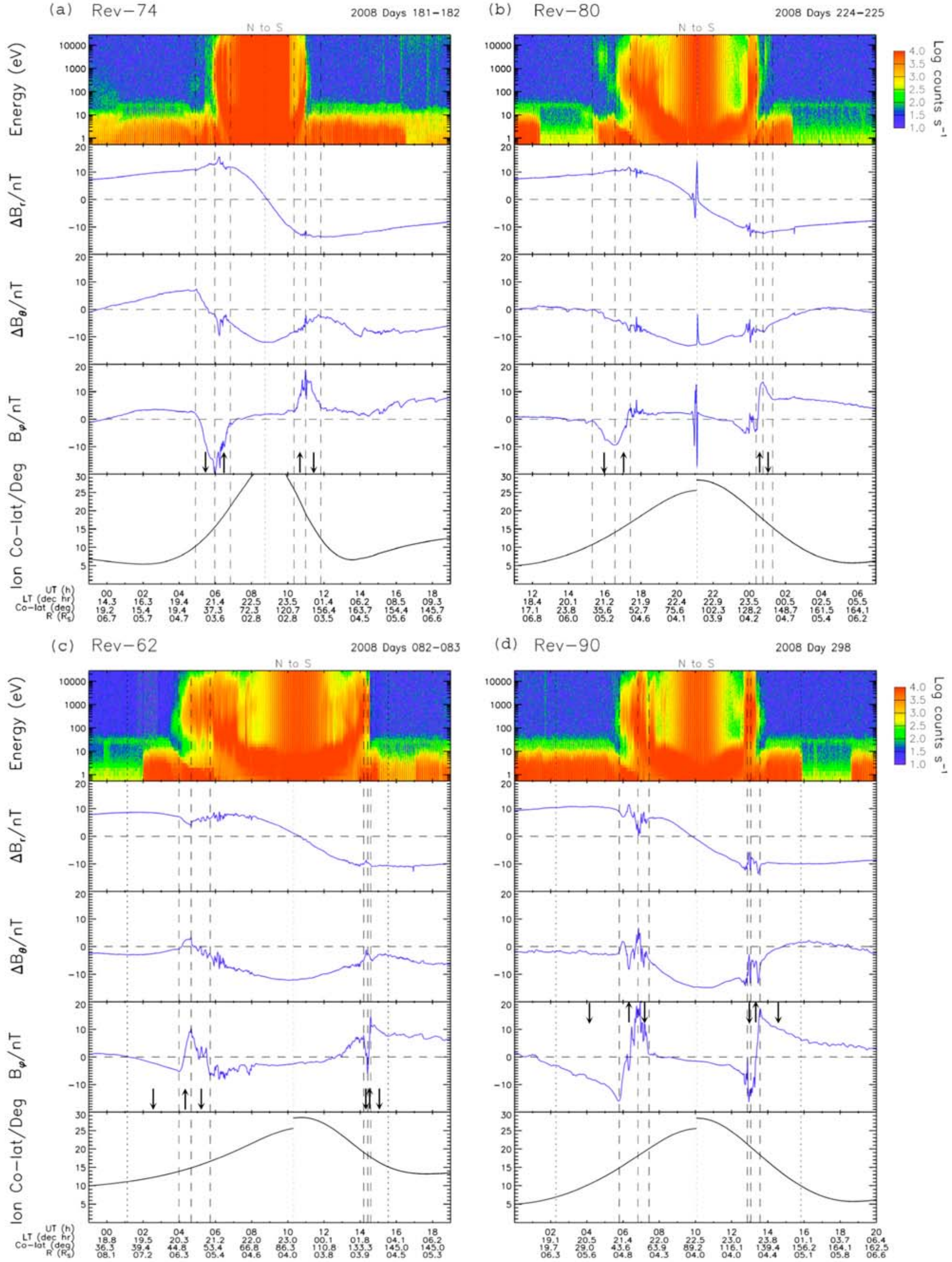

Figure 2. Plots of Cassini field and plasma data for (a) Rev 74, (b) Rev 80, (c) Rev 62, and (d) Rev 90, showing from top to bottom an ELS spectrogram, three spherical polar components of the magnetic field with internal field subtracted, and the spacecraft co-latitude mapped to the corresponding ionosphere.

schematically in Figure 1d by the blue region bounded by dashed lines, which generally merge with the dayside emissions via dusk to form a spiral structure [*Grodent et al.*, 2005]. The corresponding locations in Figure 1c were obtained by mapping the southern boundaries along field lines into the northern hemisphere. They lie closer to the pole in the north than in the south due to the quadrupole term in the internal field model. The main point here, however, is that during the periapsis pass the spacecraft made a few-hour near-perpendicular crossing through the expected northern auroral region in the pre-midnight sector (∼21 h) on the inbound pass, and a similar crossing through the expected southern auroral region in the midnight and post-midnight sector (∼1 h) on the outbound pass. In the ∼6 h interval between these crossings the spacecraft also penetrated deeply into the closed-field region of the inner magnetosphere. Similar passes, with minor modifications, occurred throughout 2008.

3. Field-Aligned Current Signatures in Saturn's Nightside Magnetosphere

[6] A survey of magnetic field data from all ∼40 orbits passing through the northern and southern nightside auroral regions during 2008 reveals the consistent presence of field-aligned current signatures associated with magnetosphere-ionosphere coupling. Although a range of signatures are observed in both form and amplitude, the typical behavior is well exemplified by the data from the four passes shown in Figure 2. Figures 2a–2d each display 20 h of data centered near periapsis, showing from top to bottom an electron spectrogram from the Cassini plasma spectrometer (CAPS) electron spectrometer (ELS) instrument employed here as an aid to region identification, three spherical polar components of the magnetic field referenced to the planet's spin axis, and the co-latitude of the spacecraft mapped to the appropriate ionosphere. The radial (r) and co-latitudinal (θ) field components shown are residual components having the 'Cassini SOI' internal field model subtracted, while the azimuthal field (φ) is as measured, since the azimuthal component of the axi-symmetric model planetary field is zero. The data at the foot of Figures 2a–2d show the universal time (h), spacecraft local time (decimal hours), co-latitude with respect to the northern spin axis (deg), and radial distance (R_S). The vertical dotted line marks the equatorial plane crossing.

[7] We first examine the data from the periapsis pass of Rev 74 shown in Figure 2a, corresponding to the trajectory shown in Figure 1. The residual r and θ components show effects principally associated with the ring current in the near-planet magnetosphere, consisting of radial perturbation fields peaking at ∼10 nT that reverse from positive to negative across the equator, and principally negative co-latitudinal perturbation fields that maximize at similar magnitudes on the equator. This remains a consistent pattern in all of the examples shown. The azimuthal field component, however, shows a sequence of structured perturbations of comparable or larger magnitude that are highly related to the plasma regions identified in the ELS spectrograms. On this pass, the azimuthal field perturbations are relatively weak and positive at highest latitudes in both northern and southern hemispheres on field lines identified as open lines mapping to the tail lobes on the basis of the lack of warm or hot electrons in the ELS spectrogram (the intense fluxes below ∼10 eV are spacecraft photoelectrons). However, on moving towards lower latitudes and the region containing hot plasma that we take to correspond to closed field lines, strong negative and positive azimuthal field deflections are observed in the northern and southern hemispheres respectively, peaking at magnitudes of ∼15–20 nT, consistent with a 'lagging' field in both hemispheres. A 'lagging' field implies the transfer of angular momentum from the ionosphere to the magnetosphere, indicative of sub-corotation of the plasma relative to the conjugate neutral atmosphere. The main current regions are identified by vertical dashed lines in Figure 2 with their direction indicated by the arrows, upward and downward with respect to the corresponding ionosphere. These consist of downward-directed currents (i.e., directed towards the ionosphere) in both hemispheres as the perturbation grows in strength from high to low latitudes, and upward-directed currents (i.e., directed away from the ionosphere) as the perturbation subsequently declines to small values. Comparison with the ELS spectrogram shows that the downward currents begin to grow in strength on open field lines just poleward of the open-closed field boundary, and terminate in the outer region of closed field lines at the boundary between the main hot plasma (ring current) region and the warm outer magnetospheric plasma sheet. The upward currents then extend further into the hot plasma region (whose extent in this case is somewhat obscured in the ELS spectrogram by the counts produced by penetrating radiation near to closest approach). The downward currents required by these perturbations are ∼1.9 MA per radian of azimuth in the northern hemisphere and ∼1.3 MA rad^{-1} in the south (estimated as by *Talboys et al.* [2009]), centered at ∼13.5° mapped co-latitude in the northern ionosphere and at ∼15.8° co-latitude in the south. Correspondingly, the upward currents are ∼1.9 MA rad^{-1} in the north and ∼1.4 MA rad^{-1} in the south, centered at ∼18.2° co-latitude in the northern ionosphere and at ∼22.4° co-latitude in the south. The locations of the northern and southern upward currents thus approximately correspond to the nightside auroral regions sketched in Figure 1, based on the results of *Grodent et al.* [2005]. We note that the azimuthal field perturbations in this case are similar in form to those previously reported in the pre-dusk northern hemisphere auroral region by *Talboys et al.* [2009]. Here, however, we now observe corresponding anti-symmetric azimuthal field perturbations in the both the northern and southern hemispheres, the latter at slightly larger colatitudes than the former as expected. This represents strong evidence supporting our previous identification of these features as the signatures of field-aligned currents associated with plasma sub-corotation on outer magnetospheric field lines.

[8] Between the main field-aligned current signatures in the azimuthal field in Figure 2a we observe at lower latitudes a weaker few-nT field that increases from small negative to small positive values over the interval shown. We identify this field as the quasi-uniform perturbation field in the interior region that rotates in the sense of the planetary rotation with a period near to the planetary period [*Espinosa et al.*, 2003; *Andrews et al.*, 2008; *Provan et al.*, 2009]. We note that the time required for the spacecraft to cross the region between the northern and southern auroral

regions containing the field-aligned current signatures is comparable to half a planetary rotation, so we expect the field in this region typically to change sign from positive to negative or vice versa during such intervals. The specific phasing of Rev 74 is such that this field increased from negative to positive values across the interval, thus resembling 'lagging' fields in both hemispheres. An example in which the polarity happened to be opposite is shown in Figure 2b from Rev 80, in which strongly 'lagging' field signatures in the outer regions as before reverse in sense in the inner region to weaker azimuthal fields that are positive in the northern hemisphere and negative in the southern hemisphere (the large structured fields observed near the equatorial crossing in this case are due to an Enceladus flyby). It can thus be seen that these periodic field variations are associated with a correspondingly periodic modulation of the field-aligned current system, which adds a downward-directed current in both hemispheres in the case of Rev 74 (though approximately half a rotation period apart in time), and an upward-directed current in both hemispheres in the case of Rev 80.

[9] In addition to these relatively simple 'lagging' field behaviors, more complex field-aligned current signatures were observed on about a quarter of these passes, involving strong anti-symmetric 'leading' field signatures in both hemispheres, similar to those reported in the pre-noon sector by *Talboys et al.* [2009]. Examples are shown in Figures 2c and 2d from Revs 62 and 90, respectively, again showing cases in which the polarity of the interior azimuthal field varied from negative to positive in the first case and from positive to negative in the second. In these examples, 'lagging' fields were observed over extended intervals in both the northern and southern open field regions (as was also observed in the southern hemisphere for both Revs 74 and 80 in Figure 2), which grow in strength towards lower latitudes associated with distributed downward-directed field-aligned currents. The high-latitude extent of these currents is thus uncertain, and so is indicated by a vertical dotted (instead of a dashed) line. These 'lagging' perturbations then not only decline to smaller values inside the boundary of open field lines, but reverse in sense to form anti-symmetric regions of 'leading' fields in both hemispheres, positive in the north and negative in the south, whose peak perturbations of ~10–20 nT are at least comparable to those observed in the regions of 'lagging' field. Such anti-symmetric 'leading' field signatures, observed over intervals of hours on a given pass, are again indicative of quasi-static current systems which now imply the transfer of angular momentum from the magnetosphere to the ionosphere, indicative of super-rotation of the outer ring current plasma relative to the conjugate neutral atmosphere. These fields then decline at lower latitudes to the weaker fields of the interior region, from which they are distinct, whose sign depends on the phase of the rotating field at the time of the pass. These observations do not therefore support the suggestion of *Southwood and Kivelson* [2009] that the occurrence of 'leading' field signatures is linked to the sense of the adjacent rotating field at the time of the pass, Figure 2c showing one of a number of counter-examples.

[10] Overall, the pattern of field-aligned current flow in the latter cases consists of three main adjacent regions in each hemisphere, with (from high to low latitudes) a distributed downward-directed current flowing on open field lines, followed by a major layer of upward-directed field-aligned current located in the outer plasma sheet/ring current region, and then a further downward-directed current in the inner ring current. The total currents flowing in these regions in Rev 90 (shown in Figure 2d), for example, are downward currents of ~1.6 and ~1.8 MA rad^{-1} on open field lines in the north and south respectively, upward currents of ~5.1 and ~4.4 MA rad^{-1} flowing on outer closed field lines, and downward currents of ~2.7 and ~2.0 MA rad^{-1} flowing in the inner ring current. The upward-directed currents observed on this orbit are centered at ionospheric co-latitudes of ~16.5° in the north and ~19.4° in the south, again corresponding to the nightside auroral region shown in Figure 1.

4. Summary

[11] We have reported the results of a first survey of near-simultaneous and near-conjugate field perturbations observed in the northern and southern hemispheres of Saturn's nightside magnetosphere on ~40 periapsis passes of the Cassini spacecraft in 2008. Structured azimuthal fields were observed at auroral latitudes during all passes, which were generally anti-symmetric in form between the northern and southern hemispheres, and thus indicative of the presence of quasi-static field-aligned currents associated with magnetosphere-ionosphere coupling. Although a variety of signatures and amplitudes are observed, the azimuthal field patterns can broadly be divided into two categories. In the first, which accounts for ~60% of cases, the azimuthal field grows with decreasing latitude into a strong 'lagging' field configuration as the open-closed boundary is approached, indicative of a region of downward-directed field-aligned current, and then decays to smaller values inside the boundary, associated with a layer of upward-directed field-aligned current. The downward-directed current at higher latitudes thus generally spans the open-closed field line boundary into the outer magnetosphere on closed field lines, followed immediately by an upward-directed current that begins on outer closed field lines and extends further into the hot plasma region. Investigation of the electron distributions, to be reported in detail in a separate communication, indicates that the regions of intense downward-directed current near the open-closed field boundary are often associated with beams of ~1 keV electrons directed out of the ionosphere. The total currents carried in the two layers typically lie in the range ~1–3 MA rad^{-1}, with the region of upward current mapped to the ionosphere typically centered at ~17° in the northern hemisphere and ~18° in the south. These signatures are similar to those for the pre-dusk northern hemisphere auroral region at Saturn reported by *Talboys et al.* [2009], and suggest the presence of a layer of sub-corotating field lines in the outer closed-field magnetosphere in these cases that may stretch at least from the pre-dusk sector to past midnight. Smaller fields in the inner region are taken to be associated with the quasi-uniform field that rotates near the planetary period, observed at differing phases of oscillation on differing passes, which is clearly associated with modulations of the field-aligned current system.

[12] In the second category, which accounts for ~25% of cases (~10% in Figure 2c and ~15% in Figure 2d), the lagging fields observed on open field lines in the vicinity of the open-closed field boundary are not only reduced across the boundary, but reversed in sense to form a significant 'leading' field layer. The perturbations then again reduce to smaller values, modulated by the unrelated phase of the rotating field. In this case, downward-directed currents again flow on open field lines, followed by upward-directed currents located in the outer plasma sheet/ring current region, and then further downward-directed currents in the inner ring current. The total currents typically carried in these three regions are ~1–2 MA rad^{-1} in the outer downward current region, ~2–5 MA rad^{-1} in the middle upward current region, and ~1–4 MA rad^{-1} in the inner downward current region. The ionospheric locations of these currents in the northern hemisphere are ~16° for the upward current and ~17° for the inner downward current, while the corresponding values for the southern hemisphere are ~18° for the upward current and ~19° for the inner downward current. These signatures are similar to those reported by *Talboys et al.* [2009] in the dawn and pre-noon southern hemisphere auroral region, and suggest the intermittent presence of a layer of significantly super-corotating field lines in the outer closed-field magnetosphere in these cases that may sometimes stretch from pre-midnight to the pre-noon sector via dawn. Future work is required to establish the physical conditions under which these two types of field-aligned current signature occur. It will also be of interest to examine the relationship between the location and structure of these field-aligned currents and the night-side auroras observed at UV and IR wavelengths by Cassini.

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C. S. Arridge and A. J. Coates, Mullard Space Science Laboratory, University College London, Dorking RH5 6NT, UK.

E. J. Bunce, S. W. H. Cowley, and D. L. Talboys, Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK. (dean.talboys@star.le.ac.uk)

M. K. Dougherty, Blackett Laboratory, Imperial College, London SW7 2BZ, UK.

K. K. Khurana, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA.