Saturn's Erratic Clocks:
Searching for the Rotation Rate of a Planet

J.F. Carbary[1], M.M. Hedman[2], T.W. Hill[3], X. Jia[4], W.S. Kurth[5], L. Lamy[6], and G. Provan[7]

[1] Johns Hopkins University Applied Physics Laboratory, USA
[2] Department of Physics, University of Idaho , USA
[3] Physics and Astronomy Department, Rice University, USA
[4] Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan, USA
[5] Department of Physics and Astronomy, University of Iowa, USA
[6] LESIA-Observatoire de Paris, CNRS, France
[7] Department of Physics and Astronomy, University of Leicester, UK

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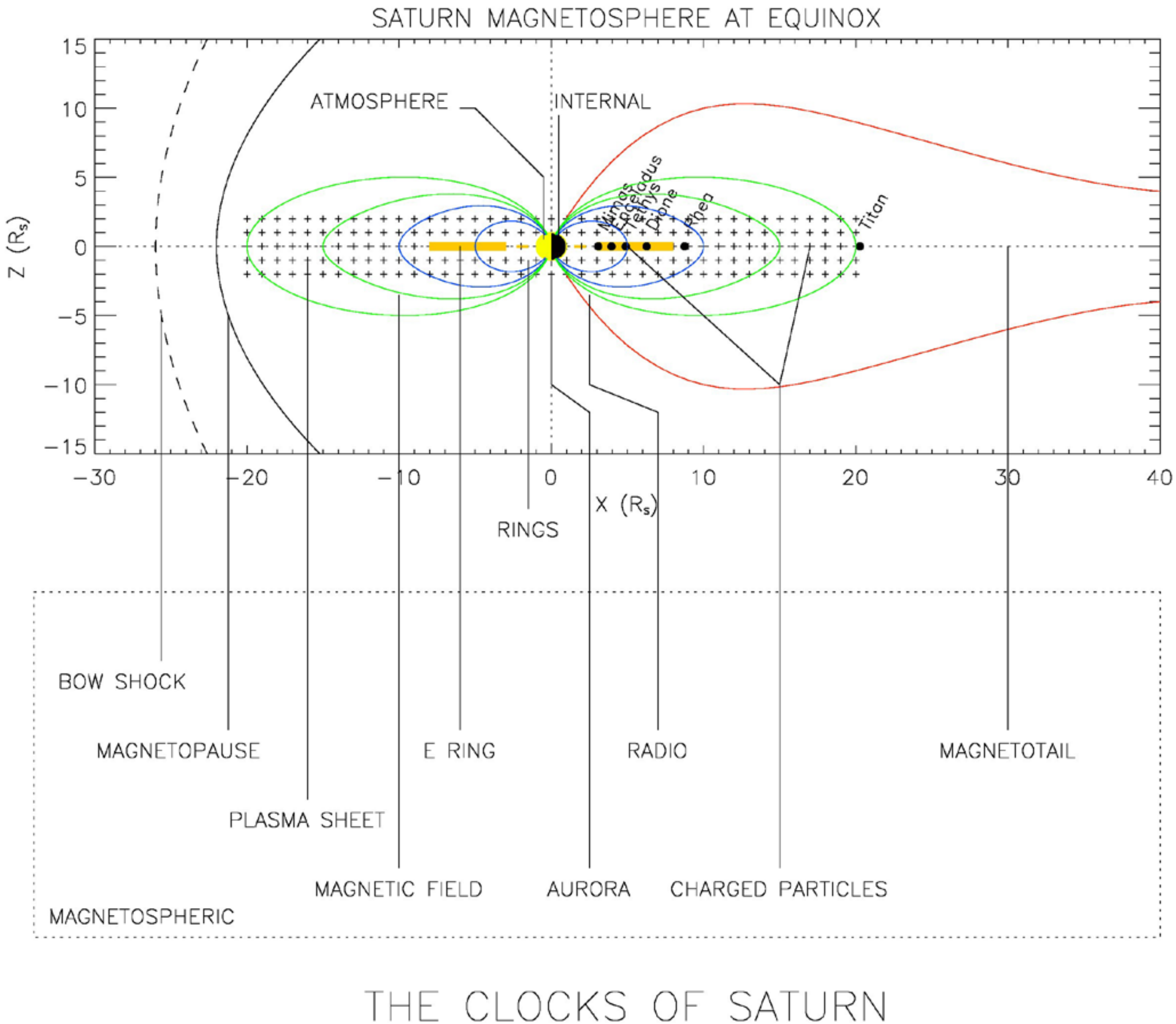
What is a Clock?

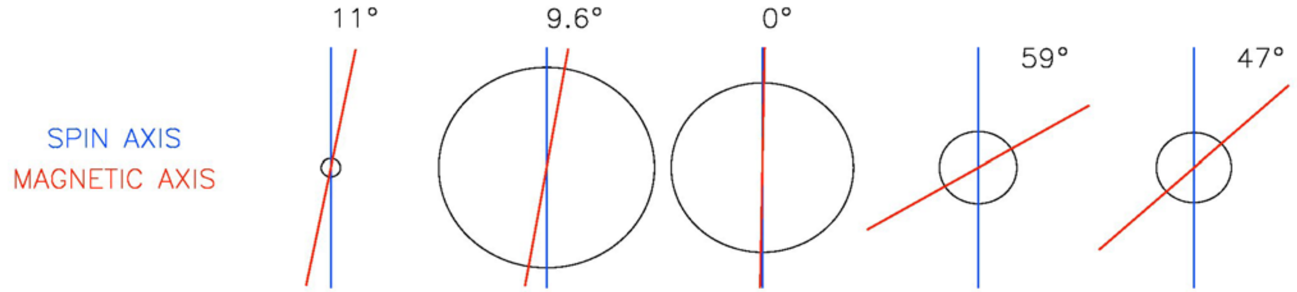
A clock is something that repeats itself over and over, with such regularity that one may measure time using its periodicities. This regularity can be very precise (e.g., an atomic clock or a pulsar), or very imprecise (e.g., bird migrations, geyser eruptions). Planetary rotation is *the* ultimate clock and here on Earth it has regulated our activity since life began. All the planets rotate, and all of them except one keep very good time by their rotation. That one exception is Saturn (at least by any known observable).

Saturn's Clocks



Comparing Planets — How is Saturn Different?

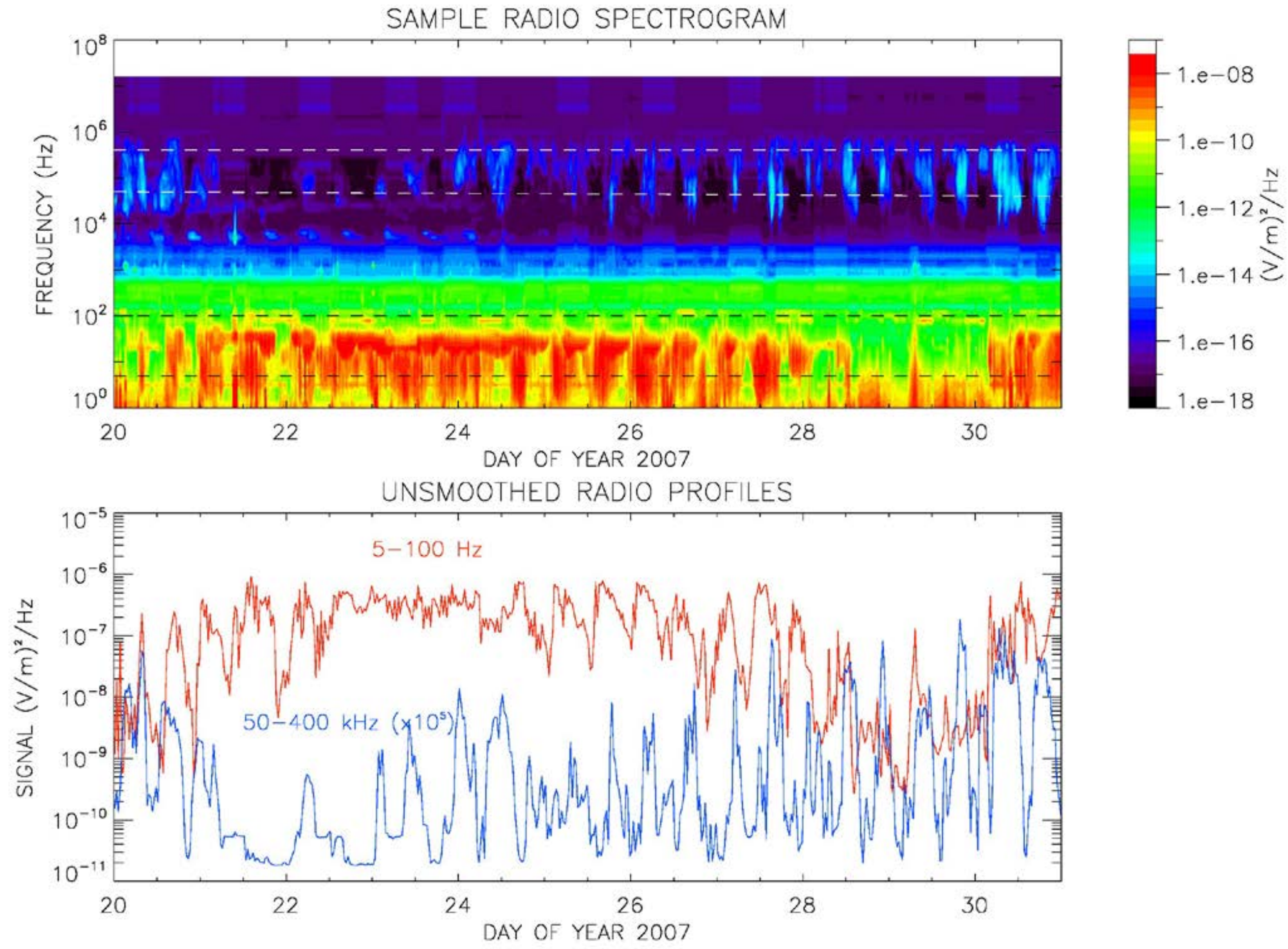
PLANETARY MAGNETIC FIELDS



PLANET	EARTH	JUPITER	SATURN	URANUS	NEPTUNE
DIP-MOMENT (Nm/T)	8.0×10^{22}	1.6×10^{27}	4.6×10^{25}	3.0×10^{24}	1.6×10^{24}
PERIOD (days)	1.0	0.41	0.44	0.72	0.74
RADIUS (km)	6400	71400	60300	25600	24800
OBLIQUITY	23.5°	3.1°	26.7°	97.9°	29.6°

The Radio Clock

Sample Radio Periodicities



The radio clock is considered the "standard" clock of Saturn. Periodicities in the kilometric band (50-400 kHz) define the Saturn kilometric radiation (SKR) clock (blue, bottom). However, similar periodicities appear in other frequency bands, notably the lower-frequency bands (red, bottom).

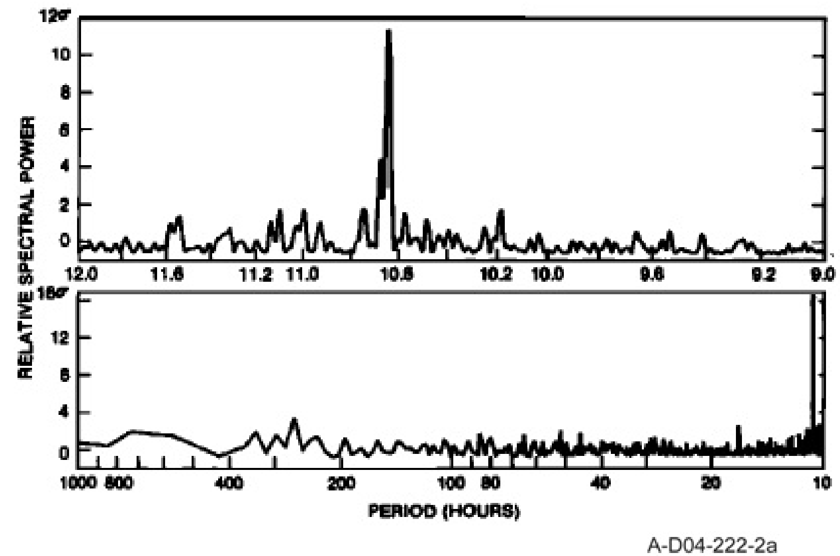
The Radio Clock

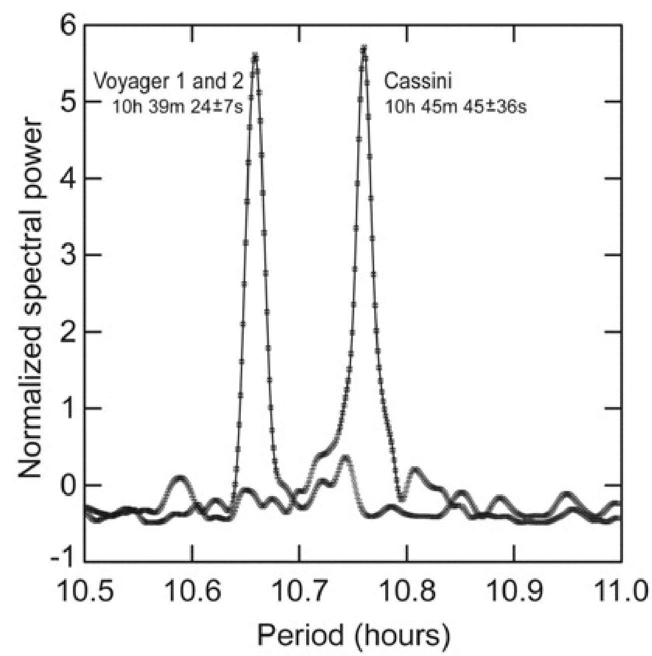
To define the clock, periodicities in the SKR band identified by standard spectral analyses techniques (Fourier or Lomb-Scargle) to obtain a definitive frequency. The Voyager flybys in the 1980's first discovered the SKR period to be 10.65 h (10h 39m 24s). This clock was initially thought to be stable, and led to the formation of the original Saturn Longitude System (SLS).

But the clock later found to be unstable. Radio measurements by the Ulysses spacecraft in 1990's found that Saturn's SKR period was slowly changing over several years by a noticeable amount of ~1%.

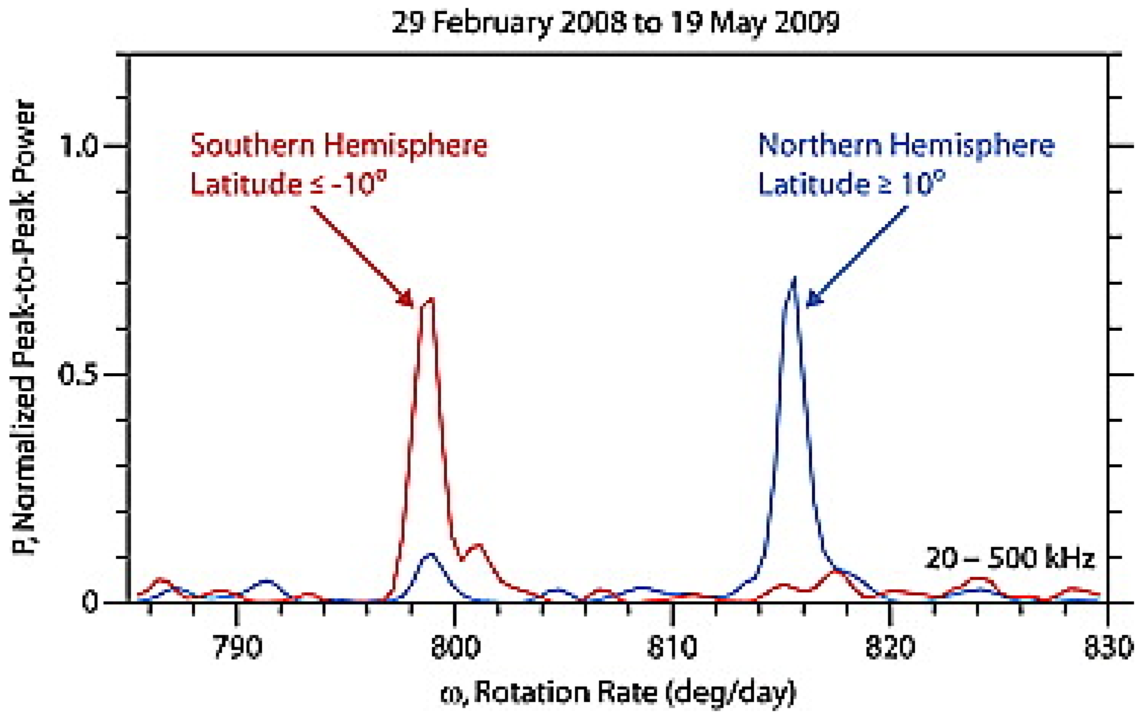
This changing period was confirmed by the initial observations by the RPWS instrument when Cassini entered the Saturn system in 2004. The new SKR period was 10.76 h (10h 45m 45s).

Top: Desch and Kaiser (1981)
Bottom: Gurnett et al. (2005)



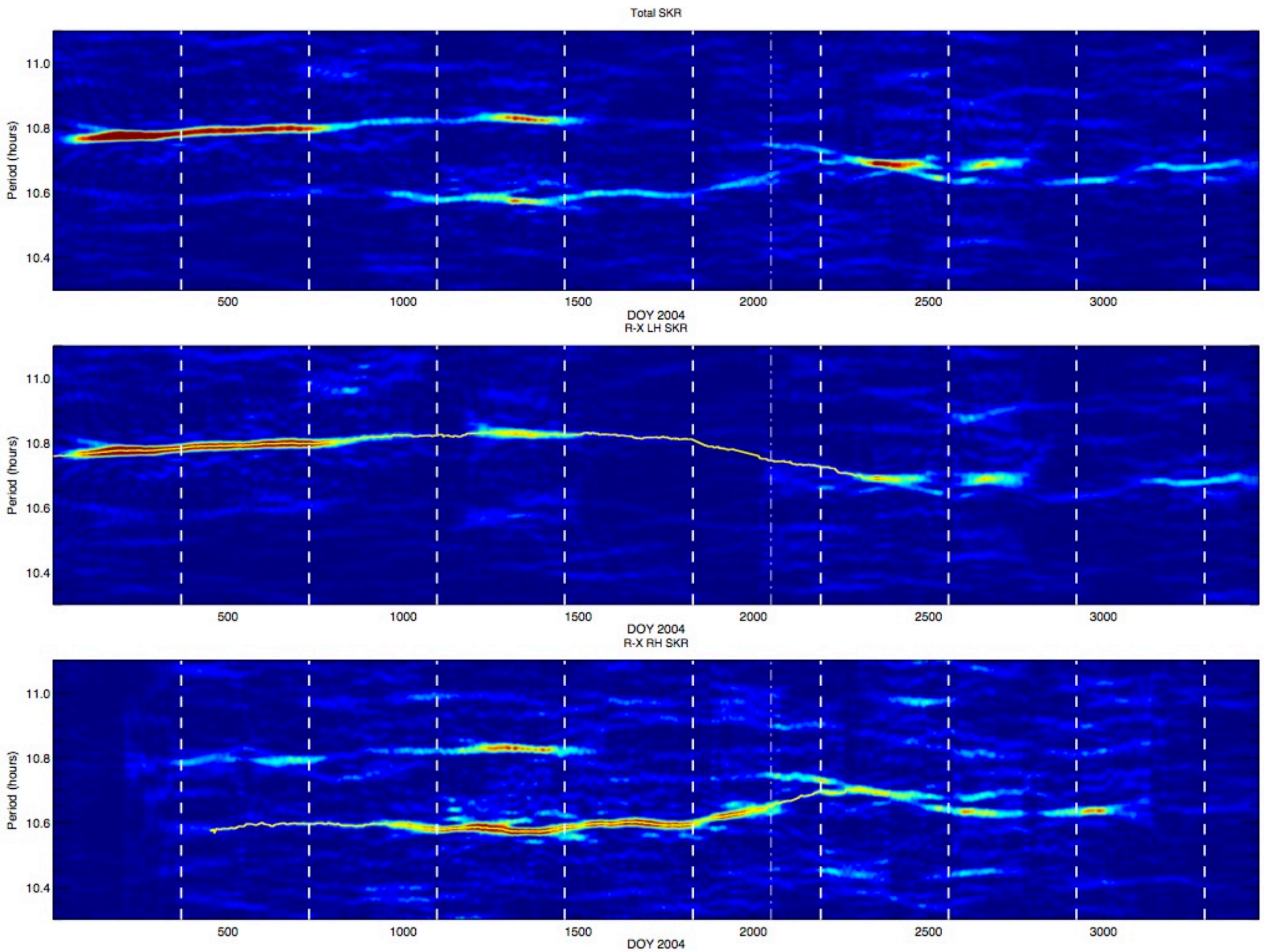


An Added Complication – Dual Periodicity



As radio observations of Saturn continued, a new complication arose. A second SKR periodicity was observed with a faster period. So Saturn now had two periods: one at ~10.8 hours and one at ~10.6 hours. The slower ("original") period was generally observed from southern latitudes, while the faster ("newer") period was observed from northern latitudes, so the periods obtained "SKR south" and "SKR north" appellations. [Gurnett et al., 2009]

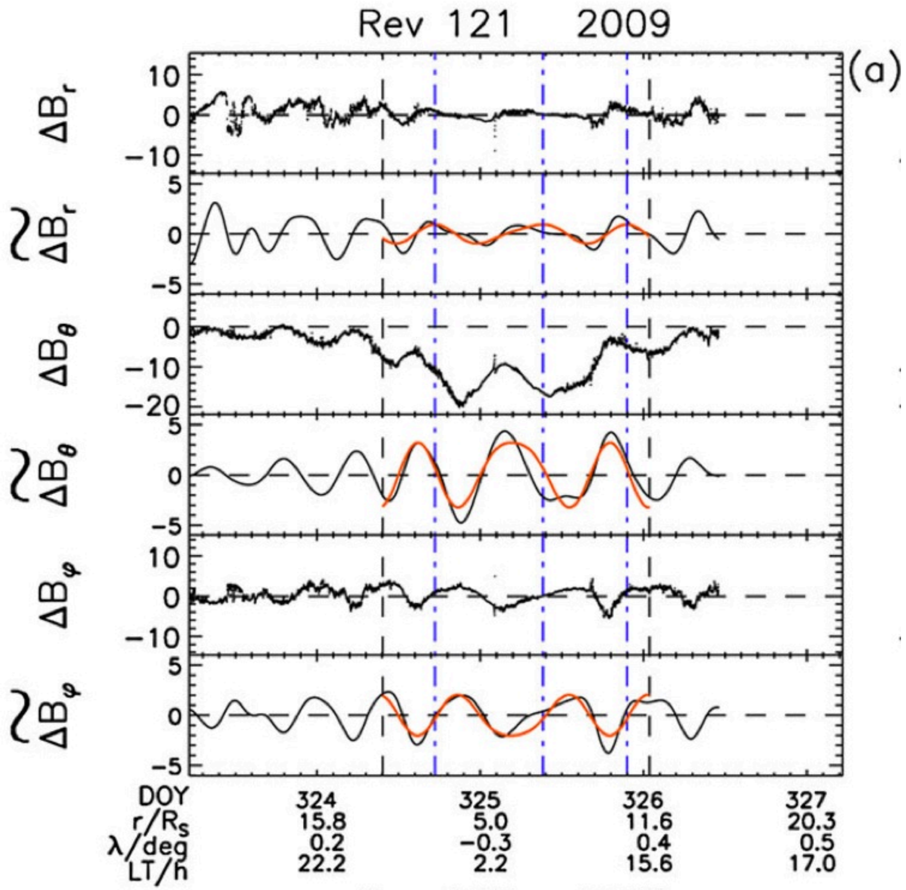
Summary of Radio Periodicity through the Years



This is a summary of the SKR periodicity from 2004 to the middle of 2013. In this case, the SKR north and south periodicities were separated by the polarity of the radio signal. Because SKR arises from the gyro-motions of electrons about field lines, SKR from the southern hemisphere should be RH polarized, while SKR from the north should be LH polarized. That is roughly what is seen here. Note that the north and south “branches” tend to converge shortly (and cross) after Saturn equinox in 2009. A post-equinox convergence and crossing were thought to be due to seasonal effects. [Lamy, 2011, & pvt com]

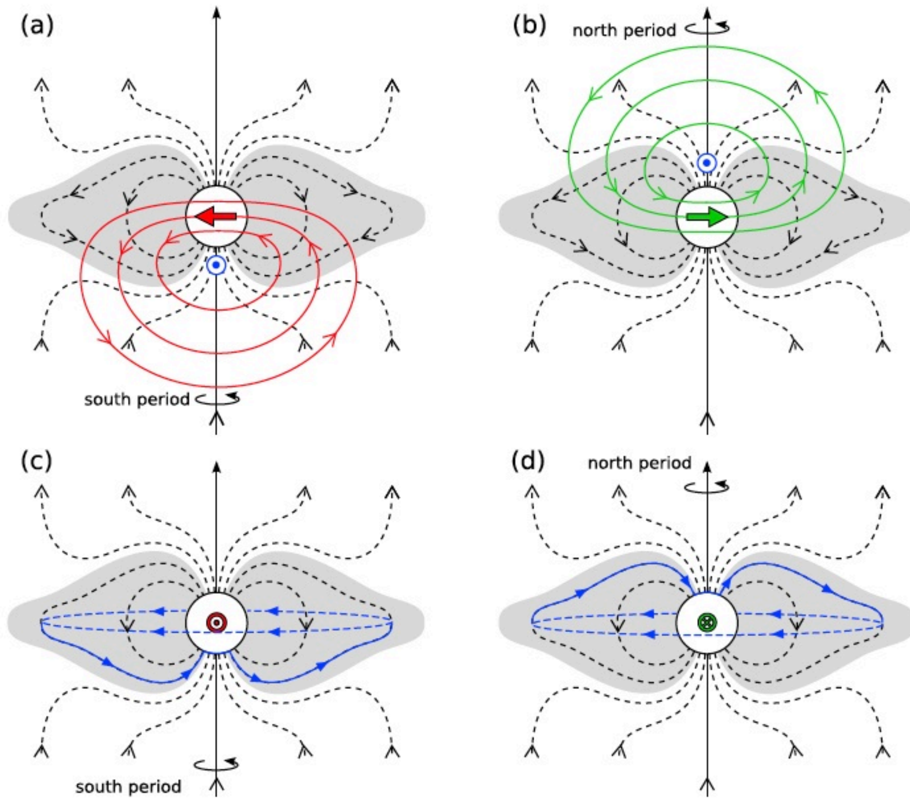
The Magnetic Clock

Sample Magnetic Fields



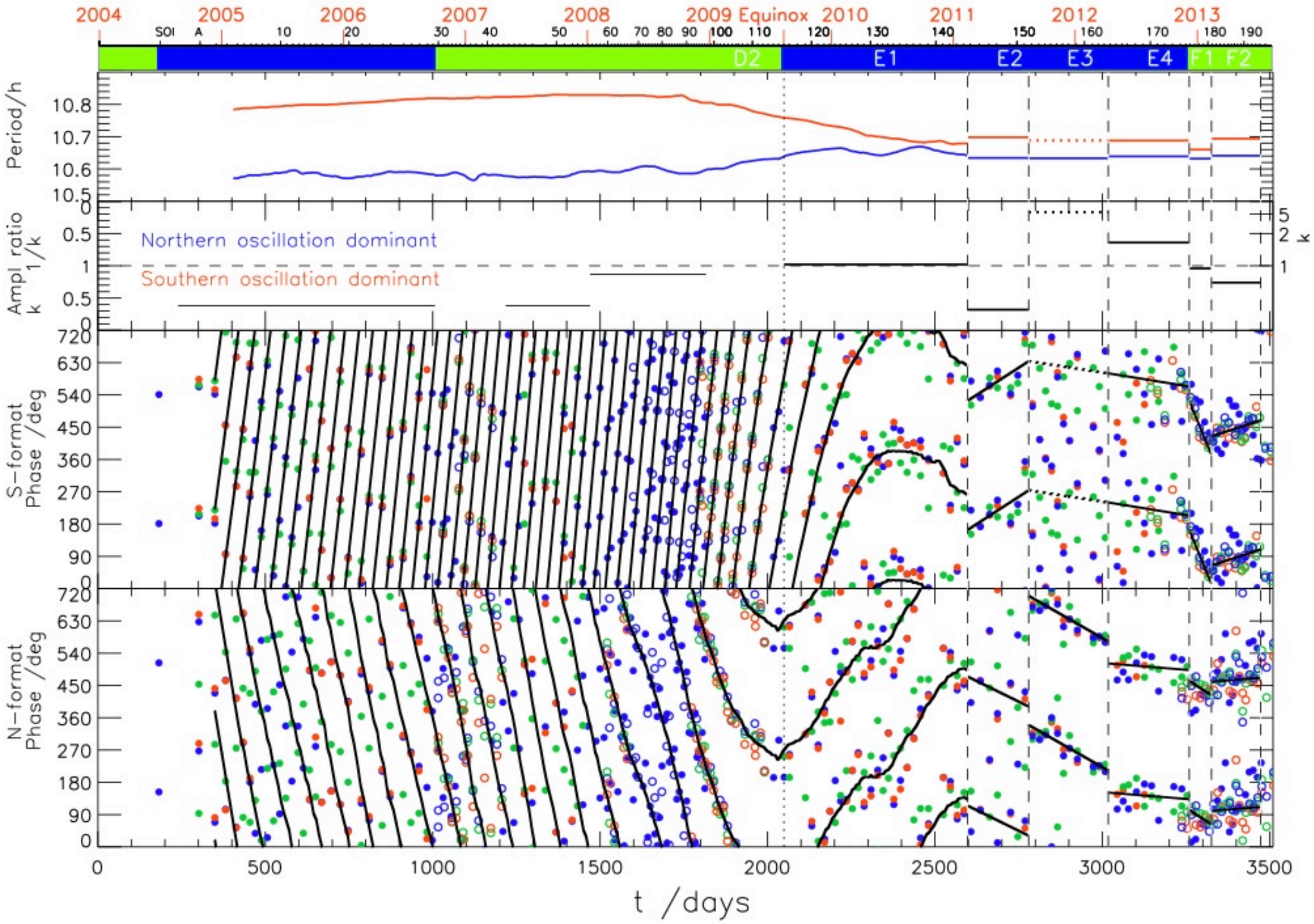
Main field (an offset but spin-aligned dipole) is subtracted from the observed field to give the "perturbation" field, which is periodic. The remaining field is then smoothed and detrended using a Lanczos filter to remove signal outside the 5-20 h window. Then the signal is fitted to a function of the form: $B_i(\phi,t) = B_{0i}\cos[\Phi_i(t)-\phi-\Psi_i]$ (red curves) where $\Phi_i(t)=2\pi t/\tau_i$ is the "guide" phase having a period τ_i, ϕ is the (local time) phase of the spacecraft, and Ψ_i is the signal phase, and where the "i" index refers to the B_r, B_θ or B_ϕ components of the magnetic field. [Provan et al., 2013]

Interpretation of the Magnetic Field Periodicities



The southern (left) and northern (right) magnetic perturbatory loops (top panels) and Birkeland (field-aligned) current systems (bottom panels). The magnetic field perturbations are quasi-dipolar in the northern and southern polar regions and quasi-uniform in the equatorial core region (L<15 R_S). These perturbations are consistent with two "loops" of magnetic field lines. One loop passes over the southern polar region, the other over the northern region, and both through the equatorial region. The northern loop rotates at the northern period, while the southern rotates at the southern period. Within the core region, the two systems constructively and destructively interfere in a manner described by "beating." The two magnetic field systems are consistent with two systems of Birkeland currents. For the southern loop, B_r and B_θ are in phase; for the northern loop, B_r and B_θ are in anti-phase, allowing N-S separation. [Andrews et al., 2011]

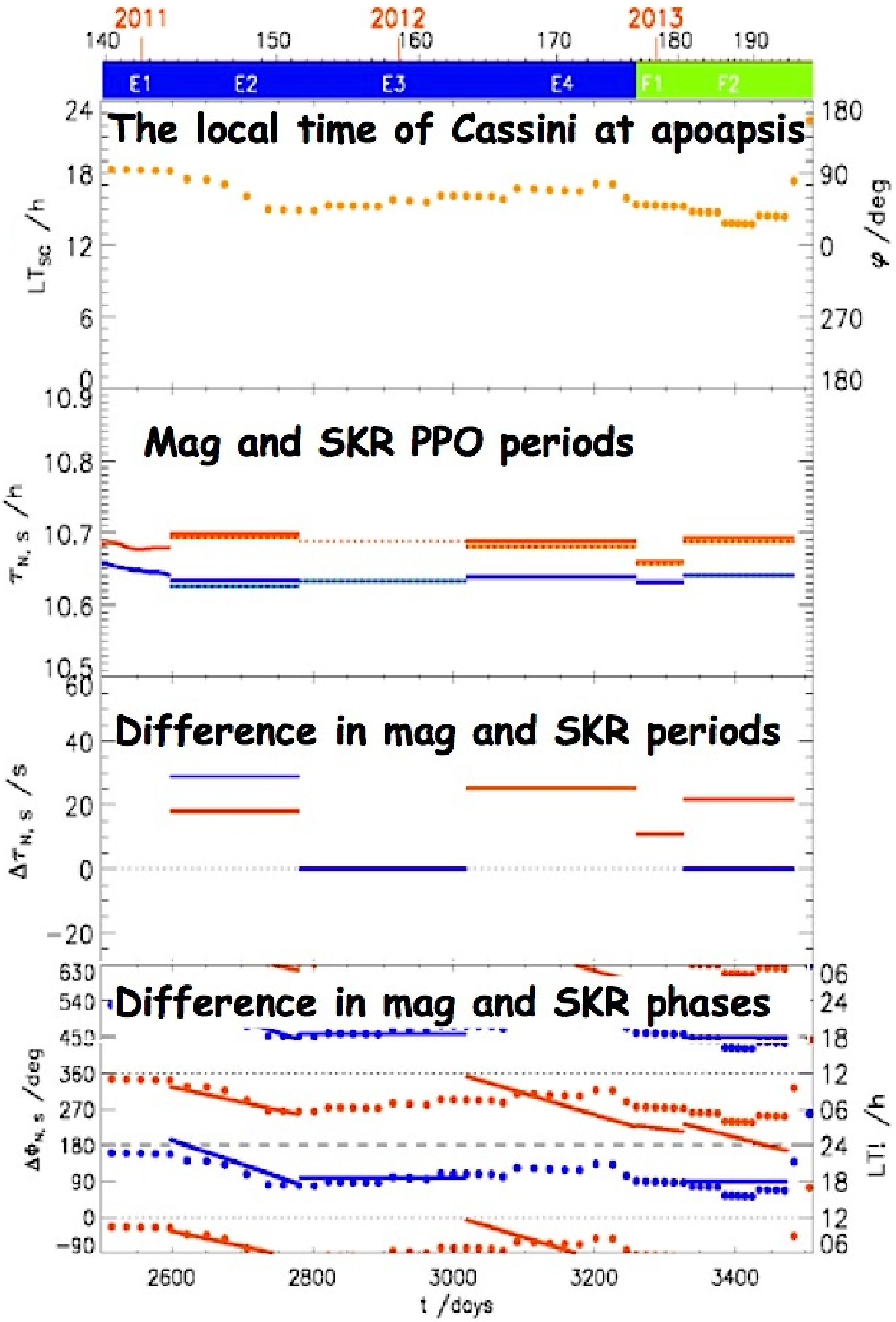
The Magnetic North and South Periodicities



The periods (top panel), N/S amplitude ratio (second from top), and phases of the oscillations (bottom two) for the Cassini mission through mid-2013. The relative amplitude 'k' is the northern amplitude divided by the southern; if less than 1, then the southern oscillations dominate. Since early 2011, there have been several abrupt changes in the behavior of the N and S oscillations, mainly in the period of the oscillations, but also in their relative amplitudes. These abrupt changes may be associated with solar activity. [Provan et al., 2014]

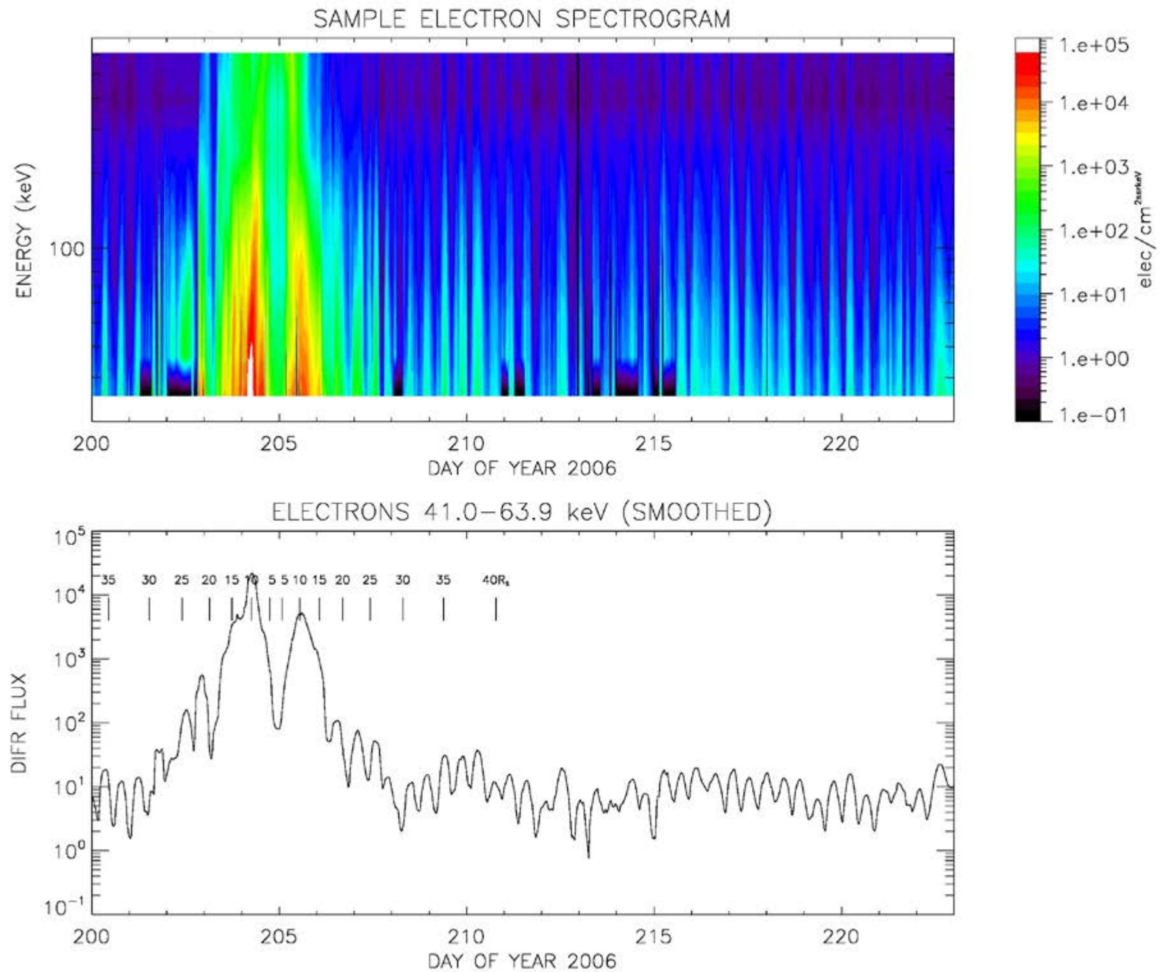
Comparison between Magnetic Field and SKR Periods & Phases Since 2011

This figure compares results from Lomb-Scargle periodograms of SKR emission with northern (blue) and southern (red) magnetic field PPO's. There is generally good agreement between SKR (dotted) and MAG periods (solid). SKR periods and intensities show abrupt jumps like the MAG periods. However, some disagreement exists post equinox (the epoch shown here) about the convergence of the north and south branches: the SKR periodicities "meet", but the MAG periods do not. Post equinox, small differences in periods are consistent with Cassini observing different SKR phases at different local times – as evidenced by the difference in phases between the MAG and SKR planetary period oscillations (PPOs) changing with local time. [Provan et al, 2014]



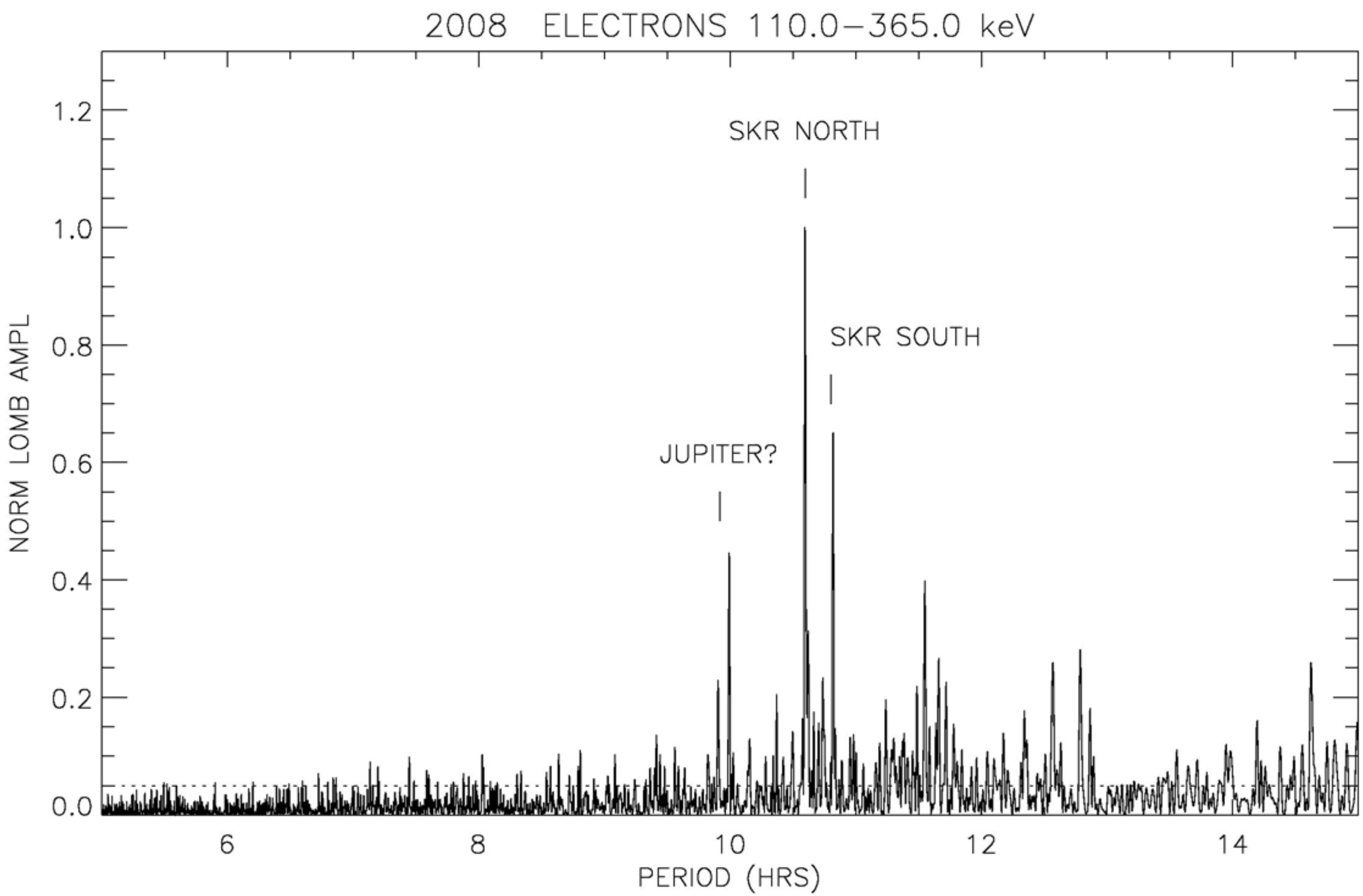
The Charged Particle Clock(s)

Sample Charged Particle Periodicities



~~All~~ Charged particles of all energies exhibit planetary-period oscillations regardless of their energies (indicating the periodicities are NOT a drift phenomenon). Some charged particles show these PPO's more clearly than the others. What does a periodogram analysis reveal?

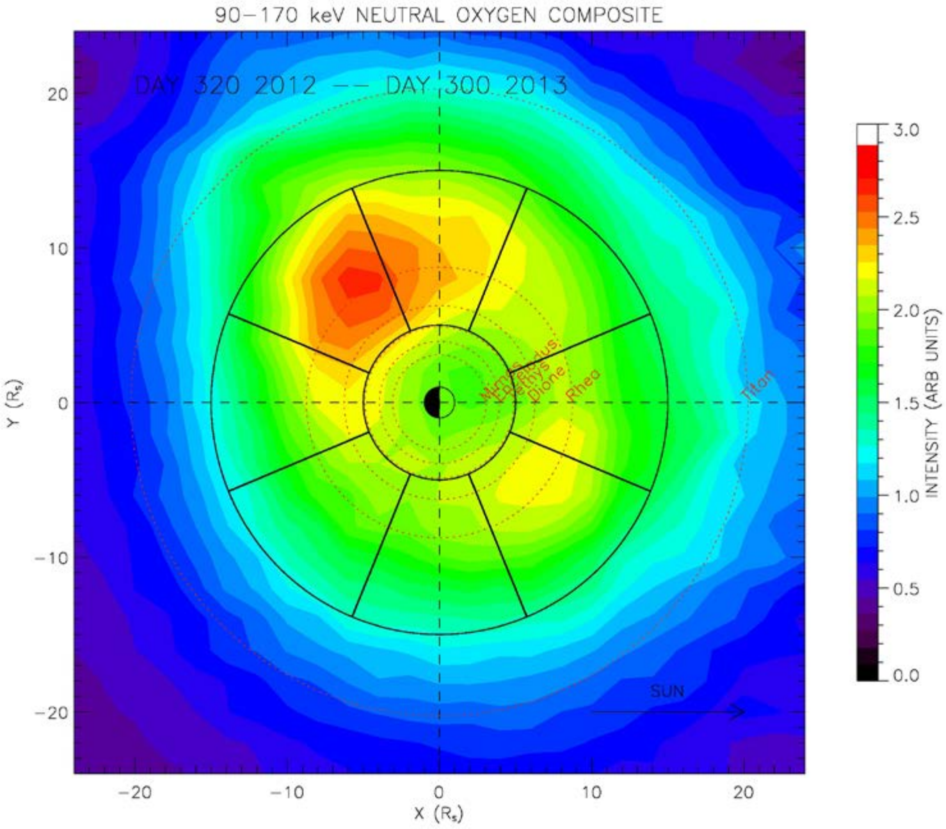
Charged Particle Periodogram for One Year

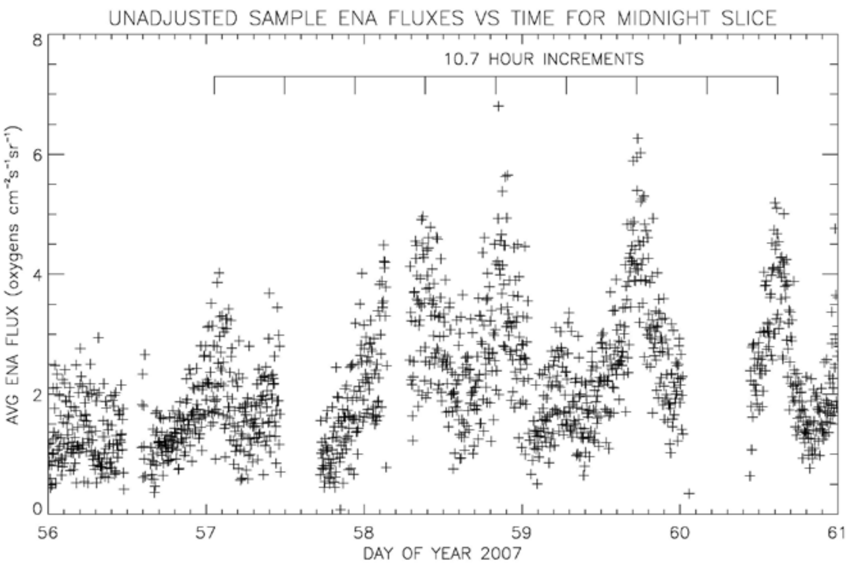


The usual north and south SKR periods are evident, but so are other periodicities that may (or may not be) relevant. For example, sometimes a period very close to that of Jupiter (9h 55m) appears. This is not so strange as it sounds, since relativistic electrons with Jupiter's period are occasionally seen in Earth's magnetosphere! If the same is true for Saturn, then we know something about the source of these particles. Notice also that other features appear in the spectrum.

The Neutral Particle Clock

Energetic Neutrals in Saturn's Magnetosphere



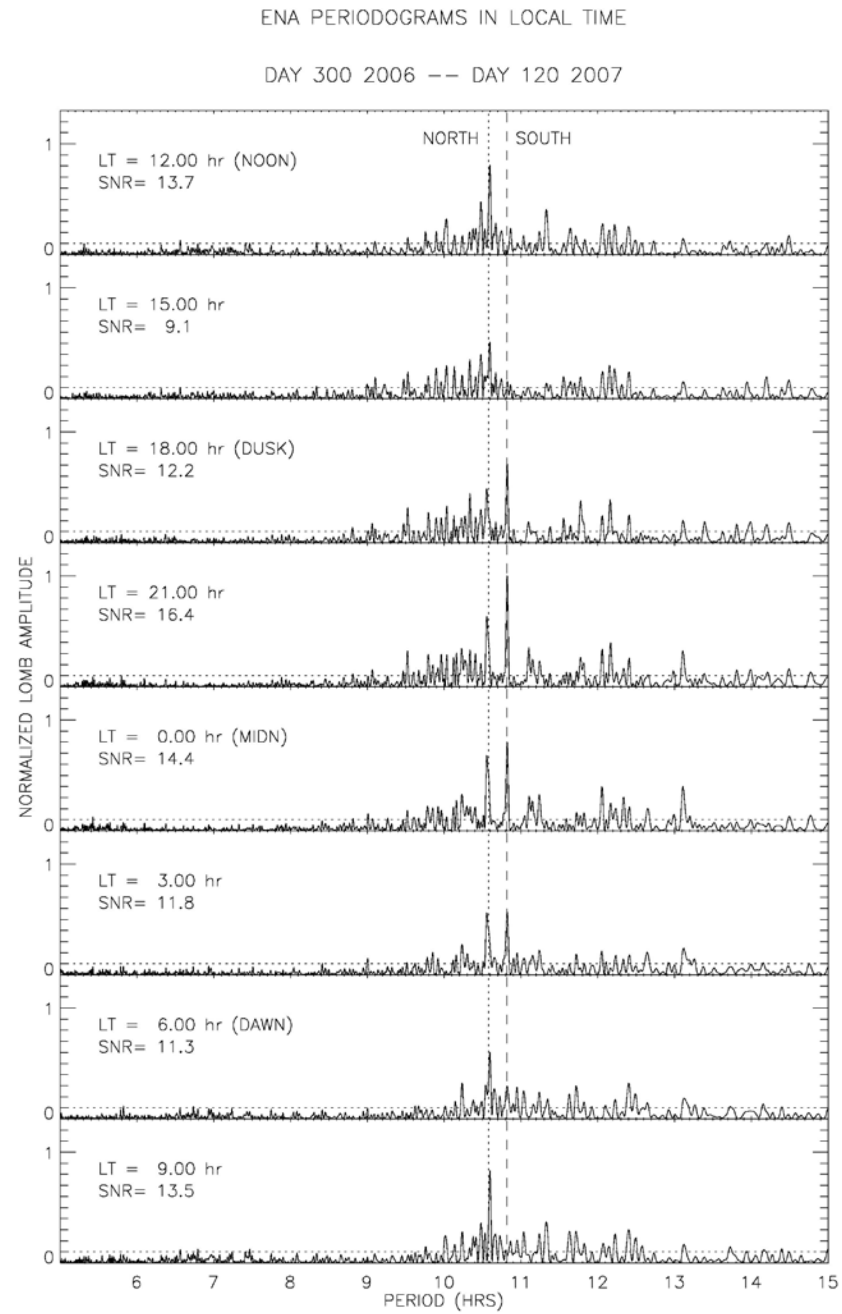


Energetic neutral atoms (ENA) originate from collisions between energetic ions (E>5 keV) and cold neutral atoms, which are abundant in the E ring. The ENA can be imaged using the MIMI/INCA detector, in a manner similar to photon imaging by UVIS or VIMS. Unfortunately, INCA has rather poor angular resolution (~8°x4° per pixel), but can clearly image the ring current in the equatorial plane of Saturn (left). By tracking the intensities in eight local time sectors (pie slices, left), one can obtain the ENA periodicities as a function of local time (right). [Carbary et al., 2014]

Local Time Dependences of ENA Periodicities

INCA can only observe local time periodicities from high latitudes (above ~20°) where its FOV can encompass the entire ring current. These periodograms are from one high latitude interval (2006-2007). The data are from energetic oxygen atoms (90-170 keV). Note the dual periodicities on the nightside, but a mono-period (at the SKR north period) on the dayside.

In other intervals, the dual periodicities may vanish altogether or may merge into a single period or may even shift to a different period (a 10.3 hour dayside period has been observed). [Carbary et al., 2014]

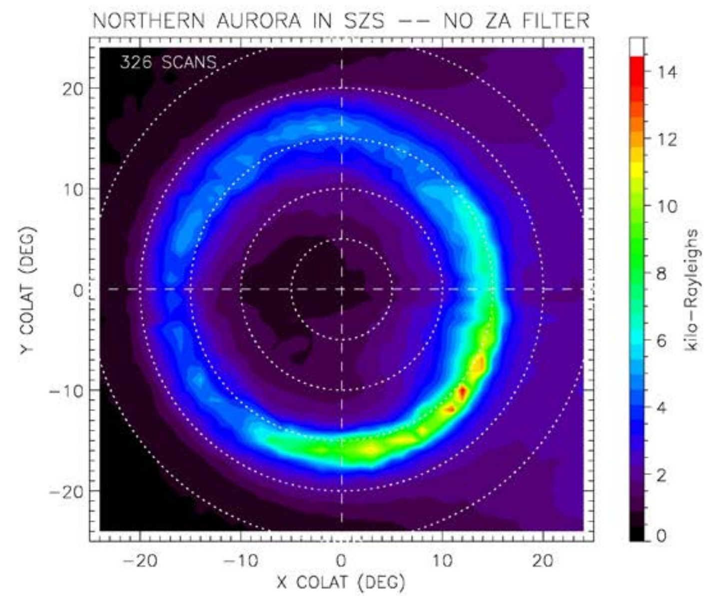


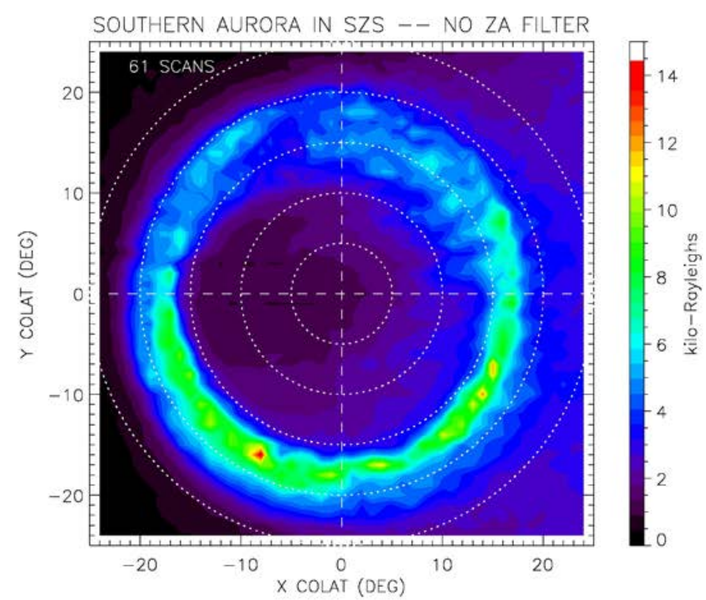
The Auroral Clock

Saturn’s Aurora

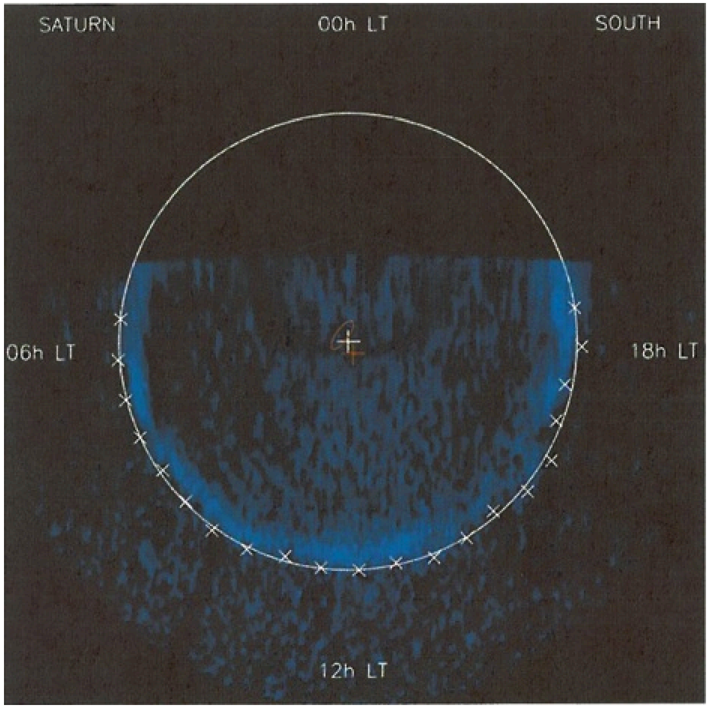
Like all magnetized planets, Saturn has northern and southern aurora. The aurora are located between ~10° and 20° co-latitude from the respective poles, and the northern “oval” is somewhat smaller in diameter than the southern because of the slight offset of the main field of Saturn. The aurora originates in the ionosphere at ~1100 km, is usually brighter near dawn, and shows features reminiscent of dayside merging, Kelvin-Helmholtz vortices on the flanks, etc. Auroral features (or “blobs”) **do** rotate in the sense of planetary rotation, but at a rate well below nominal corotation (that is, their rotational periods are ~50-60% longer than ~10.7h). Therefore, auroral blobs **cannot** be used to define a period (or a clock).

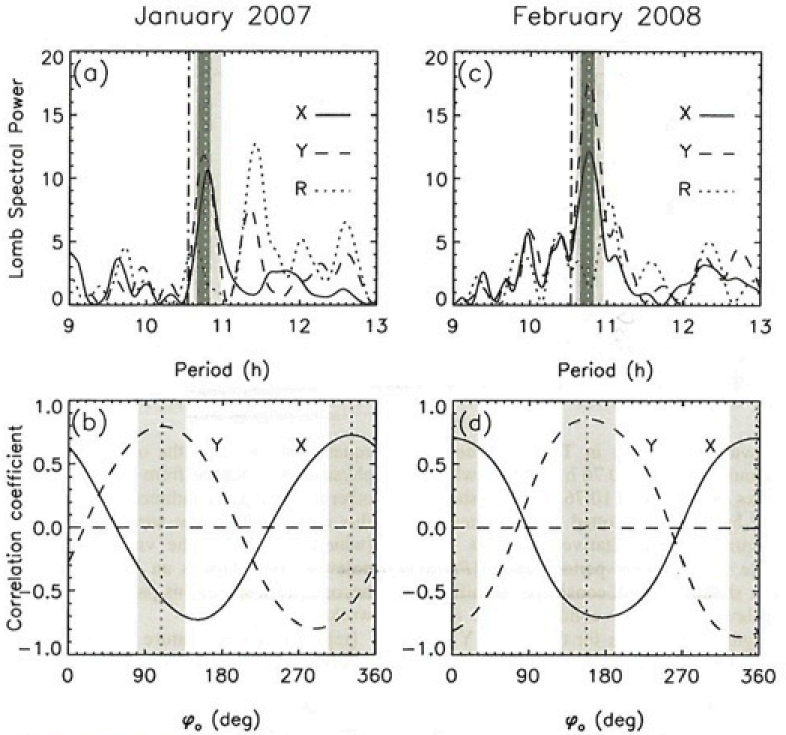
But there are other ways to define a clock….
[Carbary, 2012]





Oscillation of Aurora Center as a Clock

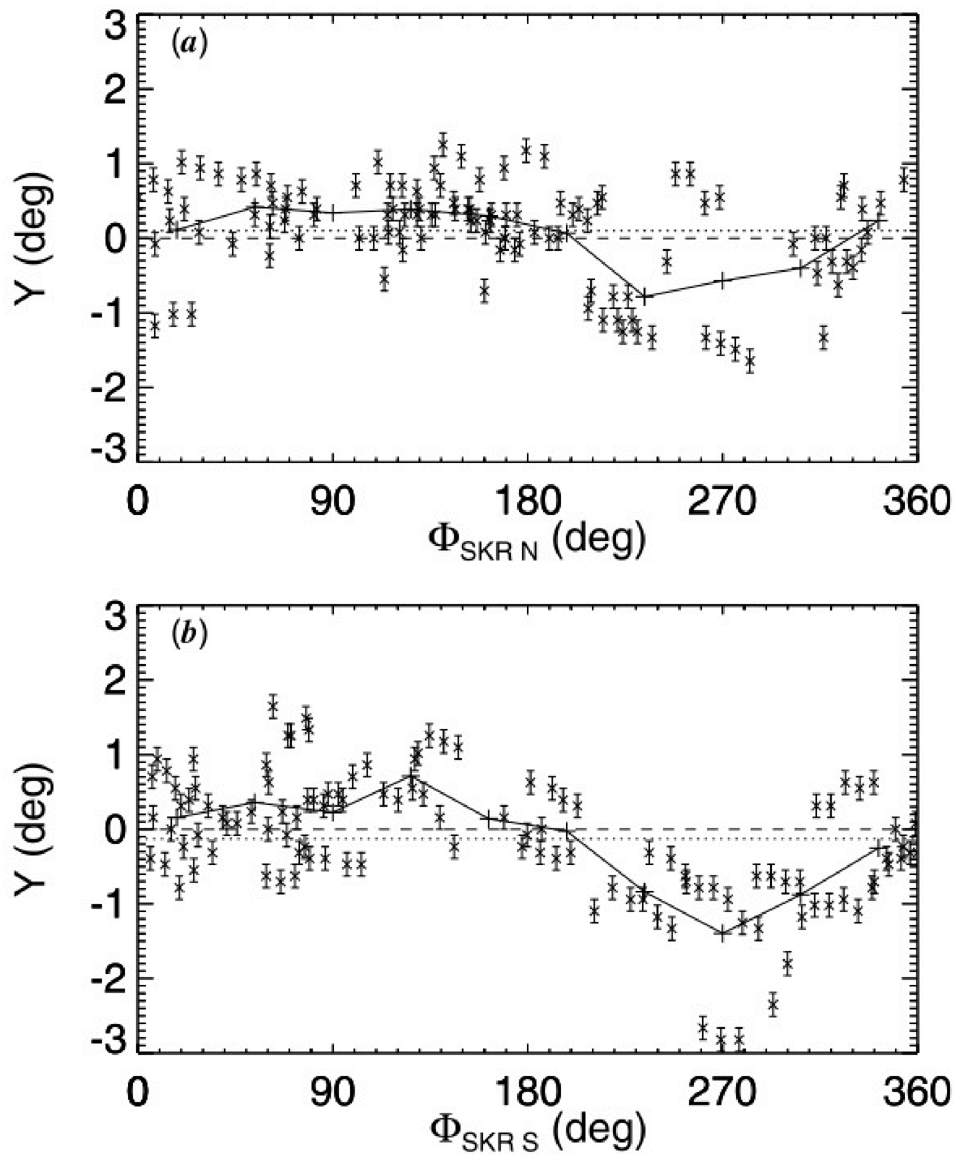




The equatorward boundary of the oval (here, the southern oval) is defined and fitted to a circle for each image (HST UV images are used in this exercise). The {X,Y} centers of the oval are determined, giving a time series X(t) and Y(t). These coordinates are analyzed using a Lomb periodogram and the SKR (south) period emerges! This study [Nichols et al., 2008] was carried out before the SKR north and south periodicities were separated, but since this is the southern aurora, the southern period is appropriate.

Dual Aurora Clock?

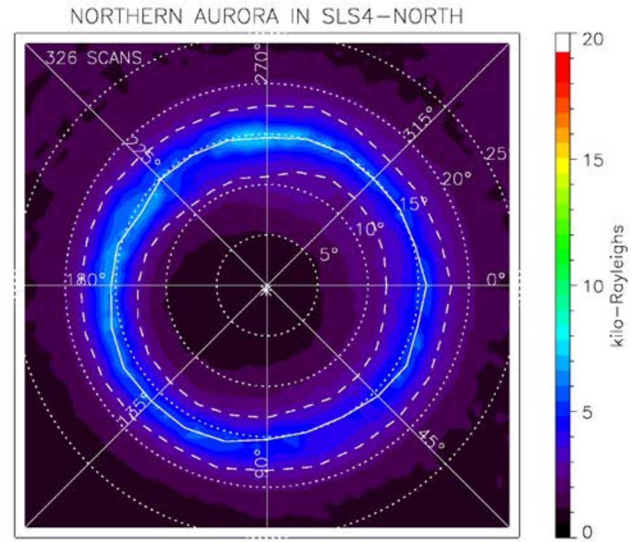
Does the aurora exhibit a dual periodicity? That is, does the northern aurora rock back and forth with the northern SKR period and the southern aurora with the southern SKR period? Claims have been made to that effect. Organization of the auroral circle centers in SKR phase (N or S) is murky at best. In any event the oscillation of the oval is very small ~1°. The dawnside aurora power also exhibits a statistically significant modulation at the SKR period.
[Nichols et al., 2010]

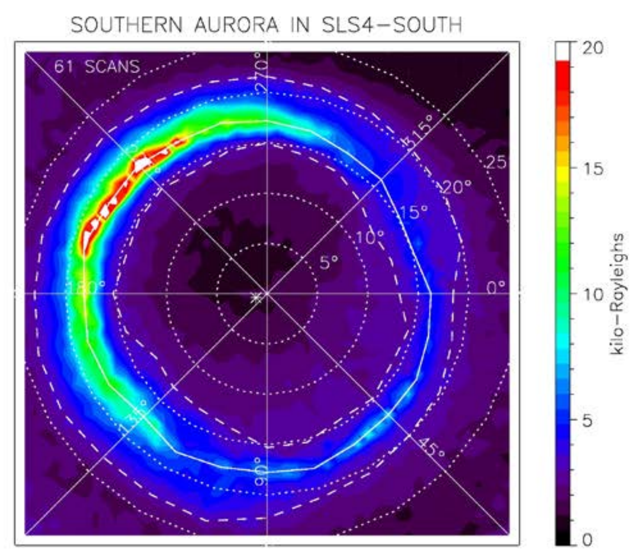


Auroral Morphology in SKR Longitude

A final note on the auroral clock: if such a clock really exists, then one may reasonably assume it would be organized in a longitude system based on the SKR clock. The SLS4 system was devised to accommodate both the northern and southern SKR clocks. These composites, from two years of auroral observations by Cassini UVIS, show how the aurora would appear in the SLS4-North and SLS4-South longitude systems. (The solid lines indicate the center of the oval, and the dashed lines indicate its 5 kR boundaries.) Clearly, the **southern** auroral FUV emissions do concentrate near ~225° SLS4S, but there is much less organization in the north.

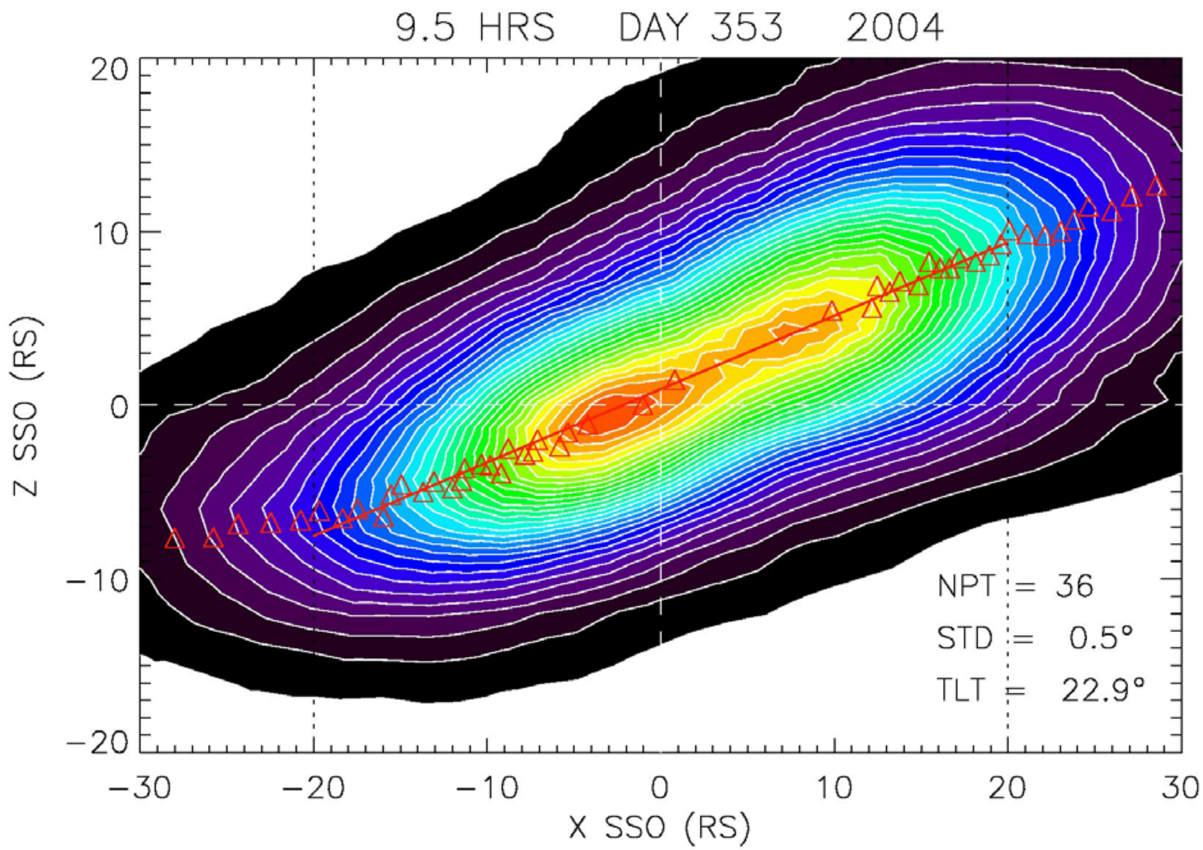
If you compare this to the first auroral intensity map in local time, you see that the local time variations are just as strong as these longitudinal variations.
[Carbary, 2013]





Magnetospheric Morphology Clock

Clocks Related to Morphological Features



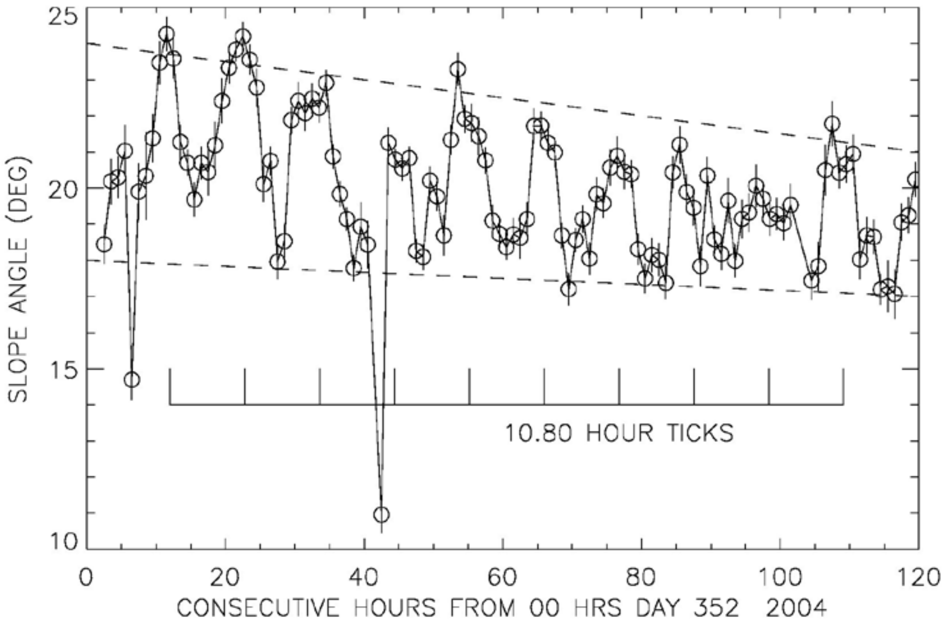
First consider the plasma sheet, which can be defined as the center-line of ENA emissions seen edge-on. The centerline has a certain slope (in a Sun-referenced coordinate system). This slope, or tilt angle, sometimes (not always) can be seen to physically rock up and down. “Flapping” motions of the magnetotail in charged particles and magnetic fields are also observed to be periodic. [Carbary et al., 2008]

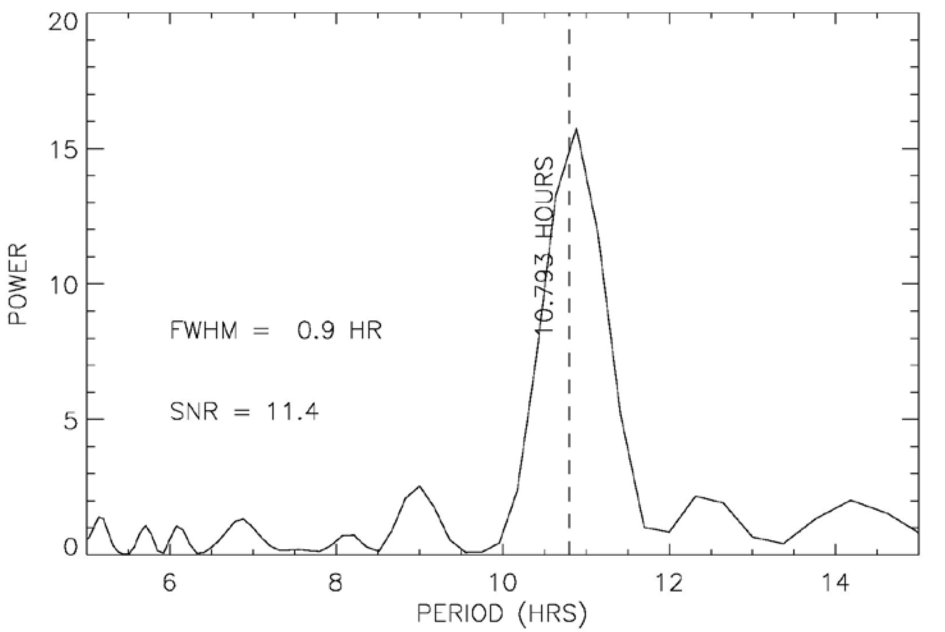
Plasma Sheet Clock

The plasma sheet clock refers to the periodicity in the tilt angle that is sometimes seen in edge-on ENA images.

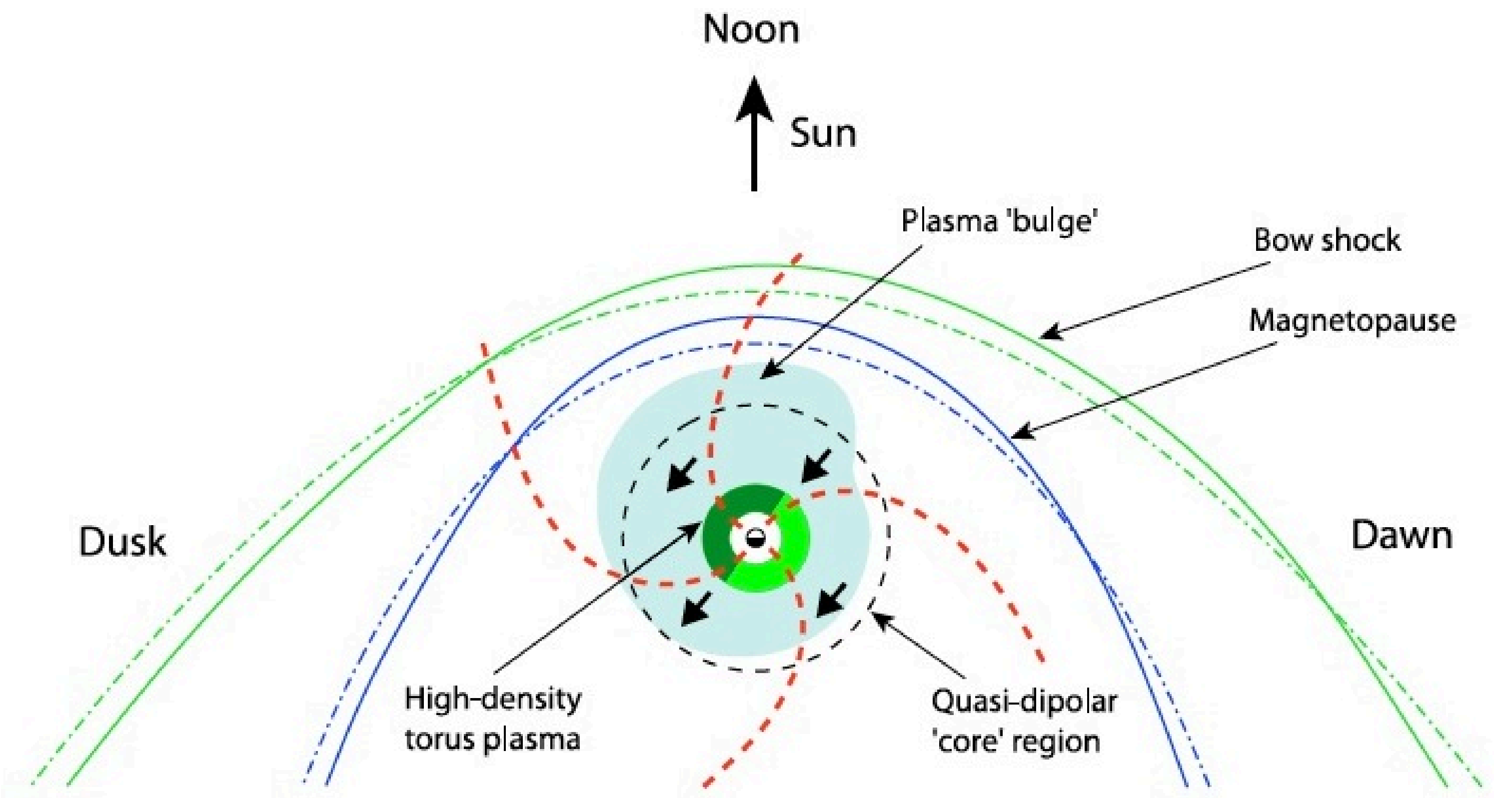
Top panel shows variation in this angle over several days. Note that the tilt angle has a decreasing amplitude envelope.

Bottom panel shows the period of this clock from a periodogram analysis. The period is very close to that of the SKR-south period (10.8 hours at this time).
[Carbary et al., 2008]





Summary of Magnetospheric Clocks



Analyses of magnetic field observations also report periodic motions of the bow shock and magnetopause boundaries at the SKR period(s). These motions are interpreted in the framework of the "cam" wave generated in the inner magnetosphere and propagating outwards to the magnetopause and bow shock. [Arridge et al., 2011; Lamy et al., 2012]

The Ring Clock

The Spokes in Saturn's Rings

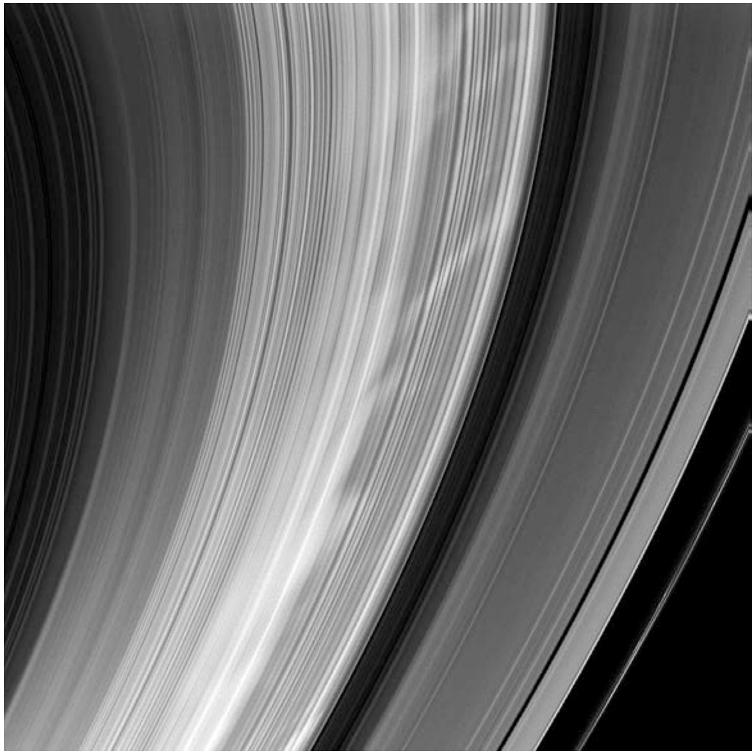


Photo from NASA Voyager 1 archive http://photojournal.jpl.nasa.gov/catalog/PIA11452

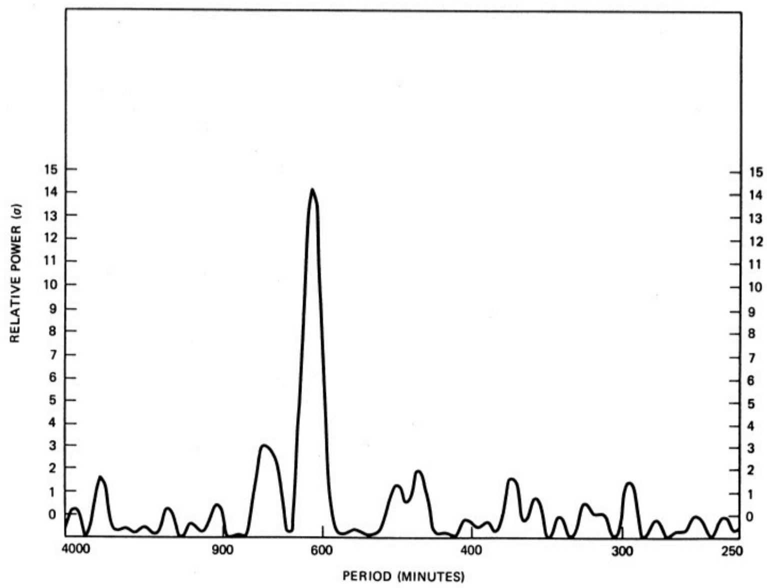
Voyager 1 and 2 discovered near-radial features in the B ring. Spokes are typically 10 000-20 000 km long, observed over widely varying phase angles, and exist in that part of the B ring that includes synchronous orbit (Kepler period = corotation period). The spokes themselves do **not** move at corotation speed, but (mostly) at Keplerian speed. They are most frequently observed in the morning ansa. They are sheared away from the radial in the trailing sense. Spokes are thought to consist of micron-sized particles elevated above the ring plane.

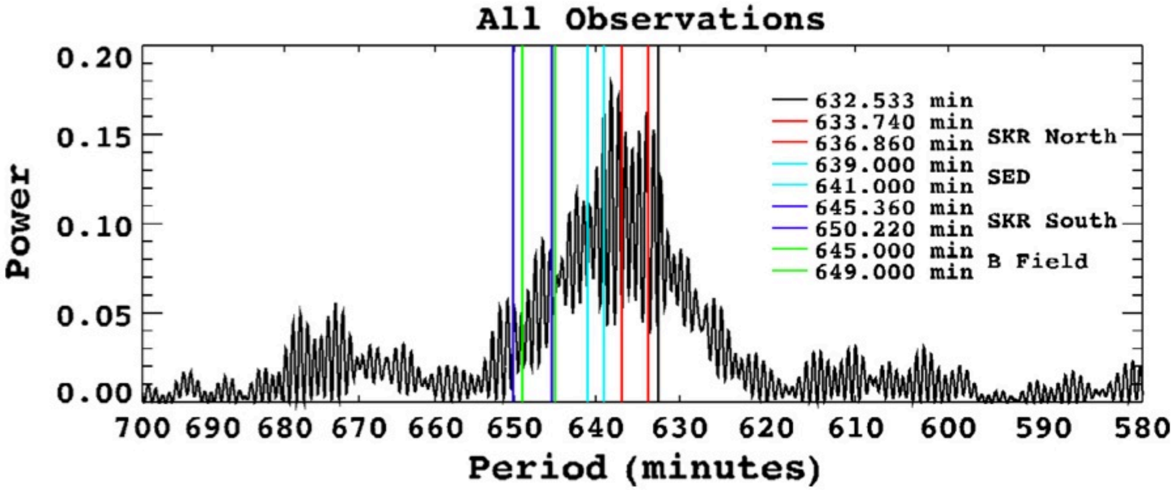
Spoke Activity as a Clock

From 5.5 days of Voyager observations (top), spoke activity — number and contrast of the spokes, not speeds — was subjected to a Fourier analysis, and a period of 621±22 min = 10.35 hr was clearly delineated.

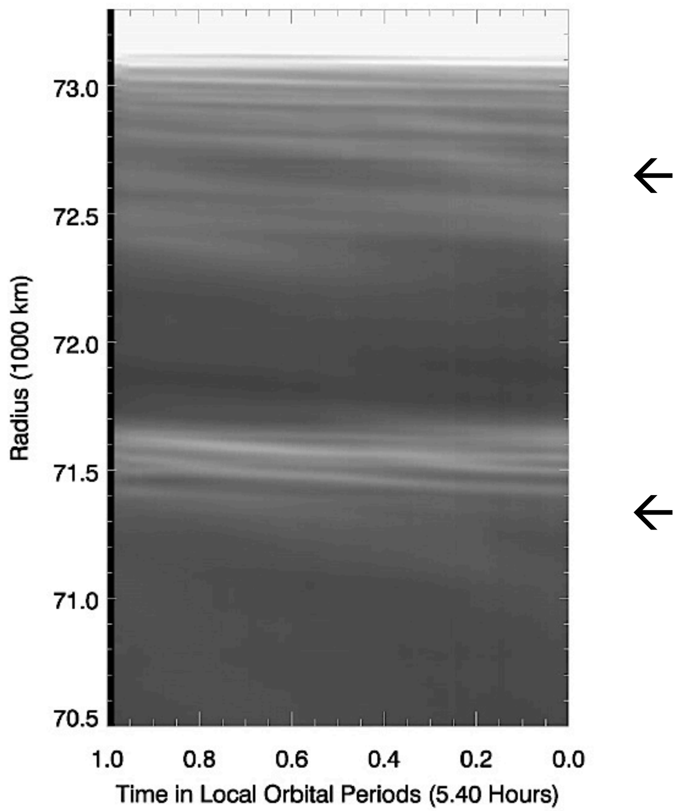
More recent work on spoke periodicities (bottom), show that the periods are close to those of the SKR and MAG periods.

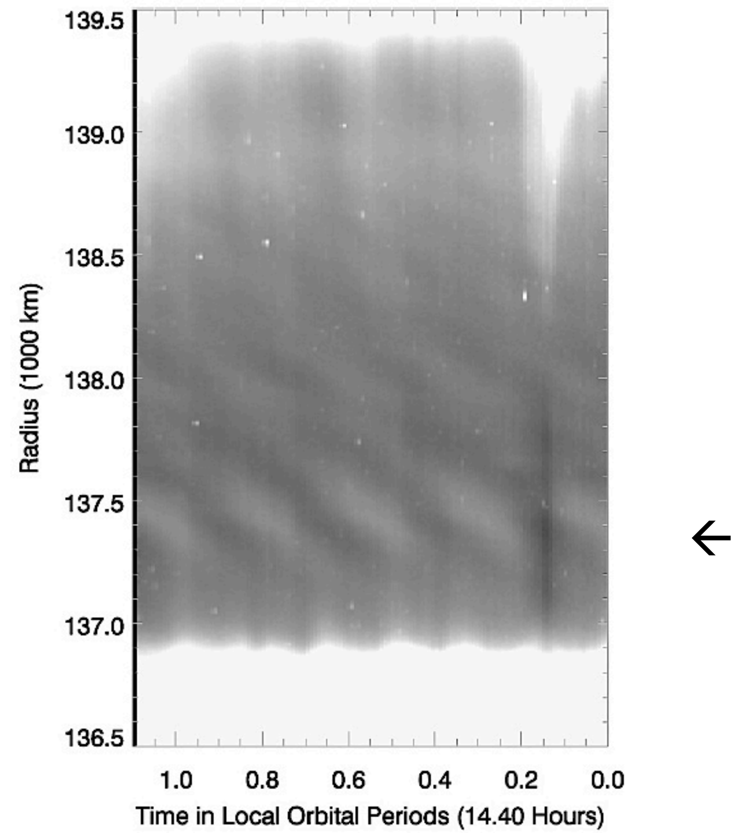
Porco and Danielson (1982, top)
Mitchell et al. (2013, bottom)





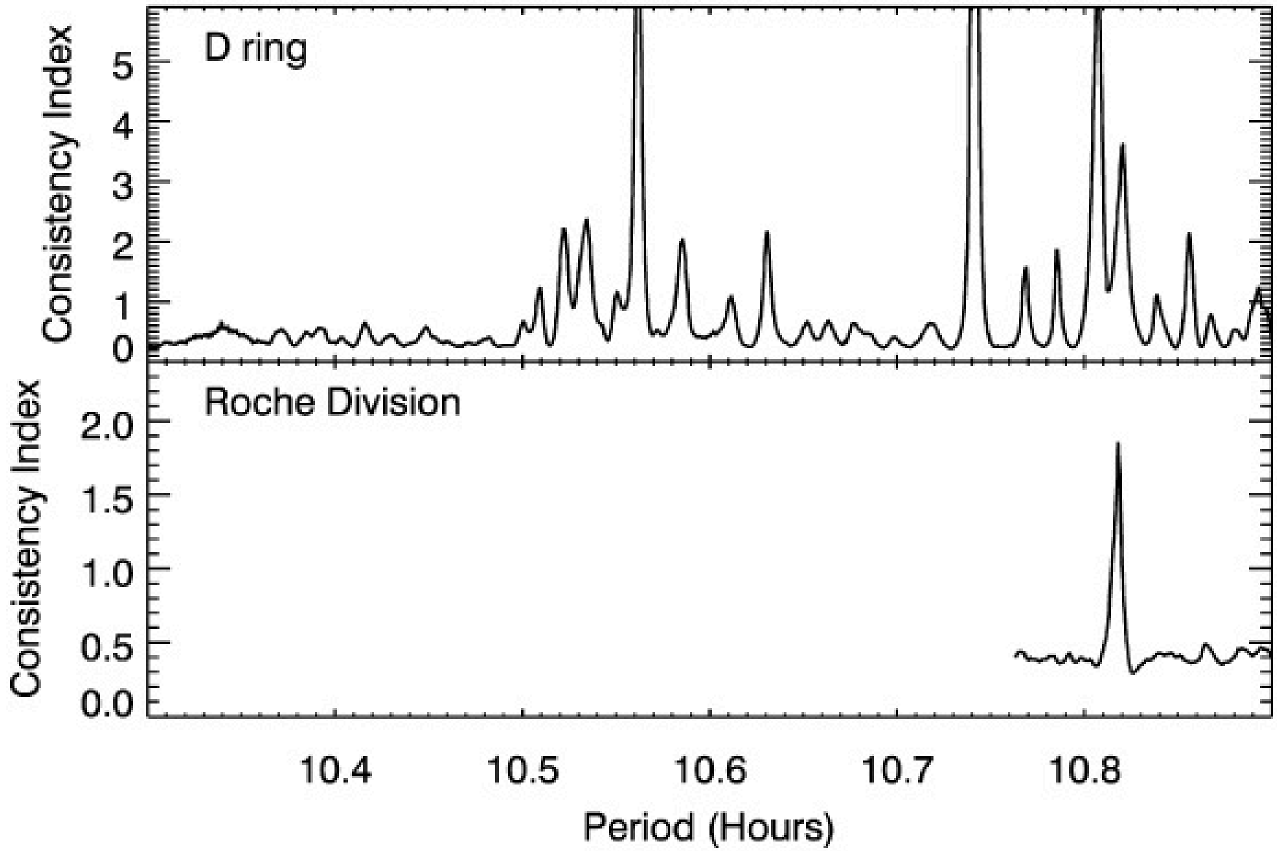
D-Ring and Roche Gap





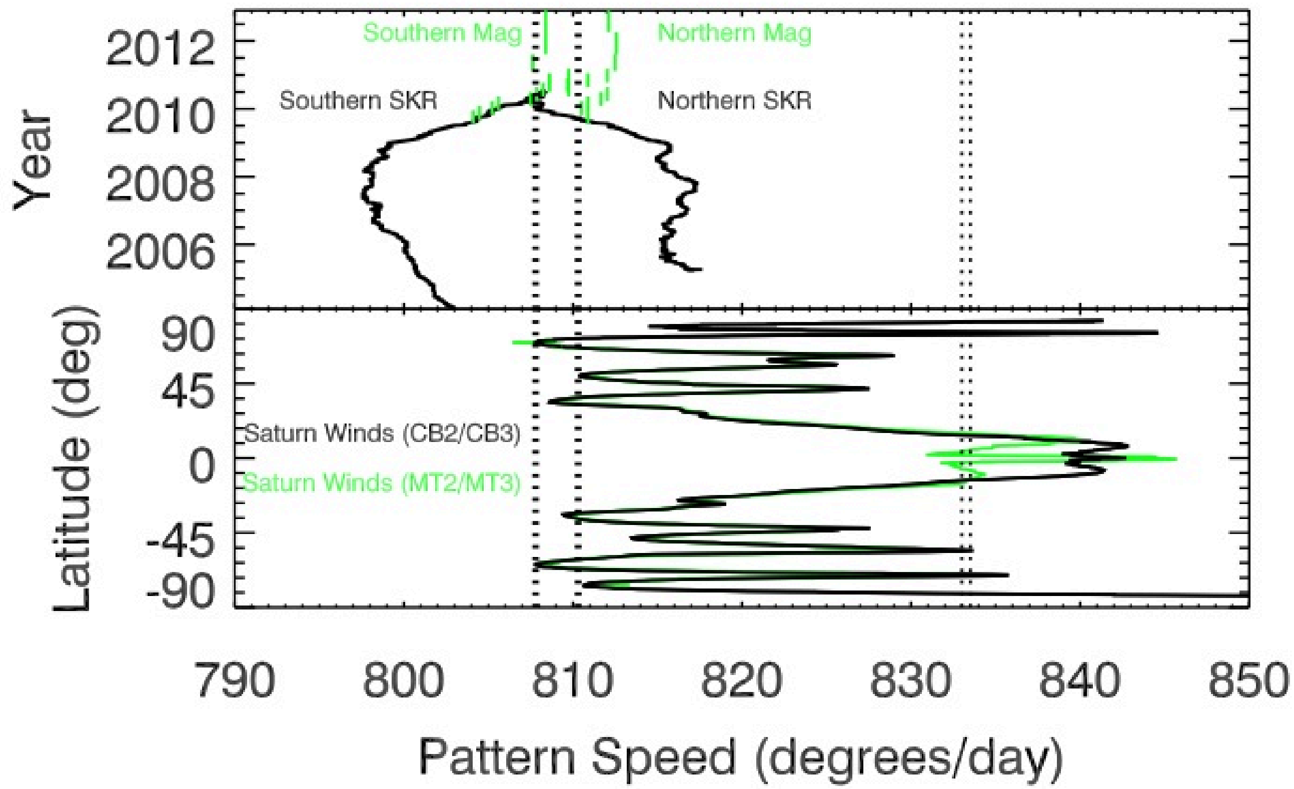
Periodicity has also been glimpsed in Cassini "maps" of the D-ring (left) and the Roche gap (right). These maps are constructed from azimuthal profiles at the radii indicated, organized by the local orbital period. The arrows indicate where (periodic) structures may be detected. [Hedman et al., 2009]

Ring Periodicities



The azimuthal maps may be converted to periodicities using a statistic analogous to a chi-square for different periods. This statistic is called a “consistency index” for a given period. The periods represent rotational speeds of the features. Several periods appear in the consistency index for the D ring, and one strong one in the (limited) spectrum of the Roche division. [Hedman et al., 2009]

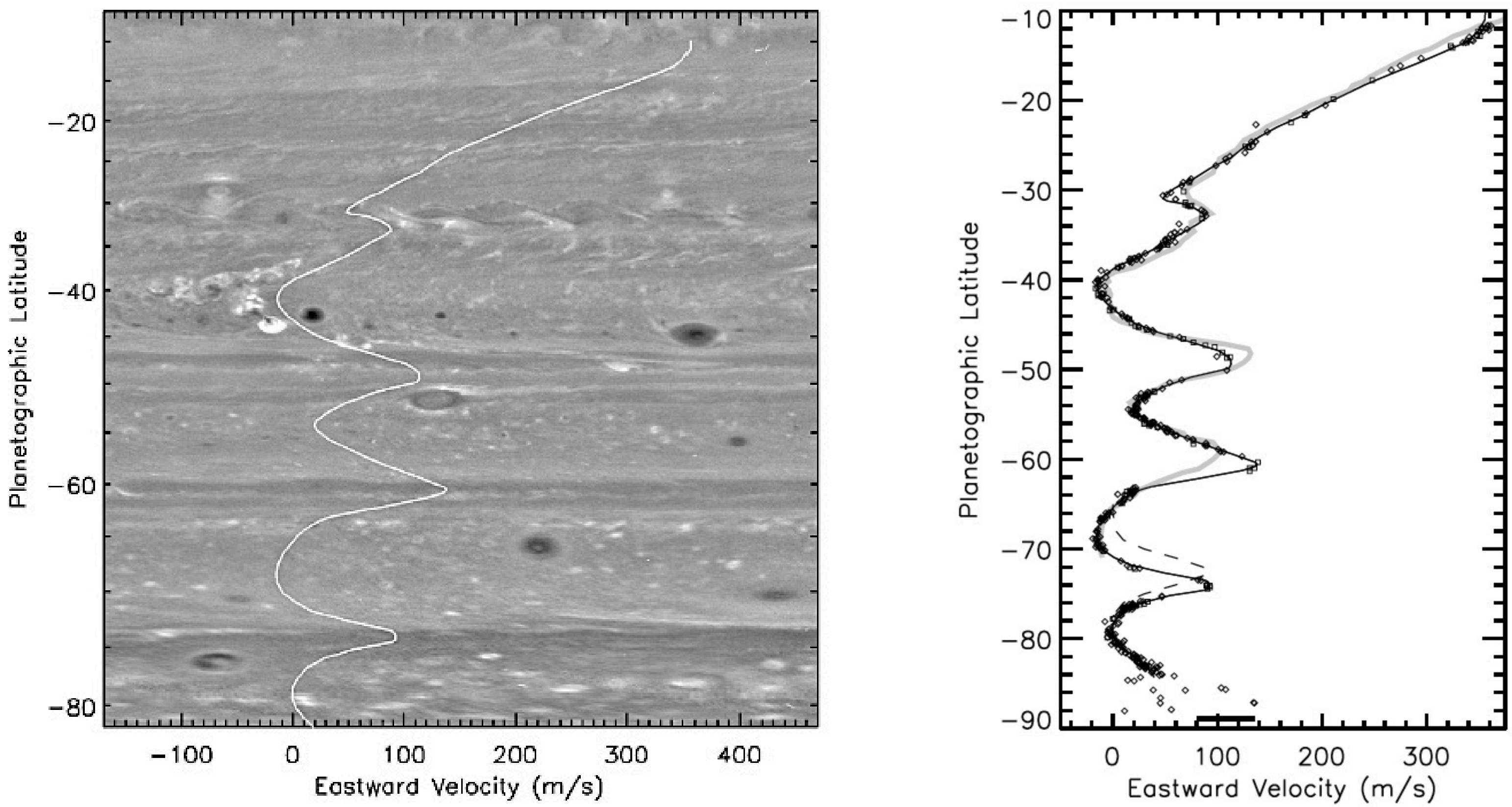
Multiple Ring Periodicities



A recent study of waves in Saturn's C ring has found wave-like patterns whose speeds have periods between 10.365 hr and 10.698 hr (dotted vertical lines above). These pattern speeds are very similar to the zonal wind speeds and to the SKR/MAG "speeds." One of the waves appears to be a one-arms spiral pattern. [Hedman and Nicholson, 2014]

The Atmospheric Clock

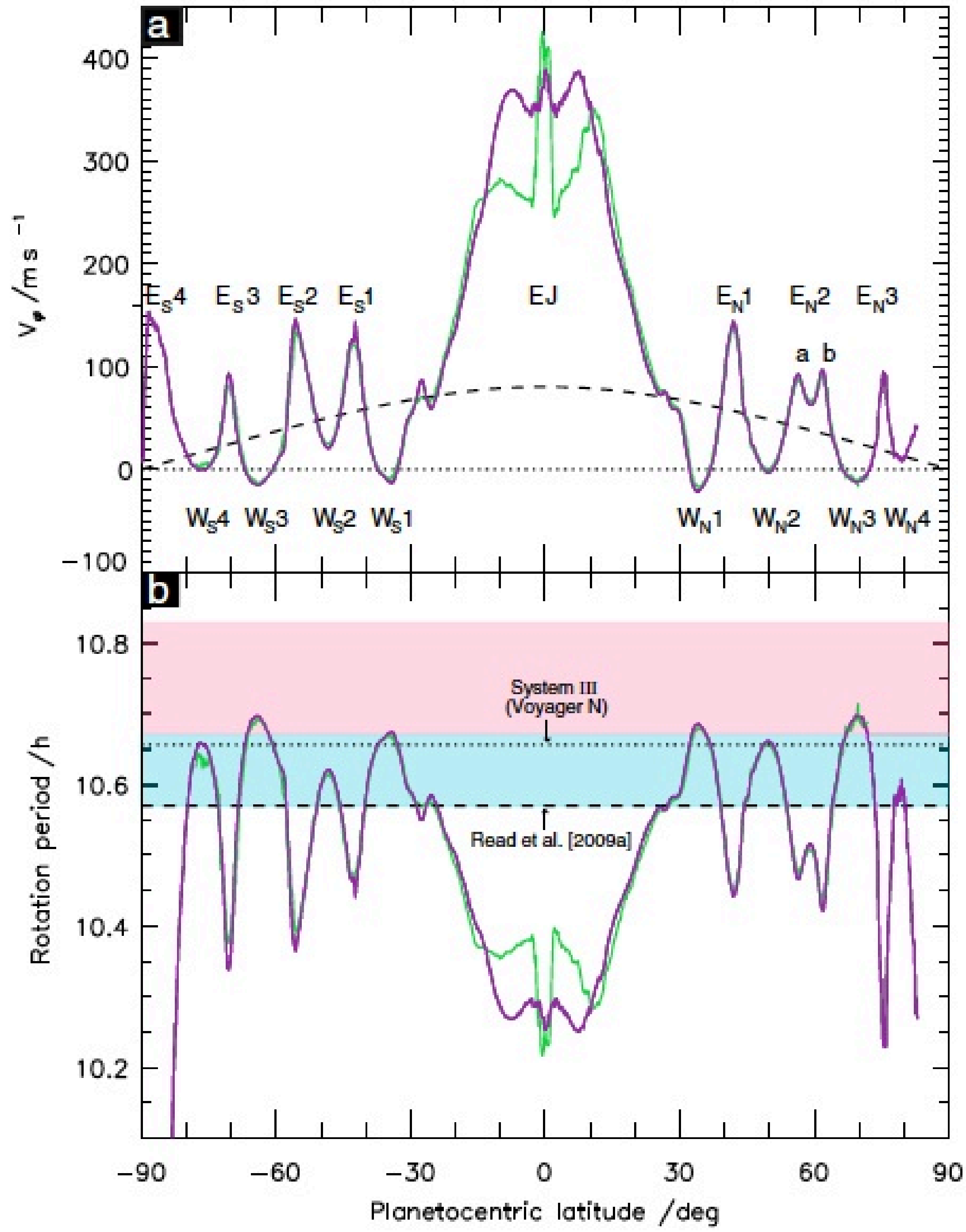
Measurement of Cloud Motions



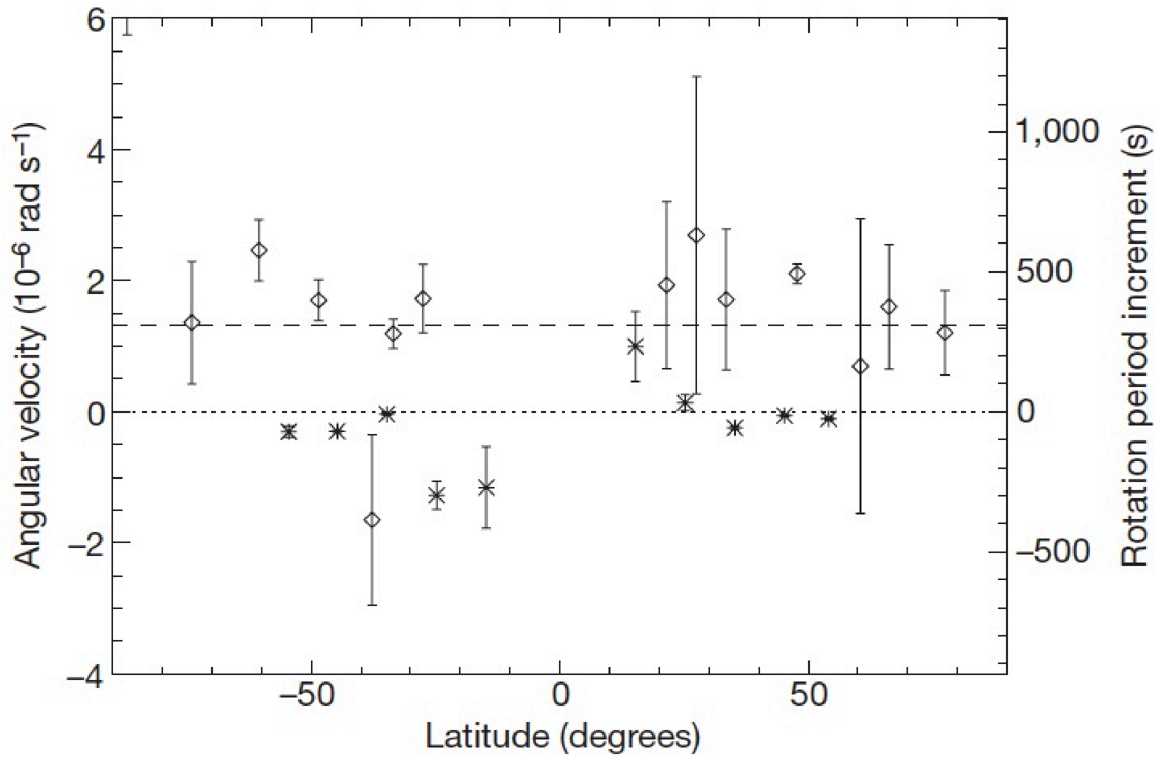
While Saturn's winds are generally considered unreliable for measuring the planetary period, there are some interesting coincidences about them. [Vasavada et al., 2006]

High-Latitude Wind Periods

First, if you convert the wind speeds to inertial period of the winds, you find periods suspiciously close to the SKR periods. This observation led workers to initially suspect upper-altitude winds in the polar regions might be driving some ionospheric anomalies to which the radio periods might be attached. [Cowley and Provan, 2013]

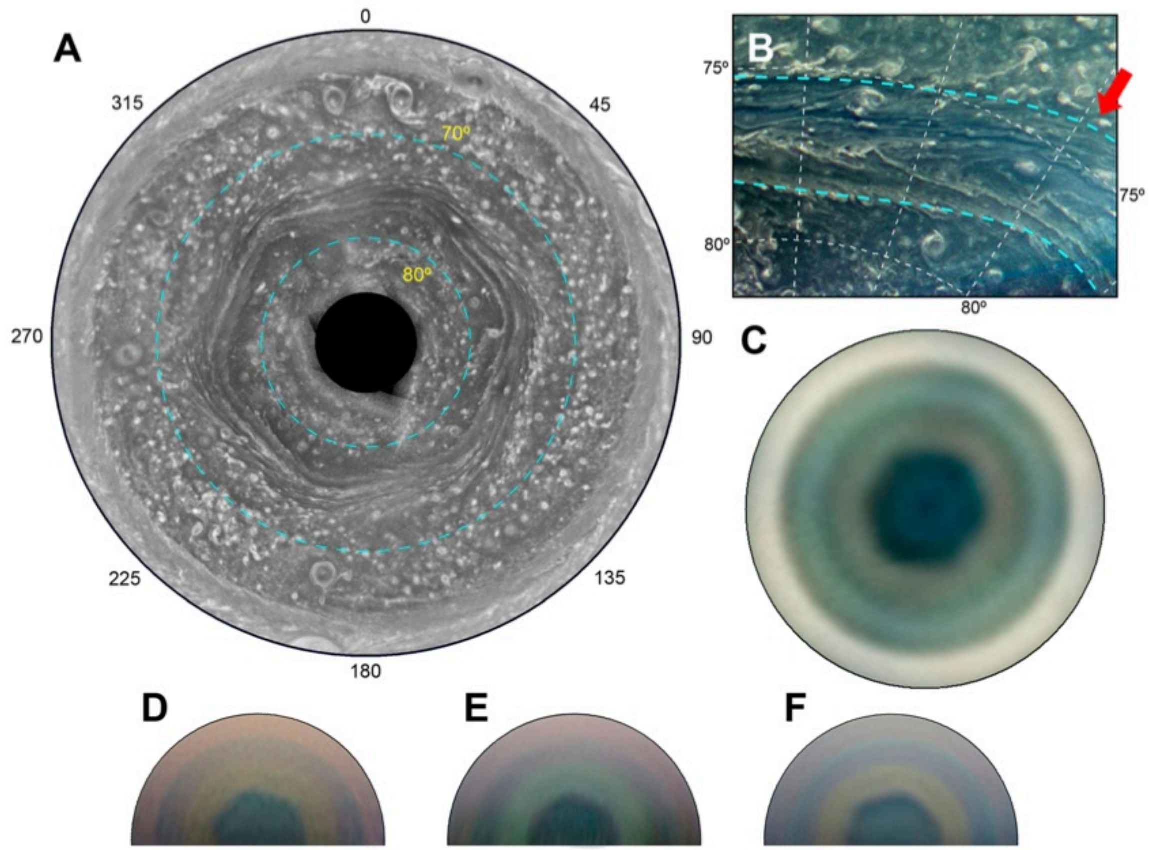


A Potential Vorticity Clock



The bulk rotation period for Saturn (diamonds) is here based on analyses of the distribution of zonally-averaged potential vorticity, obtained from cloud speeds, using a stability theorem in its limiting case. A similar analysis for Jovian winds (asterisks) gives excellent agreement with the known period of that planet. The potential vorticity analysis gives a period of 10.5703 hours (10h 34m 13s ± 20s) for Saturn. [Read et al., 2009]

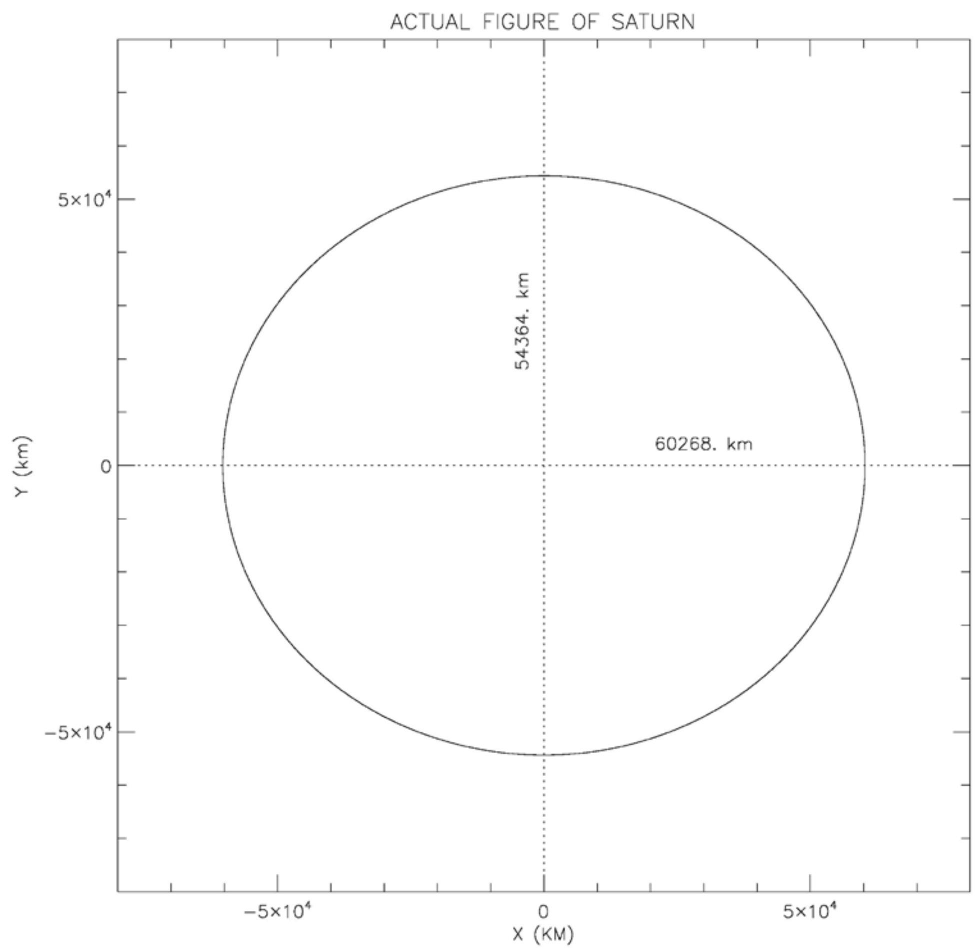
The Hexagon Clock



The northern polar hexagon was originally thought to rotate at the planetary period. However, when you plot its vortex locations in SLS longitude, you notice that it drifts linearly. Going one step further, you can find the rotation period of the hexagon is 10.6564 hours (10h39m23s). The polar hexagon is interpreted as a stationary trapped Rossby wave extending deep into the atmosphere. [Sanchez-Lavega et al., 2014]

Internal Features Clocks

The Gravity Clock



Because Saturn is **very** oblate, presumably owing to its spin, one might expect to learn something about its rotation rate from its gravitational structure. (You could do the same for all the other gas giants).

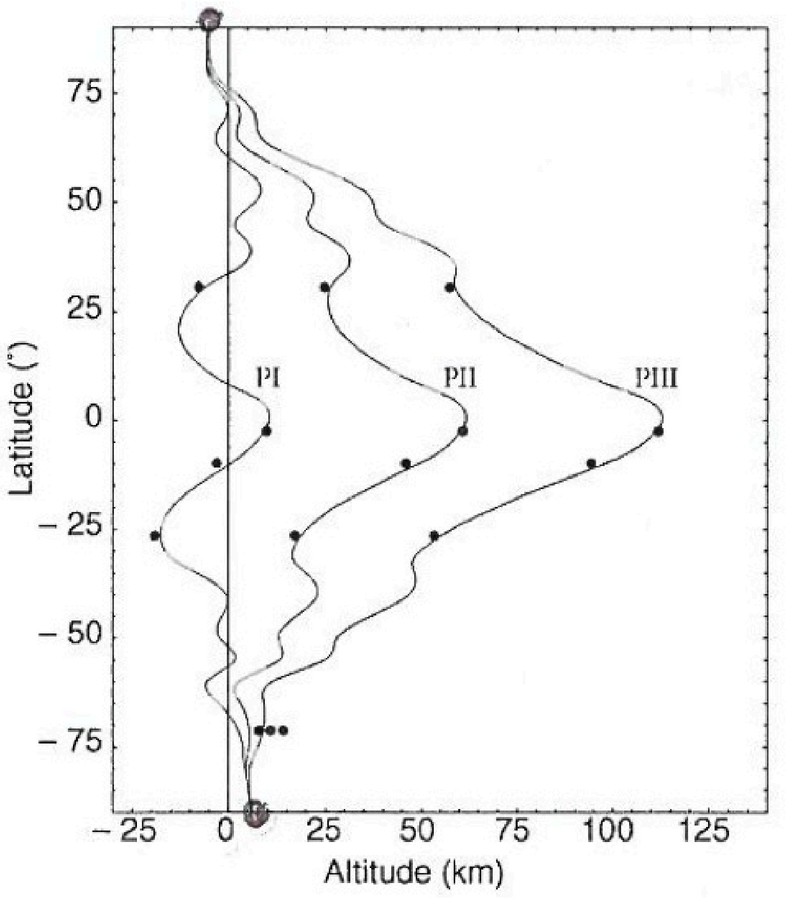
Interior Models and the Spin Rate

Given some model for the interior of Saturn, one can compute (for example) the 100mb isobaric pressure above a reference geoid. Several authors have done this for different spin rates. Here, the isobaric surfaces are shown for three different models with three spin rates:

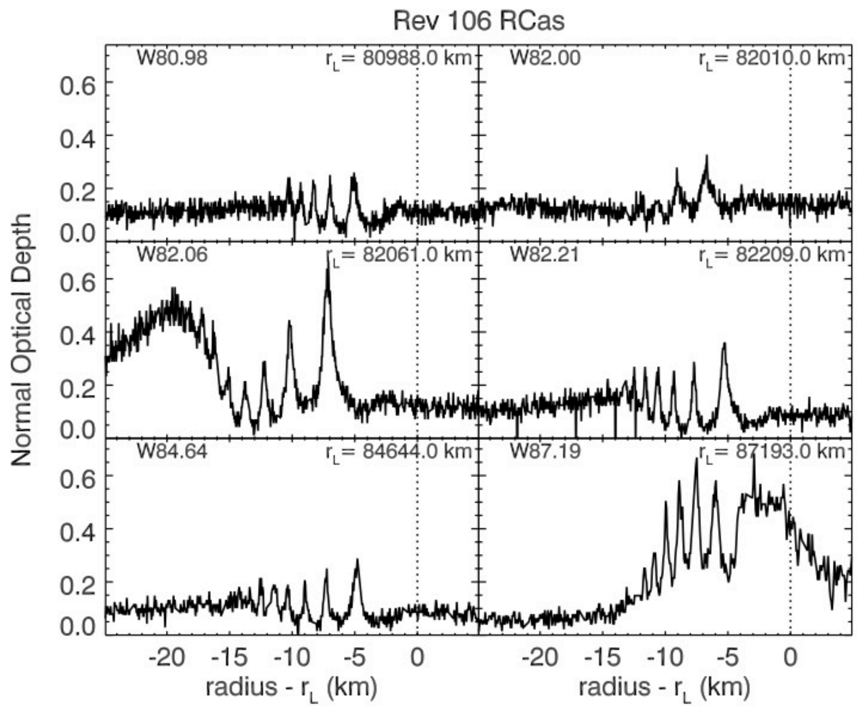
PI = 10.5431 hours
PII = 10.5931 hours
PIII = 10.6431 hours

The dots represent radii measured by Voyager and Pioneer occultations.

The problem is that accurate models rely on accurate measurements of the spin rate. You should really only use this approach if you have an accurate model of Saturn's interior. Furthermore you don't know exactly how deep the winds extend, which influences the shape you fit. [Anderson and Schubert, 2007]



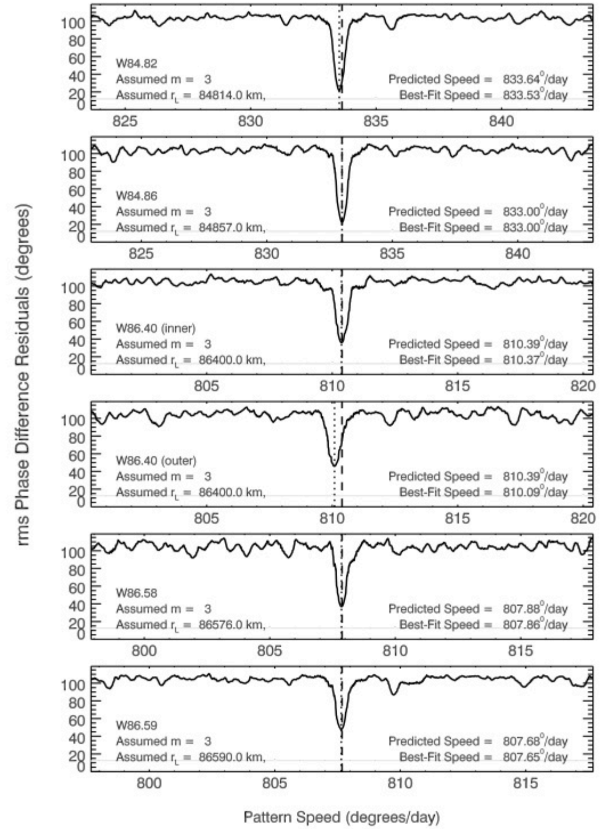
Effects on Rings : Kronoseismology Clocks



In some parts of C ring, inwardly-propagating waves have been discovered using the occultations of stars by the ring. Because they are inwardly propagating, they cannot be caused by Saturn's moons, but must be caused by the internal structure of Saturn. They may be associated with normal mode oscillations in the interior. In principle, the oscillation frequency of each normal mode depends on a different combination of the planet's density and rotation rate, so with multiple modes one should be able to constrain both these parameters. The problem is that we have detected multiple variants of each mode, which was not predicted by standard models— and that problem has not been solved out yet. [Hedman and Nicholson, 2013]

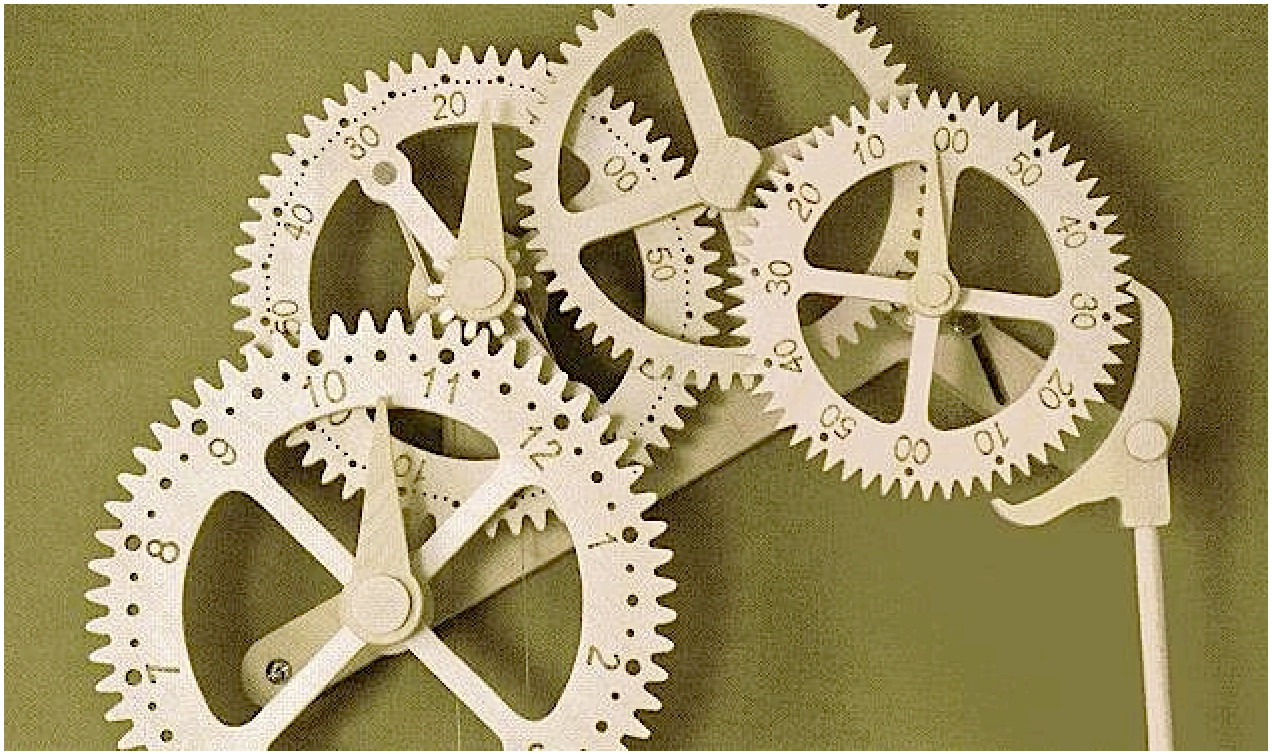
Mass Con Effects

Ring measurements may be able to determine the rotation rate, especially if there are "anomalies" ("mass cons") in the deep interior, which there actually seem to be. Several waves in the C ring can be tied to these anomalies, which have rotation periods close to those of Saturn's winds. But there are five (5) rotation periods, not one! The speeds range from 807 to 835 degrees per day (periods between 10.71 hours and 10.35 hours). Figure at right shows how least squares residuals from wave fits as function of pattern speeds. Bottom table compares these speeds to other pattern speeds. [Hedman and Nicholson, 2014, submitted].

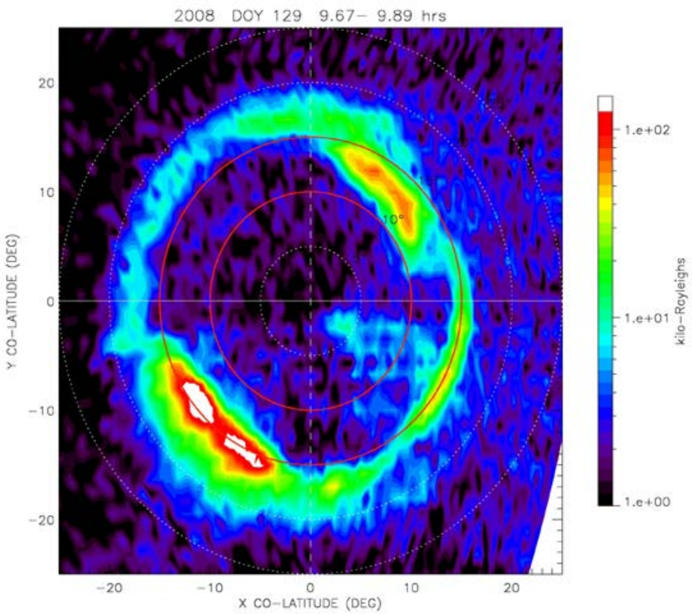


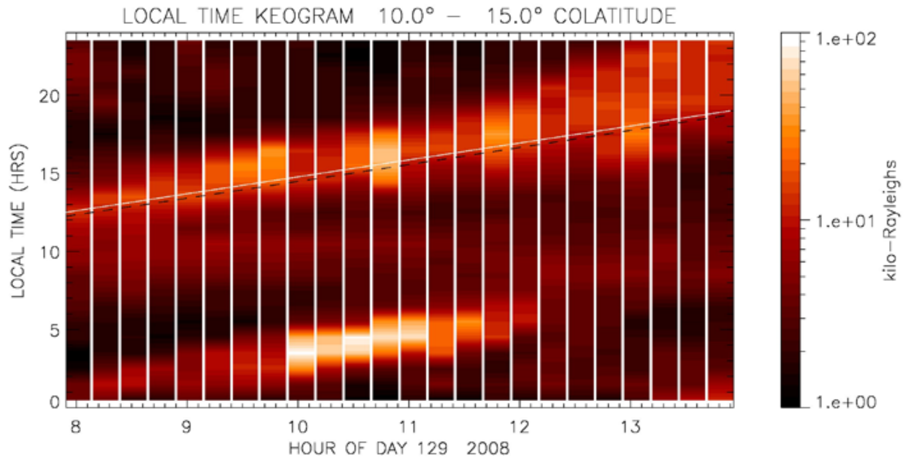
Phenomena	Rotation Period	Pattern speed	Reference
W84.82	10.365 h	833.5°/day	This work
W84.86	10.372 h	833.0°/day	This work
Estimate of bulk rotation from occultations	10.543 h	819.5°/day	Anderson and Schubert (2007)
Estimate of bulk rotation from potential vorticity	10.570 h	817.4°/day	Read *et al.* (2009)
IAU System III	10.656 h	810.8°/day	Davies *et al.* (1983)
North Polar Hexagon	10.656 h	810.8°/day	Sánchez-Lavega *et al.* (2014)
W86.40	10.662 h	810.4°/day	This work
Great White Spot Vortex	10.667 h	810.0°/day	Sayanagi *et al.* (2013)
String of Pearls	10.686 h	808.5°/day	Sayanagi *et al.* (2014)
Great White Spot Head	10.693 h	808.0°/day	Sayanagi *et al.* (2013)
W86.58	10.695 h	807.9°/day	This work
W86.59	10.698 h	807.7°/day	This work

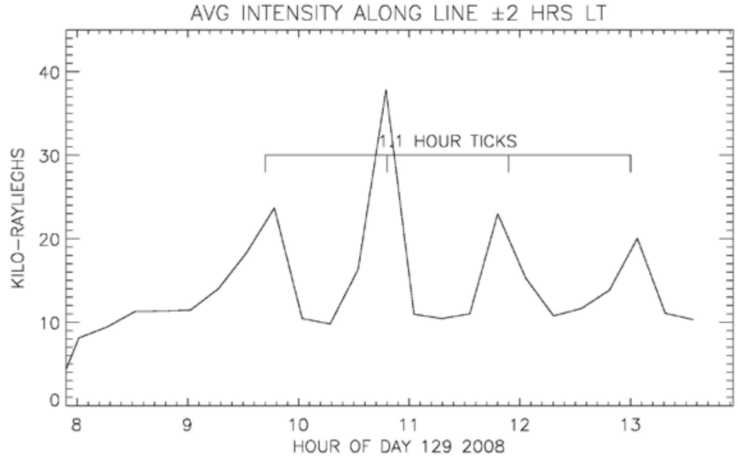
Non-Rotational Clocks



Short Period Clocks





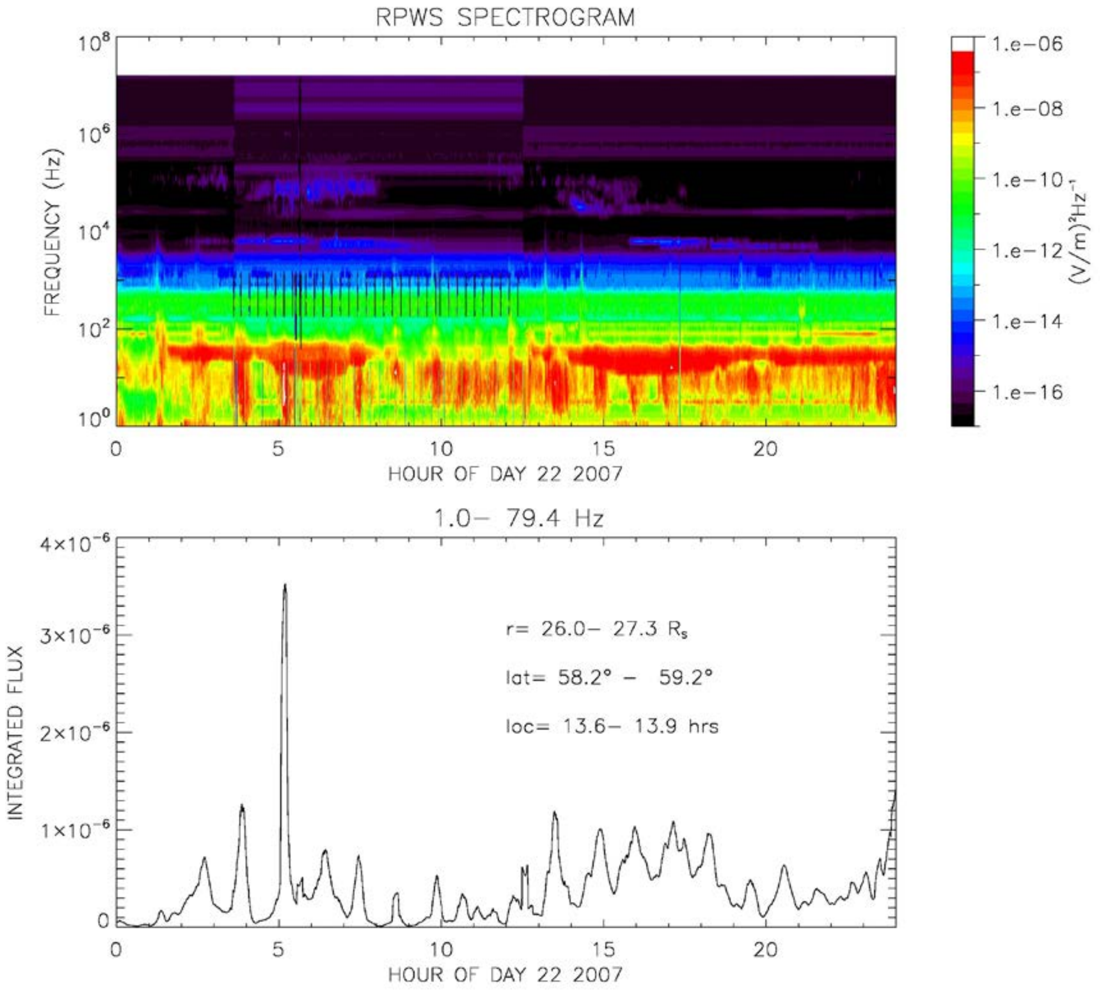


A short-period (~1-hour clock) can be seen at high latitudes. For example, when auroral keograms are constructed in local time (say, between 10° and 15° co-latitude, as shown here), one can often recognize oscillations of ~1 hour period in the intensities of certain auroral hot spots (right). [Interestingly, the motion of this particular blob seems to track the orbit of Mimas— coincidence?] [Mitchell et al., 2014]

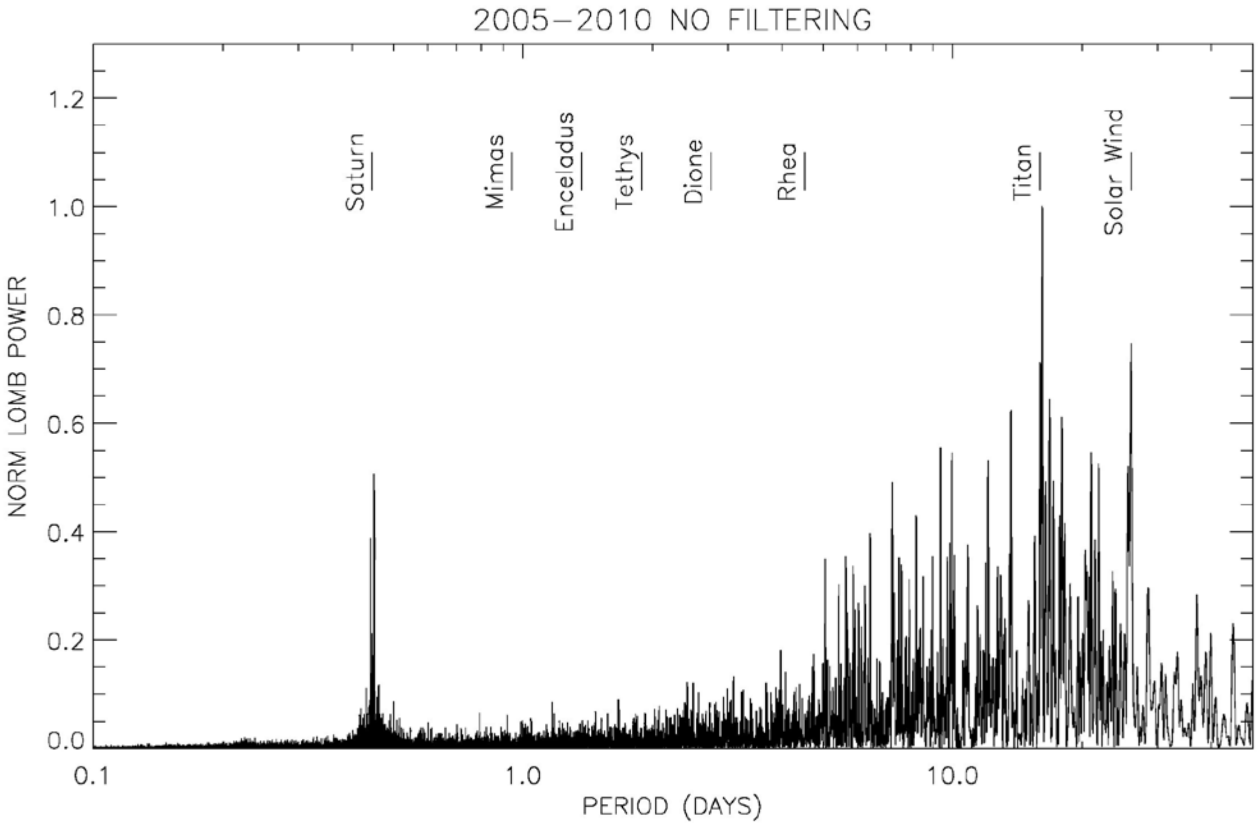
Other Instances of the Short Period Clock

The 1-hour clock can also be ~~seen~~ observed at high latitudes in several other phenomena including radio waves (shown here) and the magnetic field.

A period of ~1 hour is very close to what one would expect as the round-trip travel time of an Alfvén wave between north and south polar regions.



Long Period Clocks in SKR Observations



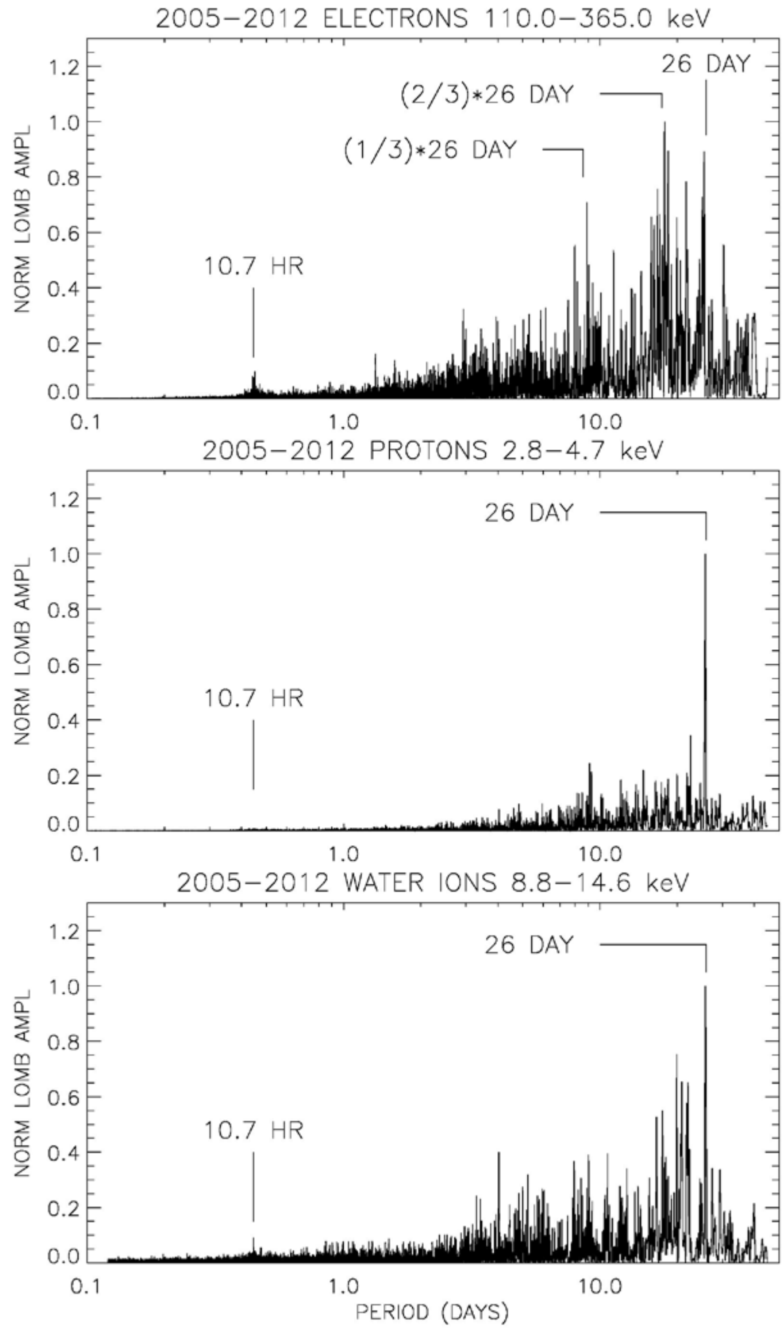
When extended to 50 days, a periodogram of SKR (100-400 kHz) observations reveals "long-period" signals. Sometimes a signal is seen at Titan's orbital period, and a signal is usually seen at the solar wind period (26 days). The solar wind clock has been known since the days of Voyager, but not much remarked upon during the Cassini era. The Titan signal is relatively unknown, but suspected because of some radio and magnetometer observations.

Long Period Clock Signals in Charged Particles

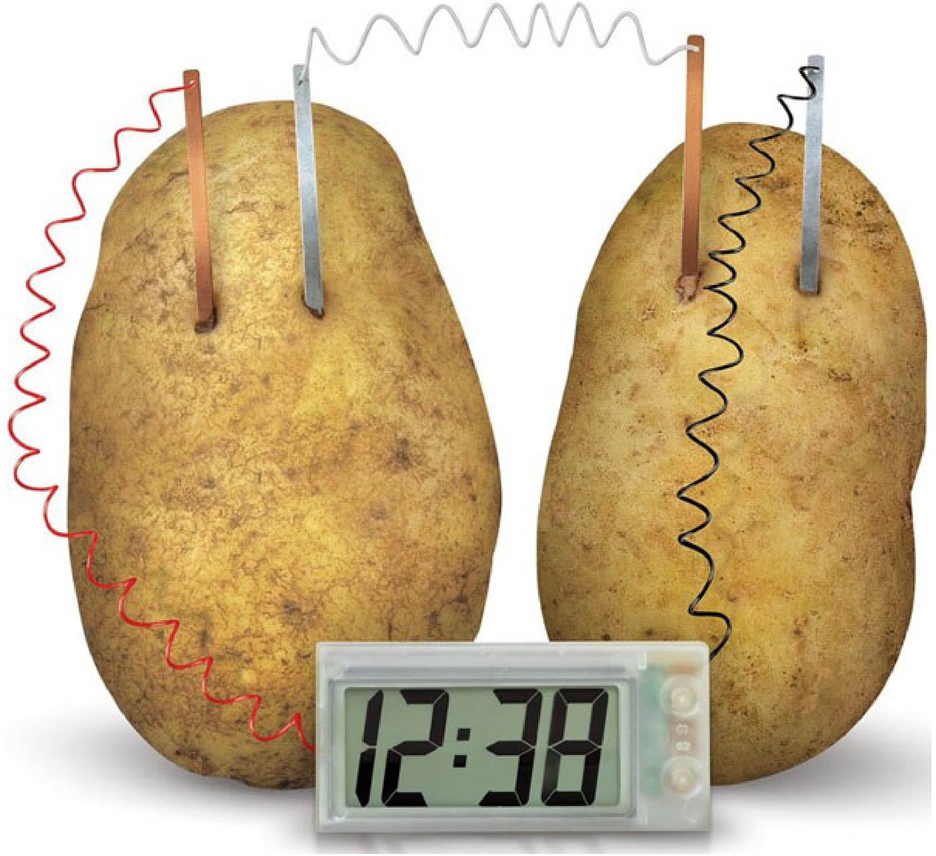
Solar wind periodicities are readily observed in energetic particle periodograms. The electrons not only exhibit the solar wind 26-day period, but also its sub-harmonics. These sub-harmonics are thought to be caused by multiple corotating interaction regions in the solar wind during the epoch of the observations.

The energetic protons and oxygen ions also manifest a solar wind periodicity.

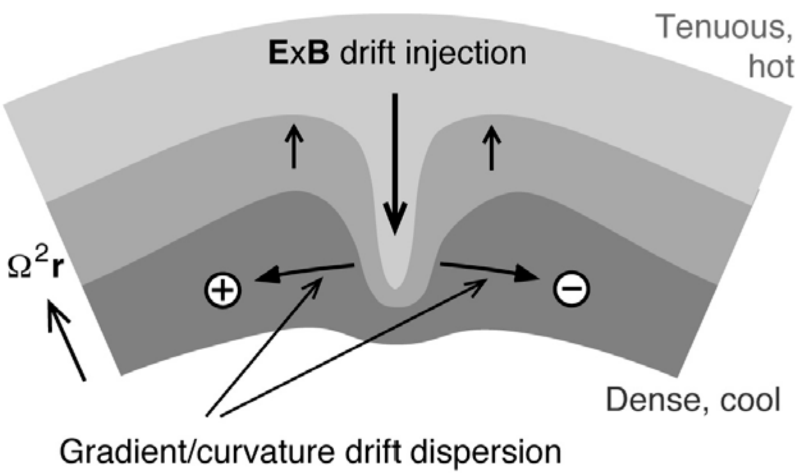
In ALL cases, the solar wind signal is FAR stronger than the planetary rotation signal at ~10.7 hours— a fact not generally appreciated by periodicity experts.

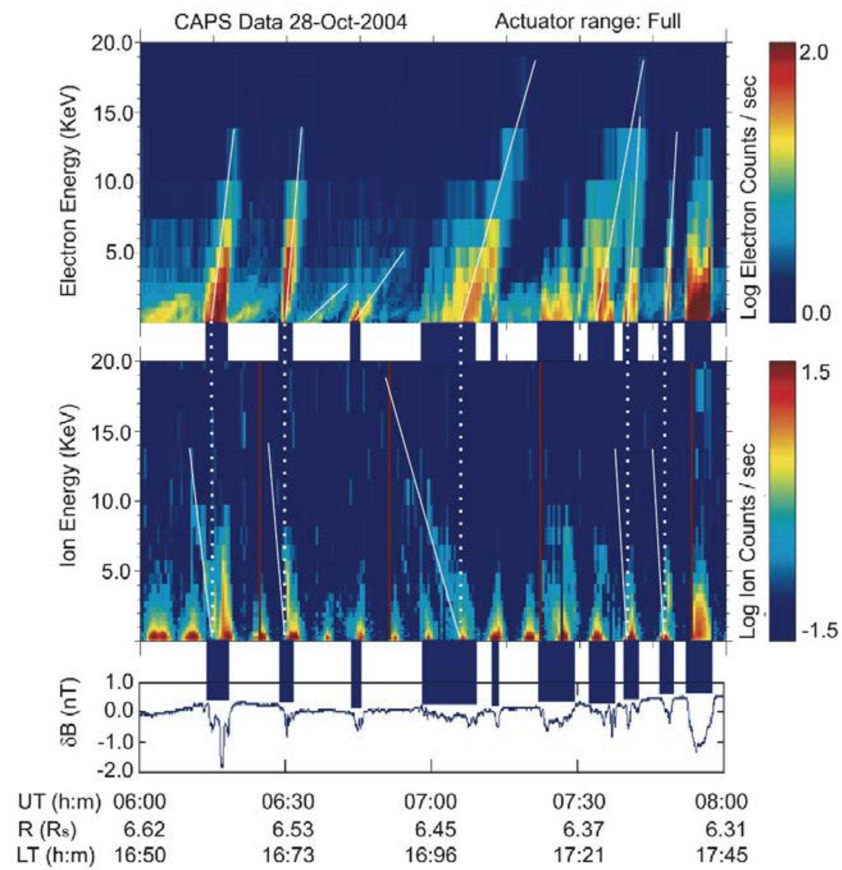


Clock Models



Centrifugal Interchange Instability (CII)



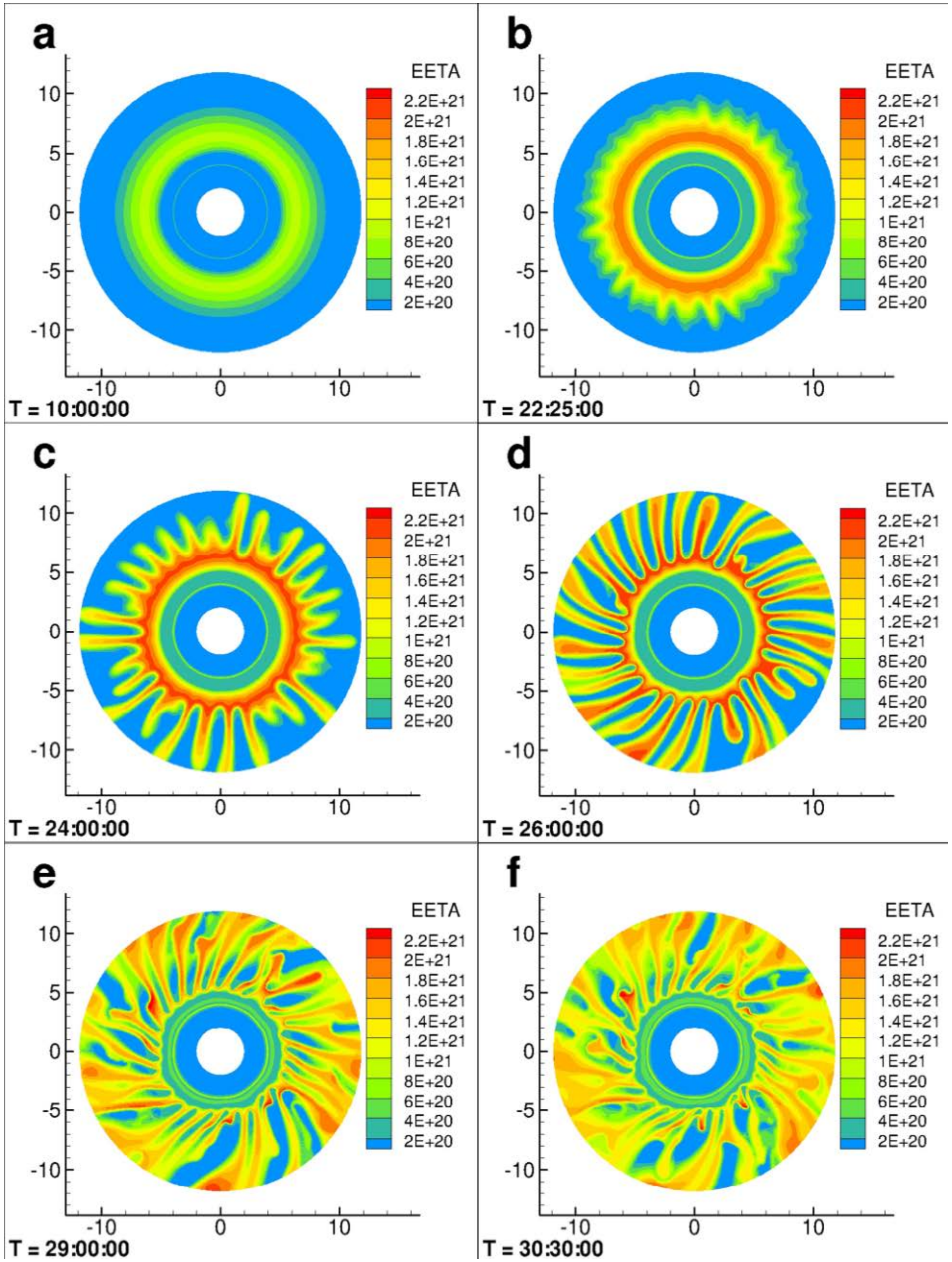


Saturn's magnetosphere rotates rapidly. The inner magnetosphere contains cool, dense plasma, while the outer magnetosphere contains hot, tenuous plasma. The interface between these two regimes is subject to an MHD dynamical instability called the "centrifugal interchange instability" wherein the hot tenuous plasma is "injected" inwards and "exchanged" with the outwardly pressing cold plasma (left). Many examples of this type of interchange have been observed, in both the low energy plasma (right) as well as in the energetic particles. [Hill et al., 2005]

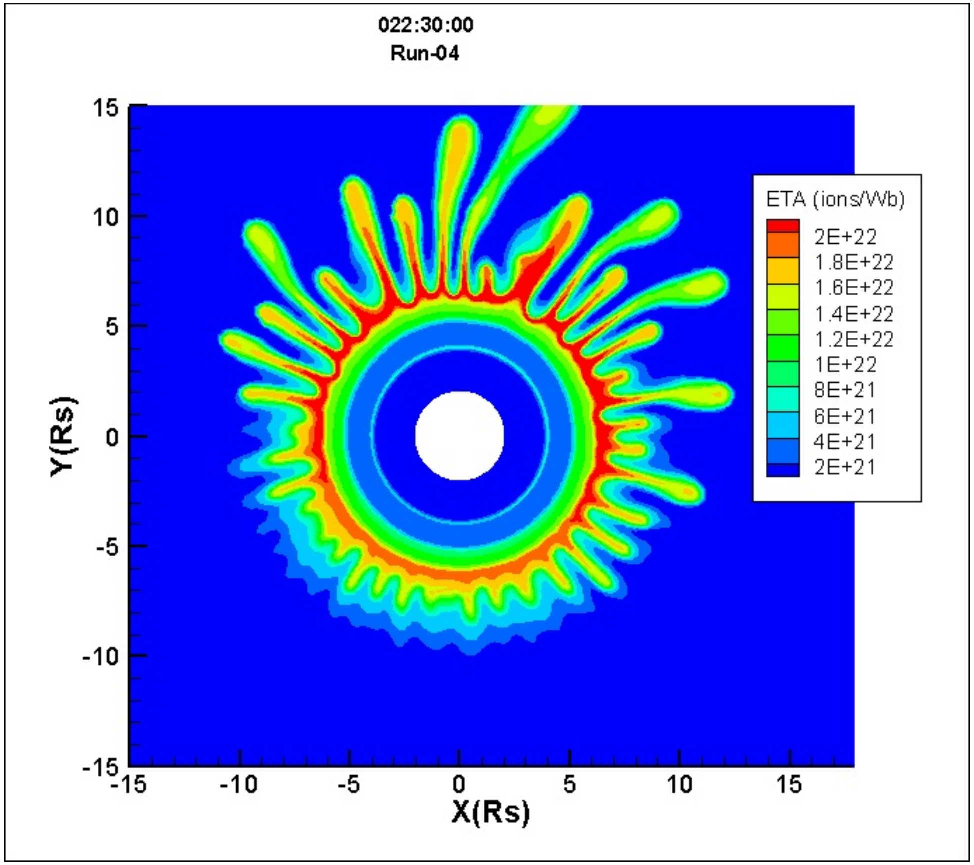
Modeling the CII

Several models of the centrifugal interchange instability have been developed, for both Jupiter and Saturn. For Saturn, the model shown here assumes a longitudinally symmetric, radially distributed plasma source derived from ionization of water vapor from the Enceladus' geysers, and allows the dynamics to unfold. After a few hours of simulation, the distribution develops numerous “fingers.” The widths and numbers of the fingers are comparable to those observed.

If one finger or a group of neighboring fingers becomes dominant, an m=1 wave mode might result… [Liu et al., 2010]



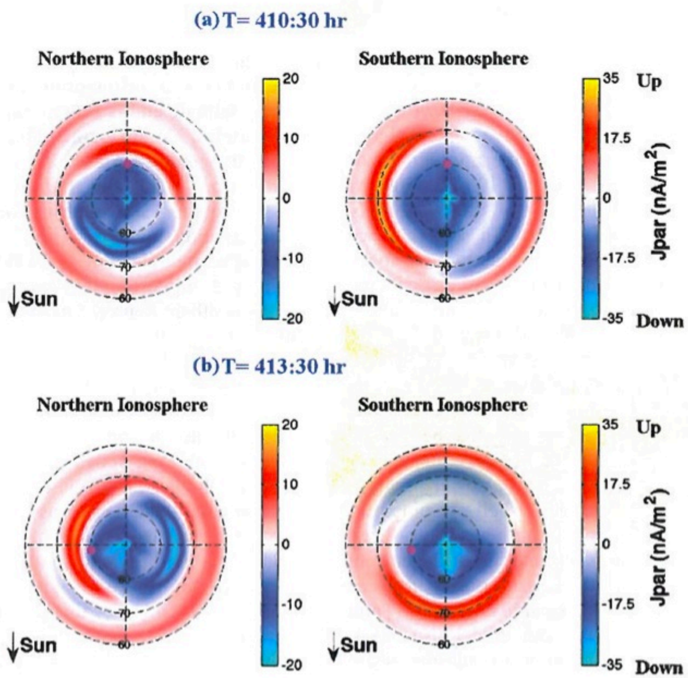
Longitudinal Anomaly in Magnetosphere



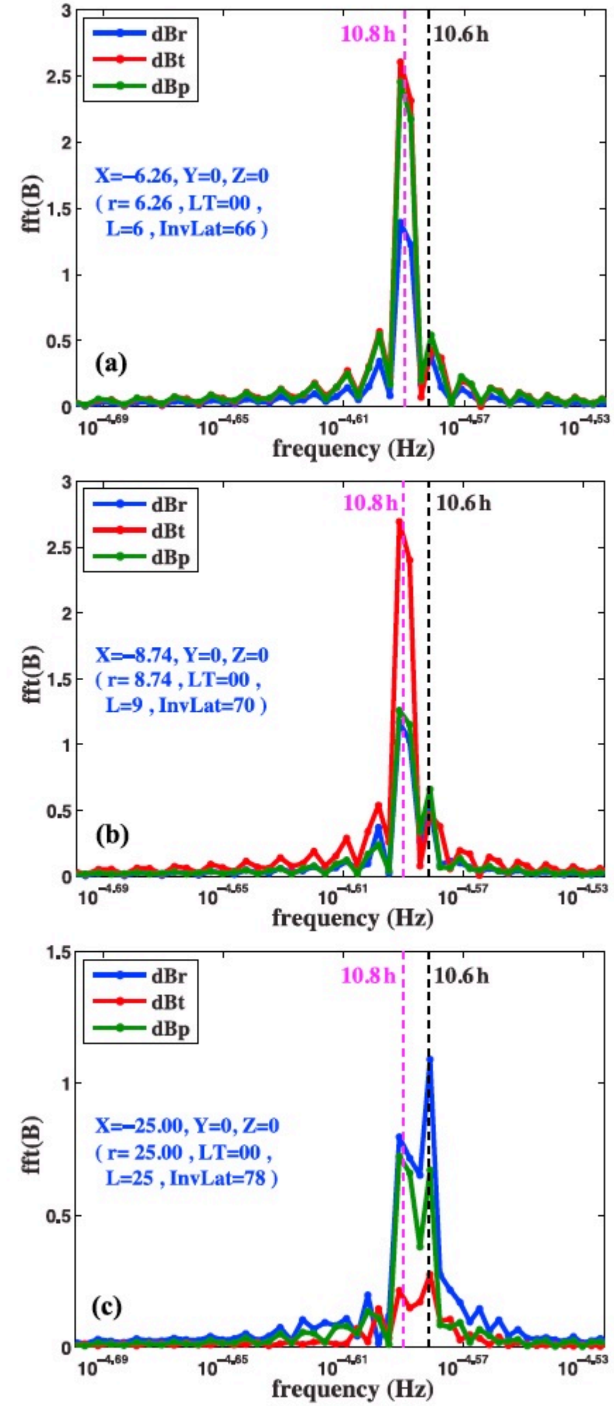
Of course, if only a ~1% longitudinal asymmetry is originally present in the plasma source, then the CII model quickly produces a longitudinal asymmetry (m=1 wave structure) in the magnetosphere. This structure would be recognized as a periodic phenomenon — a "clock.". [Jaggi and Hill, pvt comm, 2014]

One may also transfer such a longitudinal asymmetry to the ionosphere, which has been done for another species of model—

Longitudinal Anomaly in Thermosphere



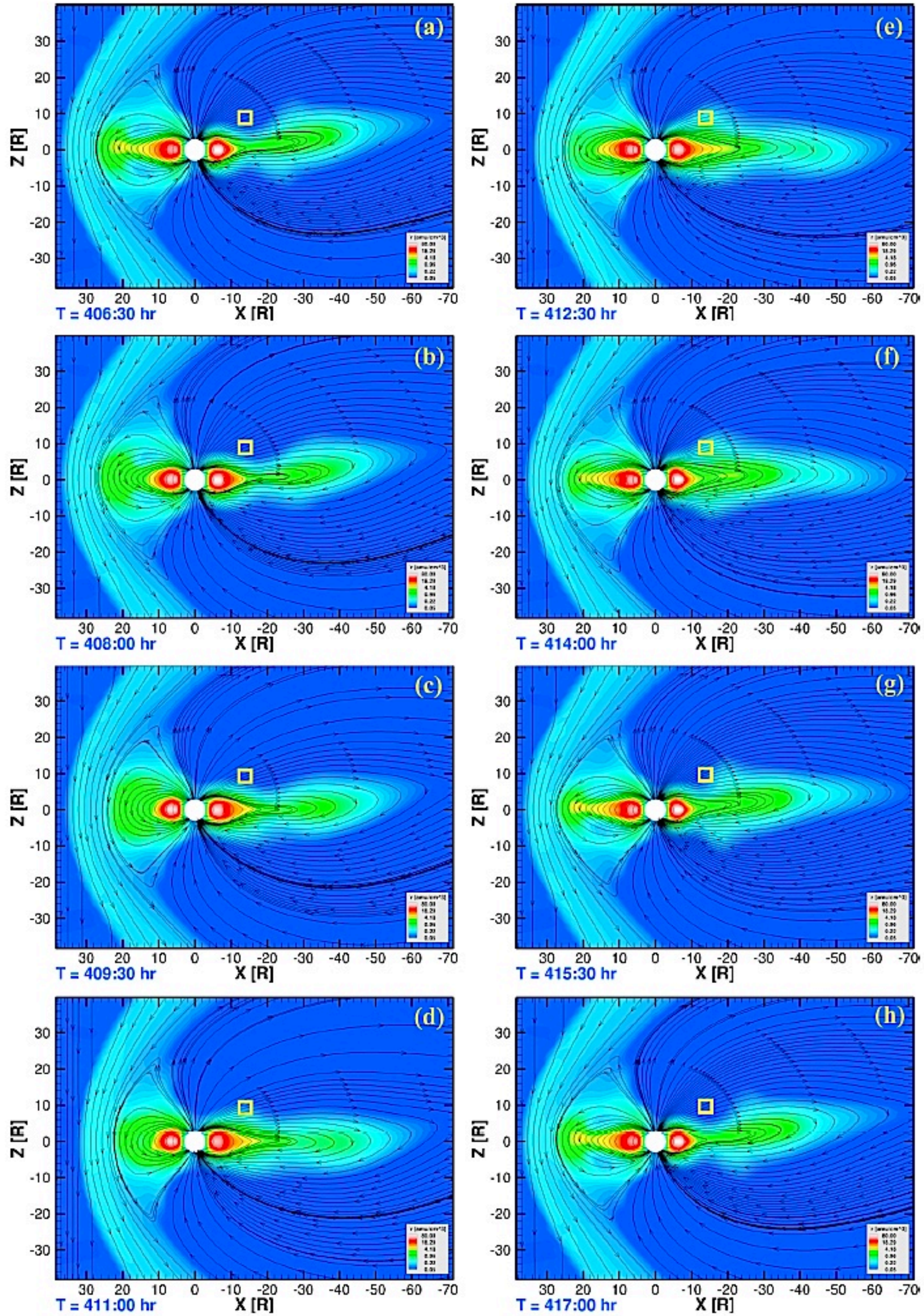
An MHD model has been developed wherein a longitudinal asymmetry in the currents is introduced in both the north and south polar regions (left). If the asymmetries rotate at the N and S radio/mag periods, then the magnetosphere faithfully reproduces these periodicities in a manner consistent with observations (right). [Compare the ionospheric anomaly above to the observed auroral anomaly in SLS4 longitude] [Jia et al., 2013]



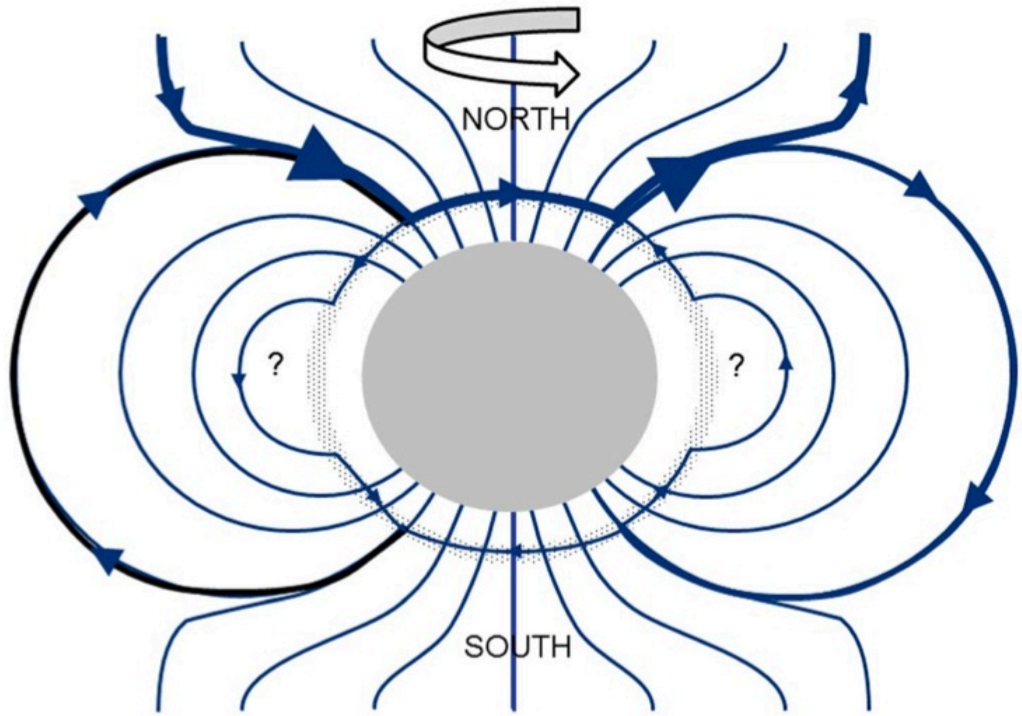
Even Tail Flapping—

According to this model, the ionospheric anomaly communicates its periodicity to the entire magnetosphere, including the observed “flapping” of the tail, move-ments of the plasma sheet and the magnetopause and bow shock.

The problem is finding such an anomaly! [As stated before, one such anomaly may have been found in the aurora— but what causes this anomaly remains unknown.] [Jia et al., 2013]

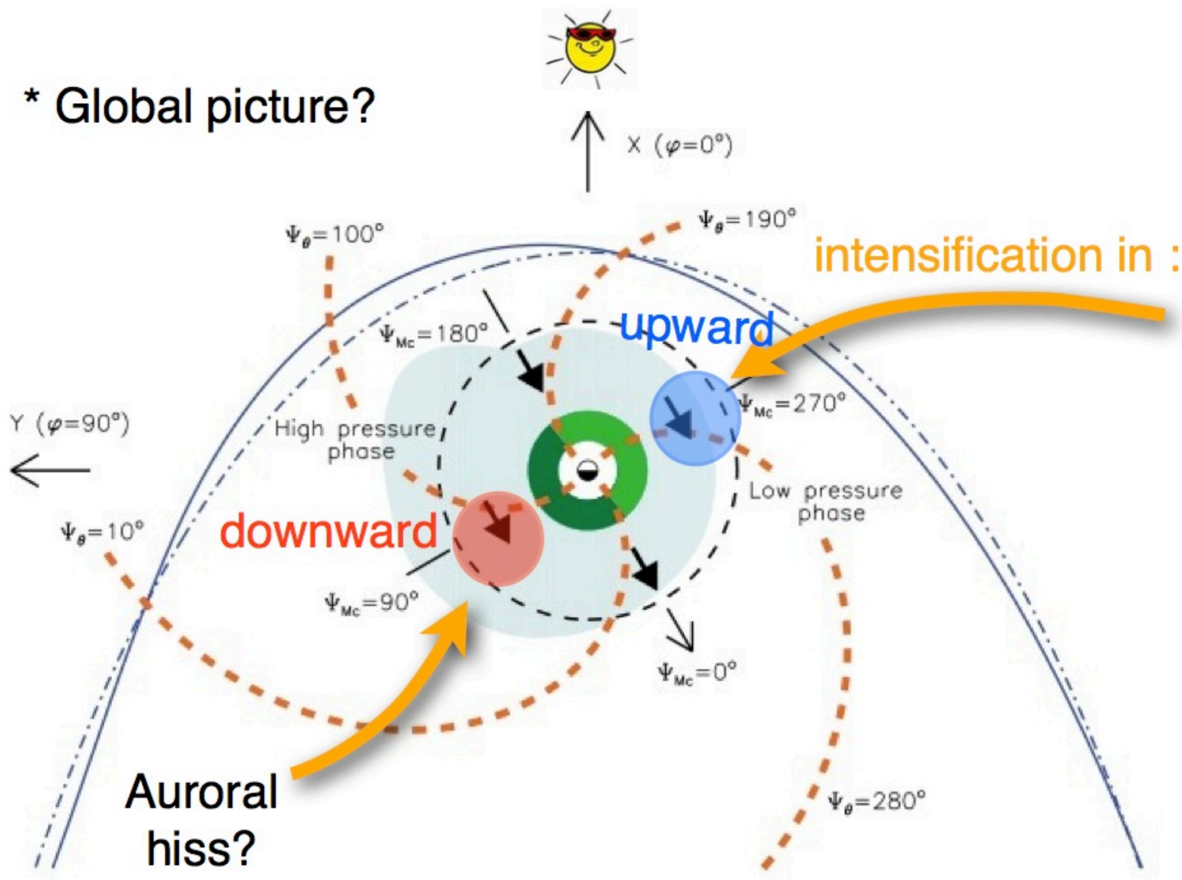


Birkeland Current Systems



How is the ionospheric anomaly communicated to the rest of the magnetosphere? Through Birkeland (or field-aligned) currents. Such currents are, in fact, observed by the magnetometer at high latitudes, and they appear to have the correct flow "sense" to encourage such communication. Birkeland currents are also responsible for the magnetosphere-ionosphere (MI) coupling whereby a rotating planet ionosphere imposes (or partially imposes) its rotation on the magnetosphere. Saturn's magnetosphere is know to sub-corotate with azimuthal speeds ~60% of rigid corotation, meaning that the MI coupling is not perfect— and also that azimuthal flow is **not** responsible for the periodicities. [Southwood and Cowley, 2014]

The Cam Model



Once the Birkeland currents communicate the anomaly to the magnetosphere, the magnetosphere generates an outwardly-travelling spiral wave— not dissimilar to the Parker spiral known in the solar wind. This spiral wave was originally referred to as a "cam" because of its resemblance to a mechanical cam. The wave itself actually bears the periodicities, and is responsible in the outer magnetosphere for flapping the tail, moving the magnetopause, etc. [Lamy et al., 2013]

Concluding Remarks

1. Saturn has about a dozen clocks relating to planetary rotation, each with a period (usually) near ~10.7 hours.

2. Sometimes, the rotational “clock” splits into two branches, a southern branch and a northern branch. (The two branches merged shortly after equinox and have remained the very similar).

3. Only a few of the clocks have been observed (quasi) continuously for long periods of time (e.g., the radio clock, the magnetic clock, the particle clock), and these clocks **do not** maintain a constant period.

4. All the clocks are assumed to have a common source, but what that source is, or whether it is in the magnetosphere, ionosphere, or interior, remains debatable.

5. At present, none of these clocks tell us the true rotation period of Saturn, and the length of Saturn’s day remains an unknown basic property.