Vol 000|00 Month 2007|doi:10.1038/nature06237 nature

LETTERS

Modulation of Saturn's radio clock by solar wind speed

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The internal rotation rates of the giant planets can be estimated by cloud motions, but such an approach is not very precise because absolute wind speeds are not known a priori and depend on latitude[1]: periodicities in the radio emissions, thought to be tied to the internal planetary magnetic field, are used instead[2–5]. Saturn, despite an apparently axisymmetric magnetic field[6], emits kilometre-wavelength (radio) photons from auroral sources. This emission is modulated at a period initially identified as 10 h 39 min 24 ± 7 s, and this has been adopted as Saturn's rotation period[3]. Subsequent observations[7,8], however, revealed that this period varies by ±6 min on a timescale of several months to years. Here we report that the kilometric radiation period varies systematically by ±1% with a characteristic timescale of 20–30 days. Here we show that these fluctuations are correlated with solar wind speed at Saturn, meaning that Saturn's radio clock is controlled, at least in part, by conditions external to the planet's magnetosphere. No correlation is found with the solar wind density, dynamic pressure or magnetic field; the solar wind speed therefore has a special function. We also show that the long-term fluctuations are simply an average of the short-term ones, and therefore the long-term variations are probably also driven by changes in the solar wind.

Low-frequency magnetospheric radio emissions have been used until now to measure the rotation of giant planets because they are produced by keV electrons moving along planetary magnetic field lines that are presumed to rotate with the planet's interior[9]. These emissions are anisotropic; that is, they are preferentially directed in a hollow conical beam aligned with the direction of the local magnetic field[10]. Combined with the rotation of the usually non-axisymmetric planetary magnetic field[11], these properties lead to a rotational modulation of the observed intensity of the emission. At Saturn, the intense auroral kilometric radiation (SKR) was found in the Voyager era to be strongly modulated at a period $P_{\mathrm{SKR}} = 10\,\mathrm{h}\,39\,\mathrm{min}\,24 \pm 7\,\mathrm{s}$, which is close to that observed for atmospheric cloud features[3]. However, Saturn's magnetic field is very nearly axisymmetric, and the auroral sources are not co-rotating with the planet; rather, they are fixed in local time[12,13]. This makes it difficult to understand the strong SKR modulation without appeal to the existence of a magnetic anomaly that escaped detection by magnetometers on the Pioneer and Voyager spacecraft[14–16]. The uncertainty of ±7 s on $P_{\mathrm{SKR}} = 10\,\mathrm{h}\,39\,\mathrm{min}\,24\,\mathrm{s}$ was thought to be limited only by the available time span (nine months), under the implicit assumption of a constant rotation period. However, 24 years later, the SKR period measured by the radio experiment on board Cassini[8] is $P_{\mathrm{SKR}} = 10\,\mathrm{h}\,45\,\mathrm{min}\,45 \pm 36\,\mathrm{s}$. The difference of more than 6 min cannot be due to a change in Saturn's rotation rate, owing to the large inertia of the planet. Ulysses[7] and Cassini[8,17] radio measurements actually showed that P_{SKR} continuously varies over the long term (several months to years), with ~1% relative amplitude.

Two models were proposed to explain these variations. The first[18] invoked an external cause, with nonrandom fluctuations in the solar wind speed at Saturn causing SKR source displacement in local time, leading to an apparent radio period that is different from the planet's true rotation period. The other[19] invoked an internal cause, namely mass injection from Enceladus in the magnetosphere's plasma disk and a variable electrodynamic coupling between this disk and Saturn's ionosphere.

Standard techniques for harmonic signal analysis, such as Fourier transform, require a 100-period window to provide 1% accuracy, and thus permit only long-term variations to be addressed[17]. Taking advantage of Cassini's quasi-continuous radio observations, we developed a method to address faster fluctuations. By integrating the received flux over the range 100–400 kHz, where most of the SKR power is emitted, we obtained a time series of SKR power in which one broad peak was observed for each rotation of Saturn (see Supplementary Figs 1 and 2). This time series is displayed in Fig. 1 in a format that reveals variations in the phase of SKR peaks relative to a fixed reference period. In addition to the previously noted long-term variation[17], we see quasi-periodic oscillations of the SKR phase—and thus of the SKR period—on a timescale of 20–30 days. Smoothing the SKR time series and cross-correlating consecutive peaks (as described in Supplementary Figs 1–3) allowed us to estimate P_{SKR} with an accuracy of ±2 min (0.3%) at timescales down to ~1 week. Results are displayed in Fig. 2a over the 1,186-day interval studied (2003 June 30 to 2006 September 27). Ubiquitous fluctuations of ~2% peak-to-peak amplitude are detected on a timescale of 20–30 days, superimposed on the long-term trend measured by previous authors[17].

What is the origin of these variations? A timescale of 20–30 days is characteristic of variations in the solar wind at Saturn, already known to control the SKR intensity and power[20,21], as can be seen in Fig. 1. However, the duration of Cassini's orbits around Saturn has also varied between 18 and 30 days since mid-2004. Orbital parameters such as the planetocentric distance and latitude of the spacecraft affect observations of SKR: decreasing distance increases SKR signal strength, and hence detectability, and changes in latitude influence SKR visibility as a result of the change in the geometry of observation, SKR being emitted from high-latitude sources in conical patterns centred on the local magnetic field[9,10,13]. Thus, Fig. 2a includes the fluctuations in the solar wind speed ballistically projected to Saturn; variations of spacecraft range and latitude are displayed in Fig. 2b. In Fig. 2c we compare the Fourier power spectrum of the fluctuations of P_{SKR} over the entire interval studied with those of the solar wind speed, spacecraft distance and latitude. Peaks appear in P_{SKR} fluctuations at ~21.5, 23.0 and 25.5 days. The last of these coincides with the same peak in solar wind speed fluctuations. Spacecraft latitude peaks with an 18–19-day period. We simulated possible beatings between solar-wind-induced and orbit-induced variations by the product

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(versus time) of the solar wind speed multiplied by the spacecraft latitude. The spectrum of this quantity shows main peaks at ~20.0, 21.5, 24.0 and 26.5 days, all in the same range as—and some of them matching—main peaks in P_{SKR}. Study of subintervals from our data set confirms these results: within the interval day of the year (DOY) 2004 = 415–670 (DOY = 1.0 corresponds to 2004 January 1 at 0 h UT), where both distance and latitude are regularly modulated, strong P_{SKR} peaks precisely match peaks in solar wind speed, spacecraft latitude variations, and their product; in the interval between DOY 280 and 620, after Cassini's Saturn orbit insertion, the main peak of both P_{SKR} and the solar wind speed is at about 22 days. Both solar wind speed and orbit-dependent viewing geometry therefore seem to contribute to observed variations in the SKR period.

For better quantification of the influence of the solar wind, we analysed separately the interval before Cassini's Saturn orbit insertion (left of the dotted vertical line in Fig. 2a), over which the SKR viewing geometry remained fixed with no expected influence of orbital parameters on SKR visibility. We found a linear correlation[22] coefficient $C > 40\%$ between P_{SKR} and the solar wind speed (Fig. 3a). For comparison, the well-known correlation between SKR power and solar wind speed gives here a similar coefficient $C = 44\%$. The probability of obtaining $C > 40\%$ with two random data sets of the same length as in Fig. 3a is $\sim 10^{-7}$; the correlation found is therefore highly significant. A similar study of other subintervals leads to correlation coefficients of up to +70% between P_{SKR} and the solar wind speed (for example, within the interval between DOY 640 and 760, where the spacecraft's latitude remained fixed and near zero). The lack of a perfect phase relationship ($C \approx 100\%$) comes from the inevitable inaccuracies in the ballistic projection of the solar wind to Saturn (at most ±4 days[23,24]), time-variable solar activity (for example coronal mass ejections) causing azimuthal variations in the structure of the solar wind[25], and details of the interaction between the solar wind and Saturn's magnetosphere (the solar wind might function as a trigger, efficient only when energy has previously been stored in the magnetosphere, so that SKR peaks may sometimes be 'missing').

The correlation found above between short-term (<1 month) fluctuations in Saturn's radio period and variations in the solar wind speed indicates an external origin for P_{SKR} variations. As we did not find any significant correlation between P_{SKR} and other solar wind parameters such as density, dynamic pressure (Fig. 3b) or magnetic field, its speed must have a special function. This result validates the assumptions of the model[18] proposed to explain these variations in terms of SKR source displacement in local time caused by fluctuations in the solar wind speed. An additional internal cause[19] is not excluded, which could be another reason for not finding a one-to-one correlation between P_{SKR} and the solar wind speed.

When averaging P_{SKR} fluctations over >1 month, one obtains the long-term fluctuations already noted by previous authors[17], which are therefore merely an average of the short-term ones (Fig. 1). The long-term variations could therefore also be driven by changes in the solar wind. In the long term, there does indeed seem to be a relationship between the solar wind speed and P_{SKR}: the slow overall decrease

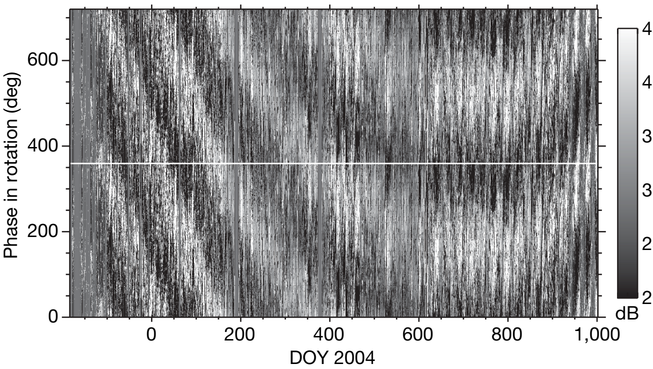

Figure 1 | Evidence of short-term variations in P_{SKR} and their relation to long-term variations. The SKR power–time series (derived as explained in Supplementary Figs 1 and 2) is displayed here over the 3.25-year interval studied, in a format similar to that of Fig. 1 in ref. 17. Variations in SKR power during consecutive rotations are plotted as consecutive vertical lines with a power scale in grey levels, using an assumed fixed period of 10 h 48 min. Time is in day of the year (DOY) 2004. Data gaps are displayed in flat grey (major ones are before DOY −137 and at about DOY 191 ± 4 and 377 ± 5). Each rotation is plotted twice for clarity, separated by the white horizontal line. The origin of phases—and thus the absolute phase—is arbitrary. Previous authors[17] noted that the fact that the SKR peak wanders with variable slope over the time interval means that a fixed period does not organize the SKR modulation well. We see here the same long-term behaviour. In addition, the quality of our data processing (see the legend to Supplementary Fig. 1a) reveals quasi-periodic oscillations of the SKR period on a timescale of 20–30 days. Those are especially clear after DOY 400, where the long-term drift is small and fewer data gaps are present. The amplitude of these fluctuations is large (~2% peak to peak), and their long-term averaging results in the slow, smaller-amplitude (<1% peak to peak over the studied interval) variation of P_{SKR} noted by previous authors.

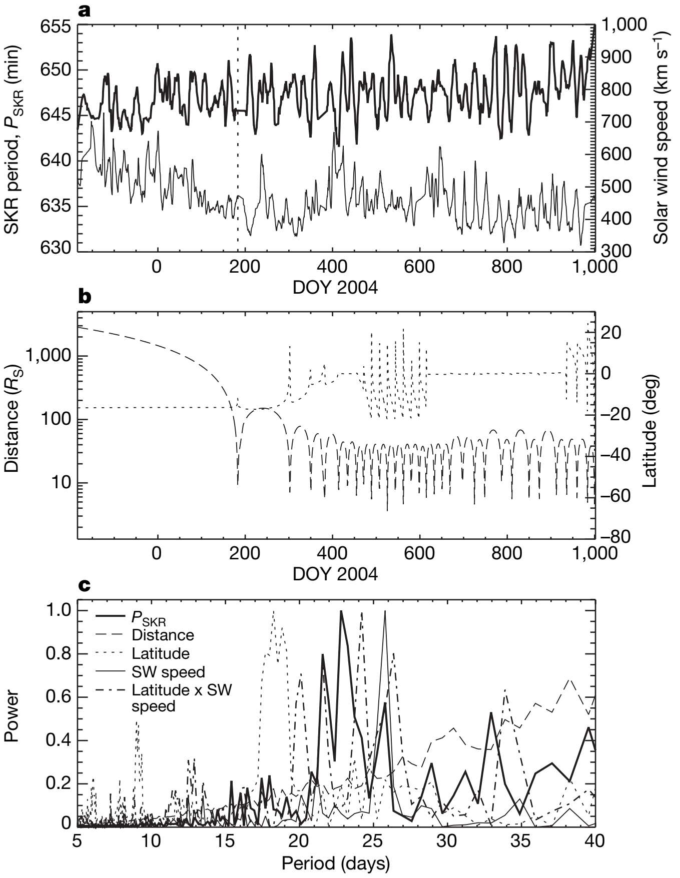

Figure 2 | 'Short-term' variations in P_{SKR} compared with solar wind speed at Saturn and with variations in orbital parameters of Cassini. The same 3.25-year interval as in Fig. 1 is shown. **a**, Variations in P_{SKR} (heavy line; left scale) obtained as explained in the text and in Supplementary Figs 1–3. The solar wind speed plotted below (light line; right scale), measured by the ACE and WIND spacecraft near the Earth's orbit (http://omniweb.gsfc.nasa.gov/) and projected to Saturn, shows similar fluctuations on a timescale of 20–30 days. Solar wind projection includes ballistic radial projection from ~1 to 10 AU, plus a delay compensating for the longitude difference between Earth and Saturn. The dotted vertical line indicates Cassini's Saturn orbit insertion. **b**, Cassini orbital parameters: distance to Saturn (dashed; left scale; $1\,R_{\mathrm{S}} = 1$ Saturn radius = 60,300 km) and latitude (dotted; right scale). **c**, Fourier power spectrum of the fluctuations of all the above quantities, plus the quantity (latitude × solar wind speed) which provides a simple way of simulating beating between latitudes (and thus visibility of the radio emission) and variations in the solar wind (SW) speed.

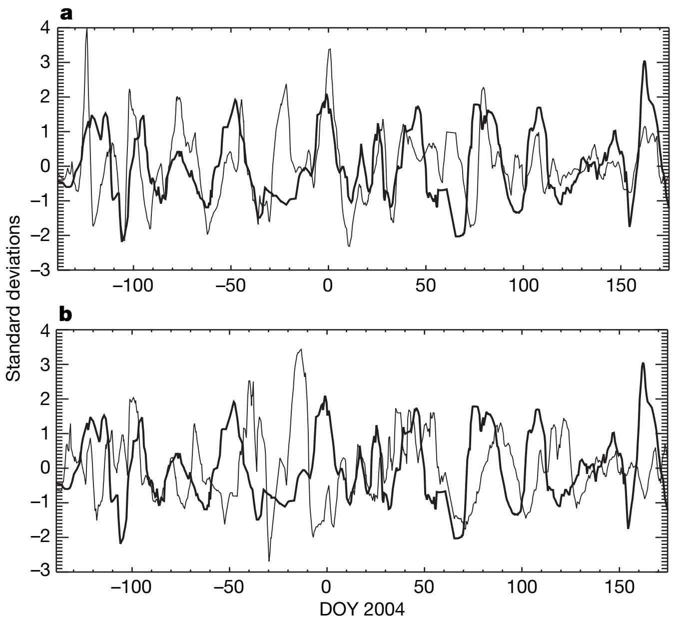

Figure 3 | Comparison of SKR period variations with solar wind speed and dynamic pressure at Saturn. In the time interval before Saturn orbit insertion shown here, the spacecraft latitude remains quasi-constant and its distance to Saturn steadily decreases; no influence of orbital parameters on SKR visibility is therefore expected. This interval is therefore best suited to searching for a correlation between P_{SKR} variations (heavy lines) and the solar wind parameters (light lines), not polluted by other variabilities. For a better comparison of their fluctuations on a timescale shorter than ~1 month, the two displayed quantities have been detrended (by subtraction of a running average over ~2 months) and normalized by their respective standard deviations. **a**, Correlation between P_{SKR} and solar wind speed. Except for two ~10-day intervals, near DOY −25 and +65, the correlation is high, with a linear correlation coefficient $C \geq +0.4$ (see the text). In the two main 'anomalous' intervals mentioned above, a few data gaps exist in Cassini SKR data, and the solar wind speed may have been contaminated by the effect of coronal mass ejections, whose ballistic projection leads to overestimated values whenever the point at which the solar wind is measured *in situ* (here, by ACE or WIND spacecraft) and the target of the projection (Saturn) are not radially aligned[23–25]. **b**, Correlation between P_{SKR} and solar wind dynamic (ram) pressure. Correlation is low, with $C \approx -0.1$.

in the solar wind speed from ~550 km s^{-1} to ~400 km s^{-1} in Fig. 2a seems to be anticorrelated with the trend of P_{SKR} increasing from <646 min to >649 min.

Long-term variations similar to those of P_{SKR} have been found to affect Saturn's azimuthal magnetic field component[26–28] and possibly also the electron density in the inner magnetosphere[19] and the position of the magnetopause[29]. Short-term fluctuations are very difficult to address for these quantities because they are measured *in situ* by Cassini during a small fraction of each orbit. Their dependence on fluctuations in the solar wind remains to be investigated. If variations in P_{SKR} are indeed caused by SKR source displacement in local time[18], then the use of Cassini's instantaneous radio imaging capability[30] for monitoring motions of the SKR source should permit their deconvolution from P_{SKR} measurements, thus permitting a more accurate determination of Saturn's true (internal) rotation rate.

Received 24 January; accepted 10 September 2007.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements We thank D. Southwood for a seminar at Meudon Observatory; F. Mottez, S. Hess and J.-M. Griessmeier for early inputs; B. Kurth for comments on the manuscript; D. Pelat for advice on the statistical analysis; Cassini Radio and Plasma Wave Science (RPWS) engineers at the University of Iowa and the Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique for support on instrumental questions and ephemeris; and N. Letourneur for processing RPWS data. The French co-authors acknowledge support from the Centre National d'Études Spatiales.

Author Contributions P.Z., L.L., B.C. and R.P. contributed equally to this work. H.O.R. contributed to the projection of solar wind data. P.Z. wrote the paper. All authors discussed the results and commented on the manuscript.

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