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S. Cowley, P. Zarka, G. Provan, L. Lamy, D. Andrews. Comment on “A new approach to Saturn’s periodicities” by J. F. Carbary. *Journal of Geophysical Research Space Physics*, 2016, 121 (3), pp.2418-2422. 10.1002/2015JA021996 . hal-02453278

**HAL Id: hal-02453278**

**<https://hal.science/hal-02453278>**

Submitted on 10 Sep 2021

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## COMMENT

10.1002/2015JA021996

This article is a comment on *Carbary* [2015] doi:10.1002/2015JA021571.

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## Citation:

Cowley, S. W. H., P. Zarka, G. Provan, L. Lamy, and D. J. Andrews (2016), Comment on "A new approach to Saturn's periodicities" by J. F. Carbary, *J. Geophys. Res. Space Physics*, 121, 2418–2422, doi:10.1002/2015JA021996.

Received 5 OCT 2015

Accepted 18 FEB 2016

Accepted article online 28 FEB 2016

Published online 18 MAR 2016

## Comment on "A new approach to Saturn's periodicities" by J. F. Carbary

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The phenomenon of "planetary period oscillations" in Saturn's magnetosphere was first observed by the Voyager spacecraft via modulations near the planetary rotation period in the intensity of radio emissions at kilometer wavelengths [Warwick *et al.*, 1981; Desch and Kaiser, 1981], together with related oscillations in particles and magnetic fields in situ within the magnetosphere [Carbary and Krimigis, 1982; Espinosa and Dougherty, 2000]. Subsequent remote observations of Saturn kilometric radiation (SKR) by the Ulysses spacecraft showed that the period can change by of order ~1% over yearly intervals, such that the modulations cannot be connected directly to the rotation of the body of the planet [Galopeau and Lecacheux, 2000]. A more recent Cassini discovery has been that two such variable modulations are generally present in SKR data, with periods of ~10.6 and ~10.8 h during Saturn southern summer conditions early in the mission [Kurth *et al.*, 2008; Gurnett *et al.*, 2009a], though later becoming closer together, more variable, and with intervals of only one detectable period postequinox [Provan *et al.*, 2014; Fischer *et al.*, 2014; Cowley and Provan, 2015]. As will be indicated below, in subsequent discussions these two periods have generally been taken to correspond to planetary period oscillation (PPO) phenomena associated with the Northern and Southern Hemispheres of the planet. In a recent paper, however, Carbary [2015] has suggested a "new approach" to these findings, pointing out the simple fact via a number of elementary demonstrations that if a single sinusoidal oscillation is modulated in amplitude, frequency, or phase, its frequency spectrum is no longer monochromatic and may become split into a number of peaks near that of the principal period, suggested to correspond to the observed dual PPO modulations. The simplest illustrative example is that of a signal  $S(t)$  consisting of a "carrier" of frequency  $\omega_2$  whose amplitude is modulated by a sinusoid of frequency  $\omega_1$ , for which it can be shown by elementary trigonometry that

$$S(t) = A \cos(\omega_1 t) \cos(\omega_2 t) = \frac{A}{2} [\cos((\omega_2 + \omega_1)t) + \cos((\omega_2 - \omega_1)t)]. \quad (1)$$

The sinusoidal amplitude modulation thus results in the carrier becoming split into two equal amplitude monochromatic oscillations with frequencies  $(\omega_2 \pm \omega_1)$ . Equivalently, we may say that two monochromatic sinusoids of equal amplitude combine to produce an oscillation at their mean frequency which is amplitude modulated at half their difference frequency, producing "beats" as the two oscillations go into and out of phase. Some more complicated examples are provided by Carbary [2015] involving, e.g., periodic or random variations in signal frequency or phase which produce spectra with multiple peaks, though we note that only two enduring peaks have been found in SKR spectra for most of the Cassini observations [Lamy, 2011; Gurnett *et al.*, 2011; Andrews *et al.*, 2012]. Although the two interpretations of the signal in equation (1) are formally identical, either an amplitude-modulated carrier or two interfering monochromatic oscillations, the distinction may have significant implications for the physical mechanism envisaged, not yet definitively identified for the PPO phenomenon. In the former case (amplitude-modulated carrier) we might envisage an equatorial phenomenon such as those discussed, e.g., by Gurnett *et al.* [2007] and Carbary [2013], which could be modulated by some influence such as the solar wind or moon gas emission rates, while the latter case (two interfering oscillations) may instead suggest the presence of two related phenomena driven from the northern and southern polar regions as modeled, e.g., by Jia and Kivelson [2012].

A principal point we wish to emphasize, however, is that the in situ measurements of PPO-related field oscillations together with radio emission and plasma wave modulations, as extensively discussed in the literature to date, point unequivocally to the second of the above pictures that two systems of modulation are present with generally clearly separated periods, one associated with the northern polar region and the other with

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the southern. With regard to the magnetic data, tracking of the oscillation phases obtained from pass to pass over the two polar regions on highly inclined Cassini orbits has clearly demonstrated the presence of oscillations with distinct periods in the two hemispheres that are closely similar to those deduced from near-simultaneous SKR modulation data (typically to better than  $\sim 0.1\%$ , corresponding to a period difference of a few tens of seconds) [Andrews *et al.*, 2010, 2011; Southwood, 2011; Provan *et al.*, 2014]. These separate polar periodicities have also been shown to be present, with propagation phase delays, in the two lobes of Saturn's magnetic tail to distances of at least several tens of planetary radii [Provan *et al.*, 2012].

In the inner quasi-dipolar magnetosphere, however, and in the plasma sheet in the magnetic tail, oscillations are observed which exhibit both amplitude and phase modulations as discussed by Carbary [2015], but which analysis shows can be described in detail in terms of the vector superposition of two oscillatory systems whose phase and period are related directly to those observed singly over the two poles and in the tail lobes. The close relationship between the phase and period of the near-equatorial and polar oscillations was first established by Provan *et al.* [2009] early in the Cassini mission for the southern system alone, then dominant under southern summer conditions. With the discovery of the second modulation in SKR data by Kurth *et al.* [2008] and Gurnett *et al.* [2009a], it was subsequently proven by Provan *et al.* [2011] that the small phase fluctuations ("jitter") previously observed by Andrews *et al.* [2008] in these equatorial data were due to the presence of a secondary signal which bore an equivalent phase and period relationship with the oscillations observed over the northern pole by Andrews *et al.* [2010]. A methodology was subsequently developed to determine the phase, period, and relative amplitude of the two magnetic signals directly from the near-equatorial beat-modulated phase data, together with the amplitudes of the two signals from the corresponding beat-modulated amplitude data [Andrews *et al.*, 2012]. The scheme is based on a generalization of equation (1) which models the detailed phase and amplitude modulation effects resulting from the combination of two rotating vector systems of generally unequal amplitude with different relative polarizations of the three field components. This methodology has been used to track the evolution of the PPO periods and amplitudes over the  $\sim 10$  year Cassini mission to date, from southern dominance during southern summer as mentioned above, to near-equal amplitudes and converging periods during equinoctial conditions centered on mid-2009, and to postequinox abrupt  $\sim 100$ – $200$  day transitions in period and relative amplitude starting in early 2011 [Provan *et al.*, 2013]. Application of the same methodology to the polar data, however, reveals no evidence for the presence of secondary oscillations in these regions, to within a  $\sim 10\%$  experimental limit by amplitude [Andrews *et al.*, 2012; Hunt *et al.*, 2015]. The close equivalence of the two single phases and periods observed in polar data with the dual phases and periods deduced from near-equatorial data has been established both by direct comparison on special sequences of highly inclined Cassini orbits that sampled the oscillations in all three regions, together with the temporal continuity of the derived phases and periods as the spacecraft transitioned from near-equatorial orbits to highly inclined, and back again [Andrews *et al.*, 2010, 2012; Provan *et al.*, 2013, 2014].

Turning now to the corresponding observations of radio modulations, we note that SKR is generated primarily in the extraordinary mode by cyclotron maser instability of accelerated auroral electrons [Zarka, 1998; Lamy *et al.*, 2010, 2011] and is emitted from auroral field lines at all local times (LTs), though with a strongly peaked intensity midmorning at  $\sim 08$  h LT [Lamy *et al.*, 2009]. The conically beamed emissions from the Northern Hemisphere are thus predominantly right-hand circular polarized and illuminate the northern region down to  $\sim 20^\circ$  latitude in the Southern Hemisphere outside of a shadow zone extending to  $\sim 4$  planetary radii in the equatorial region, while those from the Southern Hemisphere are similarly left hand circular polarized and illuminate the southern region up to  $\sim 20^\circ$  latitude in the Northern Hemisphere [Lamy *et al.*, 2008a, 2008b; Kimura *et al.*, 2013]. Somewhat similar to the magnetic observations, therefore, emissions from both hemispheres can thus be detected simultaneously within  $\sim \pm 20^\circ$  of the equator (though with a restricted view of the sources in LT), corresponding to a majority of the Cassini data, while only individual hemispheric emissions can be observed outside of this region. Emissions from the two hemispheres can thus be separated either by latitude of observation or by state of circular polarization in the case of equatorial data. Following the discovery by Kurth *et al.* [2008] of dual PPO modulations in the SKR intensities, Gurnett *et al.* [2009a] employed SKR intensity measurements outside of  $\pm 10^\circ$  latitude during intervals of inclined Cassini orbits to show that the northern data strongly selected the shorter of two periods then present ( $\sim 10.6$  h), while the southern data similarly strongly selected the longer period ( $\sim 10.8$  h), in essential agreement with the subsequent magnetic field studies discussed above. Lamy [2011] then separated the emission data by circular polarization state, employing all the data within the above  $\pm 20^\circ$  hemispheric limit, thus now also including data from the equatorial region. This

procedure was also found to strongly select separate modulation periods as above, though intermittent intervals of dual modulation in the polarization-separated data were also detected, whose origins remain to be elucidated. As indicated above, the northern and southern SKR periods so determined have generally been found to agree with those derived independently from magnetic field data, when both could be detected, typically to better than  $\sim 0.1\%$  [Andrews *et al.*, 2010, 2011, 2012; Provan *et al.*, 2014].

The phasing of the radio modulations has been found to be such that maxima in the SKR emission occur when the upward field-aligned current of the rotating system that produces the magnetic field oscillations is centered on the LT-dependent sources being observed at any time, thus enhancing the auroral electron acceleration and radio emissions in that sector [Southwood and Kivelson, 2009; Andrews *et al.*, 2010; Southwood and Cowley, 2014; Hunt *et al.*, 2014, 2015]. Corresponding modulations in ultraviolet and infrared auroral emissions have also been observed [Nichols *et al.*, 2010; Badman *et al.*, 2012; Lamy *et al.*, 2013]. The SKR modulations are thus fundamentally rotational in nature, though giving rise to strobe-like effects independent of LT in the wide dawn sector due to the dominance of the midmorning sources [Lamy, 2011; Andrews *et al.*, 2011; Provan *et al.*, 2011, 2014]. On the opposite side of the auroral zone where the PPO-related field-aligned currents are directed downwards, however, whistler-mode auroral hiss associated with upward accelerated electrons is correspondingly enhanced, leading to modulated emissions at  $\sim 1$ – $100$  Hz being observed on high-latitude Cassini passes over the northern and southern auroral regions [Gurnett *et al.*, 2009b]. Analysis indicates that these modulations also rotate around the planet as expected and have separate rotation periods in the Northern and Southern Hemispheres that are also in close agreement with the separate northern and southern periods determined from both SKR and magnetic field data. Overall, these observations of magnetic fields, SKR emissions, atmospheric auroras, and auroral hiss thus leave little doubt that two separate periods are involved in the PPO phenomenon, associated with Saturn's northern and southern polar regions, which are observed combined together in the equatorial regions. Carbery's [2015] suggestion that the dual periods instead result from modulation of an oscillation with a single planetary period is thus evidently incorrect, ignoring as it does the results of the large published body of work cited above.

It should not be inferred from these remarks, however, that modulations such as those discussed briefly and qualitatively by Carbery [2015] have insignificant influence on the PPO phenomenon, only that these are clearly not the source of the basic dual PPO periodicity. Indeed, short-term fluctuations in PPO phase and period have been observed in both magnetic field and SKR data [Provan *et al.*, 2011; Fischer *et al.*, 2014; Cowley and Provan, 2015], which the results of Zarka *et al.* [2007] have shown are likely associated with variations in solar wind speed. The latter paper also considered the effect of the orbital period of Cassini on SKR modulations and showed that it was clearly decoupled from the solar wind influence by separately analyzing SKR data obtained during a 6 month approach phase prior to Saturn orbit insertion. In addition, Provan *et al.* [2015] have recently provided evidence that implicates large changes in the size of the magnetosphere induced by large variations in the solar wind dynamic pressure as being involved in producing the postequinox  $\sim 100$ – $200$  day abrupt amplitude and period variations mentioned above. The influence of the Saturn moons on SKR modulations, on the other hand, has been found by Menietti *et al.* [2007] to be marginal, such that it is very unlikely that such effects give rise to two well-defined long-lasting periods in the wide range of magnetospheric phenomena observed as speculated by Carbery [2015].

We finally point out that far from being a new approach to Saturn's periodicities, Carbery's [2015] discussion actually represents a simple variant of the approach developed previously by Cecconi and Zarka [2005] in their attempt to explain the slow variability, and possible multiplicity, of Saturn's radio period. These authors constructed an illustrative physical model of such SKR variations based on the role of the Kelvin-Helmholtz instability on the SKR source and the influence of the observed sawtooth variations in solar wind speed on the LT position of the source. Cecconi and Zarka [2005] also studied the role of noise in the SKR phase modulation by the solar wind speed. This paper thus constitutes a physically based foundation for simple models such as those discussed, without clear physical motivation, by Carbery [2015].

In summary it is our view that Carbery's [2015] paper yields no significant contribution to an understanding of Saturn's periodicities. First, the discussion does not apply to the physical reality of Saturn's periodicities for which the existence of two polar sources with generally differing periods has been clearly established by the many previous works cited above. Second, it brings no new insights to the discussion of modulation effects driven, e.g., by the solar wind, that have been more thoroughly analyzed in previous works.

### Acknowledgments

S.W.H.C. and G.P. were supported by STFC consolidated grant ST/K001000/1, P.Z. and L.L. were supported by CNRS and PNP & PNST programs from CNRS, and D.J.A. was supported by SNSB grant 162/14 and Vetenskapsrådet grant 621-2014-5526. This paper employs no data other than those in the references cited.

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