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Formation of Saturn's ring spokes by lightning-induced electron beams

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[1] Spokes are near-linear markings sometimes visible on Saturn's rings. They are widely accepted as being electrostatically-levitated sheets of ∼0.6 micron-radius charged grains. Previously-suggested causes of the grains' charging do not agree with all spoke characteristics, which include their rapid generation, localized formation primarily in Saturn's midnight-dawn sector, the seasonality of their apparitions, and, crucially, their morphologies. We contend that spokes are caused by lightning-induced electron beams striking the rings, at locations magnetically-connected to thunderstorms. This view is supported by a semi-quantitative spoke morphology simulation. Spokes' formation locations are further controlled by Saturn's ionospheric density, which reaches a near-dawn minimum where electron beams can most easily propagate to the rings. The beams may generate observed X-ray emission, supply particles to Saturn's radiation belts, and over time will modify the rings' constituents. Finally, we report Cassini MIMI instrument observations of an electron burst which displays some characteristics expected of a lightning-induced event. **Citation:** Jones, G. H., et al. (2006), Formation of Saturn's ring spokes by lightning-induced electron beams, *Geophys. Res. Lett.*, *33*, L21202, doi:10.1029/2006GL028146.

1. Introduction

[2] Saturn's ring spokes were a major discovery of the 1980/1981 Voyager flybys [*Smith et al.*, 1982]. These perplexing, generally near-linear structures appear dark and light in back- and forward-scattered light, respectively. Their nature as sheets of ∼0.6 μm-radius grains [*McGhee et al.*, 2005] elevated above the rings is widely accepted, as is the cause of their levitation being the electrostatic charging of their constituent grains. Recent debate on spokes has concentrated on the conditions under which electrostatic dust charging will be manifested as spoke formation [*Mitchell et al.*, 2006; *Farrell et al.*, 2006]. Here, we concentrate instead on the fundamental cause of dust charging. Spokes' morphologies provide important clues to their formation process (Figure 1), and several of these structures' characteristics cannot be reconciled with previously-proposed dust-charging models. Though still debated [*Farmer and Goldreich*, 2005], the most widely-accepted model invokes meteoroid impacts on the rings to form radially-moving plasma columns electrostatically levitating dust along their paths [*Goertz and Morfill*, 1983]. Although linear isolated spokes can be explained by such impulsive, sporadic meteoroid impacts, they cannot account for the observed sustained build-up along a spoke's central azimuth, moving almost in step with Saturn's rotation (Figure 1). This would require an extremely unlikely sequence of recurring impacts at the same ring location. The leading alternative to the meteoroid impact scenario invokes an interaction between the solar wind's convective electric field and Saturn's magnetospheric plasma to cause magnetic field-aligned drops in potential [*Hill and Mendis*, 1981]. This process, however, only operates at auroral regions magnetically-connected to Saturn's magnetotail, whereas the main rings reside in a dipolar magnetic field region [*Dougherty et al.*, 2005] unconnected to the tail. Although the electrostatic charging invoked for the above models to levitate the spoke dust is not disputed, the underlying charging process must be one capable of occurring at the mid-latitudes to which the rings map, at a point co-rotating with the planet for >1 hour, and being most active in the morning sector. Neither of the two models above can meet all these conditions.

2. Spoke Formation by Thunderstorms

[3] Figure 2 outlines the formation process proposed here, which invokes an electron source unknown when spokes were discovered. Knowledge of high-energy particle processes peripheral to terrestrial thunderstorms advanced significantly after the scientific community's acceptance of transient luminous events such as sprites [*Franz et al.*, 1990], a decade after the Voyager encounters. These processes are associated with positive and negative cloud-to-ground and in-cloud lightning [*Ohkubo et al.*, 2005; *Barrington-Leigh and Inan*, 1999; *Stanley et al.*, 2006]. Above terrestrial thunderclouds, cosmic rays are thought to seed highly nonlinear runaway electron breakdown, where electrons are accelerated to >1 megaelectronvolt (MeV) [*Lehtinen et al.*, 2001], generating observed atmospheric γ-rays [*Lehtinen et al.*, 2000; *Smith et al.*, 2005]. For ∼1 ms, these avalanche electrons beam along magnetic field lines into space [*Lehtinen et al.*, 2001]. Particle drift and scattering will form "curtains" of energetic electrons that evade atmospheric absorption. It is reasonable to believe that this also occurs at Saturn: cloud-top magnetic fields approximate those at Earth, and Saturnian lightning

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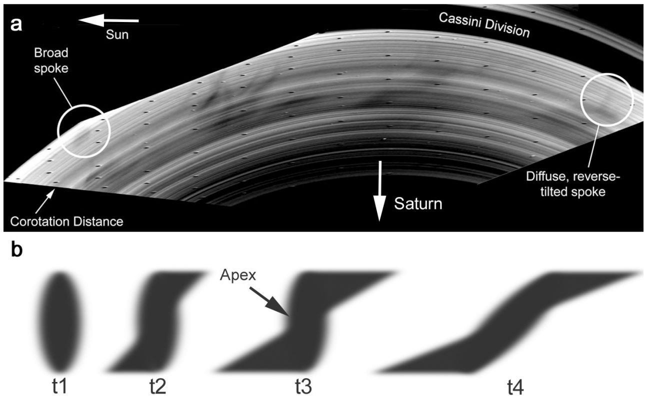

Figure 1. Spoke morphologies, as observed by Voyagers 1 and 2. (a) A reprojection of a Voyager 2 morning ring ansa image (FDS 43897.41) showing spokes (dark features) as if observed from above Saturn's north pole. Black spots are camera artefacts; planetary rotation is counterclockwise. Several spokes are near-linear, but few are radially-aligned. Two spokes referred to in the main text are labelled. (b) Spokes' changing morphologies, as reported by *Grün et al.* [1983]. Most easily-observable spokes form by sustained generation along a central axis, combined with Keplerian velocity shear that extends the spoke ahead and behind (t1, t2 and t3), over an average period $\sim$1.8 hours [*Grün et al.*, 1983], pivoting about an apex near the corotation distance, where Keplerian and planetary rotation periods coincide. Following this "active" period, the whole spoke's bow-tie morphology is gradually distorted by Keplerian velocity shear (t4).

strokes release $\sim 10^4$ times more energy than their terrestrial counterparts [*Fischer et al.*, 2006]. Consequently, thunderstorm-associated electric fields and their electron beams are probably significantly stronger at Saturn.

3. Spoke Characteristics' Agreement With the Thunderstorm Model

[4] Spoke generation by thunderstorms explains many of their characteristics, e.g., their initial formation can be practically instantaneous if induced by electron bursts. Near corotation, ring particles' prolonged alignment with a storm explains the triangular morphologies of sometimes complex spoke systems (Figure 3). The altitude of sprite generation is lowest on Saturn's dayside due to heightened ionospheric conductivity, where the electric field threshold for atmospheric breakdown is elevated [*Stanley et al.*, 2000]. Dayside electron beams are therefore uncommon, but non-abrupt ionospheric conductivity changes at the terminator [*Moore et al.*, 2004] delay and prolong spoke generation post-dusk and post-dawn, respectively (Figure 4). This is consistent with the Voyagers and Hubble Space Telescope (HST) mainly observing spokes in the outer B ring's morning sector [*Smith et al.*, 1982; *McGhee et al.*, 2005], with most formation occurring during 03:00–07:00 LT [*Grün et al.*, 1992].

[5] Saturn's rings and their atmosphere [*Young et al.*, 2005] can impede electrons' equator crossings (Figure 4); spoke formation may occur when thunderstorms' latitudes map to the rings. As electron acceleration within Saturn's atmosphere yields a magnetic field-aligned equatorial beam, electrons' likelihood of interaction with ring material is proportional to ring optical depth, explaining the latter's parallelism with spoke contrast [*Grün et al.*, 1992]. The spoke will form on the ring side that faces the thunderstorm's hemisphere. Ring plane-crossing electrons are partially lost to atmospheric precipitation [*Lehtinen et al.*, 2001].

[6] Simulations suggest that typical terrestrial electron avalanches may release $\sim 3 \times 10^{18}$ electrons into space [*Lehtinen et al.*, 2000], while an electron number density of $\sim 100\ \mathrm{cm}^{-3}$ is probably necessary for submicron dust to leave the rings [*Goertz and Morfill*, 1983]. Hence, for a 10 m effective ring depth, a terrestrial-scale event at Saturn could potentially generate a spoke covering $\sim 3 \times 10^3\ \mathrm{km}^2$. For comparison, recently-observed spokes [*Mitchell et al.*, 2006] covered $\sim 3.5 \times 10^5\ \mathrm{km}^2$, so although terrestrial-scale bursts cannot generate such extensive spokes, given the higher energies of Saturnian lightning [*Fischer et al.*, 2006], equivalent electron beams at Saturn could create features observable by Cassini.

[7] Spokes' linearity is primarily explained by the fact that circular storms at the corotation latitude map to 1:2.8 elliptical regions at the rings. Inspection of reprojected Voyager images reveals that, at any moment, most spokes are linear in morphology, but are primarily oriented in the sense expected for a Keplerian velocity shear. This shear accentuates their linearity, and their apparently radial orientations primarily result from low inclination viewing geometry effects. Indeed, a significant number of spokes approach the morning ansa with a diffuse morphology, and, when linear, are sometimes actually oriented against the sense of Keplerian velocity shear (Figure 1a). Orbital dynamics lead to the reorientation of these spokes past radiality to Keplerian-sheared structures. This variety of spoke morphologies at formation is consistent with a random distribution of electron beam footprint sizes and orientations, and hence also with a variety of electron acceleration region characteristics, consistent with intracloud and cloud-cloud lightning morphologies. Truly filamentary spokes [*Grün et al.*, 1992] may be explained by strong electric fields above narrow intracloud and cloud-cloud lightning channels; linear discharges aligned north-south will produce radially-aligned, narrow spokes. Those inclined more east-west would be less prominent features, masked by the rings' fine structure.

[8] In 1980–81, spokes' recurrence periods [*Porco*, 1988] were $10^{\mathrm{h}}41^{\mathrm{m}} \pm 5^{\mathrm{m}}$, and $10^{\mathrm{h}}11^{\mathrm{m}} \pm 4^{\mathrm{m}}$, near the magnetic field and Saturn electrostatic discharge [*Fischer et al.*, 2006] periods, respectively. Thunderstorms' atmospheric motion may mean that these two periods reflect wind speed differences, being consistent with speeds of ~ 65 and $\sim 400\ \mathrm{ms}^{-1}$, respectively, within observed ranges [*Smith et al.*, 1982]. The few spokes that temporarily exhibited non-Keplerian motion during formation [*Grün et al.*, 1992] may also have reflected thunderstorms' motion. Spokes' apices nominally lie at corotation, but the latter's radial position is sensitive to Saturn's rotation period. A

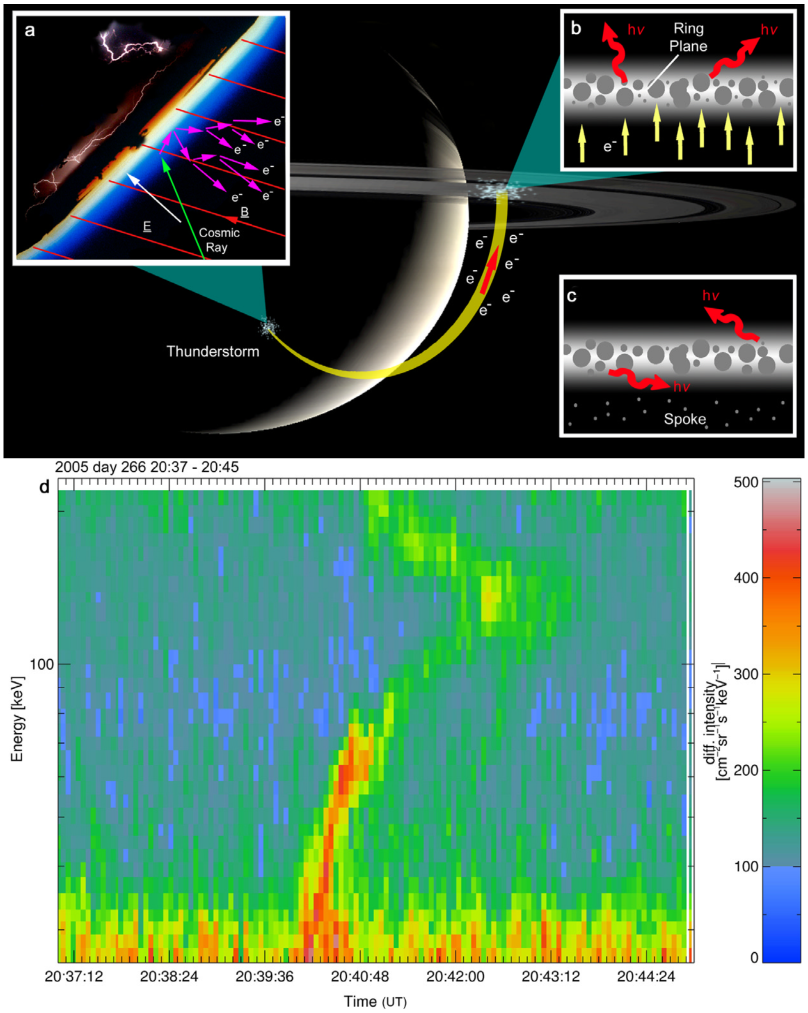

Figure 2. The spoke formation process. (a) A cosmic ray particle triggers an upward electron avalanche above a thunderstorm. (b) The electrons propagate along Saturn's magnetic field lines, and on striking the rings induce rapid negative charging of ring grains and high-energy bremsstrahlung emission. The ring atmosphere is also ionized, dissociated, and excited by electron impact. Auroral emission emanates from excited gases, including in the X-ray range. (c) Large ring particles lose their small grain regoliths [*Doyle et al.*, 1989], which are repulsed by the ring to form a spoke [*Mitchell et al.*, 2006]. (d) A highly unusual electron burst consistent in some respects with a thunderstorm origin, observed at 17:48 local time (LT) by Cassini.

recent revision of this period [*Giampieri et al.*, 2006] shifted corotation outwards by ~900 km from the location implied by the previously-accepted value. Spoke apex positions appear on first consideration to facilitate independent determination of Saturn's elusive rotation rate, but thunderstorms' wind-driven motion will complicate this parameter's determination.

[9] The rings are a source of 200–900 eV X-rays [*Ness et al.*, 2004], dominated by oxygen Kα fluorescence [*Bhardwaj et al.*, 2005], which is consistent with emission from ring material [*Young et al.*, 2005]. The morning ansa outshines the evening ansa in soft X-rays [*Ness et al.*, 2004; *Bhardwaj et al.*, 2005], and varies in brightness [*Ness et al.*, 2004] – possible parallelism with spoke formation has been noted [*Bhardwaj et al.*, 2005]. As it is unknown how fluorescent scattering of solar X-rays could depend on local time, the X-rays may represent auroral emission from ring material collisionally-excited by electron beams. We suggest that the X-ray excess from Saturn's equatorial atmosphere [*Ness et al.*, 2004] may be direct emission from above thunderstorms [*Lehtinen et al.*, 2000].

[10] Following successful HST spoke observations during 1996–1998, no spokes were detected during 1999–2004 [*McGhee et al.*, 2005]. Cassini's single September 2005 sighting [*Mitchell et al.*, 2006] occurred immediately before a 10 month preclusion of spoke observations. Spokes' invisibility to Cassini until then countered a prediction that they are only observable when viewed obliquely [*McGhee et al.*, 2005]. Alternative or possibly additional reasons for spokes' occasional absence include grain trajectories' dependence on background ring plasma density [*Mitchell et al.*, 2006]. Other workers have proposed that spoke formation is confined to negative ring surfaces, and that the currently sunlit face has a positive surface potential

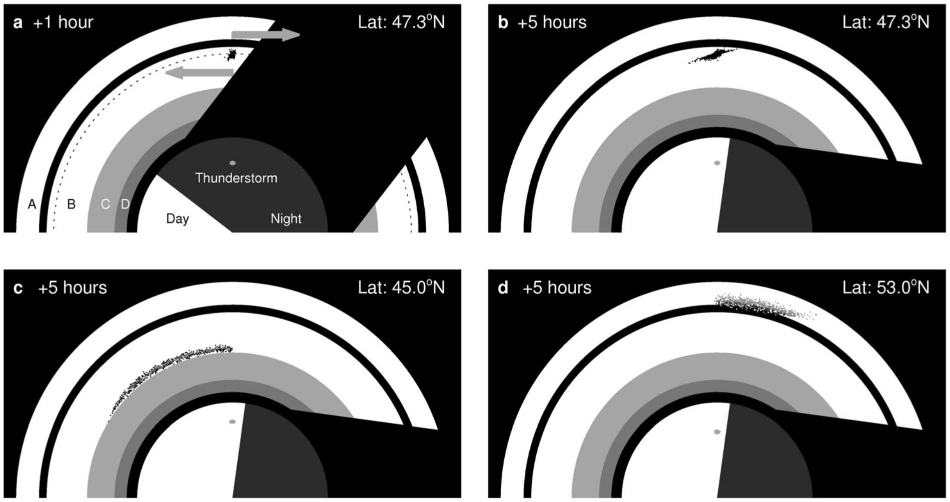

Figure 3. Phenomenological spoke formation simulation for thunderstorms at three different planetocentric latitudes. The view is from the north in a frame corotating with Saturn [*Giampieri et al.*, 2006] in $10^h47^m6^s$. (a) Arrows on either side of the 1.87 R_S corotation distance (dotted line) denote the Keplerian velocity in this frame. 1 R_S measures 60268 km. Modeled formation is initiated at 01:30 LT. Every 10 s, dust is levitated at a ring location connected to the thunderstorm, the points of origin having a Gaussian spatial distribution of 800 km full width half maximum. At this opaque ring region, a dense, radially-aligned elliptical spoke that straddles corotation gradually forms. (b) The velocity shear distorts the spoke [*Grün et al.*, 1992], while formation continues along its central azimuth, yielding a "bow-tie" morphology of two adjacent triangles that meet at corotation, as observed by Voyager (Figure 1b). Ring material continually shifts with respect to thunderstorms not near the corotation latitude, forming longitudinally-spread, low contrast spokes, at lower opacity ring regions (c, d). These broader spokes are entirely detached from the corotation radius, as observed by Voyager (Figure 1a). Sporadic electron beam release would be manifested as patchy spokes away from corotation, as observed in the spoke group [*Mitchell et al.*, 2006] of September 2005.

[*Farrell et al.*, 2006]. Spoke seasonality is probably also influenced by solar insolation, which between Cassini's arrival and spoke detection was 9.6–12.7% higher than in 1980–81. If this is a strong influence, spokes may not be common until early 2008, when insolation and ionospheric conductivity return to their levels at HST's last spoke detection. Without discounting the effects of variations in rings' surface potential [*Mitchell et al.*, 2006; *Farrell et al.*, 2006], we propose that seasonal thunderstorm latitude changes may also strongly influence spoke formation. Most thunderstorms detected by Cassini have occurred at ~35°S planetocentric latitude [*Fischer et al.*, 2006], mapping to within the inner edge of the B-ring, well inside the corotation distance, and whistler waves, incidentally not associated with concurrent SED emission, imply lightning at ~66°N in late 2004, i.e. outside the ring system [*Akalin et al.*, 2006].

[11] During Cassini's 15th orbit, at 3.1 Saturn radii, R_S, its Magnetospheric Imaging Instrument, MIMI, detected a highly-unusual, magnetic field-aligned electron beam (Figure 2d). On that orbit's outbound leg, a second, weaker, event was detected at the same planetocentric distance, at 22:19 LT. The CAPS, MAG and RPWS instruments [*Russell*, 2004] detected no coincident events, suggesting that the electron beams were not of magnetospheric origin. The electrons' curious simultaneous energy dispersion, alignment with the magnetic field, and close proximity to Saturn, make them potential candidates for thunderstorm-related energetic electron "curtains" [*Lehtinen et al.*, 2000]. In the absence of a confirmed correlation with a thunderstorm, these events cannot as yet be positively identified as being induced by lightning. Although all aspects of these events are not understood, we note that the dispersion up to ~150 keV appears consistent with an origin at a thunderstorm located westwards of Cassini.

4. Discussion and Conclusion

[12] Lightning-induced electron beams explain several aspects of spokes' morphologies that other proposed formation processes cannot account for, and provide a mechanism that is both impulsive in its nature and sustained for prolonged thunderstorm activity. The process also accounts for other observed phenomena such as the rings' X-ray emission. Voyager-observed spokes mapped to an atmospheric region to the north of the then-prominent "ribbon" wave [*Smith et al.*, 1982]. We note that during August 22–23, 1981, a particularly prominent spoke complex mapped over at least three Saturn rotations to a location trailing a laminar anticyclone within the above region. A Cassini-based search for thunderstorms at the longitudes and conjugate latitudes of spokes should be pursued; a positive correlation between storms and spokes would support the proposed model. Also worthwhile would be the monitoring of shadowed ring regions by Cassini's ultraviolet spectrometer [*Russell*, 2004] for impulsive auroral emission coincident with spoke locations. Electron beams and their by-products may provide a significant proportion of Saturn's trapped energetic particle population. If storms are most prevalent

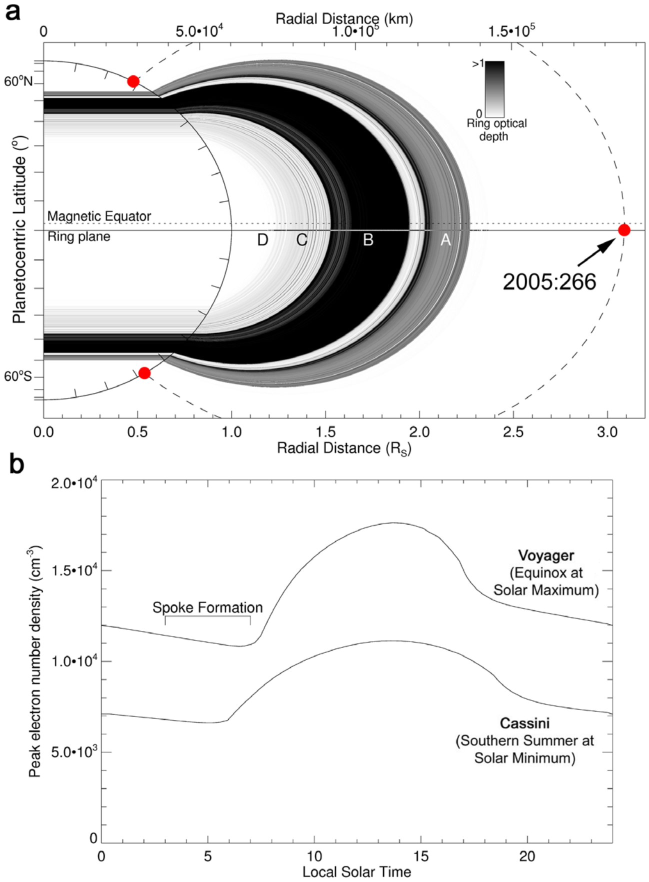

Figure 4. Constraints on spoke formation locations. (a) Accounting for the offset magnetic dipole [*Dougherty et al.*, 2005], the B-ring maps to planetocentric latitudes of $\sim$43°–52°N and $\sim$38°–46°S. Marked are the location of a Cassini-observed electron burst (Figure 2d), and its possible source latitudes if it was of thunderstorm-related origin. The northern source location is in a region exposed to very little daily sunlight at the time of observation. (b) Peak ionospheric electron number density at planetocentric latitude 40°S, from a global model [*Moore et al.*, 2004]. The two curves are for conditions similar to those encountered by the Voyagers and Cassini. The times where most spokes form [*Grün et al.*,1992] suggest a requirement for $N_e < \sim 1.2 \times 10^4$ cm^{-3}.

in equatorial regions, the C ring's low crystalline water ice content [*Poulet et al.*, 2003] may reflect long-term exposure to low-latitude electron beams and their by-products.

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References

Akalin, F., D. A. Gurnett, T. F. Averkamp, A. M. Persoon, O. Santolik, W. S. Kurth, and G. B. Hospodarsky (2006), The first whistler observed in the magnetosphere of Saturn, *Geophys. Res. Lett.*, *33*, L20107, doi:10.1029/2006GL027019.

Barrington-Leigh, C. P., and U. S. Inan (1999), Sprites triggered by negative lightning discharges, *Geophys. Res. Lett.*, *26*(24), 3605–3608.

Bhardwaj, A., R. F. Elsner, J. H. Waite Jr., G. R. Gladstone, T. E. Cravens, and P. G. Ford (2005), The discovery of oxygen Kα X-ray emission from the rings of Saturn, *Astrophys. J.*, *627*, L73–L76.

Dougherty, M. K., et al. (2005), Cassini magnetometer observations during Saturn orbit insertion, *Science*, *307*, 1266–1270.

Doyle, L. R., L. Dones, and J. N. Cuzzi (1989), Radiative transfer modeling of Saturn's outer B ring, *Icarus*, *80*, 104–135.

Farmer, A. J., and P. Goldreich (2005), Spoke formation under moving plasma clouds, *Icarus*, *179*, 535–538.

Farrell, W. M., M. D. Desch, M. L. Kaiser, W. S. Kurth, and D. A. Gurnett (2006), Changing electrical nature of Saturn's rings: Implications for spoke formation, *Geophys. Res. Lett.*, *33*, L07203, doi:10.1029/2005GL024922.

Fischer, G., et al. (2006), Saturn lightning recorded by Cassini/RPWS in 2004, *Icarus*, *183*, 135–152.

Franz, R. C., R. J. Nemzek, and J. R. Winckler (1990), Television image of a large upward electrical discharge above a thunderstorm, *Science*, *249*, 48–51.

Giampieri, G., M. K. Dougherty, E. J. Smith, and C. T. Russell (2006), A regular period for Saturn's magnetic field that may track its internal rotation, *Nature*, *441*, 62–64.

Goertz, C. K., and G. Morfill (1983), A model for the formation of spokes in Saturn's ring, *Icarus*, *53*, 219–229.

Grün, E., G. E. Morfill, R. J. Terrile, T. V. Johnson, and G. Schwehm (1983), The evolution of spokes in Saturn's B ring, *Icarus*, *54*, 227–252.

Grün, E., C. K. Goertz, G. E. Morfill, and O. Havnes (1992), Statistics of Saturn's spokes, *Icarus*, *99*, 191–201.

Hill, J. R., and D. A. Mendis (1981), On the braids and spokes in Saturn's ring system, *Moon Planets*, *24*, 431–436.

Lehtinen, N. G., U. S. Inan, and T. F. Bell (2000), Trapped energetic electron curtains produced by thunderstorm driven relativistic runaway electrons, *Geophys. Res. Lett.*, *27*(8), 1095–1098.

Lehtinen, N. G., U. S. Inan, and T. F. Bell (2001), Effects of thunderstorm-driven runaway electrons in the conjugate hemisphere: Purple sprites, ionization enhancements, and gamma rays, *J. Geophys. Res.*, *106*(A12), 28,841–28,856.

McGhee, C. A., R. G. French, L. Dones, J. N. Cuzzi, H. J. Salo, and R. Danos (2005), HST observations of spokes in Saturn's B ring, *Icarus*, *173*, 508–521.

Mitchell, C. J., M. Horányi, O. Havnes, and C. C. Porco (2006), Saturn's spokes: Lost and found, *Science*, *311*, 1587–1589.

Moore, L. E., M. Mendillo, I. C. F. Müller-Wodarg, and D. L. Murr (2004), Modeling of global variations and ring shadowing in Saturn's ionosphere, *Icarus*, *172*, 503–520.

Ness, J.-U., J. H. M. M. Schmitt, S. J. Wolk, K. Dennerl, and V. Burwitz (2004), X-ray emission from Saturn, *Astron. Astrophys.*, *418*, 337–345.

Ohkubo, A., H. Fukunishi, Y. Takahashi, and T. Adachi (2005), VLF/ELF sferic evidence for in-cloud discharge activity producing sprites, *Geophys. Res. Lett.*, *32*, L04812, doi:10.1029/2004GL021943.

Porco, C. C. (1988), Dual periodicity in the appearance of spokes, *Bull. Am. Astron. Soc.*, *20*, 852.

Poulet, F., D. P. Cruikshank, J. N. Cuzzi, T. L. Roush, and R. G. French (2003), Compositions of Saturn's rings A, B, and C from high resolution near-infrared spectroscopic observations, *Astron. Astrophys.*, *412*, 305–316.

Russell, C. T. (Ed.) (2004), *The Cassini-Huygens Mission: Orbiter In Situ Investigations*, Springer, New York.

Smith, B. A., et al. (1982), A new look at the Saturn system: The Voyager 2 images, *Science*, *215*, 504–536.

Smith, D. M., L. I. Lopez, R. P. Lin, and C. P. Barrington-Leigh (2005), Terrestrial gamma-ray flashes observed up to 20 MeV, *Science*, *307*, 1085–1088.

Stanley, M., M. Brook, P. Krehbiel, and S. A. Cummer (2000), Detection of daytime sprites via a unique sprite ELF signature, *Geophys. Res. Lett.*, *27*(6), 871–874.

Stanley, M. A., X.-M. Shao, D. M. Smith, L. I. Lopez, M. B. Pongratz, J. D. Harlin, M. Stock, and A. Regan (2006), A link between terrestrial gamma-ray flashes and intracloud lightning discharges, *Geophys. Res. Lett.*, *33*, L06803, doi:10.1029/2005GL025537.

Young, D. T., et al. (2005), Composition and dynamics of plasma in Saturn's magnetosphere, *Science*, *307*, 1262–1266.

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