Energetic Radiation From Galactic Cosmic Ray Interactions With Saturn’s Main Rings

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Abstract

Saturn’s main rings have an energetic particle and gamma ray photon radiation environment produced by ring interactions of galactic cosmic ray (GCR) protons and heavier ions penetrating the planetary dipolar magnetic field. Accurate models of this radiation environment are important for interpretation of Pioneer 11 and Cassini in situ measurements near the rings and for constraints on radiolytic contributions to neutral gas production and ice chemistry. A GEANT (GEometry ANd Tracking) based simulation is used to model flux spectra of protons, electrons, positrons, charged pions, neutrons, and gamma ray photons emitted from GCR interactions with H2O ice spheres approximating the ring material. Dependent on location in the A to D rings within the planetary magnetic field of Saturn, only GCR protons above respective energies of 20 to 72 GeV can reach the rings without being deflected away by the magnetic field. Calculated differential and integral fluxes from our simulations have good agreement with in situ Pioneer-11 measurements in selected energy channels. The charged particle and neutral radiation measurements are sensitive, respectively, to the sizes and areal mass densities of ring bodies. Computed gamma ray emission fluxes are 8% of our calculated limit for detection from the Earth by the Fermi Large Area Telescope. Addition of charged particle sensors and neutron-photon imaging spectrometers to a future Saturn Ring Observer mission would provide valuable information on the ring mass structure. The present paper provides a foundation for modeling of Pioneer 11 and Cassini radiation measurements across the main rings and future measurements of radiation from the rings.

Plain Language Summary

An invisible bath of GCRs continuously bombards Saturn’s main rings and generates showers of secondary charged particles, neutrons, and gamma rays. The Pioneer 11 spacecraft first detected these emissions during traversal underneath the A-B-C rings during its 1979 flythrough of the Saturn system. The Cassini spacecraft later traversed the same region during its 2004 orbital insertion at Saturn and in 2017 also crossed the innermost ring, the D ring, during its final Grand Finale orbits prior to final atmospheric entry. Modeling of these energetic radiation emissions can provide lower limits on the total mass of the rings, on the production of neutral gases from chemical products of the ring interactions, and on the background radiation responses of the instruments to better define Pioneer 11 and Cassini measurements. The modeling confirms the earlier Pioneer 11 result that the A-B rings are heavily populated by meter-sized bodies of ice and that there should be a significant rate of production for neutral gases such as oxygen and carbon dioxide. Understanding of the Pioneer 11 and Cassini measurements of the radiation emissions from the main rings could be improved by usage of the computed radiation flux spectra for instrument response simulations.

1. Introduction

The massive main rings of Saturn have central roles as sinks and sources for energetic particles and photons in Saturn’s inner magnetosphere. The high opacity and area densities of the A and B rings provide abundant target material for irradiation by galactic cosmic ray (GCR) protons and heavier ions, while the outer edge of the A ring at 2.27 Saturn radii (1 RA = 60,268 km) marks the inner absorbing boundary for trapped charged particles diffusing inward from the radiation belt environment beyond the main rings. To reach the main rings, GCR ions must first penetrate through the planetary magnetic field of Saturn with a vertical magnetic cutoff energy of at least 16 GeV (Cooper & Simpson, 1980; Sauer, 1980) for protons at the outer edge of the A ring, close to the energy ~14 GeV required for such protons to reach the equatorial atmosphere of the Earth. At Saturn, this cutoff energy increases to 38 GeV at the inner edge of the B ring at 1.53 RA and ultimately to...
72 GeV at the inner edge of the D ring at 1.11 Rs. The radiation belt particles are unrestricted in energy to reach the A ring but instead must survive encounters with moons, diffuse rings, and finally the narrow F ring (2.32 Rs) during inward diffusive transport from sources in the magnetosphere beyond the main rings. The radiation belt fluxes drop to background levels at the outer edge of the A ring, inward of which the radiation intensities are dominated by products of direct GCR interactions with ring bodies as we model in this paper.

The role of the main rings as sources for magnetospheric trapped radiation was first revealed by the discovery of high-energy proton radiation belts (Fillius et al., 1980; Simpson, Bastian, Chenette, Lentz, et al., 1980; Trainor et al., 1980; Van Allen, Randall, et al., 1980) beyond the rings from cosmic ray albedo neutron decay (CRAND). Neutron products of the GCR interactions, mainly in the more massive A and B rings, injected beta-decay protons and electrons into stable trapping regions between the A ring, the F ring, and the co-orbiting moons Janus and Epimetheus (2.51 Rs), Mimas (3.08 Rs), Enceladus (3.95 Rs), and Tethys (4.89 Rs). The measured radiation belt protons could not have reached these spatially confined trapping regions from other sources, for example, the outer magnetosphere, without severe losses at the moon orbits via inward diffusion from the outer magnetosphere beyond the orbit of Tethys. An in situ CRAND source from ring neutrons (Blake et al., 1983; Cooper, 1983; Cooper & Simpson, 1980; Fillius et al., 1980; Fillius & Mcllwain, 1980; Scharlt & McDonald, 1983; Van Allen, Thomsen, et al., 1980) was then proposed to account for the observed radiation belts in these regions. Another source of neutrons arose from GCR interactions in Saturn’s upper atmosphere, but the planetary magnetic field, the H-He atmospheric composition, and the high-latitude source geometry made this a relatively weak source (Cooper & Simpson, 1980). In comparison, the Earth’s inner radiation belt of trapped protons comes only from atmospheric CRAND protons (e.g., Lenchek & Singer, 1963). Van Allen, Randall, et al. (1980), Cooper (2008), and Kollmann et al. (2015) predicted variously that another CRAND proton belt would exist in the clear zone inward of the D ring. This innermost radiation belt region was first explored during the Grand Finale orbits of the Cassini Orbiter mission in April–September of 2017, but publications of the results by the Cassini investigators are still pending at present.

Pioneer 11 made the first measurements of energetic radiation directly from the A-B-C rings as it flew across these rings in 1979. Chenette et al. (1980) reported measurements of low but still significant intensities of energetic protons and electrons from the rings. These intensities declined toward Saturn as expected for the increasing energy thresholds of GCR primary ions irradiating the rings. The most comprehensive models of the ring radiation intensities were provided by Cooper et al. (1985) who modeled the GCR interactions and the resultant secondary proton, electron, neutron, and gamma ray flux spectra at Pioneer 11. Their work also confirmed that meter-sized bodies dominated the mass of the A and B rings. The very high opacity of the B ring limited definitive determinations of the B ring mass by Voyager, as cited by Cooper et al. (1985), and later by Cassini. Hedman and Nicholson (2016) have only recently confirmed the Pioneer 11 result for the B ring by analysis of hidden density waves, and a new mass determination is pending from publication of Cassini gravity science results from the Grand Finale orbits.

An updated review of the ring plasma and energetic radiation environment has recently been published by Cooper et al. (2018), including new calculations for energetic particle and gamma ray photon emissions at 10 keV to 1 TeV from the inner section of the A ring for the 20-GeV energy threshold of GCR proton irradiation. The present paper expands on these calculations for ring emission spectra closer to Saturn in the B, C, and D rings at higher vertical cutoff energies for ring body sizes now extending down to 1 cm in radius. These additional model spectra are provided to support the continuing modeling of the Pioneer 11 data, while also providing predictions of the penetrating radiation background for the more recent measurements by the energetic particle sensors (Krimigis et al., 2004) on Cassini Orbiter. For example, the energy thresholds and ranges, and the geometric factors, of specific channels in the Pioneer 11 High Energy Telescope (Cooper et al., 1985) need to be reevaluated for the expected radiation environment at Saturn’s rings as we model here. These spectra can also contribute to modeling of radiolytic chemistry for neutral gas production (Johnson et al., 2006) and evolution of non-H2O species in the rings. We also compare the computed gamma ray flux >100 MeV at Earth to the point-source detection limits of the Large Area Telescope (LAT) of the Fermi Gamma-Ray Space Telescope (Atwood et al., 2009) to determine whether Fermi LAT tracking of the Saturn ring emissions might be feasible. Far better measurements could be provided by gamma ray photon and neutron imaging spectrometers on a future Saturn Ring Observer (Abelson et al., 2006; Spilker, 2003) mission.
2. Model and Measurement Approach

The ring bodies in our model calculations are approximated as spheres of pure H₂O ice at unit density with radii in the range of 1 to 1,000 cm. Although Cooper (1983) originally did similar calculations with the approximation of the ring material as uniformly thick slabs of ice, we follow Blake et al. (1983) in using ice spheres as radiation targets. Cooper et al. (2018) have shown that the same results for secondary neutron fluxes at the 20-GeV vertical cutoff are obtained from an ice sphere of radius \( r = 75 \) cm as compared to an ice slab of thickness \( \sigma = 100 \) cm, consistent with \( \sigma = 4r/3 \) for the average column thickness of a sphere. Further results reported here extend that comparison for slabs equivalent to 300- and 1,000-cm spheres. More advanced work for the future would entail using ensembles of spherical bodies in size distributions presenting different segments of the rings, for example, as may be needed to model the angular distributions of neutron and photon emissions from the rings.

In the limit of highest ring opacity and mass density, as in the B ring, the slab approximation becomes more valid, but mass clumping in self-gravity wakes (Colwell et al., 2006, 2007) could still make the mass distribution inhomogeneous and roughly approximating the case of single spheres with some separation. We note that Blake et al. (1983) modeled the angular distributions of CRAND protons in the Saturn radiation belts beyond the main rings as arising from a planar field of discrete spherical emitters in the rings, so the parent neutron emissions may be coming from larger bodies sufficiently spaced not to block emissions from nearby bodies. This would be consistent, for example, with a differential size distribution \( n(r) \sim r^{-3} \) in which each decade of size contributes equally to optical opacity but in which total ring mass and radiation emissions are dominated by the largest and most widely separated bodies.

We use the MGEANT software suite (MGEANT, 2005; Sturner et al., 2000; Weidenspointner et al., 2004) for tracking of all primary and secondary particles and gamma ray photons in the simulations of ice sphere and slab irradiation. MGEANT is a versatile Monte Carlo simulation tool developed to expand the utility of the version 3.21 of the GEANT (GEometry ANd Tracking) Detector Description and Simulation Tool (Brun et al., 1994) developed originally at Conseil Européen pour la Recherche Nucléaire. MGEANT adds built-in primary particle spectral and beam models as well as various output options, while retaining the physics and tracking routines inherent to GEANT. MGEANT was developed mainly for simulations of gamma ray instruments on spacecraft but with wider applications, for example, to the full range of radiation in Saturn’s rings.

MGEANT/GEANT stores and transports all simulated energetic particles and gamma ray photons and simulates electromagnetic interactions from 10 keV to a few TeV, the energy range addressed in the present work. MGEANT uses GCALOR (Zeitnitz, 2005) for hadronic (proton, helium and heavier nuclei, neutron, pion) interactions and computations of resultant energy deposits in irradiated volumes of potentially complex geometry. GCALOR includes an updated version of the High Energy Transport Code used in the earlier ring radiation modeling of Cooper (1983) and Cooper et al. (1985) but covers lower (<15 MeV) energies, down to 10 keV, than the High Energy Transport Code. In the following text, we refer to the MGEANT/GEANT code suite due to the MGEANT heritage from GEANT.

MGEANT/GEANT covers many different kind of interactions, for example, interactions of hadronic particles (protons, neutrons, heavier nuclei, pions, and more exotic particles) with hydrogen and oxygen nuclei composing the water molecules in the ring ice. Elastic collisions exchange kinetic energy with target nuclei, as in billiard ball collisions, whereas inelastic collisions involve changes in excitation and/or composition of the target nuclei. A nuclear collision that generates secondary particles or gamma ray photons is inelastic. Electromagnetic collisions involve energy exchange of light charged particles (electrons, positrons, charged pions, and muons) or gamma rays with target particles and nuclei. An energetic electron interaction with a nucleus can, for example, involve a so-called bremsstrahlung process that emits a gamma ray or can excite the nucleus and cause emission of other particles or gamma rays. The primary tasks of the MGEANT/GEANT routines are to track the directions and energies of all incident and secondary particles and gamma ray photons, to compute the elastic or inelastic results of collisions, and to compute energies deposited during transport in the water ice of the ring bodies.

We follow Blake et al. (1983) in simulated irradiation of single spheres of water ice with different radii \( r = 1–1,000 \) cm corresponding to typical ring bodies that compose most of the mass in the main rings. For closely packed spheres in a plane, this is the approximate equivalent of irradiating a uniform slab of thickness \( d = 4r/3 \). In the densest part of the B ring, the slab approximation may better represent the average area density of
closely packed bodies, but elsewhere, there would be significant separation of the ring bodies so the single sphere approximation becomes more appropriate. In this work, we use the single sphere approach, so the simulations do not include blocking of incident GCR primary or escaping secondary radiation by neighboring bodies. As per Cooper et al. (2018), simulation of irradiation for a large ensemble of variously sized bodies more accurately representing the ring body distributions could provide better results on anisotropy of neutron and gamma emission but is beyond the scope of the present work.

The simulation begins with an isotropic bath of the outer surface of the target sphere with protons from the differential GCR proton distribution $J(E) = 1.6E^{-2.6}/cm^2 s sr GeV$ (Hayakawa, 1969) at energies of 20 GeV to 1 TeV where the approximation of a single power-law distribution remains valid. The low-energy threshold, which ranges from 20 to 72 GeV, is determined (Cooper & Simpson, 1980) by radial position within the planetary magnetic field. Surface fluxes into the target bodies are then $F(E) = \pi J(E)$. These threshold energies correspond to vertical magnetic cutoffs that approximate cutoffs averaged over all incident directions. Vertical cutoffs for incident directions aligned parallel or antiparallel to the local magnetic field from Saturn are constant everywhere along that field line for a dipolar field. The cutoff calculations otherwise remain rough approximations since we have not accounted for earlier interactions of GCR protons with other parts of the rings enroute to the computed point of incidence.

The computed fluxes are generally a sum computed from primary particles entering the sphere and secondary particles or gamma ray photons escaping from the spheres. For protons, we sum the incident and escaping fluxes of primary and secondary protons; otherwise, for gamma ray photons and other secondary particles, we compute only the escaping flux. The primaries enter from all directions isotropically onto the full surface of the sphere, and we average the escaping particle fluxes over all directions and the surface area of the sphere. We typically start the run with $N = 10^5$ primaries isotropically incident into the sphere surface. The integral incident flux $J_0$ into the surface of area $A = 4\pi R^2$ is used to normalize the flux calculations by the relation $J_0 = N_{\text{prim}}/A\Delta t$ to compute the time duration $\Delta t$ of the simulation interval. For $\Delta N_{\text{esc}}$ escaping particles or gamma ray photons in an energy interval $\Delta E$, the omnidirectionally averaged differential flux is then $J_{\text{esc}} = \Delta N_{\text{esc}}/(A\Delta t\Delta E)$. In all cases, the computed fluxes simulate incident and escaping radiation at the surfaces of the spheres as approximations to fluxes locally within the main rings. An instrument measuring this radiation would report a count rate related to the field of view of some part of the rings and to the geometric factor of the instrument.

Within the target body, the MGEANT/GEANT code tracks the energy losses to elastic collisions with atomic electrons and nuclei and the inelastic collisions with nuclei that generate secondary emissions of photons, protons, neutrons, electrons ($e^+$, $e^-$), pions ($\pi^+$, $\pi^-$, $\pi^0$), muons ($\mu^+$, $\mu^-$), and more short-lived particles. Each secondary particle or photon is similarly tracked, so that the result can become a shower of many secondary, tertiary, and even higher-order species, in addition to the residual flux of the primary proton. We then compute the average flux of primary protons into and out of the target sphere and the escaping fluxes of the secondary and higher order interaction products. The fluxes into and out of the sphere are all isotropic when averaged over millions of incident proton events, again on the approximation that incident and emitted fluxes are not blocked by neighboring bodies.

We have also simulated isotropic irradiation of uniformly thick ice slabs with similar calculations of the incident and exiting fluxes. The computational domain is limited by approximating the slabs as circular disks with axial radii larger than the disk thicknesses. The slabs are modeled as circular disks, typically with radii of 2,500 cm and the specified thickness 1–1,333 cm for each run. The disks are uniformly and isotropically irradiated on both sides from a larger cylindrical and noninteracting surface completely containing each disk. Increasing the radii of the disks does not change the results. Fluxes are computed similarly for spheres, except that the target area is the horizontal area of the disks. Escaping particle or gamma ray photon fluxes are averaged for both sides of the disks.

These simulations describe the direct emissions from the target spheres and slabs but do not include effects of charged particles mirroring back toward the ring bodies in the dipole magnetic field of Saturn. The maximum proton energies for mirroring and stable trapping increase from 2 GeV at 2.3 $R_S$ to 11.5 GeV at 1.1 $R_S$ (Cooper & Simpson, 1980). Cooper (1983) found that only the first interactions of primary GCR protons with the A and B ring material were significant and that mirroring particles there contributed little to total secondary production. But the higher trapping energy at 1.1 $R_S$ near the D ring could increase total yields of GCR
interactions due to <12-GeV secondary charged particles that mirror back to the ring plane and interact with ring bodies. Cooper (1983) did not model interactions in this region.

In this report, we reference the Pioneer 11 energetic particle and photon measurements of Cooper et al. (1985) that came from the High Energy Telescope of the Charged Particle Instrument suite (Simpson, Bastian, Cheneette, McKibben, et al., 1980) from the University of Chicago. The High Energy Telescope used a stack of solid-state Si and Csl detectors to measure the types and energies of incident charged particles and was designed with an active anticoincidence shield to minimize interference from side-penetrating radiation. This configuration included a neutral mode in which only photons and neutrons could register events in an internal stack of detectors without triggering the shielding detectors. Energy thresholds of some detectors were set high to avoid response to gamma rays below 3 MeV from the spacecraft's Radioisotope Thermal Generators. But the radiation environment of Saturn's rings and magnetosphere was completely unknown in the instrument development phase prior to the 1973 launch of Pioneer 11, so the design could not completely account for anomalous responses to the very energetic radiation from the rings as we model in the present paper. The ring radiation spectra that we compute now with the MGEANT code suite will in future work be used to recalibrate the foreground and side-penetrating background responses to the ring radiation environment. For example, a particular energy channel for lower energy protons could be partially or even wholly responding to ring radiation protons and other particles or gamma ray photons at much higher energies. For now, we assume the same instrument energy channels and geometric factors as used by Cooper et al. (1985) for the measured fluxes we compare to the model fluxes.

3. Model Results

3.1. Protons

The energetic proton radiation environment of the main rings has contributions from primary GCR and secondary protons and from neutron decay protons, as shown in Figure 1. Most protons below 20 GeV in these flux spectra, except some primaries emitted after energy loss, originate either as proton or neutron secondaries from interactions of the GCR protons with ring bodies of various sizes that we model in Figure 1 as water ice spheres of selected radii of 1, 15, 75, and 200 cm. Later, we show that ice spheres and equivalently thick ice slabs give similar results. Penetrating GCR and secondary production fluxes are dominated by ring bodies of radii < 1 cm, as shown by the present simulations, so we have not included calculations for smaller bodies that may otherwise dominate optical opacity. Occasionally, some interactions will arise from GCR passage through a series of smaller to larger particles, but we are not yet able to include such events in our simulation.

Peak fluxes occur from source bodies between 200 and 300 cm, and results from these two sizes are nearly the same. Simulations for ring body radii up to 1,000 cm give spectra comparable in magnitude to those from 75-cm spheres and mainly consisting for the
larger spheres of contributions to the total emitted flux from radiation that reflects back from the irradiated surface and not from radiation penetrating through the sphere from other directions. That is, the fluxes rise to a maximum for 200–300 cm spheres and then decrease to a roughly constant lower level for larger bodies. In Figure 1 we additionally show the flux spectra for each size that are produced at GCR proton energy thresholds of 20, 34, and 72 GeV that correspond to equatorial distances from Saturn of 2.1, 1.5, and 1.1 Saturn radii (Rₙ) that span the A to the D rings. The primary and resultant secondary fluxes decrease toward Saturn as expected for the power law form of the primary GCR proton spectrum and the energy-dependent production yields of secondary radiation.

The secondary proton flux spectra clearly show variations in shape and intensity with source body size. Ring bodies of radii much larger than 1 cm generate secondary spectra with peaks around 100 MeV, for which the proton stopping range from ionization energy loss (SRIM, 2013) is 7.6 cm. The peak flux energy shifts downward to 10 MeV (stopping range ≈ 0.12 cm) for 1-cm bodies and presumably to lower energies for smaller bodies that we have not yet modeled. A 100-MeV proton deposits most of its energy within our model bodies of radii ≥5 cm but leaves little of its energy in the 1-cm bodies, for which the stopping energy is 33 MeV at 1 cm. We attribute the falling proton spectra below 10–100 MeV to ionization energy losses and spectra decreases above these peak-flux energies to nuclear interactions.

The neutron-decay proton spectra shown in Figure 1b have very different shapes from those of the direct protons and reflect mainly the spectra of the source neutrons, as shown later in Figure 3, and undergoing losses only from nuclear interactions and not energy losses from atomic ionization. The decay proton injection rates (p/cm² s² sr MeV) are first computed from jₚ/τₚ, in terms of neutron flux jₙ (n/cm² s MeV), relativistic Lorentz factor γₚ, and neutron rest-frame lifetime τₙ = 882 s, and then multiplied by a trapping lifetime ~1 s, approximately the latitudinal bounce time in the local dipole magnetic field (Thomsen & Van Allen, 1980), for reabsorption by the rings to give the decay proton flux (p/cm² s sr MeV).

The neutrons have a mean pathlength λ for decay given by their mean relativistic lifetime γₚ, the relativistic Lorentz factor γₚ times their velocity vₐ. The differential probability of decay in any smaller distance interval Δλ < λ, even close to the source point, is just Δλ/λ. The decay length for the lowest energy neutrons we simulate at 10 keV is 1.2 × 10⁸ km or 20 Rs, so there is negligible drop in flux within the main ring and inner magnetospheric regions. Interestingly, the decay pathlengths of 1–10 eV neutrons are 0.20–0.63 Rs so thermal neutrons from the rings would contribute to the thermal proton population of the rings and the inner part of the magnetosphere beyond the rings.

The computed neutron spectra are steepened at GeV and higher energies by the relativistic increase of the neutron lifetime in the reference frame of the ring environment. The energy loss collisions flatten all the computed spectra below 100 MeV for larger bodies and 10 MeV for smaller bodies, but the fluxes still increase slowly toward the lowest energies. Subsequent interactions with small grains in the rings would preferentially deplete the lower energy protons, since these have higher ionization energy loss rates (dE/dx) than higher energy protons, so the equilibrium flux spectra of trapped protons, balanced between sources and losses, could have minima at lowest energies.
These proton model results are partially constrained by Pioneer 11 measurements (Chenette et al., 1980; Cooper et al., 1985) from the spacecraft traversal underneath the A, B, and outer C rings during its 1979 encounter with the Saturn system. The differential proton fluxes from Table 2 of Cooper et al. (1985), as plotted here in Figure 1, fall in the model range for secondary proton emission from single source bodies of radii 1–200 cm on the low mass side and 300–1,000 cm on the high side. Here we take these limits from the model data (not all shown in the figure) for the 20 and 34 GeV vertical cutoff energies that span the Pioneer 11 traversal of the A and B rings. If we discount the 20–30 MeV flux measurement with the largest error limits, the low mass range increases to 10–200 cm. The 67–400 MeV flux has the smallest error bar and puts the low mass range at 30–200 cm. Integral fluxes from that same table (Cooper et al., 1985) for proton energies above 67 and 400 MeV are shown in Figure 4 and fall closer to integral versions of the model flux spectra from 75-cm ring bodies for trapping energy limits at several GeV.

### 3.2. Electrons and Pions

The total electron (electron + positron) model spectra in Figure 2 show broad maxima centered around 1 MeV for all source body sizes and radial positions within the rings. This is apparently because the $dE/dx$ ionization energy loss is more constant for electrons than protons in this energy range, so the peak flux energy does not vary as much as for protons from $r = 15$ to 1 cm in Figure 1. The electron fluxes below 100 MeV generally exceed the proton fluxes from Figure 1 at these energies for large ring bodies. The plotted total electron fluxes from Pioneer 11 show both the expected increase toward 1 MeV for all spectra and the large electron/proton ratio only consistent with larger source bodies. The lower limit on the ice sphere radius is 75 cm for the 2–8 MeV flux and 100 cm for 8–25 MeV. Later in Figure 4, we show that the model integral electron flux above 25 MeV from the 75-cm ring body source is close to the Pioneer 11 value.

The flux spectra for escaping charged pions, those not decaying already within the source bodies, resemble those of direct protons in Figure 1A from larger ring bodies with peak fluxes near 100 MeV. Along the 1979 trajectory of Pioneer 11 under the A-B-C rings, the short-lived ($\tau_p = 2.6 \times 10^{-8}$ s) charged pions would have all decayed first to muons and neutrinos and then subsequently from muons ($2.2 \times 10^{-6}$ s) to electrons and neutrinos. The spacecraft would have only seen the final decay electrons, and significant fractions of the charged pion energies would have escaped with the decay neutrinos. In similar calculations for other GCR interaction environments, for example, the atmosphere of the Saturn moon Titan, we have found that about 36% of the incident GCR proton energy is lost to neutrinos. The percentage of energy loss from only charged pions and muons, the main neutrino sources, is higher.

### 3.3. Photons and Neutrons

Figure 3 shows that the dominant flux component below 100 MeV from the larger ring bodies is photonic. The different shapes of photon spectra from large and small bodies arise from higher probability of tertiary interactions within the larger bodies and of direct escape from the smaller bodies. The 10-MeV spectral minimum separating the neutral pion ($\pi^0$) decay source of higher energy photons from the bremsstrahlung, nuclear line emission, and other source processes at lower energies is most evident for the 1-cm sources and increasingly smeared out by internal scattering for the larger sources. The narrow spectral peaks for 0.511- and 2.2-MeV photons arise, respectively, from $e^- e^+$ annihilation and neutron capture in hydrogen nuclei, both processes being more likely in larger bodies as compared to $e^-$ and neutron escape from small bodies. Other photonic emission lines at 6.129, 6.917, and 7.117 MeV from oxygen nuclei in water ice are present but not visible in the low-resolution broad-band spectra presented here. These lines have been shown at higher spectral resolution by Cooper et al. (2018), who also modeled the strong 4.438-MeV line for carbon in mixed ices.

The spectral characteristics of the model neutron spectra in Figure 3 include a shift in the spectral break at 100 MeV for large source bodies to 10 MeV for smaller ones. This is the same shift occurring for the
neutron-decay proton spectra in Figure 1. In all cases, the neutron fluxes increase only slowly toward lower energies, because low-energy neutrons rapidly lose energy in elastic collisions with hydrogen nuclei in water ice. Energetic proton measurements from Voyager (Krimigis & Armstrong, 1982) and Cassini (Armstrong et al., 2009; Roussos et al., 2011) have shown a rapid increase below 10 MeV in CRAND proton fluxes beyond the main rings. Kollmann et al. (2013) modeled the radiation belt fluxes with the assumption that this increase arose from the source neutron spectrum, but the present work rules that out for neutrons from the main rings. This confirms the similar result of Cooper et al. (2018) for the ring neutrons, but they also found no large low-energy increase in fluxes of neutrons from GCR interactions in Saturn’s upper atmosphere. Any actual increase in the proton fluxes below 10 MeV, if not from penetrating radiation background in the low-energy proton channels, would then need to come either from non-CRAND sources such as local ionization and trapping of energetic neutral atoms from the magnetosphere or from energy-dependent time evolution of the proton spectrum during trapping.

The Pioneer 11 measurement of gamma ray flux at 15–40 MeV (Cooper et al., 1985) best matches the model curves for minimum ice sphere radii of 33 cm at the 20-GeV GCR energy threshold and ~45 cm at the 34-GeV threshold. As we have already discussed for the proton and total electron measurements, the maximum size could be much greater than 200 cm up to the 1,000-cm extent of our modeling. As we discuss later in section 4, the gamma ray measurement may be more indicative of the areal mass density, as averaged over the A and B rings, than of ice sphere size that is better represented by the proton and electron-positron measurements.

### 3.4. Integral Fluxes

In Figure 4 we address relative contributions from low- and high-energy segments of the distributions through the integral flux spectra and average energies of those spectra. One can also clearly see the relative integral fluxes of the different radiation components, for example, as dominated by gamma rays at energies below 100 MeV and by direct protons at higher energy. The neutron-decay protons would only become the dominant charged particle component in radiation belt regions beyond the rings where there was no direct in situ production of electrons. The e⁻ and e⁺ flux spectra are shown separately, differing slightly below 10 MeV but becoming identical above 100 MeV, and are consistent with pair production at high energies by π⁰-decay gamma rays and some e⁺ annihilation at lower energies. In other work with our MGEANT/GEANT simulations, we have found no significant difference in how a solid-state detector system such as the Pioneer-11 High Energy Telescope responds to these opposite charge states of electrons.

In the same figure we compare integral flux measurements from Pioneer 11 to the model integral spectra and find good agreement for neutrons >15 MeV and electrons >25 MeV. The integral flux measurements for protons >67 and >400 MeV are below the model curve for direct protons if the maximum energy is not limited. However, these proton flux points are closer to the trapped proton curve when we limit the proton energy to 2.5 GeV as per the formula \( P = 15/L^2 \) GeV for maximum momentum \( P \) of trapped charged particles in terms of McIlwain \( L \) value (Cooper, 1983; Cooper & Simpson, 1980). In conjunction with the present ring radiation model, the differential and integral flux measurements from Pioneer 11 could collectively support ring mass densities \( \geq 100 \) g/cm\(^2\) but do not really provide an upper limit. Even a lower mass density ~60 g/cm\(^2\) (Cooper et al., 1985) is not yet ruled out, since the measurements have not yet been calibrated with MGEANT/GEANT calculations in respect to the broad energy ranges of penetrating gamma ray photon and particle fluxes from the present work.

### 4. Spheres, Slabs, and Areal Mass Density

Finally, we show in Figure 5 the comparison of flux spectra for neutrons and gamma ray photons from the two extreme approximations of ring material as ice spheres and flat slabs of ice. Sparser distributions of meter-sized bodies in the A, C, and D rings might be best approximated as single spheres, whereas the
high opacity and mass of the B ring might be more appropriate to the slab approximation. But for the results shown from ice spheres of radii 300 and 1,000 cm in comparison to the equivalent 400- and 1,333-cm slabs, there are no significant differences in spectral shape and only small differences in absolute flux magnitudes. We pick these two comparisons mainly to test our assumption that scattering out of the edges of the circular slabs does not introduce errors. All the simulated slabs have radii of 2,500 cm, so thinner slabs would be even less likely to show edge scattering effects. The 1,000-cm sphere and 1,333-cm slab curves have similar fluxes to those for 75-cm spheres in Figure 3, so there is no great drop in flux in the limit of larger bodies. As discussed below, this results in our not being able to limit the maximum mass of the rings by comparison to Pioneer 11 flux measurements.

In our treatment of slabs, we have not addressed any further secondary production by charged particles mirroring back to the rings in the planetary dipole magnetic field. In Figures 1–3 we have shown however the earlier results for 100-cm ice slabs at the 20-GeV primary proton energy threshold. These results came from earlier generation radiation transport models but did include multiple mirroring through the ring plane of charged particles and escape of neutrons and gamma ray photons. The neutron result (gray open circles in Figure 3) shows close agreement to the MGEANT/GEANT results but only included neutrons above 15 MeV that could be transported by the older codes. The new fluxes show significant differences for protons and gamma ray photons below 100 MeV and electrons below 10 MeV. These differences have shifted the comparisons of the computed fluxes to the Pioneer-11 measurements in these figures from the earlier comparison of Cooper et al. (1985).

Now we address the question of whether the particle flux measurements constrain the areal mass density or the average sizes of ring bodies in the rings. Except for the integral flux data shown in Figure 4, the Pioneer 11 measurements are all at energies far below the trapping limits for protons and electrons, so those measurements are associated with charged particles that are magnetically trapped as long as they are not stopping in ring bodies.

Do longer trapping times of secondary charged particles in less dense rings compensate for fewer source body sites of GCR interactions to determine the time-averaged trapped flux? If the average mass density is for example 25 g/cm², for example, in the A ring, but the average pathlength through each of the ring bodies is 100 g/cm² for spherical radii of 75 cm, then we could assume that 75% of the ring plane area is empty of bodies large enough to significantly stop mirroring charged particles. Such particles have then only a 25% chance of impacting a ring body during each pass through the ring plane and survive on average for two latitudinal bounce periods, for example, for several seconds.

For more general cases we imagine an infinite row of ice spheres of the same size, but only every Nth (1 to infinity) sphere, for example, N = 4 for 25% areal coverage by massive bodies, has a mass sufficient to emit secondary protons from GCR interactions with that sphere and stop charged particles produced by other Nth spheres of the same mass. Any other spheres between the massive spheres are empty with no mass, produce no secondaries from GCR interactions, and are transparent to charged particles passing through them. The massive spheres emit secondary charged particles with a certain outward flux as we compute from our GCR interaction model. But because of magnetic mirroring, the omnidirectional flux from the total of the secondary and mirroring protons is everywhere constant, even at locations of the empty spheres. This would also be true for a planar field of massive and empty spheres located anywhere in the main rings, as well as for any value of N ≥ 1. The GCR proton flux is defined as constant everywhere in this planar field, but interactions and secondary proton production occur only at the massive spheres. The result is that the average secondary + mirroring proton fluxes in any direction near the rings, and below the magnetic latitudes of mirroring, are everywhere equal to the outward surface fluxes of secondary protons from any massive sphere.

This means that measurements of the average directional fluxes of charged particles near the ring plane by Pioneer 11 and Cassini are actually measurements of the outward surface fluxes from the massive spheres. This then allows us to determine average sizes of the massive bodies in conjunction with the model surface fluxes given in this paper and earlier by Cooper et al. (2018) using the same MGEANT/GEANT software. This does not, however, allow us to constrain the areal mass density of the rings but only the average ring body sizes that are sources of secondary protons at low enough energies to stop in these massive bodies, for example, less than 500 MeV (SRIM, 2013) for ice sphere pathlengths of 1 m. The integral flux spectra in Figure 4 show that much of the secondary proton flux is below this energy.
A similar approximation applies for electrons and positrons with a maximum energy of 70 MeV (ESTAR, 2018) for the 1-m pathlength, but not for neutrons and gamma rays that do not of course mirror in the magnetic field. Measurements of the latter are sensitive only to the areal mass density, for example, inversely proportional to $N$, and not to the average sizes of massive ring bodies. Together, however, the charged and neutral flux measurements can determine the average sizes and ring areal density. The Pioneer 11 measurements of gammas and neutrons are therefore unique since Cassini energetic particle instrumentation (Krimigis et al., 2004) could not measure these neutral energetic species.

This situation changes when the secondary particle energies are so high that their subsequent encounters with ring bodies generate tertiary particles, which might then further interact to produce further generations in cascading showers of interaction products. This could occur, for example, in the D ring at 1.1 $R_S$ where all secondary and higher generation protons (electrons) are trapped up to 11.5 (12.4) GeV. The average trapped flux would then be determined by the total yield of all these interactions after the initial interaction of the parent GCR proton. This effect could boost the trapped fluxes predicted by Kollmann et al. (2015) for an innermost radiation belt in the D ring region from the CRAND source.

Next, we consider the case of the densest part of the main rings where an incident GCR proton may pass through multiple large bodies and trapped secondaries again survive for only one-half bounce period. The best approximation to this situation would be an ice slab of thickness $\geq 1,000$ cm, for which there would no significant increase in secondary flux for increasing thickness, because secondary particles then escape only from the outer edges and not from the centers of the slabs. In this case, the trapped particle fluxes would be independent of the ring mass mostly distributed among the largest ring bodies, so measurements of the fluxes would not constrain an upper limit on ring mass.

Lastly, the least dense parts of the main rings, for example, within the Cassini Division between the A and B rings, could be characterized by an absence of larger bodies swept up in gravitational interactions with shepherding moons. Low trapped particle fluxes would then arise from low yields of secondary trapped particles from GCR interactions with smaller ring bodies, for example, of spherical radii 1–15 cm for which we show the proton and electron emission fluxes in Figures 1 and 2. Overall, the trapped particle fluxes would correlate via the secondary production yields to the average size of ring bodies but not to areal mass density or opacity.

**5. Discussion and Conclusions**

The main ring emissions and interactions are central to the understanding of Saturn’s magnetospheric environment including the neutron source of CRAND proton belts outward and inward from the main rings and indirect limits on the A and B ring masses in conjunction with the GCR interaction model extended here. The simulation data on GCR interactions with the main rings can also be used to calibrate the responses of the more recent energetic radiation measurements of Cassini as compared to the first measurements in the Saturn ring system by Pioneer 11. That is, it is crucial to understand how penetrating radiation at higher energies than the nominal response energy ranges of the Pioneer 11 and Cassini energetic radiation detectors can add to the detector channel counting rates and affect the measured flux values, for example, those reported from Pioneer 11 data by Cooper et al. (1985). Finally, we address whether the gamma ray emission might be detectable from the Earth and what instruments might be desirable for inclusion on future missions to Saturn.

In our comparisons above of the model flux spectra to the Pioneer 11 fluxes, we use the measured fluxes from Table 2 of Cooper et al. (1985). These fluxes were based on nominal energy channels and geometric factors determined from laboratory and Monte Carlo code calibrations available at the time. However, these calibrations did not include anomalous response effects that will be addressed by MGEANT/GEANT simulations in our future work, so our conclusions now on the model versus measurement comparisons remain preliminary. For example, higher energy particles and gamma ray photons can scatter within the instrument and interact to produce secondaries that trigger valid events in the nominal response ranges. We also expect some contamination of the instrument’s neutral mode for neutron and gamma ray data from charged particles that happen to pass through small gaps between the active shielding detectors. Our computed ring radiation spectra from this paper can be applied to background calibration for Cassini’s Magnetospheric Imaging Instrument (Krimigis et al., 2004), for example, for the Low-Energy Magnetospheric Measurement System (LEMMS) sensor that employs passive but not active shielding to minimize side-penetrating radiation.
Measurements of charged particle, neutron, and gamma ray radiation constrain only the minimum mass of the rings, since the secondary emissions from GCR interactions reach constant levels for ring body sizes greater than several meters. In Section 3 we have indicated what ranges of ice sphere radii \( r \), or equivalently of ice slab thicknesses \( 4r/3 \), are consistent with the Pioneer 11 measurements. For this analysis, we used our full set of model curves for spheres of radii 1, 5, 15, 30, 75, and 200 cm, the curves for 5, 30, and 50 cm not being shown in the figures of Section 3. Minimum sizes from secondary proton data of Figure 1 and our full set of model curves are 1–50 cm, but the 67–400-MeV data have the smallest error limits and put the minimum at 30–50 cm. The electron-positron data of Figure 2 have relatively narrower error limits for minimum sizes of 75–100 cm. The gamma ray data of Figure 3 also have smaller error limits than the proton fluxes and indicate minimum sizes of 33–45 cm. Overall, we put the minimum size (slab thickness) at about 40 (53) cm and cannot constrain the maximum size. This remains consistent with the original results of Cooper et al. (1985), who found 50-cm slab thickness averaged over the entire Pioneer 11 traversal of the A-B-C rings and 60–90 cm for only the B ring. Our results supersede theirs with our more advanced MGEANT/GEANT modeling capability but do differ in not being able to constrain the upper mass limit of the rings.

The maximum size of the main ring bodies could be tens of meters in radius, consistent with the observed thicknesses of ~5–30 m of the A, B, and C rings but which are not directly detectable by imaging. There are observed moonlets of size 10^2 m, for example, S/2009 S 1 in the B ring, observable only by their shadows and by dynamical (e.g., propeller) effects on the bulk of local ring material. Massive ancient rings (Charnoz et al., 2009; Esposito et al., 2008) with average area densities of \( \geq 100 \text{ g/cm}^2 \) (\( r \geq 75 \text{ cm} \)) have been suggested. These massive rings could consist of “granola bar” clumps of self-gravitating material (Colwell et al., 2006, 2007) separated by clear regions, all still far below optical limits of detectability. Contrary to our earlier assessments in Cooper et al. (1985, 2018), we now find that we cannot rule out such massive rings.

We also find that different types of energetic radiation reveal separate mass characteristics of the rings. Fluxes of charged particles at energies below local magnetic trapping limits would correlate to the average size of ring bodies interacting with incident GCR protons but are insensitive to areal density of bodies in regions where there are open areas between the bodies. Areal mass density is however probed by measurements of neutral emissions for neutrons and gamma rays. Both charged particle and neutral radiation fluxes from GCR interactions could be higher than earlier expected from models (Kollmann et al., 2013) for emissions from the D ring where secondary charged particles are magnetically trapped at 10-GeV energies and can increase radiation yields through continuing interactions with ring material, for example, with larger bodies in the ring body size distribution that are not detected through opacity measurements dominated by smaller bodies. This secondary interaction effect could increase the trapped particle intensity in that region, soon to be reported from Cassini LEMMS measurements during the Grand Finale orbits of 2017, above the level predicted by Kollmann et al. (2015).

Ring mass also potentially connects to the problem of how much the GCR and secondary interactions contribute to the ring neutral gas atmosphere through radiation chemistry. Neutral gas production by radiolysis, the radiation-induced decomposition of water and other ring molecules into volatile gases such as H₂, OH, and O₂, potentially provides an upper limit on total ring mass and hence also on maximum ring body size, since more GCR energy (Cooper et al., 2018) becomes available for radiolytic processing in bodies of increasing size. Johnson et al. (2006) computed a photolytic flux of \( 10^6/\text{cm}^2 \text{s} \) for neutral O₂ emission from the rings from solar ultraviolet irradiation but found the radiolytic flux from GCR interaction products to be an order of magnitude lower. However, strong seasonal variability up to several orders of magnitude (Christon et al., 2013, 2014; Elrod et al., 2012, 2014) of the magnetospheric O₂⁺ and other heavy ion population beyond the rings argues against the GCR energy source that varies only slightly over decadal time scales at energies above 20 GeV. Roussos et al. (2011) report long-term changes of CRAND proton fluxes by less than a factor of 2 during the Cassini mission; the GCR flux at the ring neutron source for CRAND in the radiation belts would vary comparably.

There is also the problem that GCR fluxes and the resultant radiolytic production rates of O₂ gas would be highest at the 2009 solar activity minimum when the measured O₂ densities were at minimum levels. A solution to this problem could be that GCR-driven radiolysis in the volume ring ice could be biased against O₂.
production (Cooper et al., 2018) in favor of other oxidants such as H$_2$O$_2$ that cannot escape from the ice at seasonally varying ring temperatures below 80 K. These trapped oxidants could then oxidize hydrocarbon contaminants in the rings to produce escaping mass-28 CO molecules that are detected in the outer magnetosphere as CO$^+$ ions (Christon et al., 2014). In any case, the observed O$_2^-$ density and its seasonal variation in the inner magnetosphere does not constrain the total ring mass and the maximum sizes of ring bodies.

Finally, we address whether the Large Area Telescope (LAT) of the Fermi Gamma-Ray Space Telescope (Atwood et al., 2009) could remotely detect the Saturn ring photons from the Earth orbit. If the gamma ray emission could be measured as a function of seasonal variance, that is, the angle of the Earth to the ring plane, this could provide (Cooper et al., 2018) a probe of mass distributions in the main rings and put further constraints on GCR interactions as a source for CRAND radiation belt protons within and beyond the rings. Extrapolated to the ring boundaries, our model fluxes integrated above 100 MeV are, respectively, 0.052 and 0.040/cm$^2$ s sr for isotropic photon emissions at peak flux from model bodies of 200-cm radius in the A and B rings. The LAT has a three-sigma sensitivity of $\sim$1.5 $\times$ 10$^{-9}$/cm$^2$ s above 100 MeV for point sources observed away from the galactic disk for 10 years. Note that this disk is tilted at 60° to the Ecliptic so that Saturn is more often in celestial sky regions of high LAT sensitivity. The seasonally averaged projected areas of the visible A and B rings (16% partially blocked by Saturn) with respect to the Earth are about 2.2 $\times$ 10$^{19}$ and 3.2 $\times$ 10$^{19}$ cm$^2$. At 10 AU, the total A-B ring flux onto the LAT is then 1.2 $\times$ 10$^{-10}$/cm$^2$ s, 8% of the detection limit.

However, our calculation above is for omnidirectional emission of >100 gamma ray photons from the rings. However, Blake et al. (1983), as later discussed by Cooper et al. (2018), showed in the comparable case of neutrons that the fluxes would be highly directional with peak flux tangential to the ring plane. This is because the density of ring body sources in the field of view is more concentrated at tangential than vertical angles to the ring plane. This effect dominates over the decreasing projected area of the rings at tangential angles. So our computed gamma ray flux at Fermi may be a lower limit, and the cumulative directional flux toward the Earth over many years of observation could be closer to the Fermi limit.

Better results for gamma ray and neutron radiation measurements from the rings could be obtained by placing even smaller instruments in far closer proximity to the Saturn system. A suggested Saturn Ring Observer mission (Abelson et al., 2006; Spilker, 2003) could for example carry imaging spectrometer instruments measuring gamma rays and neutrons from the rings, while also conducting in situ measurements of charged particles within the rings. Cooper et al. (2018) noted the potential value of gamma ray and neutron anisotropy measurements in probing the ring mass structure and of gamma-spectroscopy in probing non-H$_2$O composition, for example, carbon perhaps associated with methane and more complex hydrocarbons. Detection of relatively strong emission lines from oxygen, neutron capture on hydrogen, and electron-positron annihilation would provide benchmarks for detection of other elemental species in the rings.

References


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