A Photometric Model of Saturn’s Inclined F Ring

Britt Scharringhausen
brs@astro.cornell.edu

Department of Astronomy, Cornell University
Outline

- An introduction to the F ring.
- F ring photometric properties.
- The F ring and ring plane crossings.
- The inclination of the F ring.
- A photometric model including inclination.
Discovery of the F ring

- First detected by Pioneer 11 in forward-scattered light.
- “Shepherd” moons Prometheus and Pandora detected by Voyager 1 in 1980.
F ring complexity

- Strands, braiding due to interactions with Pandora and Prometheus
Longitudinal variations

- In spacecraft images, the brightness of the F ring varied by as much as a factor of 4 over 150° in longitude.

- Clumps observed in Voyager images, persist for weeks, but not months.

Voyager 1 image.
Longitudinal variations

- In spacecraft images, the brightness of the F ring varied by as much as a factor of 4 over 150° in longitude.

- Clumps observed in Voyager images, persist for weeks, but not months.

Voyager 1 image.

But we are going to ignore all this . . .
F ring photometric properties

- Geometric albedo depends on the phase function, \( g(\alpha) \), and the single-scattering albedo, \( \bar{\omega}_0 \). The F ring is typically modeled using a two components:
  - Macroscopic particles, \( r \gg \lambda \)
    - Strongly backscattering, “Callisto type” phase function.
  - Dust, \( r \sim \lambda \)
    - Strongly forward scattering, Mie scattering.
- The light scattered by the F ring is dominated by dust, (>98%) even in back-scattering.
Ring Opening Angle

![Graph showing the opening angle of rings over time. The graph includes lines for Earth, Sun, and the ring plane, with data points for 1995, 1996, and 1997.](image)
How thick are the rings?

- Scattering of radio waves from the Voyager 1 occultation experiment find a physical thickness of $<200 \text{ m.}$
- Voyager 2 photopolarimeter observations of a stellar occultation imply a thickness $<50 \text{ m.}$
- RPX observations find a photometric thickness $\approx 1–2 \text{ km.}$
How thick are the rings?

- Scattering of radio waves from the Voyager 1 occulation experiment find a physical thickness of <200 m.
- Voyager 2 photopolarimeter observations of a stellar occultation imply a thickness <50 m.
- RPX observations find a photometric thickness \( \approx 1–2 \) km.

Why are RPX thickness estimates larger?
F ring dominates at RPX

- Unlike the main rings, the F ring probably has considerable vertical extent.
- Since the F ring is usually lost in the light of the main rings, RPX is the only chance to study the F ring from Earth.
Poulet Model

Based on images from the 1995 RPX, Poulet et al. 2000 modeled the F ring as a "ribbon" of uniform radial optical depth

- $\tau_r \approx 0.2$
- $h=21\pm4$ km.
- Despite very limited phase angle coverage, solved for the phase function and albedo.
  - Two populations of ring particles: large particle and dust
  - $>90\%$ dust.
RPX brightness asymmetry

HST image
10 Aug 1995
$\sim$22 h UT

August 1995 ring plane crossing

Vertically integrated $\Psi$ (km)

UT (hr), 10 August 1995
Inclination of the F ring

The dark side of the rings, Nov. 1995

- HST observations of a stellar occultation in 1995 by Bosh et al. (in prep.) show that the F ring is inclined by \(0.0067 \pm 0.0006^\circ\).
F ring photometric models

Poulet-type uniform ribbons.

Uninclined F Ring

Vertical scale exaggerated 2000 ×. Ring opening angle: 0.005°.
F ring photometric models

Poulet-type uniform ribbons.

Uninclined F Ring

Inclined F Ring

Vertical scale exaggerated 2000×. Ring opening angle: 0.005°.
Changing geometry

1995/8/10 20.5 UT

1995/8/10 22.0 UT

1995/8/10 23.5 UT

1995/8/10 25.0 UT
Unitless reflectance.

- $I$ = intensity of reflected light, $\pi F$ = received sunlight
- Lambert scatterer has $I/F = 1$.
- We compute the $I/F$ of the rings using the following formulae:
  - Reflected sunlight:
    $$I/F = \frac{1}{4} \omega_0 g(\alpha) \frac{\mu_s}{\mu + \mu_s} e^{-\tau(1/\mu + 1/\mu_s)}$$
  - Diffusely transmitted sunlight:
    $$I/F = \frac{1}{4} \omega_0 g(\alpha) \frac{\mu_s}{\mu - \mu_s} \left( e^{-\tau/\mu} - e^{\tau/\mu_s} \right)$$
  - Ring light transmitted through the F ring:
    $$I/F = I/F_0 e^{-\tau/\mu}$$
Vertically integrated I/F

- $VIF = \int I/F \, dz$
- Because I/F is a unitless reflectance, VIF has units of length, corresponding to the equivalent height of a Lambertian reflector.

Average VIF

- $\langle VIF \rangle = \frac{1}{120,000 - 80,000 \text{km}} \int_{80,000 \text{km}}^{120,000 \text{km}} VIF \, dr$
- Characterizes the total brightness of the rings.
Model Layers: Image
Model Layers: Plots

1995/8/10 25 UT.

Distance from Saturn Center (1000 km)

Vertically integrated reflectance (km)

East

West

Back of F ring, masked by main rings
Main Rings
Light blocked by the F ring
Front of F ring, reflected light
August 1995 ring plane crossing

Vertical integrated | (km)

- east
- west

UT (hr), 10 August 1995

CU Astronomy Department Colloquium, 31 October 2002. – p.20/31
We model the F ring with a gaussian profile of 

$$\tau_r(h) = \tau_0 e^{-(h/h_0)^2}.$$  

We can then vary the following parameters:

- $h_0$: Shape of profile.
- $\tau_0 = \tau_r(h = 0)$: vary the overall opacity of the F ring.
- $g(\alpha) \cdot \omega_0$: the albedo of the F ring particles.
Parameters: $h_0$ and $\tau_0$

- Constrained by equivalent depth:
  \[ D = \int \tau_r dh = \int \tau_\perp dr \sim 3-7 \text{ km}. \]

- Since $\tau_r = \int n dr$ or $\tau_\perp = \int n dz$, it doesn’t matter whether $D$ is measured $\perp$ or radially.

![Equivalent depth: 7 km](chart.png)
Parameters: \( g(\alpha) \cdot \omega_0 \)

- Not enough phase angle coverage to disentangle the two factors.
- Chosen to match the observed brightness of the dark side of the rings, when the contribution from the main rings is negligible.
Tuning Parameters

- Increasing $h_0$:
  - Creates more uniform ring.
  - Decreases asymmetry.

- Increasing D:
  - Increases asymmetry.
  - Requires a lower albedo for the dark side, lowering the lit side fluxes produced by the model.
Eq Depth: 3 km, \( h_0 = 15 \)

With a low equivalent depth and "flatter" ring, the asymmetry is small and lit side values are high.
Eq Depth: 7 km, \( h_0 = 15 \)

Increasing the equivalent depth increases the asymmetry, and the lower albedo means that the
Eq Depth: 7 km, $h_0 = 5$ km

With a the same equivalent depth but a more concentrated ring, the asymmetry is increases even further, but again, lit side values are high.
Depth: 3 km, $h_0 = 15$ (first plot again)

With a low equivalent depth and "flatter" ring, the asymmetry is smaller.
Data

Note the difference in the behavior of the dark side, and the lower lit side values.
Some very tentative conclusions

- We cannot reproduce the behavior of the rings on the dark side, and our values are consistently too high on the lit side; perhaps our method for scaling the albedo using dark side $\langle VIF \rangle_s$ needs to be refined.

- However, we can reproduce the sense of the asymmetry in the lit side HST observations using an inclined F ring.

- The F ring must be centrally-condensed, not uniform like the model of Poulet, to provide the observed asymmetries.
Happy Halloween!