The opposition effect in Saturn’s rings seen by

Cassini/ISS:

I. Morphology of phase curves

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ABSTRACT

The Cassini cameras have captured the opposition effect in Saturn’s rings with a high radial resolution at phase angles down to 0.01° in the entire main ring system. We derive phase functions from 0.01° to 25° of phase angle in the Wide-Angle Camera clear filters with a central wavelength $\lambda_{cl} = 0.611 \ \mu m$ and phase functions from 0.001° to 25° of phase angle in the Narrow-Angle and Wide-Angle Cameras color filters (from the blue, $\lambda_{bl} = 0.451 \ \mu m$ to the near infrared $\lambda_{ir} = 0.752 \ \mu m$). We characterize the morphology of the phase functions of different features in the main rings. We find that the shape of the phase function is accurately represented by a logarithmic model (Bobrov 1970, in Surfaces and Interiors of Planets and Satellites, Academic, edited by A. Dollfus). For practical purposes, we also parametrize the phase curves by a simple linear-by-part model (Lumme and Irvine 1976, Astronomical Journal, 81, p865), which provides three morphological parameters: the amplitude and the Half-Width at Half-Maximum (HWHM) of the surge, and the slope $S$ of the linear-part of the phase function at larger phase angles. Our analysis demonstrates that all of these parameters show trends with the optical depth of the rings. These trends imply that the optical depth is a key-element determining the physical properties which act on the opposition effect. Wavelength variations of the morphological parameters of the surge show important trends with the optical depth in the green filter ($\lambda_{gr} = 0.568 \ \mu m$), which implies that grain size effects are maximum in this wavelength.

Keywords: Saturn’s rings; phase curves; opposition effect; coherent backscattering; shadowing; shadow hiding
1 Introduction

When one views the rings of Saturn with the Sun directly behind the observer, a phenomenon called the opposition effect can be seen. The opposition effect, also known as the opposition surge, is a sudden, nonlinear rise in brightness with decreasing phase (Sun–ring–observer) angle that occurs as the phase angle approaches zero. The opposition effect, which was observed for most Solar System bodies (e.g., Helfenstein et al., 1997; Shkuratov et al., 1999; Belskaya and Shevchenko, 2000; Belskaya et al., 2003; Simonelli and Buratti, 2004; Verbiscer et al., 2005, 2007; Rosenbush et al., 2006) and (Rabinowitz et al., 2007) was discovered in the course of Müller’s long-term photometry of the Saturn system, beginning in 1878 (e.g., Müller, 1885, 1893). Seeliger (1884, 1887) inferred that the opposition effect was due to the rings, since Jupiter did not show a comparable opposition brightening (Pollack, 1975).

Most recent studies of the opposition effect in the Saturn’s rings were based on ground-based and spatial data which resolved the main rings (Lumme and Irvine, 1976; Esposito et al., 1979; Poulet et al., 2002; French et al., 2007). Earth-based observations, though valuable, have a low to moderate spatial resolution (for the Hubble Space Telescope, 1 pixel at Saturn =285 km and the full-width at half-maximum (FWHM) of the point-spread function of Hubble’s Camera =7 pixels, see Cuzzi et al., 2002). This indicates that the signal is averaged over large regions in the rings. Unfortunately, the rings are highly heterogeneous features that may present rapid spatial variations of their optical properties (Esposito et al., 1987). So the interest of spacecraft observations is the ability to probe the signal in very narrow ring features (~40 km in the present paper), which may have much more uniform optical properties. This allows an easier study of the opposition effect which is an already complex phenomenon.

Pioneer 11, Voyager 1 and Voyager 2 did not observe the rings at phase angles near zero. However, Cassini, which became an artificial satellite of Saturn in 2004, is the
first spacecraft to observe the opposition effect in the rings, with several instruments (Nelson et al., 2006; Altobelli et al., 2007), including the Narrow Angle (NAC) and Wide Angle (WAC) cameras of the Imaging Science Subsystem (ISS). For our data set (Table 1), typically for the WAC 1 pixel=40 km and the FWHM is 1.8 pixels, for the NAC 1 pixel=5 km and the FWHM is 1.3 pixels (Porco et al., 2004). With Cassini images we are thus able to characterize how the surge varies throughout individual features in the ring system.

The opposition effect is now known to be the combined effect of the coherent backscatter (at small phase angles) which is a constructive interference of photons in a medium of using grains of wavelength size and the shadow hiding (at larger phase angles) which consists of shadows cast by particles on other particles that become invisible to the observer (Helfenstein et al., 1997). Some analytical models have tried to combined these two effects (Shkuratov et al., 1999; Hapke, 2002), but recent laboratory measurements and data analysis show that models’ results could be compromised by some physical assumptions on the scatterer elements, the wavelength-dependence and the the angular size of the source (Shepard and Helfenstein, 2007; Shkuratov et al., 2007; Déau et al., 2008).

Two other effects, the external near-field effect and the single scattering internal-field coherence, were never been observed solely because they are intrinsically inseparable from the coherent backscatter effect and are for the moment only numerically simulated (Petrova et al., 2007; Muinonen et al., 2007).

Both shadow-hiding and coherent backscattering are likely to play roles in determining the shape of the phase curves of Solar System bodies at low phase angles (Helfenstein et al., 1997; Hapke et al., 1998). Shadow-hiding probably dominates at phase angles greater than a few degrees, while coherent backscattering takes effect at the very smallest phase angles. The shadow-hiding effect gives clues about the three-dimensional structure of a layer of ring particles which, according to Kawata and Irvine (1974), could have a typical size of \( \bar{r} = 15 \) m (see also Salo and Karjalainen, 2003; French et al., 2007). By contrast, the coherent
backscattering component sheds light on the nature of the ring particle surfaces at a scale not much larger than optical wavelengths. Indeed, previous photometric studies which investigate the opposition effect in the Saturn’s rings determined ranges of typical size for coherent-backscattering effect of about $d = 10 \, \mu m$ (Mishchenko and Dlugach, 1992a; Poulet et al., 2002; French et al., 2007). Thus, the shape of the opposition effect provides constraints on features vastly smaller than the camera’s resolution.

Like Poulet et al. (2002), we refer to particles as macroscopic and individual objects in the rings and grains as microscopic objects at the surface of rings’ particles. Using this terminology, ring particles might be covered by regolithic grains.

This is the first of a series of papers dealing with the opposition effect in Saturn’s rings as seen by ISS/Cassini. In the present paper, we focus on the characterization of the morphological modeling of the shape of opposition effect in the rings. Since the recent theories have difficulties to link the behavior of the opposition effect with the physical properties of the surface material (Nelson et al., 2000; Shepard and Helfenstein, 2007), we think it is necessary to have an experimental approach, consisting in (1) deriving the shape’s parameters and (2) trying to find correlations among themselves, and with the optical depth. In the second paper (D´eau et al. in preparation), we will use recent analytical photometric models to derive some of the physical properties of the ring material. Indeed, to constrain completely the physical properties of the ring material, photometric and polarimetric phase curves are needed, however, Cassi/ISS did not captured the opposition spot with its polarized filters.

In section 2 of the present paper, we describe the ISS/Cassini data set and our procedure for extracting photometric data from images and fitting empirical models to the data. In section 3, we characterize the morphology of the opposition surge at different locations in the main rings and focus our attention on cross-correlations among the morphological parameters and correlations of these parameters with the optical depth and the wavelength. Finally, in section 4 we discuss these results and examine to which extents photometric
models may explain the morphological trends derived in section 2.

2 Observations and reductions

2.1 The Cassini Imaging Data Set

The Cassini ISS instrument is composed of two cameras, a wide angle camera (WAC) and a narrow angle camera (NAC) equipped with 1024×1024 CCD matrices. Both use a set of about twenty filters ranging from near-infrared to ultraviolet (Porco et al., 2004).

Here, we focus only on filters in the optical domain, with first the blue, green, red and near infrared filters, that will be called hereafter COLOR filters. According to (Porco et al., 2004), COLOR filters from NAC and WAC cameras do not have exactly the same central wavelength. For the blue filters, the NAC can have two different combinations of filters (CL1,BL1) or (BL1,CL2) which lead to two central wavelengths: \( \lambda_{bl}^{NAC} = 0.440 \mu m \) and \( \lambda_{bl}^{NAC} = 0.451 \mu m \). In contrast, for the WAC, the blue (CL1,BL1) filter is characterized by a wavelength of about \( \lambda_{bl}^{WAC} = 0.460 \mu m \). Because the spectral width of these filters is about \( \pm 0.050 \mu m \), we consider all images from blue filters of the NAC and the WAC as a consistent whole. The green filter (CL1,GRN) has almost the same spectral characteristics for the two cameras since the central wavelength of \( \lambda_{grn}^{NAC} = 0.568 \mu m \) for the NAC and \( \lambda_{grn}^{WAC} = 0.567 \mu m \) for the WAC. The red filter for the NAC corresponds to the filter (RED,CL2) with a central wavelength of \( \lambda_{red}^{NAC} = 0.650 \mu m \). For the WAC, the combination (CL1,RED) is at a central wavelength of \( \lambda_{red}^{WAC} = 0.649 \mu m \), which does not change to the that of the NAC at one nanometer. Finally, the filter (CL1,IR1) in the near infrared shows a difference of 10 nanometers between the central wavelength of the NAC (\( \lambda_{ir}^{NAC} = 0.752 \mu m \)) and that of the WAC (\( \lambda_{ir}^{WAC} = 0.742 \mu m \)). In summary, with this moderately high spectral resolution, the combination of images that are not coming exactly from the same filters are responsible for a shift of the central wavelength from 0.001
to 0.010 micron. Because each filter has a non negligible spectral range (±0.050 µm), we consider without distinction the COLOR filters from the NAC and WAC cameras and in the rest of the paper, we take as a reference the following wavelengths ($\lambda_{bl} = 0.451$ µm; $\lambda_{grn} = 0.568$ µm; $\lambda_{red} = 0.650$ µm and $\lambda_{ir} = 0.752$ µm) to designate each COLOR phase curve.

The other part of images discussed in the present paper has been taken in CLEAR mode of the WAC, designating the absence of filters resulting in a spectral bandwidth spanning from 0.20 to 1.10 µm (the central wavelength is $\lambda_{cl} = 0.611$ µm and the spectral range is ±0.450 µm).

For the present paper, the selected observation campaign of the opposition effect on the Saturn’s rings is divided in four sequences from May 2005 to July 2006 (Table 1).

[Table 1]

These observations were conducted conjointly by the VIMS, CIRS and ISS instruments. Three of ISS sequences were obtained using the WAC only and the last one using the BOTSIM mode (using both cameras simultaneously). Depending on the sequence, different filters were used and different spatial and angular resolutions were achieved. In the present paper, the first of a series aimed at a detailed study of the opposition effect, we will focus on sequences obtained using the WAC camera in CLEAR filter mode and sequences using NAC and WAC cameras in COLOR filter mode, Table 1. Images of the B and C ring are shown in Fig. 1 and 2 to illustrate the quality of the data set.

[Fig. 1, Fig. 2]

In the CLEAR filter mode, the wide angle camera captured rings at zero phase angle two times in 2005, on June 7 and June 26 (they will be designated as June 7 and June 26 sequences in the rest of the paper, for practical purpose).

In the June 7 sequence, the WAC images have an average resolution of ~ 44 km per pixel; the rings are observed in reflexion. In each individual image, the phase angle varies...
by about 3 degrees. In the majority of the set, the opposition point at zero phase angle is visible with a very good sampling: about 0.005 degree per pixel. This set covers the full ring system by tracking the opposition spot. Most of the set has an excellent photometric quality, however in dark regions the strong Saturnshine produces ghost images of the secondary mirror perturbing the signal significantly. The amplitude of this artifact is quite constant, about 0.05 in I/F (I/F is the phase-corrected reflectivity, see Porco et al., 2004), which does not significantly affect the photometry of the bright regions as A and B rings. However it is very troublesome for dark regions like the D ring, the C ring and the Cassini Division. This is why images from the June 7 sequence have not been considered for these two regions. The same instrument artifact has been observed and discussed in (Hedman et al., 2007a).

The June 26 sequence has similar characteristics, see Table 1, with a better radial resolution of about 30 km per pixel and spans the B and C rings. The presence of the ghost signal in the C ring is not clear. A detailed photometric analysis in these images (cf. section 3.1.1) shows that the derived phase function is consistent with an unperturbed signal, very differently from images in which the ghost were clearly identified. It is why the images of the C ring taken on June 26 have been considered for the C ring phase function.

The July 23 sequence has the best radial resolution (∼13 km.pixel⁻¹) and spans all A, B, C rings and the Cassini Division (the radial location of the opposition spot in each image is represented in the Fig. 3). In this set, the ghost artifact is absent owing to a much larger angular separation with the bright Saturn globe. Some images of this sequence provide also the larger phase angles.

In COLOR filters mode, the ISS instrument uses the BOTSIM mode in the May 20 sequence, using both cameras simultaneously for a ride in A and B rings, Cassini Division and the outer C ring (Fig. 3). However, because the boresight of the NAC and the NAC
are not exactly the same, NAC images did not represent a zoom of the opposition spot in WAC images. Thus, WAC and NAC images captured at the same time have opposition spots that are not exactly at the same location in the rings. The radial resolution in NAC images is 4.6 km.pixel$^{-1}$ and spans from 44 to 66 km.pixel$^{-1}$ for WAC images in COLOR filters. The other sequences (Dec 31, Feb 20 and Apr 25), did not have the opposition spot but provided the larger phase angles.

2.2 Data reduction

2.2.1 Calibration

Raw images are calibrated first with a standard pipeline described in (Porco et al., 2004) and called CISSCAL, using the 3.4 version. The DN values are converted into the I/F units. This ratio is dimensionless, with $I$ is the specific intensity measured by Cassini, and $\pi F$ is the incident flux from the Sun. So it is a measure of the local reflectivity under the current observing geometry.

Cassini images are not directly exploitable to study the photometric behavior of rings. In order to do this, the relevant data we need are the so-called phase function which is linked to the I/F ratio as a function of the phase angle, and corrected from effects of observation geometry. A full procedure has been designed to reconstruct the phase function from different images with different observation geometry and resolutions and is detailed below.

2.2.2 Extraction procedure

The first step is to reproject the images in a (Radius, Longitude) frame, in which features at a same radius from Saturn are horizontally aligned. This procedure critically depends on the quality on the navigation. When possible, the edges of the A, B, C rings as well as ring features reported in (Esposito et al., 1987) were used as fiducial references. Distances
reported in (Esposito et al., 1987) were corrected according to (Nicholson et al., 1990).

The resulting navigation error on WAC images varies from 1 to 1.5 pixels from the center to the edge of the image.

The I/F in a ring at constant distance from Saturn is obtained by extracting the data on a line of constant radius (i.e. an horizontal line) in the reprojected map of calibrated brightness. Other geometrical parameters are extracted in the same way: phase angle $\alpha$, cosine of incidence angle $\mu_0$, cosine of the emission angle $\mu$, optical depth of the rings obtained from the PPS Voyager instrument ($\lambda = 0.260 \, \mu$m) (Esposito et al., 1987); radius scale has been corrected with the procedure of Nicholson et al. (1990).

This procedure works very well for structures with width larger than the navigation accuracy. However radial structures are visible at all scales down to one pixel, (Fig. 2). For structures radially smaller than 5 pixels, navigation errors make false the extraction along a line of constant radius close to the edges of the image, inducing accidental extraction in nearby different features. To overcome this problem and to ensure that we always extract the same ring feature, we developed a ring tracking technique using a basic pattern recognition algorithm to follow a single feature. Extensive visual check of the result shows the method is reliable down to 1 pixel of radial width.

2.2.3 Construction of the phase function

The ultimate information we need is the phase function of individual ring particles to characterize their surface properties. Unfortunately, the signal from an individual particle is heavily altered because of the finite thickness of the rings (Porco et al., 2007). Also, the signal’s intensity depends on observation angle with respect to the ring’s normal. Inverting such complex collective photometric effects would require the use a detailed light scattering code with many assumptions concerning the photometric properties of particles. Such code has been developed by Salo (1992, 1995); Richardson (1994); Porco et al. (1999, 2007) and French et al. (2007). However, for our present purposes, they cannot used to de-
rive the phase functions in hundreds of different regions as we wish to do here. Conse-
sequently, as a first approximation, we use in the present paper the classical approach of
Chandrasekhar (1960) linking the I/F to the phase function with the following assump-
tions: homogeneous layer of particles and single scattering. This latter assumption may be
justified for phase angles smaller than \( \sim 30^\circ \) (Cuzzi et al., 2002). In reflexion, the phase
function \( \varpi_0 \cdot P(\alpha) \) is derived from the solution to the radiative transfer equation (the
designation phase function is not strictly accurate since what we really determine is the
product of the single scattering albedo, \( \varpi_0 \), times the particle phase function, \( P(\alpha) \)):

\[
\varpi_0 \cdot P(\alpha) = \frac{I}{F} \times \frac{4(\mu + \mu_0)}{\mu_0} \times \left( 1 - e^{-\tau(\frac{1}{\mu} + \frac{1}{\mu_0})} \right)^{-1}
\]

(1)

with \( \tau, \mu, \mu_0, \alpha \) standing for: the normal optical depth, cosine of emission angle, cosine of
incidence angle and phase angle respectively. In order to allow future comparisons with
detailed numerical models, numerous analytical parametrization of the observations are
provided by morphological model in section 2.3. As one can see, the value of the optical
depth is necessary to derive the phase function. Preceding works has shown that the
exponential factor can be neglected in first approximation for Earth-based observations
(Cuzzi et al., 2002; Poulet et al., 2002). However, we noticed that we obtained much more
coherent results when taking into account the exponential factor, when comparing results
from different geometry of observations. Consequently, we keep the initial formula of
Chandrasekhar (1960), as previous photometric studies based on spacecraft observations
of Saturn’s rings (Doyle et al., 1989; Cooke, 1991; Ferrari, 1992; Showalter et al., 1992;
Dones et al., 1993).

\( P(\alpha) \) obtained with Eq. 1 is the particle’s disk integrated phase function which determines
the angular distribution of single scattered radiation from the body as a whole. The
phase function is normalized over the solid angle \( \Omega \) to the single scattering albedo :

\[
\varpi_0 = \frac{1}{4\pi} \int P(\alpha) \, d\Omega.
\]
phase angle, must be known. In this study, we have restricted our data (0<α<25 degrees), so that we may avoid separating the albedo from the phase function. The derivation of the albedo will be presented in the second paper which relates ISS data from 0 to 180 degrees.

2.2.4 Finite size of the Sun

Generally speaking, all phase curves present a bright opposition surge below 1° and a slope decreasing linearly for α > 1°. Whereas WAC images go down to \(~0.01°\) of phase angle (Fig. 1), NAC images taken in COLOR filters capture the opposition spot at better angular resolution (Fig. 2), the resulting phase functions from NAC images go down to \(~0.001°\) (Fig. 4). This is the first time the opposition spot is imaged at such fine scale.

Note that we define the phase angle as the angle between the vector pointing to the Sun’s center, and to the spacecraft, from the observed point. So from a strictly mathematical point of view there is no lower limit to the phase angle value despite the source’s finite size. For an extended illumination source, the phase curve should be the integral of a point source phase function over the Sun angular radius. Thus on a more physical point of view it is not possible to observe the phase function at angle below the Sun’s angular radius (Kawata and Irvine, 1974; Shkuratov, 1991).

Fig. 4 demonstrates that the opposition surge flattens (in all rings and at all wavelengths) at phase angles below 0.029°, in good agreement with the Sun’s angular radius at the date of observations (0.0291 degree, given by \(\alpha_{\odot\min} = \arcsin \frac{r_\odot}{R_\odot - R_{\odot - \text{Saturn}}}\) where \(r_\odot = 6.96 \times 10^5\) km is the radius of the Sun and \(R_\odot - R_{\odot - \text{Saturn}}\) is the heliocentric distance of Saturn (Murray and Dermott, 2000).
2.3 Data fit with Morphological models

The purpose of the present paper is to provide an accurate description of the morphological behavior of the observed phase curves. This is the very first step prior to any attempt of further modeling, which will be the subject of a forthcoming paper. As a consequence, special care has been given to parametrize the phase functions conveniently. In addition, morphological parametrization is necessary to compare efficiently hundreds of phase curves at different locations in the rings and derive statistical trend as will be done in section 3.

Several morphological models have been used in the past to describe the shape of the phase functions: the logarithmic model of Bobrov (1970), the linear-by-part model of Lumme and Irvine (1976) and the linear-exponential model of Kaasalainen et al. (2001). The specific properties of these three models make them adapted for different and complementary purposes. The logarithmic model is interesting for direct comparisons with numerical models, the linear-by-part model is convenient to describe the shape in an intuitive way, and finally the linear-exponential model is adapted for comparison with other studies previously published.

2.3.1 The logarithmic model

As Bobrov (1970), Lumme and Irvine (1976) and Esposito et al. (1979), we remark that a logarithmic model describes very well the solar phase curves of the Saturn’s rings. It depends on two parameters \((a_0 \text{ and } a_1)\). This first morphological model has the following form:

\[
\varpi_0 P(\alpha) = a_0 + a_1 \times \log(\alpha)
\]  

(2)

In general, this model is the best morphological fit to the data. It is reasonably accurate
down to 0.029° of phase angle. This is due to the finite angular size of the Sun which flattens data below 0.029°, whereas the logarithmic function continues increasing (see section 2.2.4 and Fig. 4a). For large phase angles, the fit is satisfactory up to α ≃ 15 degrees, this was also noticed by Altobelli et al. (2007) who fitted temperature phase curves of the C ring with CIRS/Cassini.

Whereas the meaning of $a_0$ and $a_1$ are not easily interpretable in term of shape, to allow an easy comparison with future numerical simulations the values of these two parameters are reported in Table 1 of Electronic supplement material.

2.3.2 The linear-exponential model

This model describes the shape of the phase function as a combination of an exponential peak and a linear part. Its main interest is that it has been used in previous work for the study of the backscattering of Solar System’s icy satellites and rings (Kaasalainen et al., 2001; Poulet et al., 2002; French et al., 2007). We give the details of this model: the 4 parameters are the intensity of the peak $I_p$, the intensity of the background $I_b$, the absolute slope of the linear part $I_s$ and the width of the exponential $w$, such that the phase function is represented by:

$$\varpi_0 P(\alpha) = I_b + I_s \cdot \alpha + I_p \cdot e^{-\frac{\alpha}{2w}}$$

With these 4 parameters, we characterize the shape of the phase function by introducing three morphological parameters: $A$, HWHM and $S$ designating the amplitude of the surge, the half-width at half-maximum of the surge and the absolute slope at large phase angles respectively, so that:

$$A = \frac{I_p + I_b}{I_b} \quad \text{HWHM} = 2 \cdot \ln 2w \quad \text{and} \quad S = -I_s$$

(4)
As French et al. (2007), we noticed that this model did not fit well the phase curves, in particular, the derived model parameters appeared to depend substantially on the phase angle coverage (see section 2.3.4), preventing a robust comparison of data. This is due to the fact that we did not use the converging procedure of Kaasalainen et al. (2001) but rather the common downhill minimization technique, as done by the previous users of the linear-exponential model (Poulet et al., 2002; French et al., 2007). Moreover, it seems that the angular scale at which the phase function is observed may strongly influence the model parameters. So to avoid this problem, we used a much simpler morphological model that appeared much more robust for the comparison of heterogeneous data set: the linear-by-part model of Lumme and Irvine (1976), also we found a much better match of the data with the linear-by-part model of Lumme and Irvine (1976) (see below).

However, the linear-exponential was considered in the present study only to understand variations of $A$, HWHM and $S$ between the (Poulet et al., 2002; French et al., 2007) phase curves and our phase curves (see section 2.3.4 and section 3.2.3).

2.3.3 The linear-by-part model

For an intuitive description of the main features of the phase curves, the linear-by-part model is the most convenient one. It is constituted of two linear functions fitting both the surge at small phase angle ($\alpha < \alpha_1$) and the linear regime at higher phase angle ($\alpha > \alpha_2$):

$$\varpi_0 P(\alpha < \alpha_1) = -A_0 \times \alpha + B_0 \varpi_0 P(\alpha > \alpha_2) = -A_1 \times \alpha + B_1$$

Lumme and Irvine (1976) and Esposito et al. (1979) use $\alpha_1 = 0.27^\circ$ and $\alpha_2 = 1.5^\circ$. However, we encountered difficulties with the value of $\alpha_1$. By testing several values of $\alpha_1$, it appears that for our data set, values of $\alpha_1$ less than $0.3^\circ$ yield a general overestimation of $A_0$, especially in the C ring and values of $\alpha_1$ greater than $0.3^\circ$ yield an underestimation of $A_0$ only in the B ring. Consequently, we found the our data were better reproduced using $\alpha_1 = 0.3^\circ$ which is now adopted in the rest of the paper.
With this four outputs : the two absolute slopes $A_0$ and $A_1$ and the two y-intercepts $B_0$ and $B_1$, the shape of the curve is characterized by the morphological parameters $A$, HWHM and $S$ are then defined by :

$$A = \frac{B_0}{B_1} \quad \text{HWHM} = \frac{(B_0 - B_1)}{2(A_0 - A_1)} \quad \text{and} \quad S = A_1 \quad (6)$$

The purpose of this model is not, of course, an accurate description of the data but rather a convenient description of the main trends of the phase curve.

2.3.4 Stability of the morphological parameters

In order to compare properly our results with those of [Poulet et al. (2002)](http://example.com) and [French et al. (2007)](http://example.com), for which the Saturn’s rings phase curves did not have the same phase angle coverage, we have tested the influence of the portion $0.05^\circ-0.4^\circ$ and $6^\circ-25^\circ$ on the converging solution. Indeed, phase curves of [Poulet et al. (2002)](http://example.com) do not have data under $0.3^\circ$, and both studies of [Poulet et al. (2002)](http://example.com) and [French et al. (2007)](http://example.com) do not have data over $6.5^\circ$ (the maximum phase angle reached from Earth is about $\alpha_{\text{max}} = \arcsin \frac{R_{\odot-\text{Earth}}}{R_{\odot-\text{Saturn}}} \lesssim 6.5^\circ$ where $R_{\odot-\text{Earth}}$ is the heliocentric distance of the Earth and $R_{\odot-\text{Saturn}}$ is the heliocentric distance of Saturn computed with orbits of [Murray and Dermott, 2000](http://example.com).

With two typical Saturn’s rings phase curves of ISS (Fig. 5), we have removed data by section of $0.1^\circ$ and fit the pseudo-incomplete phase curve with the linear-exponential model, which provides the new solution, designated by $A_{\text{remove}}, \text{HWHM}_{\text{remove}}$ and $S_{\text{remove}}$. The initial solution found for fuller phase function ($0.01^\circ-25^\circ$) is called $A_{\text{optimal}}, \text{HWHM}_{\text{optimal}}$ and $S_{\text{optimal}}$. Both solutions are obtained with a downhill minimization technique, to reproduce the fitting method used by [Poulet et al. (2002)](http://example.com) and [French et al. (2007)](http://example.com). It is wise to recall that [Kaasalainen et al. (2001)](http://example.com) proposed a converging procedure more accurate, however because (e.g. [Poulet et al., 2002](http://example.com); [French et al., 2007](http://example.com)) did not used it, and because we want to reproduce not the best converging solutions but the deviations lead by the fits
driven by Poulet et al. (2002) and French et al. (2007), that is why we use the downhill method and not the probability distribution method of Kaasalainen et al. (2001).

[Fig. 5, Fig. 6]

In Fig. 6, we represent the ratio of the morphological parameters of the incomplete phase curve over the morphological parameters of the fuller phase curve, called \( A_{\text{remove}}/A_{\text{optimal}} \), \( \text{HWHM}_{\text{remove}}/\text{HWHM}_{\text{optimal}} \) and \( S_{\text{remove}}/S_{\text{optimal}} \). We observe a slight underestimation of \( A \), a strong overestimation of HWHM and a moderate underestimation of \( S \).

The deviation of the optimal value is quite weak for \( A \) (\( A_{\text{remove}}/A_{\text{optimal}} \approx 0.96 \) at a cut-off of 0.3\(^{\circ}\)) but its variation depends on the morphology of the surge. For the typical B ring phase curve (which has a narrower peak), we note a slight decrease of the ratio \( A_{\text{remove}}/A_{\text{optimal}} \) and for the C ring, we note a slight increase of the ratio. However the both ratios lead to an underestimation, which means that incomplete data fitted by the morphological model will have a smaller amplitude that data which cover the full surge.

HWHM shows the strongest deviation of \( A_{\text{remove}} \). Indeed, HWHM is overestimated for the typical B ring phase curve (\( \text{HWHM}_{\text{remove}}/\text{HWHM}_{\text{optimal}} \approx 1.4 \) at a cutoff of 0.3\(^{\circ}\)) but is strongly overestimated for the typical C ring (\( \text{HWHM}_{\text{remove}}/\text{HWHM}_{\text{optimal}} \approx 2.0 \) at a cutoff of 0.3\(^{\circ}\)) which has a wider peak.

For the slope, we notice an overestimation in the order of \( S_{\text{remove}}/S_{\text{optimal}} \approx 1.3 \) at a cutoff of 7\(^{\circ}\) for the B ring phase curve and of \( \approx 2.5 \) for the C ring at the same cutoff. This means that the slope of the linear part is stabilized at roughly 15\(^{\circ}\).

These comparisons are important when we compare morphological trends found by Poulet et al. (2002), in section 3.1.2 and French et al. (2007), in section 3.2.3.

2.3.5  Linking morphological parameters with the physical parameters of the models

The use of a simple morphological model is generally not adapted to derive the physical properties of the medium. However, the theories developed for the coherent backscatter-
ing and the shadow hiding effects deduce their properties by parameterizing the opposition phase curve (Mishchenko and Dlugach, 1992a,b; Mishchenko, 1992; Shkuratov et al., 1999; Hapke, 1986, 2002). Recent laboratory experiments raise some doubts on the meaning of the physical parameters of these models and their correlation with the real physical properties of the medium (Shepard and Helfenstein, 2007; Shkuratov et al., 2007). However, because there is no better modelization, we connect the morphological parameters A, HWHM and S with the physical characteristics of the medium derived from these models.

\( A \) is the amplitude of the opposition peak and describes the behavior of the phase function at the smallest phase angles (\( \alpha < 2^\circ \)). What we know about the opposition effect is that it occurs at the smallest phase angles and acts on the multiple scattered light in the regolith on the surface of the particles: the underlying phenomenon is the coherent backscattering effect. The coherent-backscattering effect increases in brightness by almost a factor two, while using grains size smaller than the wavelength of the incident light, (Mishchenko and Dlugach, 1992b; Shkuratov et al., 1999). In contrast, the second phenomenon of the opposition effect, the shadow hiding effect, is known to produce a wide peak from 0 to 2 degrees, and to decrease the brightness up to 20 degrees (Hapke, 1986; Stankevich et al., 1999). The combination of the two effects at very low phase angle is still a matter of debate and today two theories disagree in order to explain the peak of the opposition. The theory of Mishchenko (1992); Mishchenko and Dlugach (1992b) assumes that the opposition peak is a pure coherent backscattering effect whereas the theory of Hapke (2002) shows that the opposition peak results from a coupling of coherent-backscattering and shadow hiding, even at low phase angles. This coupling should be due to the fact that the coherent backscattering could act on both multiple and single scattered light whereas the shadow hiding is a single scattered light effect (Hapke, 2002). Thus, this theoretical model defines two amplitudes as output parameters: the coherent backscatter amplitude \( B_{C0} \) and the shadow hiding amplitude \( B_{S0} \). As a consequence, using this theory, it does not seem to
be possible to ascribe the morphological parameter $A$ solely to the coherent backscatter-

ing effect. For most laboratory measurements (Shkuratov et al., 1999; Nelson et al., 2000), the

amplitude of the opposition peak is a function of grain size in such way that $A$ decreases

with increasing grain size. This anti-correlation finds a natural explanation by the fact

that macroscopic irregularities ($>\lambda$) create less coherent effects than microscopic irreg-

ularities ($\leq \lambda$). Laboratory measurements of Kaasalainen (2003) also confirmed that the

opposition surge increases when irregularities are small. Mishchenko and Dlugach (1992b)

and Mishchenko (1992) underline the fact $A$ is linked to the intensity of the background

$I_b$ which is a decreasing function of increasing absorption (Lumme et al., 1990), thus

$A$ must increase with increasing absorption or decreasing albedo $\omega_0$, which was also

confirmed by laboratory measurements of Kaasalainen (2003) who found that the peak
decreases with increasing sample albedo.

$\text{HWHM}$, the half-width at half-maximum, is generally associated to the coherent backscatter-

effect. It can be related to the grain size, index of refraction and packing density of regolith

(Mishchenko, 1992; Mishchenko and Dlugach, 1992a; Hapke, 2002). The HWHM

is maximum for an effective grain size near $\lambda/2$ and increases when the regolith grains filling factor $f$

increases. For high values of $f$, the HWHM shifts towards the greater grain size. However, as for the amplitude, the model of Hapke (2002) defines two HWHMs: the coherent backscatter angular width ($h_c$), which is defined similarly that in the model

of Mishchenko (1992), and the shadow hiding angular width ($h_s$). This reinforces the idea that the observed surge results from a coupling between the coherent backscattering and the shadow hiding.

$S$, the slope of the linear part, seems to be due only to the shadow hiding effect: the

interferences caused by coherent backscattering effect seem not to be very significant

at larger phase angles (Mishchenko et al., 2006; Hapke, 2002). This means the shadow hiding light is not affected by the coherent backscattering at larger phase angles.

Also, according to recent analytical and numerical models, the shadow hiding acts solely
on the linear part of the phase function (Stankevich et al., 1999; Shkuratov et al., 1999). We define here the absolute slope, whereas it is naturally a negative parameter, because the phase function always decreases in brightness from $10^\circ$ to $40^\circ$ of phase angles (Kawata and Irvine, 1974; Stankevich et al., 1999; French et al., 2007).

The slope depends on the volume filling factor $D$ and the optical depth of the slab (Kawata and Irvine, 1974; Stankevich et al., 1999). Two models has been developed for different regimes of the particle volume density $D$ and predict opposite behavior of $S$ as the function of $D$ and $\tau$.

The shadowing model of Irvine (1966) and Kawata and Irvine (1974), also called inter-particle shadow hiding by Goldreich and Tremaine (1978), consists in shadows of macroscopic particles ($\bar{r}=15$ m, see Kawata and Irvine, 1974) in a particulate medium, such as $8D<1$ (Irvine, 1966). The smaller the volume density $D$, the steeper the phase function for increasing phase angle (Kawata and Irvine, 1974). Other refinements of this model exists (Esposito, 1979; Hapke, 1986; Stankevich et al., 1999; French et al., 2007) but lead to the same results: the opposition peak due to the shadowing sharpens and the absolute slope increases with decreasing packing density (or filling factor).

Another model exists, the intra-particle shadow hiding, which is valid for higher particle volume density according to Goldreich and Tremaine (1978); Muinonen (1994). Buratti and Veverka (1985) underlined the fact that the mutual shadowing among regolithic grains could be suited for understanding the textural properties of the regolith.

As a consequence, this mechanism operates at the surface of ring material: e.g. in the regolith layer.

However, other physical parameters need to be taken into account. In the analytical inter-particle shadow hiding model of Hapke (2002), the slope can be linked to the angular width of the shadow hiding $h_{sh}$. Thus a normalized and absolute slope would be $S = \frac{1}{2h_{sh}} = \frac{D}{Q_{\text{ext}}(\lambda, \bar{r}) \ln(1-D)}$, with $D$ the volume filling factor, $Q_{\text{ext}}(\lambda, \bar{r})$ the extinction coefficient and $\bar{r}$ the mean radius of particles. Then, the slope should depend on the wavelength and on the particle size. Interestingly, laboratory experiments of
Kaasalainen (2003) showed that the slope increases when the sample’s size increases. However, the microscopic and/or macroscopic roughness of the medium need also to be taken into account in the shadow hiding models, as underlined by Hapke (1984, 1986); Shkuratov et al. (1999); Kaasalainen (2003) and Shepard and Helfenstein (2007). For example, laboratory experiments of Kaasalainen (2003) showed that the slope increases when the sample’s roughness increases.

Then laboratory measurements and recent theoretical models could significantly increase the number of physical parameters on which S depends.

From the above arguments, the HWHM and the amplitude A are governed by both coherent backscatter and shadow hiding effects whereas the slope S provides information of the shadow hiding effect solely.

3 Shape of the phase curves at opposition

3.1 The opposition effect in CLEAR filters

Due to the automation of extraction and fitting procedures (cf section 2.2) and due to the high images resolution, phase functions were extracted in as many as 211 different locations, in the D, C, B rings, Cassini Division and A ring (in increasing distance from Saturn, left column of Table 1 of Electronic supplementary material). In this section, we first present the typical behavior of some selected phase curves in different regions of the main rings (section 3.1.1), then we discuss similarities and differences and what are the general trends from sections 3.1.2 to 3.1.4.
3.1.1 *Overview of the CLEAR phase curves*

Examples of phase curves in various ring regions are presented in Fig. 7. Each pair of
graphs show on the left side a zoom from 0.01 to 2.5 degrees and on the right side,
the fuller phase curve from 0 to 25 degrees. These curves were obtained by combining
several WAC images with a large distribution of viewing geometries (Table 1) each curve
is built from the merging of 10 to 70 different images with various values of emission angle,
incidence angle, phase angle etc. The dispersion of points is not due to the measurement
uncertainty but reflects mainly the limits of the *Chandrasekhar (1960)* inversion formula
that was used to extract the phase function from the measured values of I/F. It seems
that some important physics may be missing (like multiple scattering), that could explain
the scattering of points. Curves for the A and D rings (Fig. 7) are incomplete between 3
to 20° which is due to removal of images because of an artifact (cf section 2.1).

[Fig. 7]

Whereas the general shape is similar from one ring to another (Fig. 7), some details in the
shape may vary significantly. First pair of graphs in Fig. 7 shows the phase curve derived
in the D ring from images of June 26. Due to short exposure time (10 ms), the D ring
ringlets are too faint to be detected. In images of June 26, a bright spot is visible from
67 000 km to the inner boundary of the C ring: this corresponds to the expected location of
the background sheet of material constituting part of the D ring (*Hedman et al., 2007a*).
However camera artifact may be visible in such dim regions of the image but could not
be clearly identified here. So the fact that a strong increase of brightness at the expected
location of the opposition and the coherent variation of the signal with observing geometry
between different images suggest that we indeed see the opposition effect in the D ring.
However some doubts still remain. From 0.5 to 2 degrees, the curve is similar to other
rings. Below 0.5 degree an exponential surge and a flattening at zero degree distinguish
this phase function from the other ones. Does it reflect optical properties of D ring dust?
Is it an artifact? This plateau below 0.5 degree is much too large to be explained by the finite angular radius of the Sun (0.025 degree). Because of these uncertainties, at this point it is speculative to interpret this specific behavior as real.

For the C ring (Fig. 7), the shape of the phase function is well sampled below 2 degrees. It is comparatively wider than in dense A and B rings. More precisely, HWHM of the opposition surge is wider for the C ring (HWHM=0.26°) than for the A and B ring (HWHM~0.20°). This could be also interpreted as a steeper slope of the linear regime of the phase function for α > 2°. Wavy features between 5 to 25 degrees can be attributed to images artifact. Their amplitude is about 15% of the total signal of the C ring.

The B ring opposition surge has the smallest amplitude of all rings (A=1.25 in Fig. 7). This was already underlined by the recent study of French et al. (2007) whereas previous observations of Esposito et al. (1979) and Poulet et al. (2002) give the exact opposite trend. However, their result could have a bias due to the lack of data below 0.3° of phase angle for Poulet et al. (2002) and 0.1° for Esposito et al. (1979) whereas French et al. (2007) had values much smaller (the smallest phase angles at which HST observed the B ring range from 0.0037 to 0.0132 degrees French et al., 2007). The B ring has also the steepest slope (S=0.105 ω_0 P.deg^{-1}) in the linear regime explaining why the opposition spot is so contrasty in the ISS images.

The Cassini Division has a similar amplitude and width (A~1.47 and HWHM~0.28° in Fig. 7) to the C ring (A~1.45 and HWHM~0.26° in Fig. 7). Their slope of the linear regime are also similar (S=0.033 ω_0 P.deg^{-1} for the Cassini Division and S=0.030 ω_0 P.deg^{-1} for the C ring). These similarities were first noticed by Poulet et al. (2002) and are suggestive of a strong dependence of the opposition effect on the optical depth (we will come back to this in section 3.1.4).

An example of the A ring phase function is given in the last pair of graphs in Fig. 7. At first sight, the signal appears much more disturbed than in other rings: specifically,
pieces of phase functions extracted from different images show a wide dispersion in this
graph, whereas signal from an individual image has a very low dispersion. The origin of
this is not clear and may be due to the artifact reported in section 2. The dispersion
of the data is about 15% of the signal whereas the camera artifact should represent at
most 5% of the signal only (estimated on the background). It may be possible that the
dispersion may be also due to an intrinsic photometric effect which is not corrected by
the Chandrasekhar (1960) single scattering model (equation(1)). Indeed, the A ring has
an intermediate optical depth \( \sim 0.5 \) so that it neither appears as a solid surface (like the
B ring) or as a dilute system (like the C ring). Here, we are in an intermediate regime
where many collective effects may influence strongly the apparent phase function (multiple
scattering, gravitational wakes, density waves, etc.). A sophisticated model is required here
to investigate such effect (Porco et al., 2007). However the general trends are quite clear
and the A ring phase curve has a larger peak amplitude (A=1.39 in Fig. 7) than the B ring’s
(A=1.25 in Fig. 7). We see in addition that the slope of the linear regime is shallower in
the A ring (\( S=0.078 \ \omega_0 P.\text{deg}^{-1} \) in Fig. 7) than in the B ring (\( S=0.105 \ \omega_0 P.\text{deg}^{-1} \) in
Fig. 7) but steeper than in less dense rings (\( S\sim 0.03 \ \omega_0 P.\text{deg}^{-1} \) in Fig. 7). Thus the phase
curve at opposition in the A ring is somewhat intermediate between the B and C rings,
strengthening the idea of a dependence on the optical depth.

Finally, we conclude this section by remarking that the opposition effect is very diverse
in Saturn’s rings, and could be the consequence of different properties of the surface ring
particles in various ring regions. Some general trends can be underlined, as we see in the
next section.

In a first step, we check if some correlations exist between the morphological parameters
which depend on the same portion of the curve (e.g. A and HWHM for the surge) and
also if parameters describing different parts of the phase curve can be correlated (e.g. A,
HWHM and S for, respectively, the surge and the linear part). This is the purpose of the
next section.
3.1.2 Cross comparisons between morphological parameters

In order to constrain the morphology of the surge, we correlate the amplitude $A$ with the angular width HWHM for the different main rings. We fit $A$ and HWHM with a linear function and found correlation coefficients reported in Table 2.

| Table 2 |

In Table 2 the Cassini Division, the amplitude $A$ has the steepest function of the HWHM. A linear fit gives a slope of about 1.2 with a correlation coefficient of 47%. This means that narrow surges have a low amplitude and inversely wide surges have large amplitude. In the C ring, values of $A$ and HWHM are generally greater than in the Cassini Division (but there are some exceptions). For the amplitude, this qualitative difference between the Cassini Division and the C ring is confirmed by previous study of Poulet et al. (2002) and French et al. (2007). For the angular width, although our trend of HWHM agrees with the results of French et al. (2007), it contradicts previous work of Poulet et al. (2002), this is certainly due to the overestimation of HWHM when the smallest phase angles are missing (section 2.3.4 and Fig. 6b).

For the C ring, we find a slope for $A=f($HWHM$)$ of about 0.9 with a good correlation coefficient of 79%.

The A ring shows a similar variation of $A=f($HWHM$)$ as for the C ring (1.0) with a correlation coefficient of 56%.

Finally, $A$ and HWHM in the B ring have values smaller than in the faint rings (C ring and Cassini Division). Data points of $A$ and HWHM for the B ring are concentrated in a similar range as the A ring one, however with a much shallower slope (0.6 with a correlation coefficient weakly reliable of 29%, see Table 2). This means that the shape of opposition phase curves in the B ring may have various angular width with an almost constant value of the amplitude.
To conclude, the amplitude of the surge seems correlated with the angular width, at least for the C ring, A ring and Cassini Division whereas the amplitude is independent of HWHM for the B ring. The slope of A=f(HWHM) seems to decrease from the Cassini Division to the B ring, passing by the C and A rings, suggesting that the slope is a decreasing function of the optical depth.

Whereas the slope S on the one hand, A and HWHM on the other hand are thought to be related to different portion of the phase curve (linear part and surge respectively), it is interesting to note that they are somewhat correlated. We simply note that S is a decreasing linear function the angular width and is also correlated with the amplitude.

Slopes and correlation coefficients of S=f(A) and S=f(HWHM) are reported in Table 2. This could be due to the fact that we derive our slope from 1.5° to 25° whereas analytical model of Shkuratov et al. (1999), for example, describes the shadow hiding effect as a slope which fits the phase curve from 4.5° to larger phase angles, see (Poulet et al., 2002).

3.1.3 Regional behavior

We now look for regional behavior inside each ring (Fig. 8). The Fig. 8 displays A, HWHM and S as a function of the distance from Saturn by introducing a ring type nomenclature based on the regional behavior of the C ring, well studied by Cooke (1991) and decomposed into three ring types: inner ring, background and plateaux. We have modified and extended this nomenclature to five classes of ring features, then applicable to the entire main rings system:

1) inner regions characterized by low optical depth in all the rings (for example, the dark bands in the Cassini Division, see Flynn and Cuzzi, 1989),
2) background are morphological smooth regions without abrupt variation of $\tau$,
3) bright regions (plateaux or plateaus in the C ring (Holberg et al., 1982), density and bending waves in the A ring located by Esposito et al., 1983) are the regions in each
ring with the highest optical depth,

(4) *ringlets* according to Holberg et al. (1982) are thinner ring embedded in a less dense region or a gap,

(5) *outer regions* (for example the so-called *ramp* for the C ring and the Cassini Division (Cuzzi and Estrada, 1998)) mark the transition at the boundaries of each ring.

[Fig. 8]

In Fig. 8a and b, the amplitude $A$ and the HWHM vary smoothly across the main ring system (C to A rings), with only little scattering around the main trend (apart from the Cassini Division), illustrating the stability of the linear-by-part model for comparing multiple observations in different ring regions. From the C ring to the middle of the B ring, a smooth decrease is observed. No sharp transition is observed between the C and B rings. The outer regions of the C ring which are rich in gaps, plateaux and ringlets, have a somewhat larger value of amplitude.

From the middle of the B ring to the outer of the A ring, both $A$ and HWHM increase again. The Cassini Division presents (1) larger values of $A$ and HWHM as in the C ring and (2) strongly dispersed values which may be indeed real because no image artifact is visible in this Division.

The slope has a significantly different behavior (Fig. 8c) because strong jumps are observed at the boundaries of each ring. This reinforces differences of behavior of the surge and the linear part of the phase curve with the distance from Saturn.

As a result, the behavior of $A$, HWHM ans S did not show significant variations with ring type. Cooke (1991) noticed single scattering albedo of the C ring was dependent on the ring type classification. Maybe that the absence of correlation between morphological parameters and the ring type classification implies that the morphological parameters are independent of the single scattering albedo. Since the single scattering albedo is correlated with the optical depth, (Spilker et al., 2005), we try now to correlate the morphological
parameters with the optical depth in the next section.

### 3.1.4 Optical depth variations of the morphological parameters

In order to quantify differences in terms of morphological shape in our 211 phase curves in CLEAR filters (see section 3.1.1), we use the three parameters A, HWHM and S. They are represented in the Fig. 9 as a function of the normal optical depth of the rings.

![Fig. 9](image)

Because the overall correlations of A, and S HWHM with \( \tau \) are not clear, although they seem to lead to an negative correlation for A and HWHM (Fig. 9a,b) and a positive correlation for S (Fig. 9c), we calculated with a linear fit the correlation coefficients for A=f(\( \tau \)), HWHM=f(\( \tau \)) and S=f(\( \tau \)) for each main ring, see Table 3.

![Table 3](image)

The amplitude A of the surge (Fig. 9a) is correlated with the optical depth of the rings. The following trends may be noted: first, the amplitudes of low optical depth (\( \tau <0.5 \), typically the C ring and the Cassini Division) are positively correlated with the optical depth (Table 3) and second, the amplitude at high optical depth (\( \tau >1 \), typically the A and B rings) are negatively correlated with the optical depth (Table 3). The second trend was quite clear by eye, whereas the first one is more difficult to distinguish in Fig. 9a. This is due to the fact that the C ring and the Cassini Division have an optical depth restricted in the range 0.01<\( \tau \)<0.5, which is quite compressed in the scale from 0 to 2.5 of Fig. 9. The same behavior (increasing of amplitude with increasing albedo, or \( \tau \), the two values are correlated) was noticed by Belskaya and Shevchenko (2000) for the amplitude of asteroids’ phase curves: for albedo<0.3 an increase of the amplitude with increasing albedo was noticed.

We note also that for intermediate and high optical depth (0.5<\( \tau \)<2.5, typically the A
and B rings) the amplitude has a much smaller scattering and finally, the correlation coefficient are larger (-74% for the B ring).

For the A ring, it is interesting to note that regions of lower optical depth (0.3<τ<0.5) connect well with data-points in the C ring both in terms in mean value and scattering (Fig. 9a). A good continuity with the B ring is also observed (0.7<τ<1.1).

The angular half width of the peak at half maximum (Fig. 9b) show similar correlation with the optical depth than the amplitude of the surge: increase of HWHM when the optical depth increases for the C ring and the Cassini Division and decrease of HWHM when the optical depth increases for the A and B rings. The scattering of HWHM (HWHM~ 0.3 ± 0.2) for the low optical depth regions behaves similarly as for the amplitude, and lead to small correlation coefficients (19%, see Table 3). As for the amplitude, the scattering of HWHM is narrow for intermediate optical depth (0.5<τ<1.6). Again, the behavior of the A ring is clearly intermediate between the C and B rings. To summarize, the behavior of HWHM is a decreasing function of increasing optical depth, with important scattering at low τ that could be understood as an opposite behavior of HWHM (HWHM is an increasing function of increasing optical depth).

The general trend for the slope of the linear regime (Fig. 9c) is a strong increase with increasing optical depth, with a uniform scattering and with central value well represented by S~ 0.07τ^{1/2}. This is the first time that a correlation is established between the slope S and the optical depth. Previous morphological study on asteroids’ solar phase curves showed an exponential correlation between the slope of the phase function (the so-called phase coefficient β in mag.deg^{-1}) and the albedo (Belskaya and Shevchenko, 2000). Our trend for the slope (the increase of S in π_0P.deg^{-1} with increasing τ) is thus consistent with the slope of asteroids’ phase functions (decrease of β in mag.deg^{-1} with increasing albedo, recall that the magnitude M is inversely proportional to I/F, the so-called geometric albedo: I/F = 10^{-0.4M}, see Domingue et al., 1995, so decrease of β in mag.deg^{-1} with increasing albedo leads to increase of β in I/F.deg^{-1} with increasing albedo), since we
assume that the optical depth is positively correlated with the albedo, as already noticed by Doyle et al. (1989); Dones et al. (1993). However, as for A and HWHM, low optical depth regions (as the C ring and the Cassini Division) have a distinct trend than the trend of the A and B rings.

In conclusion, whereas the slope S has a strong tendency with the optical depth (the average of the absolute correlation coefficients of $S=f(\tau)$, see values of Table 3) is 53%), the first two parameters A and HWHM have a soft tendency with the optical depth (the average of the absolute correlation coefficients for $A=f(\tau)$ is 44% and for $HWHM=f(\tau)$ is 32%). Consequently, Fig. 9 which presents A, HWHM and S according to the optical depth, yields the following trends:

1. The morphological parameters of the surge (A and HWHM) have both similar behavior with $\tau$ in the C ring and the Cassini Division. Firstly, a positive correlation of A with $\tau$ and of HWHM with $\tau$, with a strong scattering and become almost independent of the optical depth for $\tau>0.5$. Secondly, we note a negative correlation of S with $\tau$.

2. These trends are reversed (negative correlations of A and HWHM with $\tau$ and a positive correlation of S with $\tau$) for the moderate and high optical depth regions (typically the A and B rings);

3. The morphological parameter of the linear regime (S) is strongly positively correlated with the optical depth : negatively correlated in the C ring and the Cassini Division (where $\tau<0.5$) and positively correlated in the A and B rings (where $\tau>0.5$).

We conclude that the trends of all the morphological parameters are linked to the optical depth. Then the drastic differences between, on the one hand, the amplitude and the angular width of the surge and, on the other hand, the slope of the linear part across the main ring system suggests that these characteristics originate from different physical mechanisms, as predicted by physical models (see section 2.3.5).
3.2 The opposition effect in COLOR filters

3.2.1 Overview of the COLOR phase curves

Fig. 10 details examples of phase curves obtained for the C, B, A rings and the Cassini Division. A striking result is that the COLOR phase curves’ peaks are much narrower than the CLEAR phase curves’ peaks. Indeed, this is due to the fact that WAC images (exclusively used for the CLEAR phase curves) do not have the more peaked part of the phase function ($\alpha > 0.01^\circ$) whereas NAC images have it ($\alpha > 0.001^\circ$, see Fig. 4). To check this, we plot in the first column (labeled a) of Fig. 10 the phase function obtained with the camera WAC and in the second (labeled b) we plot the fuller phase function obtained with all the NAC and WAC images combined. Indeed, Fig. 10 demonstrates that the value of $\varpi_0 P(\alpha)$ when $\alpha$ tend towards $0^\circ$ is greater in the panel (b) than in the panel (a).

[Fig. 10]

The fact that WAC images do not include the peakest part of the opposition surge explains also the difference between the peak’s intensity of curves in Fig. 3 in CLEAR filters and COLOR filters because when we processed images in CLEAR filters, there was no NAC images. This explains also the shift in I/F at the minimum phase angle on NAC images and WAC images of the same filter (Fig. 3). We observe that the shift in I/F between NAC and WAC image is minimum in the blue filter (Fig. 3), which implies that the full surge is contained in WAC images for this wavelength.

In general, we noticed that the general shape of the curve is similar to that obtained previously : the C ring still has a fairly broad peak with a large amplitude (first pair of graphs at the top of Fig. 10). The B ring exhibits also narrow peaks as those of CLEAR filters comparatively to the other main rings (the second pair of graphs of Fig. 10). The Cassini division (third pair of graphs of Fig. 10) shows again a lot of scattering, which could be the consequence of the failure of the Chandrasekhar (1960) inversion when the
optical depth is not well known. Finally, the A ring, yet very dense, shows also scattering for $\varpi_0 P(\alpha)$, which could be due to the gravitational wakes, see the last pair of graphs in Fig. 10. Indeed, the Chandrasekhar (1960) inversion is very sensitive to the optical depth, and the wakes are known to modify locally the value of $\tau$ (Colwell et al., 2006; Hedman et al., 2007b).

### 3.2.2 Results in COLOR filters and comparisons with the morphological behaviors of the CLEAR filters

We now consider the variation of morphological parameters $A(\lambda)$, HWHM($\lambda$) and $S(\lambda)$ in CLEAR and COLOR filters with the distance from Saturn (see Fig. 11).

[Fig. 11]

The amplitude of the opposition in the outer parts of the C and A rings has a much broader scattering in COLOR filters that in CLEAR filters (Fig. 11a). There is, unfortunately, not enough radial coverage to generalize this effect across the C ring. The Cassini Division also shows similar behavior for the dataset at high and low spectral resolution. In the B ring, where there is a good radial coverage in COLOR filters, amplitudes of CLEAR filters are much lower than the smallest amplitudes in COLOR (typically in the blue at $\lambda=0.451 \mu m$), also noticed for the amplitudes in CLEAR and COLOR filters in the A ring. This could be due to the exclusive use of the images of the WAC to resolve the CLEAR opposition surge (section 3.2.1)

The half-width at half maximum of the peak shows a good agreement between the data in CLEAR filters and COLOR filters (Fig. 11b). The values are the same order of magnitude in all the rings and the regional effect is the same, except for the A ring where HWHM at high spectral resolution (COLOR filters) decreases when the distance at Saturn increases while at low spectral resolution (CLEAR filters), HWHM seems to start to grow.

Finally, for the slope $S$ of the linear part of the phase function, we represent a normalized
slope in order to compare data from the CLEAR filters with data from the COLOR filters. We follow the method of French et al. (2007) which divided the slope by the intensity of the background, thus the normalized slope is $S/B_1$ for the linear-by-part model and now has the deg$^{-1}$ unit. In Fig. 11c we have for $S$ similar behavior as a function from Saturn in the inner A ring and the Cassini Division for data in CLEAR filters and in COLOR filters. Finally, the B ring shows regional effects very different at high and low spectral resolution, especially in the middle of the B ring, at 107 000 km (the most optically thick region) where the CLEAR filters’ slope is significantly overestimated compared to the slope in the blue filter ($\lambda=0.451 \mu$m). In the same region, we also observed a strong scattering of HWHM (Fig. 11b).

3.2.3 Comparisons with multi-wavelength HST observations

We now compare the Cassini data (Fig. 11) with Earth-based data. For this purpose, the recent study of French et al. (2007) was chosen due to their small phase angles $\alpha>0.028^\circ$ and one point below the minimum phase angle corresponding to the angular size of the Sun. The phase curves of French et al. (2007) were obtained in I/F for the main rings and adjusted with the linear-by-part model of Kaasalainen et al. (2001) which provided morphological parameters A, HWHM and S for different wavelengths ranging from the ultraviolet to infrared (see their figure 7).

We consider first the regional effects of morphological parameters derived by French et al. (2007) with the WFPC2/HST instrument. The dispersion observed by the HST for the three morphological parameters A, HWHM and S in the C ring and the Cassini Division is also very clear with ISS (Fig. 11abc). However, it should be noted for the C ring scattering observed with our data (especially those in CLEAR filters) is highly localized (internal and external parts of the ring) and not present in the central regions, corresponding to the background according to the ring type classification of Cooke (1991).
In the B ring, French et al. (2007) noticed strong variations of A and S in the inner edge which are absent for A and are present for S in the ISS data (Fig. 11a and c). For HWHM, HST did not have the raise of HWHM in the middle of the ring that we observed (Fig. 11b). For the slope, we observe in both data set a decrease of S from the inner edge to the middle of the ring (Fig. 11c).

In the A ring, the regional trends for the amplitude A and the angular width HWHM are similar for HST in ISS (Fig. 11a), but it is not the case for S. French et al. (2007) obtained an almost constant value of S. The absolute value of the slope of French et al. (2007) in all filters is roughly S~0.04 deg^{-1}. With ISS/Cassini (Fig. 11c), we observe two distincts trends. First, S at high and low spectral resolution have similar values. Second, the regional effect observed is the same: there is a decreasing trend with increasing distance from Saturn. At the inner edge, S~0.025 deg^{-1} and at the outer edge S~0.015 deg^{-1}. There is, however, a different order of magnitude obtained by ISS/Cassini and WFPC2/HST which could be due to lack of data at large phase angles for Earth-based observation. Indeed, the factor 2 between the slope values is well explained by the overestimation of the slope when the phase angle coverage stops at 6 degrees (section 2.3.4 and Fig. 6c).

Now, we turn on the comparison on the variations of the morphological parameters with the wavelength, which leads to the following conclusions.

First, French et al. (2007) found weak variations of A(\lambda) in the B ring. Indeed, figure 3 of French et al. (2007) shows weak wavelength-variations of the amplitude in the B ring, and also in the A ring. Only one notable difference occurs in the ultraviolet. Overall, French et al. (2007) observed a decrease of A(\lambda) from the ultraviolet to the green, and then an increase in the amplitude of the green to the infrared. This is not at all what is observed for the amplitudes of ISS where a notable increase from blue to green and a decrease in the infrared to the green (Fig. 11a). The values of A(\lambda) for ISS/Cassini and WFPC2/HST are anti-correlated.

For HWHM(\lambda), French et al. (2007) remarked a strong decrease of the half-width at half
maximum when the wavelength increases, and in all the rings. No break in decreasing HWHM(λ) is observed by the HST. This decrease is very different of the behavior of HWHM(λ) with ISS/Cassini (Fig. 11b). Thus the variations of HWHM(λ) presented here are also unprecedented. There is firstly not a decrease but an increase of HWHM with increasing wavelength. Second, the order of magnitude found is not the same. The angular half-width obtained with WFPC2/HST are generally between 0.05° and 0.2° while those of ISS are between 0.1° and 0.4°. This discrepancy could be the consequence of the relative thickness of our phase functions due to the use of several images at similar phase angles whereas French et al. (2007) did not have multiple recovered data because they obtained one point per phase angle.

Finally, for S(λ), the wavelength behavior of French et al. (2007) are consistent with those of ISS/Cassini (S decreases from the blue to the red, and slightly increases in the infrared), Fig. 11c. Strangely, this agreement shows a consistency of both data sets for variations of the slope with a wavelength whereas the regional effects of S observed by the two instruments are significantly different.

3.2.4 Variations of the opposition effect with the wavelength and the optical depth

We see that the morphological parameters depend on the optical depth (Fig. 9) and also on the wavelength (Fig. 12).

[Fig. 12]

It is appropriate now to quantify the variations of A(λ), HWHM(λ) and S(λ) by fitting them with a linear model. We thus obtain for each COLOR phase curve of the rings two linear functions (one from 0.451 to 0.568 μm and another from 0.568 to 0.752 μm) which fit the behavior of A(λ) and two linear functions HWHM(λ), with the same wavelength boundaries. For the slope S(λ), two linear functions are obtained (one from 0.451 μm to 0.650 μm and from 0.650 μm to 0.752 μm), see Fig. 13 for an example.
For this study, is only kept the slope of each linear function (that we called the steepness), that we correlated with the optical depth of the rings (the linear functions and their correlation coefficients are given in Tables 4 and 5).

The slopes of $A(\lambda)$ and HWHM($\lambda$) show both an increase with the optical depth from the blue to the green (Table 4).

From the green to the infrared, we note a decrease of $A(\lambda)$ with $\tau$, but not for HWHM($\lambda$) which can increase or decrease with the optical depth.

However, the strongest trends are found for $S(\lambda)$ which lead to an decrease with $\tau$ of $S(\lambda)$ from the blue to the red and to an increase of $S(\lambda)$ from the red to the infrared. Values are given in Table 5.

It is interesting to note the similar wavelength trends for $A$ and HWHM, which are singularly distinct of the wavelength trends of $S$. This confirms the fact that the morphological parameters originate from different physical mechanisms, as predicted by the physical models (section 2.3.5).

3.3 General trends of the opposition phase curves’ morphology with the ISS data

To conclude the section 3, the ISS data set provides several trends of the opposition effect in Saturn’s rings which concern the:

1. **regional behavior of A, HWHM and S across the main ring system**: indeed, the classification of ring type features defined in section 3.1.3 shows that $A$ and HWHM vary continuously across the ring system (thus quite independently of the ring type classification), whereas $S$ varies abruptly at the boundaries of each ring (Fig. 8);

2. **morphology of the rings’ phase curves**: in section 3.1.4, strong dependences on
the optical depth of the rings of A, HWHM and S were established: anti-correlation of
A and HWHM with \( \tau \) and correlation of S with \( \tau \) (Fig. 9). A high scattering at low \( \tau \)
and high \( \tau \) is noticed for HWHM in CLEAR and COLOR phase curves;

(3) correlation between the morphological parameters: we showed in the sec-
tion 3.1.2 that the parameters of the surge A and HWHM are correlated (Table 2),
whereas there is only a weak dependence of HWHM and S on the one hand, and A and
S on the other hand (Table 2);

(4) variations of the morphological parameters in CLEAR and COLOR filters:
we remarked in section 3.2.2 that the CLEAR amplitude is smaller than the COLOR
ones, because the CLEAR data set did not includes NAC images which generally capture
the highest part of the surge (Fig. 11). We showed also that the discrepancy in the slope
of French et al. (2007) is due to their phase angle coverages which did not cover the
larger phase angles. As a consequence, their slopes are overestimated, as predicted by
our study on the influence of incomplete data (section 2.3.4 and Fig. 6c);

(5) variations of the morphological parameters with the wavelength and the
optical depth: \( A(\lambda) \) increases from the blue to the green (0.451 \( \mu \)m-0.568 \( \mu \)m) and
decreases from the green to the infrared (0.568 \( \mu \)m-752 \( \mu \)m), Fig. 12. This increase is
reinforced when the optical depth increases (Table 4) and is marked by a maximum value
of \( A(\lambda) \) in the green regardless of the rings. HWHM(\( \lambda \)) also increases from the blue to
the green, but no general trend is noticed from the green to the infrared (Table 4). \( S(\lambda) \)
decreases from the blue to the red (0.451 \( \mu \)m-650 \( \mu \)m), then rises from the red to the
near-infrared (0.650 \( \mu \)m-752 \( \mu \)m), Table 5. The wavelength-variation of \( S \) is then quite
distinct to that of the surge parameters (A and HWHM), then suggesting that they
may originate from different physical mechanisms.
4 Discussion

4.1 A combination of the coherent backscattering with the shadow hiding?

We showed in section 3.1.4 that the amplitude of the surge had a specific behavior according to the optical depth. With the model of Shkuratov et al. (1999), an estimation of the amplitude is possible but refers only to the coherent backscattering enhancement. Poulet et al. (2002) derived the following expression for the amplitude of the surge:

\[ A \sim 1 + e^{-d/L/2} \]

where \( d \) is the effective radius of grains and \( L \) is the free mean path of photons in the regolithic medium. It turns out that the amplitude could not be greater than 1.5, which contradicts our morphological results (Fig. 11a). This variation might be due to the shadow hiding effect which is not taken into account in this computation of the amplitude.

4.2 Variations of S with the optical depth

In shadow hiding numerical simulations of Stankevich et al. (1999) that take into account the optical depth and the filling factor, the absolute slope of the linear part has roughly the same value when the optical depth is greater than 1, whatever the filling factor value. This theoretical prediction is now confirmed by our results: we observed a saturation of \( S \) at \( \tau > 1 \) (Fig. 9c).

Also, we observe with the ISS data (Fig. 11c) a wavelength-dependence of the slope \( S \). This behavior was predicted by the model of Hapke (2002) because \( S \) depends on the extinction coefficient \( Q_{\text{ext}}(\lambda, \bar{r}) \) where \( \bar{r} \) is the mean radius of particles (see section 2.3.4).
4.3 Linking photometric behaviors with dynamical concepts

The present study, thanks to the quality of its data (radial and angular resolution), allows us to highlight several observational facts never reported in the history of the observation of the opposition effect in the Saturn’s system. The slope, the angular width and the amplitude of the rings’ opposition phase curves are clearly correlated with the optical depth of the rings (Fig. 9). Whereas a physical description of such a dependence would need a full new physical model, we provide here some arguments explaining how the optical depth may indeed influence these three parameters.

The optical depth is both a measure of the local volume filling factor of material, and the local collisional activity. Indeed, basic analytical computation shows that the filling factor of ring particle is proportional to \( \tau / H \) (with \( \tau \) standing for the optical depth and \( H \) standing for the vertical height of the rings). So one may expect regions of higher optical depth to have a much higher filling factor of particles. This is also in agreement with local simulation of ring dynamics (Wisdom and Tremaine, 1988), that shows that the vertical width of material increases with decrease optical depth, because of the lower efficiency of collisional damping. So one may expect the filling factor of particles to be an increasing function of the optical depth.

However, in the case the slope of the phase function for phase angles >1°, analytical and numerical models (Irvine, 1966; Kawata and Irvine, 1974; Stankevich et al., 1999) predict that S should depend on the particle filling factor D and the vertical extension of the layer of particles in such way that the steeper is the slope, the lower is the filling factor. Our morphological trends (Fig. 9c) seem unambiguously to contradict the theoretical trends of these models because our highest slopes are found in the high optical depth regions. Because high optical depth regions are known to have the highest filling factor (Salo and Karjalainen, 2003), this implies that assumptions of diluted layers (D \( \ll 0.3 \) and 8D \( \ll 1 \) respectively for Stankevich et al., 1999; Kawata and Irvine, 1974) are not suited...
to the Saturn’s rings.

As a consequence, the shadow hiding observed in the Saturn’s rings may result of *intra-particle shadow hiding*, as stated by Buratti and Veverka (1985). Another possibility is that the shadow hiding that operates in the rings are maintained in a “regime of transparency” of particles (Lumme et al., 1987; Irvine et al., 1988) that dominates the shadowing effect due to packing density.

We now turn to the case of the HWHM and the amplitude. Whereas there is still a debate on what determine their value (Mishchenko, 1992; Mishchenko and Dlugach, 1992a,b; Shkuratov et al., 1999; Hapke, 2002), authors agree to link them the coherent-backscattering process, which may be controlled by the regolith at the surface of ring particles (Poulet et al., 2002). Like for planetary surfaces, the regolith is expected to be the result of space fractionation and erosional processes at the surface of the ring-particles, due (in particular) to the on-going collisional activity inside rings. Numerical studies of the dynamics of the ring-particles have shown that the optical depth is a key parameter controlling the collisional activity of rings. On the one hand, the number of collisions per orbit per particle is proportional to \( \tau \) (in the regime of low optical depth, see Wisdom and Tremaine, 1988), on the other hand, the random velocity in a ring of thickness \( H \) is about \( H \times \Omega \) (with \( \Omega \) standing for the local keplerian frequency). Since \( H \) is a decreasing function of \( \tau \), thus impact velocities are lower in regions of high optical depth. In short, particles in low-optical depth regions may suffer rare but violent collisions, conversely, in high-optical depth regions particles suffer frequent but gentle collisions.

This may explain qualitatively why the HWHM and amplitude have different behavior in the data (Fig. 8 and 9). However, impact velocities have a lower bound \( \sim 2r \times \Omega \) (with \( r \) standing for the particle’s radius) due to the keplerian shear across the diameter of a particle. This “shear dominated limit” is reached when the optical depth is high, typically for \( \tau > 1 \). In such high filling factor regime the dynamics of collisions is entirely controlled by the keplerian shear rather than by the random impact velocities. This may qualitatively
explain why values of HWHM and Amplitude seem constant for $\tau > 1$: in this regime, the collisional activity being about independent of optical depth, the physical properties of the regolith may be about constant which is indeed observed.

In conclusion, in the absence of self-consistent physical model of the opposition effect, these qualitative arguments show that there are good reasons to believe that the optical depth is a key factor determining the opposition effect in the ring through two different mechanisms:

(1) the optical depth may influence the absolute slope S, assuming that shadow hiding is the preponderent mechanism at phase angles $\alpha > 1^\circ$

(2) the optical depth may controls the HWHM and the amplitude (at phase angles $\alpha < 1^\circ$) if the structure of the regolith is influenced by the collisional activity.

4.4 Comparison of the opposition effect in optical light and infrared light

A comparison of the solar phase curves of ISS/Cassini and the thermal phase curves of CIRS/Cassini yields to the following trends:

(1) Altobelli et al. (2007) found a prominent opposition surge for the thermal phase curves of the plateaux, well fitted by a logarithmic model. This is also the case of the solar phase curves of the plateaux observed by ISS (Fig. 8a);

(2) Altobelli et al. (2007) found that the thermal phase curves of the background (regions in the close environment of the plateaux) do not have opposition surge, whereas background has an opposition surge in the solar phase curves of ISS (Fig. 8a);

A priori, the emitted phase curves may not reflect the coherent backscatter effect (Altobelli et al., 2007) because interferences of photons did not act on heat, and thus on infrared light. However, a pure shadow hiding model such as (Lumme and Bowell, 1981) fails to reproduce the CIRS opposition surge of the plateaux (in general the shadow hiding models did not
produce high surges, [Stankevich et al., 1999]. This could be the proof that the shadow hiding cannot produce solely the opposition surge in emitted light and that the coherent backscatter could act on the shadow hiding mechanism, by multiplying the single scattered light component at small phase angles, as underlined by Hapke (2002).

Interestingly, no similar surge were observed in the background (Altobelli et al., 2007), whereas both plateaus and background have an opposition surge in the solar phase curves of ISS. Because the background regions are more dim and reflective than the plateaus (background have smaller optical depth and higher albedo than plateaus which means they reflect more than they absorb, [Cooke, 1991]), this could explain why these regions did not have an opposition peak in emitted light.

5 Conclusion

We report here the main conclusions of this morphological study on the Saturn’s rings opposition effect seen by ISS/Cassini:

(1) The amplitude A and the half angular width HWHM of the opposition surge decrease with increasing optical depth $\tau$. A and HWHM may reflect both coherent backscattering and shadow hiding, because according to French et al. (2007) the morphological parameters of the surge are greater than their coherent backscatter counterparts;

(2) All the morphological parameters are linked together. We find correlations between A and HWHM, between HWHM and S, and also between A and S, which imply that S could be more or less affected by the coherent backscattering. This could be due to the fact that we derive our slope from 1.5° to 25° whereas analytical model of Shkuratov et al. (1999) describes the shadow hiding effect as a slope which fits the phase curve from 4.5° to larger phase angles, see (Poulet et al., 2002).

(3) The absolute slope S of the linear part of the phase function increases with increasing optical depth $\tau$ (for optically thick rings) and shows distinct trends to the morpholog-
ical surge parameters, which implies that this parameter is not totally affected by the coherent backscattering. As (Lumme et al., 1987; Irvine et al., 1988), we think that the Saturn's rings could be in a regime of transparency of particles because the effect of packing density (decrease of $S$ with increasing packing density) is not that expected for the Saturn's rings (increase of $S$ with optical depth, and if we assume that the optical depth and the packing density are correlated, increase of $S$ with increasing packing density);

(4) $\tau$-dependence with the morphological parameters strengthen our assumptions saying that environmental effects are the key element determining the opposition effect because the optical depth is a direct measure of the collisional and dynamical activity in the surrounding of particles and is highly correlated with $A$, HWHM and $S$;

(5) Comparisons of ISS/Cassini solar phase curves and CIRS/Cassini thermal phase curves in the C ring show that the C ring’s plateaus can have a strong opposition surge both in solar and thermal phase curves whereas the C ring’s background has a strong opposition surge in the solar phase curve and no opposition surge in the thermal phase curve.

(6) Wavelength variations of the amplitude $A$ of the surge show a maximum in all the rings at $\lambda=0.568$ $\mu$m. The increase of $A$ from 0.451 to 0.568 $\mu$m and the decrease of $A$ from 0.568 to 0.752 $\mu$m are reinforced with increasing $\tau$;

(7) Wavelength variations of HWHM of the surge show also a maximum at $\lambda=0.568$ $\mu$m but it is not systematic, HWHM can also increase from 0.568 $\mu$m to 0.752 $\mu$m. Moreover, there is no specific wavelength variations of HWHM with the optical depth;

(8) Wavelength variations of the slope $S$ of the linear part imply that the shadow hiding depend on the wavelength, may be via the particle’s scattering cross-section of recent model (Hapke, 2002). The decrease of $S$ from 0.451 to 0.650 $\mu$m and the increase of $S$ from 0.650 to 0.752 $\mu$m are reinforced with increasing $\tau$.

The goal of this first paper was not to derive and quantify directly the physical properties obtained from the models. First, because there is a large set of models and it seemed more
convenient to separate the morphological models to the more physical and sophisticated ones. Second, because recent physical models did not implement only the opposition effect but the main photometric effects which occur in the full phase function, from 0 to 180 degrees. Consequently, more investigations will be provided for this purpose by using full phase curves and photometric analytical models in the second paper. In the future, we hope to have the linear degree of polarization at the opposition to obtain more constrains on the ring particle’ textures.
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Main observational parameters of each sequence of images for each geometry of observation ($i=\arccos(\mu)$ and $\epsilon=\arccos(\mu_0)$). CLEAR (WAC) filters designate the broadband filters in the optical domain (the central wavelength is $\lambda_{\text{cl}}^{\text{WAC}} = 0.611\mu m$). COLOR (NAC) filters designate blue, green, red and near infrared filters (at central wavelengths of $\lambda_{\text{bl}}^{\text{NAC}} = 0.440\mu m$ and $\lambda_{\text{bl}}^{\text{NAC}} = 0.451\mu m$; $\lambda_{\text{grn}}^{\text{NAC}} = 0.568\mu m$; $\lambda_{\text{red}}^{\text{NAC}} = 0.650\mu m$; $\lambda_{\text{ir}}^{\text{NAC}} = 0.752\mu m$) and COLOR (WAC) filters designate blue, green, red and near infrared filters (at central wavelengths of $\lambda_{\text{bl}}^{\text{WAC}} = 0.460\mu m$; $\lambda_{\text{grn}}^{\text{WAC}} = 0.567\mu m$; $\lambda_{\text{red}}^{\text{WAC}} = 0.649\mu m$; $\lambda_{\text{ir}}^{\text{WAC}} = 0.742\mu m$).

| date          | Nb im | $i$  | $\epsilon$ | Radial res. | Azim. res. | Filters (Camera) |
|---------------|-------|------|-------------|-------------|------------|------------------|
| June 7 2005   | 12    | 111.5| 111.9       | 44.0        | 115.1      | CLEAR (WAC)      |
| June 26 2005  | 66    | 111.3| 111.3       | 30.1        | 70.0       | CLEAR (WAC)      |
| July 23 2006  | 48    | 73.1 | 73.4        | 13.4        | 40.7       | CLEAR (WAC)      |
| May 20 2005   | 57    | 111.6| 111.6       | 4.6         | 11.5       | COLOR (NAC)      |
| May 20 2005   | 59    | 111.5| 111.9       | 44.0        | 115.1      | COLOR (WAC)      |
| Dec 31 2006   | 12    | 104.4| 108.7       | 38.4        | 104.8      | COLOR (WAC)      |
| Feb 20 2007   | 20    | 103.7| 122.7       | 66.3        | 72.5       | COLOR (WAC)      |
| Apr 25 2007   | 16    | 102.7| 110.7       | 44.4        | 92.6       | COLOR (WAC)      |
Table 2

Results of linear fits (function and correlation coefficient) obtained for A=f(HWHM), S=f(A) and S=f(HWHM) for each Saturn’s main ring and using CLEAR phase curves.

|        | A=f(HWHM) | S=f(A) | S=f(HWHM) |
|--------|-----------|--------|-----------|
|        | function  | correl. | function  | correl. | function  | correl. |
| Cass. Div. | 0.91 + 1.72τ | 59 %   | 0.04 -0.03τ | -68 %   | 0.049 -0.05τ | -35 % |
| C ring  | 1.20 + 0.91τ | 79 %   | 0.04 -0.06τ | -46 %   | 0.025 -0.04τ | -47 % |
| A ring  | 1.12 + 1.08τ | 56 %   | 0.10 -0.14τ | -84 %   | 0.079 -0.24τ | -81 % |
| B ring  | 1.18 + 0.58τ | 31 %   | 0.15 -0.33τ | -79 %   | 0.141 -0.81τ | -65 % |
Table 3

Results of linear fits obtained (function and correlation coefficient) for $A=f(\tau)$, HWHM=$f(\tau)$ and $S=f(\tau)$ for each Saturn’s main ring and using CLEAR phase curves.

| Ring     | $A=f(\tau)$ | HWHM=$f(\tau)$ | $S=f(\tau)$ |
|----------|--------------|-----------------|--------------|
|          | function     | correl.         | function     | correl. | function | correl. |
| Cass. Div.| 1.22 + 0.937 | 41 %            | 0.20 + 0.175\(\tau\) | 19 %    | 0.040 - 0.030\(\tau\) | -42 %   |
| C ring   | 1.50 + 0.024 | 25 %            | 0.33 + 0.077\(\tau\) | 19 %    | 0.024 - 0.026\(\tau\) | -68 %   |
| A ring   | 1.50 - 0.175 | -36 %           | 0.31 - 0.106\(\tau\) | -49 %   | 0.024 + 0.025\(\tau\) | 19 %    |
| B ring   | 1.42 - 0.068 | -74 %           | 0.24 - 0.016\(\tau\) | -39 %   | 0.035 + 0.031\(\tau\) | 82 %    |
Table 4

Results of linear fits (function and correlation coefficient) obtained for the steepness of $A(\lambda)=f(\tau)$ and for the steepness of $\text{HWHM}(\lambda)=f(\tau)$ using COLOR phase curves of the A and B rings ($\tau>0.5$).

| Steepness of $A(\lambda)=f(\tau)$ | Steepness of $\text{HWHM}(\lambda)=f(\tau)$ |
|-----------------------------------|------------------------------------------|
| function | correl. | function | correl. |
| $0.451 \ \mu m < \lambda < 0.568 \ \mu m$ | $1.210 + 0.3\tau$ | $55 \%$ | $0.14 + 0.011\tau$ | $38 \%$ |
| $0.568 \ \mu m < \lambda < 0.752 \ \mu m$ | $0.001 - 0.5\tau$ | $-51 \%$ | $0.04 - 0.037\tau$ | $-46 \%$ |
Table 5

Results of linear fits (function and correlation coefficient) obtained for the steepness of \( S(\lambda) = f(\tau) \) and the steepness of \( S/B_1(\lambda) = f(\tau) \) using COLOR phase curves of the A and B rings (\( \tau > 0.5 \)).

| Function Range (\( \mu m \)) | Steepness of \( S(\lambda) = f(\tau) \) \((\text{in } \omega_0 P \text{.deg}^{-1} \text{.}\mu m^{-1})\) | Correlation | Steepness of \( S/B_1(\lambda) = f(\tau) \) \((\text{in } \text{deg}^{-1} \text{.}\mu m^{-1})\) | Correlation |
|-------------------------------|-------------------------------------------------|------------|-------------------------------------------------|------------|
| \( 0.451 \mu m < \lambda < 0.650 \mu m \) | \(-0.21 - 0.043\tau\) | -73 % | \(-0.04 - 0.039\tau\) | -49 % |
| \( 0.650 \mu m < \lambda < 0.752 \mu m \) | \(0.04 + 0.018\tau\) | 67 % | \(0.02 + 0.054\tau\) | 44 % |
Fig. 1. The opposition effect in the B ring. A typical image of the 26 June sequence captured by the Wide Angle Camera (W1498453136.IMG). Concentric circles correspond to identical phase curves computed in the image (isophase). Numbers in the concentric circles represent the solar phase angles (in degrees).
Fig. 2. The opposition effect in the C ring. A typical image of the 20 may sequence captured by the Narrow Angle Camera (N1595278165.IMG). The contrast is enhanced to make more visible the opposition spot in the C ring. Concentric circles correspond to identical phase curves computed in the image (isophase). Numbers in the concentric circles represent the solar phase angles (in degrees).
Fig. 3. Radial location of the opposition spot in the images taken in CLEAR and COLOR filters (filled symbols represent WAC images and empty symbols represent NAC images). We give in the $y$-axis the normalized brightness $I/F$ of the minimum phase angle in the image, the $x$-axis is the corresponding distance from Saturn of this point. The vertical dotted lines correspond to ring boundaries. The optical depth of PPS/Voyager is plotted as a radial reference.
Fig. 4. Extracted COLOR phase curve from NAC images of the May 20 sequence in A, B, C rings and Cassini Division in linear scale (a) and logarithmic scale (b). The vertical dotted line in (a) and (b) corresponds to the angular size of the Sun. The solid curves in (a) and (b) correspond to the logarithmic model of Bobrov (1970).
Fig. 5. Typical phase curves of the B ring (a) and C ring (b) in CLEAR filters chosen for testing the stability of linear-exponential model of Kaasalainen et al. (2001) when the phase angle coverage is incomplete. Circles and squares correspond to the cutoff of the incomplete phase function and the solid curves correspond to the initial fit of the linear-exponential model of Kaasalainen et al. (2001). The vertical dotted lines correspond to boundaries of the surge domain and the linear part domain that we have tested (see Fig. 6).
Fig. 6. Deviation of the linear-exponential model of Kaasalainen et al. (2001) for the morphological parameters A (a), HWHM (b) and S (c) when the phase angle coverage is incomplete. Circles and squares correspond to the cutoff of the incomplete phase functions of respectively the B ring and C ring typical phase curves (Fig. 5).
Fig. 7. Representative CLEAR phase curves for the main rings with a zoom on the surge (a) and the full phase curve (b), fitted respectively with the logarithmic model of Bobrov (1970) (a) and the linear-by-part model of Lumme and Irvine (1976) (b).
Fig. 8. Regional behavior of the morphological parameters: (a) the amplitude $A$, (b) the angular width HWHM in degrees, and (c) the absolute slope $S$ in $\omega_0 P.\text{deg}^{-1}$ from the Linear-by-part model of Lumme and Irvine (1976) for CLEAR phase curves using the ring type classification. The vertical dotted lines correspond to ring boundaries. The optical depth of PPS/Voyager is plotted in (c) as a radial reference.
Fig. 9. Morphological parameters of CLEAR phase curves from the Linear-by-part model of Lumme and Irvine (1976): Amplitude $A$ (a), Angular width HWHM (b) and absolute slope $S$ (c) in $\omega_0 P.\text{deg}^{-1}$.
Fig. 10. Representative COLOR phase curves for the main rings with a zoom on the surge with WAC images (a) and the full phase curve with NAC and WAC images (b). Full phase curves of (b) are fitted with the linear-exponential model of Kaasalainen et al. (2001).
Fig. 11. Regional behavior of morphological parameters: (a) the amplitude A, (b) the angular width HWHM and (c) unitless absolute slope $S/B_1$ in deg$^{-1}$ from the Linear-by-part model of Lumme and Irvine (1976) using CLEAR and COLOR phase curves. The vertical dotted lines correspond to ring boundaries. The optical depth of PPS/Voyager is plotted in (c) as a radial reference.
Fig. 12. Morphological parameters of CLEAR and COLOR phase curves from the Linear-by-part model of Lumme and Irvine (1976): (a) the amplitude $A$, (b) the angular width HWHM and (c) the unitless absolute slope $S/B_1$ in deg$^{-1}$.
Fig. 13. Variations of the morphological parameters $A(\lambda)$, HWHM($\lambda$), the absolute slope $S(\lambda)$ and the unitless absolute slope $S/B_1(\lambda)$ for two typical regions of the A ring (a) and in the B ring (b). Dotted lines correspond to linear fits obtained in the spectral ranges. The slopes of these linear functions are called “steepness” and are correlated with the rings’ optical depth in tables 4 and 5.
Table 1: Outputs of the logarithmic model of Bobrov (1970) for the CLEAR phase curves representing each ring types (inner corresponds to inner regions characterized by low optical depth, background are morphological smooth regions without abrupt variation of optical depth, bright corresponds to bright regions that have the highest optical depth in each ring, ringlet corresponds to a thinner ring embedded in a less dense region or a gap, and outer corresponds to outer regions that mark the transition at each ring boundary) of each main ring. Horizontal lines correspond to the ring boundaries. We give for each ring type, the normal optical depth of the Voyager/PPS instrument and the corresponding radius (the distance from Saturn’s center). $f_{\tau_0 P \rightarrow I/F}$ is a conversion factor which corresponds to the mean level of I/F curves over the mean level of $\tau_0 P$ curves.

| Rad. (km) | $\tau_{pps}$ | Ring type | $a_0$     | $a_1$     | $f_{\tau_0 P \rightarrow I/F}$ |
|-----------|--------------|------------|-----------|-----------|-------------------------------|
| 73271.7   | 0.005        | ringlet    | 2.023     | -0.6457   | 0.000001                      |
| 74996.2   | 0.058        | bright     | 1.105     | -0.2097   | 0.0223                        |
| 75356.9   | 0.027        | inner      | 1.331     | -0.2857   | 0.1255                        |
| 75665.0   | 0.032        | inner      | 1.072     | -0.2535   | 0.1232                        |
| 76199.8   | 0.132        | bright     | 1.128     | -0.1899   | 0.1255                        |
| 76671.2   | 0.031        | inner      | 1.188     | -0.2561   | 0.1253                        |
| 77075.4   | 0.119        | bright     | 1.263     | -0.2106   | 0.0643                        |
| 77862.3   | 0.731        | ringlet    | 0.568     | -0.1074   | 0.0488                        |
| 78273.0   | 0.079        | background | 1.242     | -0.2130   | 0.0501                        |
| 78889.1   | 0.074        | background | 1.182     | -0.2030   | 0.0545                        |
| 79238.2   | 0.331        | bright     | 0.807     | -0.1237   | 0.0310                        |
| 79956.9   | 0.096        | background | 1.217     | -0.1985   | 0.1189                        |
| 80757.8   | 0.109        | background | 1.213     | -0.1962   | 0.1259                        |

Table continues on next page...
| Rad. (km) | $\tau_{\text{pp}}$ | Ring type   | $a_0$  | $a_1$ | $f_{\sigma_0P^{-1}F}$ |
|---------|-----------------|-------------|--------|-------|-------------------|
| 81661.4 | 0.117           | background  | 1.186  | -0.1845 | 0.0466            |
| 82031.0 | 0.202           | bright      | 0.969  | -0.1540 | 0.0539            |
| 82914.0 | 0.133           | background  | 1.242  | -0.1907 | 0.0621            |
| 84125.6 | 0.102           | background  | 1.352  | -0.2052 | 0.0557            |
| 84844.4 | 0.425           | bright      | 1.707  | -0.2325 | 0.0418            |
| 85234.6 | 0.099           | background  | 1.290  | -0.1953 | 0.0432            |
| 85706.9 | 0.256           | bright      | 1.335  | -0.1978 | 0.1254            |
| 85953.3 | 0.227           | bright      | 1.098  | -0.1625 | 0.1252            |
| 86158.7 | 0.075           | background  | 1.506  | -0.2179 | 0.1249            |
| 86503.2 | 0.396           | bright      | 1.853  | -0.2430 | 0.1250            |
| 86877.4 | 0.066           | background  | 1.404  | -0.1984 | 0.0522            |
| 87189.3 | 0.153           | bright      | 0.892  | -0.1213 | 0.0430            |
| 87312.8 | 0.163           | bright      | 1.019  | -0.1440 | 0.1140            |
| 87506.6 | 1.011           | ringlet     | 0.645  | -0.0566 | 0.1163            |
| 88451.6 | 0.239           | bright      | 1.869  | -0.2257 | 0.1241            |
| 88725.6 | 0.156           | ringlet     | 1.087  | -0.1390 | 0.1223            |
| 89233.7 | 0.248           | bright      | 1.695  | -0.2038 | 0.1221            |
| 89547.1 | 0.045           | background  | 1.995  | -0.2505 | 0.1232            |
| 89851.1 | 0.307           | bright      | 1.970  | -0.2265 | 0.1233            |
| 90019.4 | 0.073           | background  | 2.361  | -0.2384 | 0.0687            |
| 90163.1 | 0.713           | ringlet     | 1.373  | -0.1719 | 0.0633            |
| 90509.7 | 0.355           | bright      | 2.310  | -0.2514 | 0.0895            |
| 90685.9 | 0.076           | outer       | 2.454  | -0.2532 | 0.1144            |
| 90929.2 | 0.099           | outer       | 1.981  | -0.2161 | 0.0985            |
| 91237.3 | 0.137           | outer       | 2.060  | -0.2253 | 0.1128            |

Table continues on next page...
| Rad. (km) | $\tau_{\text{pps}}$ | Ring type | $a_0$ | $a_1$ | $f_{\sigma_0 P^{-1/F}}$ |
|-----------|-----------------|-----------|-------|-------|-----------------|
| 91788.6   | 0.170           | outer     | 2.276 | -0.2447 | 0.0857 |
| 92390.9   | 1.629           | bright    | 3.548 | -0.3668 | 0.0952 |
| 93781.3   | 1.359           | inner     | 3.398 | -0.3418 | 0.1254 |
| 94201.6   | 0.935           | inner     | 3.377 | -0.3479 | 0.1256 |
| 94751.3   | 0.706           | inner     | 3.010 | -0.3528 | 0.1253 |
| 95107.0   | 0.732           | ringlet   | 2.984 | -0.3582 | 0.1249 |
| 95527.3   | 0.936           | inner     | 3.421 | -0.3460 | 0.1252 |
| 96659.0   | 1.340           | inner     | 3.637 | -0.3472 | 0.0542 |
| 96885.4   | 0.817           | ringlet   | 3.213 | -0.3492 | 0.0608 |
| 97661.4   | 0.976           | inner     | 3.413 | -0.3394 | 0.1265 |
| 98146.4   | 0.872           | inner     | 3.497 | -0.3387 | 0.1264 |
| 99213.5   | 1.458           | background| 3.721 | -0.3418 | 0.1259 |
| 100475.   | 2.057           | bright    | 3.882 | -0.3486 | 0.1281 |
| 101671.   | 1.188           | ringlet   | 3.698 | -0.3279 | 0.0057 |
| 101800.   | 2.104           | bright    | 3.939 | -0.3401 | 0.1259 |
| 103223.   | 1.266           | background| 3.975 | -0.3634 | 0.1236 |
| 105422.   | 2.070           | bright    | 4.149 | -0.3446 | 0.0818 |
| 106327.   | 2.069           | background| 4.139 | -0.3577 | 0.0477 |
| 107847.   | 2.116           | bright    | 4.302 | -0.3634 | 0.0679 |
| 109367.   | 2.053           | bright    | 4.428 | -0.4181 | 0.1249 |
| 110789.   | 1.815           | ringlet   | 4.250 | -0.4146 | 0.1251 |
| 111953.   | 1.407           | background| 4.292 | -0.4617 | 0.0766 |
| 112309.   | 1.910           | outer     | 4.412 | -0.4370 | 0.1249 |
| 113053.   | 1.768           | outer     | 4.441 | -0.4350 | 0.1253 |
| 113441.   | 1.744           | outer     | 4.393 | -0.4334 | 0.1263 |

Table continues on next page...
| Rad. (km) | \( \tau_{\text{pps}} \) | Ring type  | \( a_0 \)  | \( a_1 \)  | \( f_{\sigma_0 P^{-1/F}} \) |
|----------|----------------|------------|---------|---------|----------------|
| 113667.  | 1.358          | background | 4.306   | -0.4675 | 0.1269         |
| 113796.  | 1.563          | outer      | 4.394   | -0.4632 | 0.1261         |
| 114411.  | 1.746          | outer      | 4.344   | -0.4653 | 0.1262         |
| 114637.  | 1.440          | background | 4.342   | -0.4818 | 0.1266         |
| 115122.  | 2.047          | bright     | 4.506   | -0.5140 | 0.1268         |
| 116254.  | 2.105          | bright     | 4.547   | -0.4917 | 0.1249         |
| 117803.  | 0.698          | ringlet    | 0.722   | -0.2112 | 0.1265         |
| 117910.  | 0.087          | ringlet    | 1.506   | -0.0942 | 0.1266         |
| 117983.  | 0.113          | inner      | 2.119   | -0.2572 | 0.1272         |
| 118084.  | 0.119          | inner      | 1.883   | -0.2250 | 0.1269         |
| 118168.  | 0.150          | bright     | 1.329   | -0.2249 | 0.1288         |
| 118241.  | 0.099          | ringlet    | 1.324   | -0.1754 | 0.0204         |
| 118365.  | 0.080          | inner      | 2.172   | -0.1818 | 0.0222         |
| 118482.  | 0.091          | inner      | 1.960   | -0.2528 | 0.0464         |
| 118668.  | 0.079          | inner      | 1.897   | -0.2426 | 0.0225         |
| 118836.  | 0.083          | inner      | 1.718   | -0.2306 | 0.0475         |
| 119061.  | 0.082          | bright     | 1.878   | -0.2338 | 0.0435         |
| 119145.  | 0.089          | inner      | 1.958   | -0.2494 | 0.1003         |
| 119229.  | 0.104          | bright     | 1.640   | -0.2175 | 0.0508         |
| 119285.  | 0.097          | bright     | 1.824   | -0.2418 | 0.0561         |
| 119476.  | 0.029          | inner      | 2.604   | -0.3045 | 0.0626         |
| 119644.  | 0.038          | inner      | 1.986   | -0.2493 | 0.0527         |
| 119768.  | 0.032          | inner      | 2.186   | -0.2975 | 0.0639         |
| 120060.  | 0.356          | ringlet    | 1.509   | -0.2411 | 0.0518         |
| 120116.  | 0.161          | background | 1.939   | -0.2629 | 0.0560         |

Table continues on next page...
| Rad. (km) | $\tau_{\text{pps}}$ | Ring type | $a_0$ | $a_1$ | $f_{\sigma_0P=1/F}$ |
|----------|----------------------|------------|-------|-------|-------------------|
| 120279.  | 0.134                | ringlet    | 1.600 | -0.2347 | 0.1158            |
| 120335.  | 0.077                | background | 1.980 | -0.2603 | 0.0448            |
| 120408.  | 0.064                | background | 2.168 | -0.2863 | 0.0423            |
| 120565.  | 0.367                | background | 2.328 | -0.3048 | 0.0370            |
| 120638.  | 0.385                | background | 2.574 | -0.3377 | 0.0051            |
| 120711.  | 0.384                | background | 2.625 | -0.3319 | 0.0326            |
| 120773.  | 0.502                | background | 2.621 | -0.3319 | 0.0465            |
| 120918.  | 0.089                | outer      | 2.637 | -0.3581 | 0.0952            |
| 121031.  | 0.116                | outer      | 2.318 | -0.2747 | 0.1058            |
| 121272.  | 0.140                | outer      | 2.427 | -0.2736 | 0.1093            |
| 121626.  | 0.156                | outer      | 2.685 | -0.2951 | 0.0563            |
| 121901.  | 0.180                | outer      | 2.786 | -0.3296 | 0.0790            |
| 122097.  | 0.458                | inner      | 2.887 | -0.3562 | 0.1254            |
| 122269.  | 0.623                | inner      | 3.366 | -0.4469 | 0.1253            |
| 122553.  | 1.092                | bright     | 3.862 | -0.4958 | 0.1247            |
| 123040.  | 0.864                | inner      | 3.696 | -0.4431 | 0.1254            |
| 123249.  | 0.681                | inner      | 3.478 | -0.4386 | 0.1235            |
| 123676.  | 1.231                | bright     | 3.911 | -0.4554 | 0.1254            |
| 123848.  | 0.951                | bright     | 3.731 | -0.4466 | 0.1251            |
| 124252.  | 0.878                | bright     | 3.576 | -0.4149 | 0.1238            |
| 124409.  | 0.690                | bright     | 3.451 | -0.4045 | 0.1246            |
| 124659.  | 0.574                | background | 3.305 | -0.3920 | 0.1245            |
| 125367.  | 0.699                | bright     | 3.075 | -0.3468 | 0.1256            |
| 125951.  | 0.590                | bright     | 3.212 | -0.3655 | 0.1256            |
| 126619.  | 0.498                | background | 3.074 | -0.3872 | 0.1256            |

Table continues on next page...
| Rad. (km) | $\tau_{\text{PPS}}$ | Ring type | $a_0$  | $a_1$  | $f_{\sigma_0P-1/F}$ |
|----------|------------------|-----------|--------|--------|---------------------|
| 127655.  | 0.495            | background| 2.929  | -0.3742| 0.1257             |
| 128977.  | 0.473            | background| 2.694  | -0.3465| 0.1256             |
| 130037.  | 0.476            | background| 2.568  | -0.3344| 0.1254             |
| 130786.  | 0.661            | bright    | 2.637  | -0.3575| 0.1254             |
| 131122.  | 0.465            | background| 2.556  | -0.3406| 0.1254             |
| 131818.  | 0.803            | bright    | 2.764  | -0.3932| 0.1253             |
| 132372.  | 0.735            | bright    | 2.478  | -0.3015| 0.1253             |
| 133105.  | 0.463            | background| 2.438  | -0.3082| 0.1253             |
| 133513.  | 0.012            | ringlet   | 3.354  | -1.0378| 0.1253             |
| 133574.  | 0.027            | ringlet   | 1.028  | -0.3205| 0.1251             |
| 133820.  | 0.509            | outer     | 2.196  | -0.1977| 0.1250             |
| 133917.  | 0.534            | outer     | 2.375  | -0.2581| 0.1250             |
| 134280.  | 0.959            | bright    | 2.390  | -0.2465| 0.1249             |
| 134493.  | 0.575            | outer     | 2.435  | -0.2647| 0.1249             |
| 134737.  | 0.585            | outer     | 2.440  | -0.2657| 0.1247             |
| 134965.  | 0.558            | outer     | 2.429  | -0.2550| 0.1246             |
| 135166.  | 0.548            | outer     | 2.340  | -0.2079| 0.1245             |
| 135595.  | 0.614            | outer     | 2.282  | -0.1600| 0.1247             |
| 135808.  | 0.596            | outer     | 2.232  | -0.1423| 0.1246             |
| 135913.  | 0.523            | outer     | 2.263  | -0.1494| 0.0234             |
| 136070.  | 0.586            | outer     | 2.194  | -0.1160| 0.0526             |
| 136288.  | 0.602            | outer     | 2.154  | -0.0992| 0.1254             |
| 136579.  | 0.627            | outer     | 1.795  | -0.0080| 0.1216             |
| 136665.  | 0.590            | outer     | 1.963  | -0.0159| 0.1206             |
| 136736.  | 0.824            | outer     | 1.714  | -0.0040| 0.1198             |

Table continues on next page...
| Rad. (km) | $\tau_{pps}$ | Ring type | $a_0$ | $a_1$ | $f_{\sigma_0 P -1/F}$ |
|----------|--------------|-----------|-------|-------|-------------------|
| 140338   | 0.065        | ringlet   | 0.240 | -0.0090 | 0.1214           |