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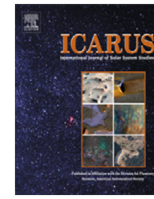

Modeling the uranian rings at 2.2 μm: Comparison with Keck AO data from July 2004

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ABSTRACT

We present a Monte Carlo model of the uranian rings, and compare this model to images of the system obtained with the Keck adaptive optics system in July 2004, at a wavelength of 2.2 μm (from de Pater et al. (de Pater, I., Gibbard, S.G., Hammel, H.B. [2006a]. Icarus 180, 186–200)). We confirm the presence of the ζ ring, but show that this ring must extend inwards much further than previously thought, although with an optical depth much lower than that in the main ζ ring component. We further confirm dust rings between rings α–4 and β–α, as well as near the λ ring. In addition, we show that a broad sheet of faint material ($\tau_0 \sim 10^{-3}$) must be present through most of the ring region, from the α ring through the λ ring.

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1. Introduction

In 2007 the rings of Uranus were seen edge-on, an event that (only) happens every 42 years. While optically thick rings fade when the ring opening angle decreases, optically thin rings brighten. Hence, the change in geometry provides views of the planet's ring system very different from what is normally seen. As discussed by de Pater et al. (2007a), the first observations during the 2007 ring plane crossing (RPX) event revealed large changes in the spatial distribution of dust in the uranian rings since they were imaged by the Voyager spacecraft in 1986. De Patter et al. (2007b) monitored the rings at a wavelength of 2.2 μm while the Earth, and later the Sun, crossed the planet's ring plane. They used both the 10-m W.M. Keck telescope in Hawaii and the 8-m VLT (Very Large Telescope) in Chile, where each telescope was equipped with adaptive optics. Although the change in geometry can be used to better characterize the ring system, at the same time outer rings block inner regions when the rings turn edge-on, complicating interpretation. Although during previous RPX events the 'onion-peel' technique has been used quite successfully (e.g., Showalter et al., 1987; de Pater et al., 2004), ideally one would like to model the rings and simulate a ring plane crossing event. Only via such a model can one derive the physical characteristics of the ring system, as e.g., particle sizes and reflectivities, optical depth, vertical extent and ring inclination angle of each ring and dust sheet separately. With this goal in mind, we developed a model for the uranian ring system. This model, together with a comparison to previously published images of the uranian system (de Pater et al., 2006a), is presented in this paper. In a future paper this model will be applied to the data taken during the uranian RPX; in that paper we will present both the new data and a detailed analysis.

Models of planetary rings have mostly focused on the saturnian system. Extensive 3-D simulations were done by Salo (1991, 1992a,b, 1995) and Daisaka and Ida (1999) using a large number of particles. These works include self-gravity to model the wake structures, and both single and realistic distributions of particle sizes. Salo and Karjalinen (2003) and Salo et al. (2004) reconciled the (optical) photometric scattering to their dynamic simulations. The wakes produced by their simulations largely explain the asymmetries in the rings as observed, including the inverse-tilt effect seen in ground-based observations, and the longitude dependence in Voyager observations in both reflected and transmitted optical light.

Dunn (1999) and Dunn et al. (2002) used Monte Carlo simulations of the saturnian ring system to produce the first (radio) synthetic images based on realistic radiative transfer calculations, which include multiple scattering and particle size distributions. These were compared to an extensive, high resolution Very Large Array (VLA) dataset. Later, Dunn et al. (2007) included wake structures to model the observed (radio) asymmetries in the rings.

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Recently, Porco et al. (2008) developed a sophisticated geometric ray-tracing code which can address multiple scattering as well as saturnian illumination. They also developed a complementary N-body tree code, with which they calculated the effects of self-gravity and collisions. Although it remains beyond computational capacity to do completely realistic simulations for the entire ring system (this would require including simultaneously a sufficient number of particles to model a large portion of the rings in three dimensional space and a broad range of particle sizes), many specific 'features' within the rings can modeled well.

Modeling the uranian system is still relatively undeveloped. The most sophisticated model is that of Karkoschka (2001a), which is based upon Irvine's (1966) scattering model. Karkoschka focused on the ϵ ring, which he modeled as a single-scattering multi-layered model filled with spherical particles of a constant size. Because his code is based on Irvine's (1966) model, Karkoschka accounts for reduced shadowing between ring particles when the planet is near opposition, as expected for a many-particle thick ring. By matching Hubble Space Telescope (HST) and Voyager data, he determined a best value of 0.06 for the average filling factor, i.e., only 6% of the ring area is filled with ring particles. (The filling factor ranges from 0.04 at apoapse to 0.18 at periapse.) Karkoschka shows, however, that this filling factor needs to be increased by a factor of $\sim$3 if a particle size distribution rather than a single particle size is used. In contrast, radio occultation data suggest filling factors of the order of 0.01 or less (Tyler et al., 1986; Gresh et al., 1988).

Karkoschka (2001a) used his model to calculate the visible area of ring particles (i.e., the total cross section of the rings minus any gaps, holes or shadows) as a function of subsolar latitude and phase angle. This visible area, multiplied by the ring particle reflectivity, results in the ring's I/F, a value that can be directly observed. Hence, using this model, observations of a ring's I/F can be used to calculate a ring particle's reflectivity. Typical particle reflectivities of $\sim$0.04–0.08 have been derived at visible and near-IR wavelengths (Karkoschka, 2001b; de Pater et al., 2002, 2006a; Gibbard et al., 2005).

As mentioned above, in this paper we present a new model for the uranian rings, which will be used to analyze the images taken during the 2007 RPX campaign (de Pater et al., 2007b). Our model is based upon the Monte Carlo code of Dunn et al. (2002), and described in detail in Section 3. Section 4 validates the model and compares it to a specific dataset; this dataset is described in Section 2. A summary of our results is provided in Section 5.

2. Observations and previous work

We compare our model to observations taken on 3, 4, 8, and 9 July 2004 with the Keck II telescope on Mauna Kea, Hawaii (de Pater et al., 2006a). These data were taken in the K′ band (1.948–2.299 μm) with the near-infrared camera NIRC2 coupled to the adaptive optics (AO) system. The 1024 × 1024 pixel-array camera was used in its high angular resolution mode, which has a pixel size of 9.94 ± 0.03 mas, corresponding to 139.96 km/pixel at Uranus at the time the observations were conducted. A wavelength of 2.2 μm was chosen, because at this wavelength sunlight is absorbed by methane and hydrogen gas in Uranus' atmosphere, which greatly reduces scattered light from the planet, enabling ring material to be traced very close to the planet (Fig. 1a).

De Patter et al. (2006a) compare scans through the ansae of the rings with simple ring models. Their "base" ring model consists of delta functions of a particular intensity, I/F, for each of the 9 main rings. After convolution with the point spread function (PSF), this model was compared to the observed scan, and the I/F values were adjusted until they matched the data. For this endeavor, the PSF was essentially taken to be equal to the observed ϵ ring profile, as this ring was unresolved in the scans. The authors used the scans through the ϵ ring away from Uranus both on the north and south sides. The PSF appeared to be symmetric, and the authors averaged

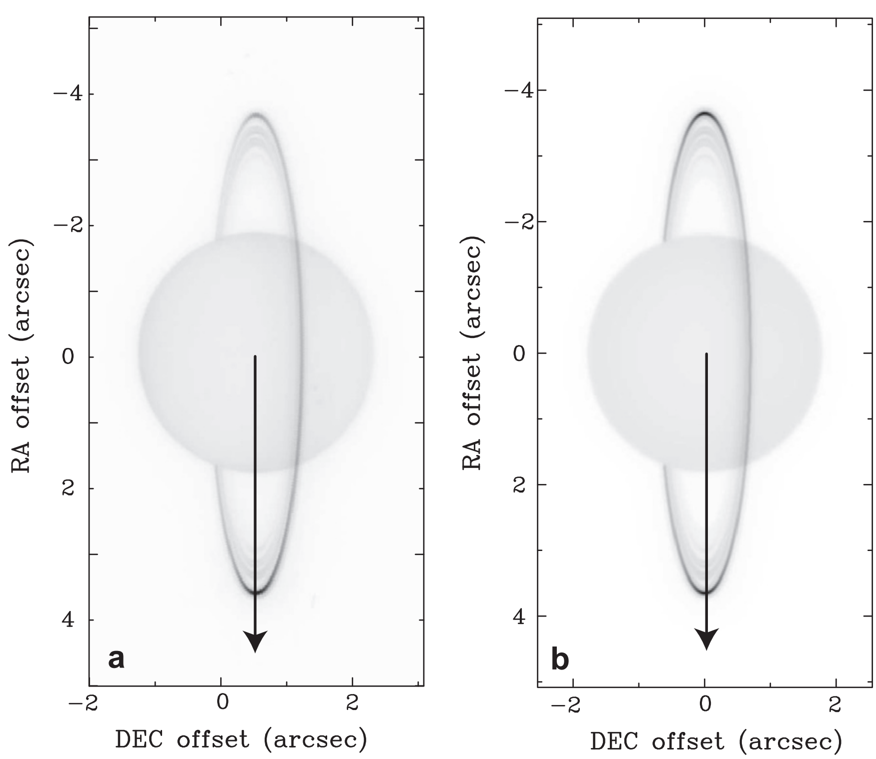

Fig. 1. (a) Image of Uranus at 2.2 μm as obtained with the Keck AO system in July 2004 (de Pater et al., 2006a). (b) A typical synthetic model. The arrows in both panels indicate the scan used in producing the plots throughout this paper.