Supporting Online Material for

**New Dust Belts of Uranus:**
**One Ring, Two Ring, Red Ring, Blue Ring**

Imke de Pater,* Heidi B. Hammel, Seran G. Gibbard, Mark R. Showalter

*To whom correspondence should be addressed. E-mail: imke@astron.berkeley.edu

DOI: 10.1126/science.1125110

This PDF file includes:

Materials and Methods
References
We observed Uranus and its ring/moon system on 23 August 2005, between 7:45 and 9:55 UT, and on 28 October 2005, between 4:50–9:10 UT, with the Keck II telescope on Mauna Kea, Hawaii. We used the adaptive optics (AO) system (S1) with the facility Near-Infrared Camera NIRC2, a 1024 × 1024 detector array. All observations were obtained in the K' band (1.948–2.299 μm). We used NIRC2 in high angular resolution mode, 0.00994" ± 0.00003" per pixel (S2), which translates to 137.5 km/pixel in August, and 140.8 km/pixel in October. The ring opening angles in August and October were 8.4° and 10.5°, respectively.

All images were processed using standard near-infrared data reduction techniques (flat-fielded, sky-subtracted, with bad pixels replaced by the median of surrounding pixels). On both nights the telescope performed essentially at its diffraction limit, which is 0.046" at K' band (S3). The Strehl ratio [the ratio of the peak intensity of the observed point spread function (PSF) to the theoretical maximum for the telescope aperture] was typically between 0.5 and 0.6 both in August and in October. Using our data from July 2004 (S2) and the planet itself for calibration, we converted the number of counts per second into units of $I/F$, a dimensionless quantity, where $I$ is the observed intensity and $\pi F$ is the solar flux density as received by Uranus at K'.

After shifting all images to a common center, we averaged all data on 23 August and, separately, on 28 October. We used both median and regular averaging techniques. Technically, median averaging should avoid traces of satellites, but in practice this was not always the case. Hence one must be careful when searching for faint rings, since rings and satellites occupy similar regions in the uranian system.
On 23 August we combined 30 images, each with an integration time of 120 seconds, for a total integration time of one hour. In October we covered a larger field (~ 25") by mosaicking images together. The integration time across the image is therefore not constant and some borders between frames are visible. Uranus itself and the main ring system had a total integration time of about 1.5 hours (individual images were 120 sec); the area south of the main rings a little over an hour, and the region north of the main rings 48 min.

To determine the equivalent width of a ring we followed de Pater et al. (S2, S4), and determined the PSF from the ε ring, which is bright and radially unresolved. We modeled ring R2 as a uniform belt of material with a width that, after convolution with the PSF, best matched the data. In August, the best fit was obtained for a belt with a width of 1540 ± 100 km, and brightness $\mu I/F = (8.1 \pm 0.9) \times 10^{-7}$, where $\mu = \sin B = 0.146$. In October, a best fit was obtained for a belt 1270 ± 100 km wide with $\mu I/F = (1.09 \pm 0.14) \times 10^{-6}$ ($\mu = 0.182$). The radially integrated values become $8.95 \times 10^{-6}$ in August and $9.8 \times 10^{-6}$ in October. The normal equivalent width, $\mu EW$ is obtained by multiplying these numbers with the pixel size in m, resulting in $\mu EW = 1.25 \pm 0.13$ m in August and $\mu EW = 1.39 \pm 0.22$ in October. A weighted average from the two epochs gives $\mu EW = 1.30 \pm 0.13$ m, with a radial extent of 1500 ± 100 km.

A conservative upper limit for an unresolved satellite is obtained from the RMS noise in a single 120-sec exposure, which results in a 1-σ value of $1.7 \times 10^{-5}$ (in $I/F$). We obtain the total $I/F$ of a putative satellite by convolving this number with a gaussian beam with a full width at half maximum (FWHM) of 0.05". Since a large fraction of the intensity from a satellite is lost in the PSF halo, we multiply our result by 1.49, the ratio of the total intensity to that in the core of the PSF as determined from observations of stars. Our 3-σ upper limit to the integrated $I/F$ of any undetected satellite is 30 km².
We determined the upper limit to any unresolved ring in our October data as follows: We first constructed a radial profile through the expected location of ring R1 by averaging 40 columns, centered at the center of our image. The image itself is an average of the original (Fig. 1b) and vertically flipped image to increase the signal-to-noise. The RMS $I/F$ noise on this profile was $7.0 \times 10^{-6}$. Since any unresolved ring would be convolved by the PSF, the radially integrated 1-σ value of a ring seen face-on becomes $\mu I/F$ is $1.4 \times 10^{-6}$. Multiplying by the pixel size in m, we obtain the equivalent width, $\mu EW = 0.20$ m. The 3-σ upper limit to any ring with a radial extent equal to or smaller than that of the PSF would thus be 3 times this value, i.e., 0.6 m.

If the ring is broader than the PSF, the upper limit determined above is too small. HST data revealed a ring profile that is triangular in shape, peaks at 97,700 km and extends from 86,000 to 103,000 km at its base. The $\mu EW$ of such a triangular ring profile, with a peak $I/F = 7 \times 10^{-7}$, is 1 m, five times larger than the 0.2 m for an unresolved ring. Since the HST ring is $\sim$ 10 times broader than our PSF, and triangular in shape, this number agrees with our calculations above. We scaled our modeled triangular profile up in brightness, by factors up to 3, and compared this to our data after convolution with the PSF. Since we are dealing with a broad diffuse ring, fluctuations in baseline may influence our observed profile more than the RMS noise. With this in mind, we arrive at a generous upper limit of 2.5 m to the presence of any ring resembling R1 in our data.

REFERENCES AND NOTES