We present adaptive optic images of Uranus obtained with the 10-m W. M. Keck II telescope in June 2000, at wavelengths between 1 and 2.4 μm. The angular resolution of the images is ∼0.06–0.09". We identified eight small cloud features on Uranus's disk, four of which were in the northern hemisphere. The latter features are ∼1000–2000 km in extent and located in the upper troposphere, above the methane cloud, at pressures between 0.5 and 1 bar. Our data have been combined with HST data by Hammel et al. (2001, Icarus 153, 229–235); the combination of Keck and HST data allowed derivation of an accurate wind velocity profile. Our images further show Uranus's entire ring system: the asymmetric ϵ ring, as well as the three groups of inner rings (outward from Uranus): the rings 6+5+4, α+β, and the η+γ+δ rings. We derived the equivalent I/F width and ring particle reflectivity for each group of rings. Typical particle albedos are ∼0.04–0.05, in good agreement with HST data at 0.9 μm.

1. INTRODUCTION

Due to Uranus’s small angular extent and lack of large-scale brightness variations, images of the planet obtained several decades ago were of limited interest. Attempts to observe Uranus were renewed after star occultation measurements by Elliot et al. (1977a,b) indicated the existence of a ring system surrounding the planet. To image this ring system, however, one had to somehow avoid contamination from Uranus’s scattered light. This could be accomplished by imaging the planet at near-infrared wavelengths in methane absorption bands where Uranus itself is dark, and/or by using coronagraphy to effectively block out the light from the planet (Matthews et al. 1982, Terrile and Smith 1986). These techniques are still widely used to image faint material next to bright planets or stars. The best ground-based infrared images of Uranus published to date are those by Baines et al. (1998) and Sromovsky et al. (2000). In both sets of images the ϵ ring with its asymmetric brightness distribution was easily observed. Due to the relatively low spatial resolution (typically at best ∼0.4–0.5") from the ground), light from this ring is blended with that of several faint inner rings. Since the ϵ ring is so much brighter than any of the other rings, light from the ring system has usually been completely attributed to the ϵ ring.

A wealth of information regarding the planet and its ring system was obtained by the Voyager spacecraft (e.g., Smith et al. 1986). The planet itself appeared to be rather uninteresting in the sense that practically no cloud features were detected. Yet the circumpolar bands on Uranus were similar to those seen on Saturn and Jupiter, although in a completely different sun–planet geometry. This provided much information regarding zonal wind systems on giant planets. Unfortunately, due to an overall lack of cloud features it was difficult to determine an accurate wind profile in Uranus’s atmosphere. Moreover, since only the southern (visible) hemisphere1 was imaged by Voyager, no information was obtained on its northern counterpart. In addition to atmospheric observations, Voyager imaged the ring system, discovered a tenth ring, and imaged sheets of dust in between rings at

1 We use the IAU convention of the location of the north pole: at the time of the observations the south pole is visible, and the planet’s rotation is retrograde, i.e., in the westward direction.
high phase angles. The individual rings were resolved via star and radio occultation experiments (French et al. 1986, 1991).

With the advent of the Hubble Space Telescope (HST), it became possible to image Uranus from near-Earth at high angular resolution. Karkoschka (1998) discovered small, bright (compared to the background) cloud features in the northern hemisphere and lower contrast features in the southern hemisphere. Several years later bright cloud features were also reported from ground-based infrared images (Sromovsky et al. 2000). On these ground-based images only the bright northern features were detected; features in the southern hemisphere had too low a contrast and/or were blended with the south polar haze. Observations of these cloud features helped to constrain the wind profile in Uranus’s atmosphere at latitudes where no prior information existed, refine the wind profile at southern latitudes, and search for time variability in the wind profile at southern latitudes as compared to the time of the Voyager encounter.

HST also provided images of the bright $e$ ring, mostly uncontaminated by other rings (Karkoschka 1997, 2001a). In these HST images the fainter inner rings show up in three groups (as seen going outward from Uranus): 6 + 5 + 4 rings, $a + \beta$ rings, and the $\eta + \gamma + \delta$ rings. The individual groups of rings could not be resolved in these images.

Adaptive optics (AO) techniques on large telescopes have opened up an entire new area of imagery, previously only feasible from space. While AO techniques on moderately sized telescopes already equal the HST spatial resolution at near-infrared wavelengths, AO on 8–10-m telescopes can reach angular resolutions four times higher than those of HST. In the past few years it has become possible to use AO at infrared wavelengths on 8–10-m telescopes. The angular resolution obtained by the 10-m Keck telescope on a star at a wavelength of 2 $\mu$m is typically 0.05", similar to that of HST at visible (0.5 $\mu$m) wavelengths, and four times higher than that of NICMOS on HST. In this report we present results on Uranus, using AO techniques on the W. M. Keck telescope. We obtained an angular resolution on Uranus of $\sim$0.06" at 1.6 $\mu$m and 0.09" at 2 $\mu$m.

2. OBSERVATIONS

2.1. Adaptive Optics System

We observed Uranus and its rings on June 17, 2000 UT and June 18, 2000 UT with the adaptive optics system on the 10-m W. M. Keck II telescope (Wizinowich et al. 2000a,b). An adaptive optics system in its simplest form consists of a wavefront sensor—a device to sense the distortions caused by atmospheric turbulence—and a device to correct these distortions, typically a deformable mirror. (See Beckers 1993 or Hardy 1998 for details of AO architecture and performance.)

The Keck AO system uses a Shack–Hartmann wavefront sensor. Such a sensor consists of many individual lenslets, which focus light in the form of many separate images on a CCD. By measuring the centroid position of the individual images the average slope of the wavefront over each lenslet’s subaperture can be determined, and hence the overall wavefront reconstructed. The deformable mirror then adjusts to compensate for any deviations of the wavefront from the desired shape. Since the wavefront sensor is looking at light already corrected by the deformable mirror the AO system operates in a closed feedback loop, updating at a rate of 500–600 Hz.

The Shack–Hartmann sensor has no particular requirement that the light used to measure the wavefront should come from a point source—in fact, since it operates at visible light wavelengths, where the AO system is providing little correction, even the image of a point-source star on each subaperture is extended by atmospheric seeing (0.5–1"). However, the accuracy with which the centroid of an object can be measured is linearly proportional to the signal-to-noise ratio in the image and inversely related to the diameter of the image. Since Uranus is very bright ($m_v = 5.7$) it can provide a relatively high signal-to-noise wavefront measurement. However, since it is large (3.65" at the time of our observations) it will provide a wavefront measurement with a signal-to-noise measurement roughly four times worse than an equivalent brightness star, or (since the measurement is photon shot-noise limited) equivalent to a star 16 times dimmer, $m_r = 8.8$. The Keck AO system includes a small (4") field stop in front of the wavefront sensor, which may reduce the flux from Uranus even more, making it equivalent to a $m_r = 9–10$ star. When we selected point-source function (PSF) reference stars, as discussed below, we generally selected stars somewhat dimmer than Uranus itself in an attempt to match AO performance. However, in retrospect our selection was not entirely successful, as explained in the next two paragraphs.

The Keck AO system uses a 64 $\times$ 64 pixel CCD for its wavefront sensor. Since the wavefront must be measured over 289 active subapertures, each subaperture is only allocated 2 $\times$ 2 pixels—a “quad cell”—for the centroid measurement, with the lenslets positioned so that each subaperture image is close to the center of the quad cell, equally illuminating all four pixels. (Individual quad cells are separated by a 1-pixel guard band of unused pixels.) The pixels on the Keck AO system correspond to a size on the sky of 2". Such an arrangement is common in adaptive optics as it also minimizes the effects of readout noise from the CCD. If the wavefront coming into the wavefront sensor were perfectly flat and undistorted, each subaperture’s image would fall precisely on the center of the quad cell. In a perfect AO system, this would be the desired state of corrected images. However, a real AO system often includes optical aberrations that are not common to both the science camera and the wavefront sensor—for example, aberrations in the optics of the wavefront sensor itself. If the AO system would attempt to counteract such noncommon path aberrations, it would produce a better image on the wavefront sensor but a worse image on the science camera, since the science camera was originally undistorted. To avoid this, the AO system is calibrated such that the desired state for each subaperture is not to have the subimage perfectly centered but slightly offset, with the offsets adjusted to produce the best possible image on the science camera.
Unfortunately, a quad cell of $2 \times 2$ pixels does not directly determine the centroid of an object. Instead, its response is linearly proportional to the size of the object being measured; a $0.5''$ image of a star displaced $0.2''$ from the center of the quad cell produces the same response as a $1.0''$ image displaced $0.4''$. Hence, when observing $3.65''$ Uranus, the true position of the Uranus subimages must be moved four to five times further than the image of a star would have to move. The deformable mirror must thus also move four to five times further, and the noncommon path optical aberrations are therefore "overcorrected" by a factor of $3$–$4$. As a result, the AO system is no longer trying to produce a "perfect" image of Uranus on the science camera, but instead an image convolved with the overcorrection of these noncommon path aberrations. Since the aberrations are generally very high order and not symmetrical, the point-spread function of an AO system locked on Uranus will be broader than expected, with asymmetric artifacts (see, for example, the ghost outer ring in Fig. 3). The Strehl ratio (the ratio of the observed peak intensity to that expected with the AO system if there are no aberrations present) in our Uranus images is in fact closer to that obtained on a $m_v \approx 11$ star than a $m_v \approx 9$ PSF reference (Section 2.4 and Fig. 9).

2.2. Observations: General

We used NIRSPEC, a near-infrared spectrometer, behind the AO system to record both images and spectra. NIRSPEC is equipped with a $1024 \times 1024$ InSb ALADDIN array for spectroscopy, and also a slit-viewing camera (SCAM) containing a $256 \times 256$ HgCdTe PICNIC array (McClean et al. 2000). Behind the AO system, SCAM has a platescale of 0.017''/pixel (245 km on Uranus). We obtained a typical resolution (full width at half maximum; FWHM) of $\sim 0.05''$ in the N5 and N6 filters on a bright star (apparent magnitude $m_v \approx 8$–9). Since Uranus itself was used as the wavefront reference required by the AO system, the AO performance on Uranus is more similar to that of an 11th mag star, as explained in Section 2.1. The FWHM for such a star was $0.06''$ in the N5 filter ($H$ band; see Table III for filter bandwidths), and $0.09''$ in the N6 filter ($H + K$ band), which corresponds to 860–1225 km at Uranus. The field of view of the slit-viewing camera SCAM is 4.48'', sufficient to encompass Uranus’s entire disk. By shifting the object to the north and south, we were able to image the entire ring system in just two pointings. These were mosaicked together afterward to construct pictures as displayed in Fig. 1. As a reference point we used the $\epsilon$-ring and its known distance to the center of Uranus at periapsis and apoapsis (e.g., Yoder 1995). Our observations are summarized in Tables I (ephemeris) and II (observations).
TABLE I
Ephemeris

<table>
<thead>
<tr>
<th>UT time (2000)</th>
<th>RA Dec</th>
<th>Δrₜ</th>
<th>Ang.</th>
<th>Obs.</th>
<th>Sun</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>date h min</td>
<td>e°</td>
<td>d°</td>
<td>lat.°</td>
<td>lat.°</td>
<td>angle°</td>
<td></td>
</tr>
</tbody>
</table>

Notes. Δ, geocentric distance; rₜ, heliocentric distance; Ang. diam., angular diameter; Obs. lat., observers’ latitude; Sun lat., Sun’s latitude.

Since NIRSPEC contains both a spectrometer and slit-viewing camera, we acquired spectra simultaneously with the images; the spectra will be discussed in a future paper. As a result of this instrument design, any individual image lacks data at the position of the slit. We minimized this “gap” by shifting Uranus between exposures. In the final image displayed in Fig. 1 we further interpolated over any remaining gaps to produce a clean looking image. All analyses, however, were made on images before interpolating over the gaps.

The images were reduced in the standard way: flat fielded using twilight and dome flats, bad pixels were removed (replaced with the median of neighboring pixels), and the sky was subtracted using a separate image of the sky taken just prior to or after the Uranus exposure itself. On June 17 we observed the photometric star HD201941 at airmass ~1.1 (Elias et al. 1982); Uranus was observed at airmass ~1.25. On June 18 we observed SJ9182 at airmass ~1.35 (our primary photometric star; Persson et al. 1998), and HD207438 (a PSF star) at airmass 1.22, while Uranus varied between 1.35 and 1.22. We converted stellar magnitudes to flux units using the spectrum of Vega (Colina et al. 1996a, assumed to be a zero magnitude star at all wavelengths), as indicated in Table III. These numbers, as well as our adopted monochromatic solar flux at 1 AU (Colina et al. 1996b), were calculated by averaging over the bandpass of our filters.

TABLE II
Observations of Cloud Features

<table>
<thead>
<tr>
<th>UT time (2000)a</th>
<th>CML b</th>
<th>Filter c</th>
<th>Image</th>
<th>N x Tₚ int</th>
<th>Cloud long d (rel. int)</th>
<th>Cloud long d (rel. int)</th>
<th>Cloud long d (rel. int)</th>
<th>Cloud long d (rel. int)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 17, 2000</td>
<td>14:49:52</td>
<td>N5</td>
<td>Ring north</td>
<td>5 x 60</td>
<td>-63° (1.05)</td>
<td>-6° (1.06)</td>
<td>-60° (1.08)</td>
<td>S5: -27°</td>
</tr>
<tr>
<td>15:07:15</td>
<td>14:56:45</td>
<td>N5</td>
<td>Ring south</td>
<td>5 x 60</td>
<td>+47° (1.01)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15:13:55</td>
<td>14:51:40</td>
<td>N5</td>
<td>Ring south</td>
<td>5 x 60</td>
<td>+43° (1.03)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15:24:00</td>
<td>14:38:30</td>
<td>N5</td>
<td>Ring north</td>
<td>1 x 60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>June 18, 2000</td>
<td>12:34:38</td>
<td>N6</td>
<td>South Pole</td>
<td>5 x 60</td>
<td>+28° (1.55)</td>
<td>+30° (1.05)</td>
<td>-50° (1.02)</td>
<td></td>
</tr>
<tr>
<td>12:47:00</td>
<td>12:58:37</td>
<td>N6</td>
<td>South Pole</td>
<td>5 x 60</td>
<td>+25° (1.54)</td>
<td>+28° (1.05)</td>
<td>-52° (1.04)</td>
<td></td>
</tr>
<tr>
<td>13:12:48</td>
<td>13:17:38</td>
<td>N6</td>
<td>Ring north</td>
<td>6 x 60</td>
<td>-29° (1.35)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13:19:51</td>
<td>13:17:38</td>
<td>N6</td>
<td>Disk</td>
<td>1 x 60</td>
<td>+52° (1.08)</td>
<td>-38° (1.25)</td>
<td>+15° (1.07)</td>
<td>+15° (1.03)</td>
</tr>
<tr>
<td>13:36:08</td>
<td>13:36:08</td>
<td>N6</td>
<td>South west</td>
<td>5 x 60</td>
<td>+47° (1.36)</td>
<td>+9° (1.37)</td>
<td>+10° (1.03)</td>
<td></td>
</tr>
<tr>
<td>13:40:22</td>
<td>13:40:22</td>
<td>N5</td>
<td>Disk</td>
<td>1 x 60</td>
<td>+44° (1.37)</td>
<td>+6° (1.35)</td>
<td>+5° (1.10)</td>
<td></td>
</tr>
<tr>
<td>13:36:08</td>
<td>13:36:08</td>
<td>N6</td>
<td>South west</td>
<td>5 x 60</td>
<td>+47° (1.44)</td>
<td>+48° (1.05)</td>
<td>+6° (1.12)</td>
<td>+6° (1.05)</td>
</tr>
<tr>
<td>13:43:11</td>
<td>13:43:11</td>
<td>N5</td>
<td>Disk</td>
<td>1 x 60</td>
<td>+52° (1.38)</td>
<td>-50° (1.08)</td>
<td>+5° (1.15)</td>
<td>+4° (1.06)</td>
</tr>
<tr>
<td>13:44:17</td>
<td>13:44:17</td>
<td>N5</td>
<td>Disk</td>
<td>1 x 60</td>
<td>+42° (1.16)</td>
<td>-52° (1.07)</td>
<td>+4° (1.27)</td>
<td>3° (1.07)</td>
</tr>
<tr>
<td>13:47:00</td>
<td>13:47:00</td>
<td>N5</td>
<td>Disk</td>
<td>1 x 60</td>
<td>+43° (1.52)</td>
<td>-54° (1.11)</td>
<td>+3° (1.30)</td>
<td>2° (1.07)</td>
</tr>
</tbody>
</table>

| June 17, 2000  | 13:48:54 | N6       | Disk        | 1 x 120    | +35°                    | +2° (2.2)              |                        |                        |
| 13:53:43       | 13:53:43 | N6       | Disk        | 1 x 120    | +29°                    | -7° (2.0)              |                        |                        |
| 13:55:26       | 13:55:26 | N6       | Disk        | 1 x 120    | +36°                    | -2° (1.7)              |                        |                        |
| 13:44:20       | 13:44:20 | N1       | Disk        | 1 x 120    | +15° (1.11)             | -17°                   |                        |                        |
| 13:44:20       | 13:44:20 | N1       | Disk        | 1 x 120    | +15° (1.11)             | -20°                   |                        |                        |
| 13:46:40       | 13:46:40 | N2       | Disk        | 1 x 120    | +12° (1.24)             | -21° (1.07)            |                        |                        |
| 13:51:40       | 13:51:40 | N2       | Disk        | 1 x 120    | +10° (1.23)             | -22° (1.11)            |                        |                        |
| 13:56:45       | 13:56:45 | N3       | Ring north  | 5 x 60     | -22° (1.04)             |                        |                        |                        |
| 15:08:00       | 15:08:00 | N3       | Ring north  | 5 x 60     | -25° (1.07)             |                        |                        |                        |
| 15:12:04       | 15:12:04 | N3       | Disk        | 1 x 60     | +3° (1.21)              | -31° (1.09)            |                        |                        |
| 15:14:41       | 15:14:41 | N3       | Disk        | 1 x 60     | +2° (1.14)              | -31° (1.06)            |                        |                        |

a Time at the midpoint of the observation.
b The central meridian longitude at the time of the observation (available at the JPL ephemeris: http://ssd.jpl.nasa.gov/).
c See Table III for the filter bandwidth.
d + sign refers to increasing planetocentric east longitude, with respect to central meridian longitude. Error in latitude is ≈1°; error in longitude is ≈1° near the center of the planet, increasing to ~2° near the limb.
TABLE III
Photometric Calibration

<table>
<thead>
<tr>
<th>Filter</th>
<th>Bandwidth (\mu m)</th>
<th>(F_{\lambda}(0 \text{ mag})^a) (10^{-19} \text{ W/m}^2/\mu\text{m})</th>
<th>Star(^b)</th>
<th>Magnitude(^b)</th>
<th>1 Count/s in (\text{W/m}^2/\mu\text{m})</th>
</tr>
</thead>
<tbody>
<tr>
<td>N6-band</td>
<td>(June 18) 1.558–2.315</td>
<td>6.799 (\times 10^{-10})</td>
<td>SJ9182 (HD207438)</td>
<td>11.085 (8.09)</td>
<td>1.70 (\pm) 0.08</td>
</tr>
<tr>
<td>K’-band</td>
<td>(June 18) 1.950–2.955</td>
<td>4.435 (\times 10^{-10})</td>
<td>HD207438</td>
<td>8.09</td>
<td>1.66 (\pm) 0.13</td>
</tr>
<tr>
<td>N5-band</td>
<td>(June 18) 1.413–1.808</td>
<td>1.177 (\times 10^{-9})</td>
<td>SJ9182 (HD207438)</td>
<td>11.142 (8.11)</td>
<td>3.4 (\pm) 0.2</td>
</tr>
<tr>
<td>N5-band</td>
<td>(June 17) 1.413–1.808</td>
<td>1.177 (\times 10^{-9})</td>
<td>HD201941</td>
<td>6.64</td>
<td>2.94 (\pm) 0.15</td>
</tr>
<tr>
<td>N3-band</td>
<td>(June 18) 1.143–1.375</td>
<td>2.946 (\times 10^{-9})</td>
<td>SJ9182 (HD207438)</td>
<td>11.479 (8.17)</td>
<td>10.4 (\pm) 0.5</td>
</tr>
<tr>
<td>N2-band</td>
<td>(June 18) 1.089–1.293</td>
<td>3.469 (\times 10^{-9})</td>
<td>HD207438</td>
<td>8.17</td>
<td>11 (\pm) 1</td>
</tr>
<tr>
<td>N1-band</td>
<td>(June 18) 0.947–1.121</td>
<td>5.521 (\times 10^{-9})</td>
<td>HD207438</td>
<td>8.20</td>
<td>34 (\pm) 3</td>
</tr>
</tbody>
</table>

\(^a\) Flux density for Vega based upon the filter function and atmospheric transmission profile (see text).

\(^b\) No photometric standards were measured in the N1, N2, and K’ filters. We derived the magnitude of our PSF HD207438 at J, H, and K bands from SJ9182. These numbers are given in parentheses. Based upon these numbers we adopted the magnitudes as listed for HD207438 in the N1, N2, and K’ bands.

and using atmospheric transmission spectra generated with the ATRAN modeling software (Lord 1992\(^2\)). The zero magnitude flux densities are very similar to those published by Tokunaga (2000); discrepancies are due to small differences in the filter functions. We estimated the magnitudes for HD207438 from our observations of SJ9182 in order to calibrate our data in the N1, N2, and K’ filters. Since the calibrators and Uranus were always observed at similar airmasses \(A(\Delta A \lessapprox 0.15)\) and the nights were photometric, any calibration errors introduced by variations in extinction are less than a few percent.

Figure 1 shows our mosaicked image of the uranian system in the N6 filter, which covers the combined \(H + K\ (1.56–2.31 \mu m)\) band. Due to the planet’s increased brightness from K to J bands (in broadband filters), Uranus’s scattered light makes observations of the rings very difficult in broadband \(J\). One can easily discern the bright asymmetric \(\epsilon\) ring in Fig. 1 (on the viewing geometry sketch in Fig. 1b we indicated the location of \(\epsilon\) ring’s periapsis). Inside of the \(\epsilon\) ring at least three more rings are visible: from the outside inward these are: (1) combined \(\delta, \gamma, \eta\) rings, (2) combined \(\beta, \alpha\) rings, and (3) combined 4, 5, 6 rings. Equivalent widths and ring particle reflectivities are derived in Section 3.2, and listed in Tables V and VI. In addition to the rings, the image shows the familiar circumpolar haze around Uranus’s south pole, two cloud features in the southern hemisphere (s4, s5), and three cloud features in the planet’s northern hemisphere (s1, s2, s3). These features are discussed in Section 3.1.

2.3. Observations: Atmosphere

We observed Uranus in several wavelength bands, as specified in Table II. In Table IV we summarize, for each filter, the monochromatic solar flux at 1 AU (Colina et al. 1996b) as integrated over the bandpath of the various filters, and different \(I/F\) values for Uranus: a disk-averaged value, and an average \(I/F\) per pixel near the south pole (at a latitude of 60\(^\circ\)S, along the central meridian longitude), and at the equator, along the central meridian longitude. Since the SCAM field-of-view in AO mode is only 4.48\(^\circ\), image frames centered on rings and/or Uranus’s south pole usually cover only a fraction (50–90\%) of the disk. Images of the disk in various bands are shown in Fig. 2. We show the original images on the left side; on the right we show images after subtraction of the original image convolved with a gaussian function \(e^{-r^2/\sigma^2}\), with the distance \(r^2 = (x_c - x)^2 + (y_c - y)^2\) in pixels, and \([x_c, y_c]\) is the pixel at the center of the gaussian. We used \(\sigma = 15\) pixels. This procedure enhances the contrast of small features and/or sharp boundaries. The black stripes across the images are caused by the spectrometer slit. Our image sharpening procedure introduced a brighter band along the slit. (Note that the figure in panels a and b is a composite of several images). At all wavelength bands, except for K’ (1.950–2.295), the south polar haze is prominent. This circumpolar band is the methane cloud or haze that condenses out near the 1.3 bar level (see below, and West et al. 1991 plus references therein). The pictures on the right side clearly show that this layer is brightest near its northern edge (\(-45^\circ\)) and around the south pole, while there is an apparent lack of haze immediately around the south pole. A similar gradation in brightness with the bright inner and outer bands was seen in ADONIS images of Uranus after deconvolution of the data (Conan et al. 2000), and in HST images (Karkoschka 2001c). This brightness contrast may be caused by an increase in the cloud column density (g cm\(^{-2}\), i.e., either through an increase in particle number density or particle size) at these locations.

A total of eight cloud features can be distinguished on the disk. Most notable are the three features at northern latitudes (+28\(^\circ\), +36\(^\circ\), and +42\(^\circ\)) on June 18, which stand out particularly bright compared to the background in the K’ filter. These cloud features are visible in all filters, though the contrast relative to the background is very low near 1 \(\mu m\) in the N1 and N2 filters. These features are probably similar to the clouds seen by NICMOS on HST (Karkoschka 1998), and the clouds reported by Sromovsky et al. (2000) from IRTF data; they are not the same features as those seen by NICMOS and IRTF, since we see several of them at higher northern latitudes, regions still in darkness when observed

\(^2\) We obtained the atmospheric transmission profile from Gemini Observatory’s Web site: http://www.gemini.edu/sciops/telescope/telIndex.html.
by NICMOS and IRTF. Our spatial resolution is higher than that in the NICMOS and IRTF data sets, and still the smallest features are unresolved in our beam; i.e., these are ≳1000 km across. Larger features may be up to 2000 km across. In Table II we summarize the locations (latitude and longitude relative to the central meridian longitude) and approximate relative intensities of the peak with respect to its immediate local environment. The latitudes and longitudes were determined both by overplotting a latitude/longitude grid on the planet, and by deprojecting the planet onto a square grid. The determination of latitudes was made jointly with Hammel et al. (2001) using HST data. We estimate the error in the latitudes to be ≲1°, and in longitudes to be ≲1° near the center of the disk, increasing to ≳2° near the planet’s limb.

On June 17 only one feature was visible at northern latitudes, at +21° latitude. Due to the combination of Uranus’s rotation and the wind speeds, none of the northern latitude features seen on June 18 were visible on June 17, and vice versa. In addition to the northern hemisphere features, we see a few clouds at southern latitudes: on both June 17 and June 18 we see cloud features at the lower edge of the polar haze (s7 and s4), and one near a latitude of −27° (s5). These features are not visible in the K’ filter, so they probably are located at nearly the same altitude as the south polar methane haze layer. Features s4 and s7 could in fact be “broken off” from the methane haze layer. Feature s5 was seen on both June 17 and June 18.

2.4. Observations: Rings

2.4.1. Images

Figure 3 shows images in the N6 and N5 filters in which we have optimized the contrast to show Uranus’s rings. The ϵ ring is the brightest of Uranus’s rings; this has been known since the rings were first detected via stellar occultation measurements, where the equivalent depth of the ϵ ring was much larger than that of any other ring (Elliot et al. 1977a,b). Clearly visible is the ϵ ring’s bright segment at apoapse (see Fig. 1b for the geometry).

Interior to the ϵ ring three faint rings can be discerned, which consist of multiple ringlets as described above in Section 2.1. The Voyager images show all nine rings as bright narrow ringlets (as well as the λ ring, not visible in our data), varying in extent from a mere 1.5 km for ring 6, up to several tens of kilometers for the ϵ ring. The width of each ring has been determined from occultation data (French et al. 1986, 1991). The ϵ ring varies in extent from 20 km at periapse to 96 km at apoapse. The optical depth of this ring varies from 0.5 to 2.3; the combination of optical depth and ring width results in the azimuthal brightness variation of the ϵ ring.

In addition to the relatively broad rings, one can discern quite narrow features in some of the images, which we attribute to PSF artifacts. In particular the ‘ring-loop’ just outside the ϵ ring in the northeast quadrant in the N6-filter image and the southwest quadrant in the N5-filter image is clearly an artifact. As discussed in Section 2.1, the images we obtain at Keck result from the true brightness convolved with a complicated point-spread function representing the incomplete correction of atmospheric distortions by the adaptive optics system. In conventional observations this function is determined primarily by atmospheric seeing, which under extremely good conditions resembles a gaussian with a full width at half maximum of ~0.4″. Using an AO system, one can overcome much of the seeing effects, so that the PSF at infrared wavelengths is about 10 times narrower. An AO PSF cannot be approximated by a well-defined gaussian but resembles a narrow core whose exact shape depends on the details of the calibration and operation of the AO system, superposed on a broad “halo.” The two-dimensional brightness distribution of this PSF, which can usually be obtained via observations of a bright star, shows a characteristic pattern, the details of which vary over time. For our Uranus observations, however, we noticed that the precise brightness distribution of the PSF cannot be obtained via observations of a bright star; it is best characterized by observing a nearby strong compact source, while the AO loop is being closed on Uranus itself. Although we were unable to obtain such images during our June
On August 21, 2000 UT we imaged Uranus’s rings at two different position angles (PA) of the image rotator, one at PA = 0° and one at 90°. The results are shown in panels a and b in Fig. 4. The overall quality of the images is lower than that seen in the June data due to poorer seeing, which translates into a lower Strehl ratio, and hence angular resolution. Nevertheless the ring-loop is clearly visible in panel a, and absent in panel b. Figure 5 shows two images of the satellite Miranda at the same position angles, while we continued to close the loop on Uranus. In these observations Miranda appears to have a companion in panel a, which is nearly absent in panel b. Similar results were obtained for the satellite Ariel. Such a PSF on rings would translate into a ring-loop, as observed for Uranus. The double-peaked PSF also explains the shape of the cloud features on the planet, which appear double-lobed on many of the images.

The artifacts in the rings complicate the ring analysis: in addition to the ring-loop, which was clearly discerned in the images, similar structures are present within the ringlets. To clean the image from such artifacts we adopted the following simple method: we rotated panel b in Figs. 4 and 5 to the position angle of a and subtracted this from panel a. In Miranda’s case, this results in an image of the secondary component (considering only positive values, with a nonzero lower cutoff), and for Uranus of ring artifacts. When these are subtracted from panels a, the artifacts get largely removed. Figure 4c shows the result for Uranus, after the cleaned image from panel a was combined with that in b (to increase the signal-to-noise ratio).

In June we had data at only one position angle, so this approach could not work. Instead, we assumed symmetry between the left and right sides of the rings. Since periapse of the \( \epsilon \) ring is almost exactly at the southernmost tip of the ring (Fig. 1b), this assumption is probably quite good. We then flipped the image over, left to right, and subtracted it from the original image. The positive artifacts (adopting a positive nonzero lower cutoff) were then subtracted from the original image to obtain the cleaned image; this image was shown in Fig. 1a (for the N6 filter). The total intensity in the subtracted artifacts was \( \lesssim 10\% \) of the total flux in the original images (summed over the same subarea in the image). This method is quite similar to that where the original and flipped images are compared and, on a pixel-by-pixel basis, the smaller of the two values is used in the final image. We note that our cleaning method does not remove artifacts along horizontal lines, i.e., near apo- and periapse. Since the total light is smeared out by the PSF, we believe that the final ring intensity near apo- and periapse is closer to reality than the intensity away from periapse. As measured from the intensity of the ring-loop, the rings away from peri- and apoapse may be too low by \( \lesssim 10\% \)–20%.

2.4.2. Radial Profiles

To get quantitative measurements of the rings and their brightness, we constructed radial profiles. To obtain a high signal-to-noise scan through the rings we (median) averaged in azimuth

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**FIG. 2.** Images of the planet taken in different filters. The images on the left are the originals; on the right we show the result after subtraction of the original image convolved with a gaussian function. The cloud features are circled on the images on the right. The black stripe is the spectrometer slit. The images in panels a and b are composite images from June 17, taken in the N5 filter. Panels c–h were obtained on June 18. Panels c and d were taken in the N5 filter, e and f in the N6 filter, and g and h in the K' filter.
along the rings: we constructed a model of elliptical rings projected onto the plane of the sky (simulating Uranus’s ring orbits) and averaged the intensity along these ringlets. The results for the N6 (H + K) and N5 (H) filters, as obtained from our cleaned images, are shown in Fig. 6. The dotted lines are scans toward the north (PA = 0\degree; positive toward the East) through the rings, averaged over 60\degree in azimuth. This scan includes Uranus’s scattered light. The solid and dashed lines show scans centered at PA = 0\degree and 180\degree (apo- and periapse of the \(\epsilon\) ring), respectively, after the scattered light contribution was subtracted.

We determined Uranus’s scattered light contribution as follows: We took a radial scan through Uranus at PA \(\approx 45\degree\) (i.e., away from the rings). Using this scan, we calculated the scattered light contribution at all positions in the image and subtracted this from the original image. Note that in reality the amplitude of the scattered light contribution is not circularly symmetric about the planet; since the south polar cap is brighter than the northern hemisphere, we have either over- or underestimated the scattered light contribution, depending on our location on the disk. We then constructed a radial profile through this cleaned image, averaged over 60\degree in azimuth and centered at PA = 0\degree and 180\degree. The difference between this profile and the original profile (i.e., the dotted line in Fig. 6) represents Uranus’s scattered light contribution. To minimize the noise introduced via this process, we made a polynomial fit through this difference profile. This smooth curve was then scaled such that when subtracted from the original ring profile, the resulting profile at a uranian distance \(r = 3.5 \times 10^4\) and \(r = 6 \times 10^4\) was close to zero. The results of this process were shown as solid and dashed curves in Fig. 6.

Superposed on Fig. 6 are the positions of all known ringlets. Since the \(\epsilon\) ring’s periapse was near the direction of the ring’s south polar axis, the south side of the rings is much weaker than the north side. This effect has been known for a long time.

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**FIG. 3.** Images of Uranus’s rings in the N5 (taken on June 17, 2000 UT) and N6 (taken on June 18, 2000 UT) filters. The north and south sides are shown separately. In contrast to Fig. 1, these images have not been processed to remove artifacts.

**FIG. 4.** Images of Uranus’s rings taken on August 21, 2000 UT at different position angles of the image rotator: (a) PA = 0\degree, (b) PA = 90\degree, and (c) combined images from (a) and (b) after artifacts had been removed as described in the text.
and can be attributed to a combination in the variation in ring width and optical depth, as mentioned above. The $\epsilon$ ring stands out clear and bright; the $\lambda$ ring cannot be discerned, while the $\delta$, $\gamma$, and $\eta$ rings, combined, result in the peak just inside the $\epsilon$ ring, the $\alpha$ and $\beta$ rings form the second peak inward, and rings 4, 5, and 6 the third peak. All three peaks inside the $\epsilon$ ring are slightly resolved. We remind the reader here that our images were mosaicked together, and that we used the distance of the epsilon ring to “glue” the north and south together; thus the relative ring positions in each hemisphere are properly measured, but the absolute scale is based upon prior knowledge of the $\epsilon$ ring.

3. DISCUSSION

3.1. Atmosphere

We detected a total of eight atmospheric features during our two-day observing period (Fig. 2, Table II). Fortuitously, Hammel et al. (2001) observed Uranus with HST on June 16, 2000 UT and June 17, 2000 UT, just prior to our observing dates. They detected the same features in the HST data. By combining our data we could derive precise wind velocities for seven of the eight features. Feature S8 was observed on the limb of the planet by both telescopes, resulting in too large an uncertainty on its exact location to allow the derivation of an accurate wind speed. The results of this work were reported by Hammel et al. (2001). For completeness we show Hammel et al.’s wind profile in Fig. 7. The red data points represent the wind velocities as derived from the combined HST and Keck data. We refer the reader to Hammel et al.’s paper for a detailed discussion of the wind profile.

The northern latitude features s1 and s2 were visible in all filters and showed a very high brightness contrast in the K$'$ filter. Uranus’s rings pass in front of feature s1; hence it is visible, but its intensity cannot be determined without extensive modeling.
Since the south polar methane haze is not visible in the K’ filter, it is clear that the northern latitude features are located above the nominal altitude of any methane haze layer. To get a rough estimate of the altitude of the northern latitude features, we used a simple model of Uranus’s atmosphere, where we calculated the atmospheric transmission (going into and out of the atmosphere) as a function of pressure level for each of our filters (Roe et al. 2001). Only CH₄, H₂–H₂ collision induced absorption (CIA), and H₂–He CIA were included as sources of opacity. If the clouds are represented by a simple reflecting (equally reflecting at all wavelengths involved) layer, a comparison of the ratio of the transmission curves with the observed I/F values in various filters can be used to determine the approximate altitude of the cloud features. We show a graph of the transmission (near the subsolar point) in the N1, N5, and K’ filters in Fig. 8. In this model we adopted the temperature–pressure
profile of Lindal (1992) and used a $H_2:He$ number ratio of 85:15, with a fraction of 0.80 for $H_2$ in ortho-para equilibrium. We assumed a methane abundance of 2.3% in the lower troposphere, while following the saturated vapor pressure curve at higher altitudes. The methane abundance was set equal to zero above the tropopause for the model with the solid lines. The resulting transmission curves are not very sensitive to small (~5%) changes in the $H_2:He$ ratio, but the transmission in some of the filters is quite sensitive to the methane abundance in the stratosphere. The dashed profiles show the sensitivity of the model if the methane abundance in the stratosphere were increased to 0.00035, the value determined for Neptune’s stratosphere (Baines and Hammel 1994).

Since the south polar haze is invisible in the $K'$ filter and bright in the N5 and N1 filters, one can deduce from Fig. 8 that the top of the south polar haze layer must be at a pressure level between 1.1 and 1.2 bar. This is indeed consistent with the interpretation that we are looking down at the CH$_4$ methane cloud which has its base at a pressure level of 1.23 bar (Lindal et al. 1987). The northern latitude clouds have a high brightness contrast in the $K'$ filter, but because the $I/F$ of Uranus in this filter is very low, the $I/F$ of the cloud features in this filter is still very low compared to that in other filters. From the transmission curves it follows that these clouds must be located at altitudes just above the 1 bar level, but below ~0.5 bar, and therefore below the tropopause.

3.2. Rings

Figure 6 showed a radial profile of the rings. To extract qualitative information on the rings, we fit models to the data to determine the equivalent $I/F$ width (EW), the width (in meters) the ring would have if its reflectivity $I/F = 1$, where $I/F$ is the observed intensity $I$ divided by $F$, where the incident solar flux is $\pi F$. As mentioned in Section 2.4, PSF artifacts in the images complicate a qualitative analysis. To get a good estimate of the EW of each ring together with a realistic error bar, we applied three different fitting procedures. Two of these techniques, our 1-D methods, are based upon an analysis of ring profiles, such as shown in Fig. 6, and the third technique, our 2-D method, involves model fitting the images with simultaneously fitting the PSF.

For both 1-D analyses, we constructed a simple model where each ring is represented by a delta function at its known location. Convolution with the proper PSF then allows determination of the relative intensities by matching the modeled profile to the data. Choice/knowledge of the proper PSF is crucial in all three methods. As mentioned in Section 2.4, the PSF generally consists of a core and broad low intensity halo (such as seen in Fig. 5), which can usually be determined by observing a star. To construct a PSF appropriate for a radial ring profile, we constructed an image with a narrow (~1-pixel wide) elliptical ring of unit intensity, shaped like Uranus’s $\epsilon$ ring. Convolution with the appropriate PSF, followed by an azimuthal averaging procedure, similar to that applied to Uranus’s rings (Fig. 6), results in the 1-D PSF used in our 1-D analyses.

3.2.1. 1-D Analysis I

In this analysis we tried to match the radial ring profiles shown in Fig. 6, i.e., profiles through our cleaned images. We convolved our model ring with an image of a star (8th mag star HD207438 and 11th mag star SJ9182), prior to the azimuthal averaging. The resulting profiles are shown in Fig. 9 (dotted line for convolution with HD207438, dashed line for SJ9182). The solid line in this figure is the observed ring profile from Fig. 6a. Since the $\epsilon$ ring is unresolved, and there are no known features exterior to the $\epsilon$ ring, its core and the right-hand side of the ring should mimic the PSF. The model profile HD207438 does not match the ring profile at all: as expected from a $m_\pi = 8$ star, it has a well-defined core and low level halo. Typical Strehl ratios for this star were on the order of 20–25% in the N5 and N6 filters. The Strehl ratio in the model profile SJ9182 is considerably lower (Strehl ratios for this star were ~5–6% in the N5 and N6 filters), and this profile does match the $\epsilon$ ring better, although the halo is still too low. Note that none of the profiles is symmetric, due to the azimuthal averaging effect.

In Section 2.3 we discussed PSF issues to explain and clean up some of the ring artifacts. The Miranda image (Fig. 5) was an excellent representation of the PSF in August (Miranda’s angular extent is 0.035”; such a small source is indistinguishable from our PSF). It is a better representation than a conventional
We convolved a model ring with an image of a star taken during our observations. The resulting radial profile is much broader; in fact it is too broad in the core of the ring (caused by poor seeing), but the halo or wings of the profile do match the ring very well. We conclude from this exercise that the use of an extended source as an AO guidestar may not only show multiple peaks, but also show a lower Strehl ratio so that the intensity ratio between the peak and the halo is decreased. To construct a radial PSF profile which best matches the PSF in Fig. 6, we combined the core of the $\epsilon$ ring as observed (solid line) with the wings from our model ring profile after convolution with Miranda (dash-dot-dash line). To avoid insertion of noise from our PSF images in the final radial PSF profile, we replaced the wings of the profile with polynomial fits. The final PSF used in our 1-D analysis is shown by the dashed lines in Fig. 10 (panels a and b).

In Table V we show the equivalent $I/F$ width in meters for each ring, which best fits our data. The fits were obtained via a least-squares fitting routine using the AMOEBA algorithm (Press et al. 1992) as implemented in the IDL programming environment. We forced rings 4, 5, and 6 to be equal, and hence fit seven independent variables.

### 3.2.2. 1-D Analysis II

In this analysis we used ring profiles through images before they were cleaned. Since the PSF from analysis I did fit the profile very well, we used the same PSF for analyses I and II. Profiles and best fits through the data are shown in Fig. 10, panels a and b. The equivalent $I/F$ widths EW derived for the individual ringlets are summarized in Table V. As in analysis I, we fit seven independent variables. In addition to listing the EW for each ring, we show the EW for the combined $\alpha + \beta$ ring, $\gamma + \delta + \eta$ ring, and $4 + 5 + 6$ ring. Both 1-D analyses were carried out for the north side of the rings, where the $\epsilon$ ring is brightest, and hence has the best signal-to-noise ratio.

### 3.2.3. 2-D Analysis

In our 1-D analysis we created an image of the $\epsilon$ ring to construct a PSF profile. For our 2-D analysis we created a model of all rings: the $\epsilon$ ring and its azimuthal brightness gradient.

### TABLE V

<table>
<thead>
<tr>
<th>Ring</th>
<th>Distance$^a$ 10$^3$ km</th>
<th>Width$^a$ km</th>
<th>$r^a$ (Voyager)</th>
<th>EW (in m) Method 1</th>
<th>EW (in m) Method 2</th>
<th>EW (in m) Method 3$^b$</th>
<th>EW (in m) Method 1</th>
<th>EW (in m) Method 2</th>
<th>EW (in m) Method 3$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>44.7</td>
<td>4.8 → 10.0</td>
<td>~0.4</td>
<td>277</td>
<td>242</td>
<td>101</td>
<td>286</td>
<td>320</td>
<td>102</td>
</tr>
<tr>
<td>$\beta$</td>
<td>45.7</td>
<td>6.1 → 11.4</td>
<td>~0.3</td>
<td>65</td>
<td>95</td>
<td>170</td>
<td>173</td>
<td>87</td>
<td>184</td>
</tr>
<tr>
<td>$\eta$</td>
<td>47.2</td>
<td>1.9 → 2.9</td>
<td>$\leq$0.4</td>
<td>127</td>
<td>63</td>
<td>28</td>
<td>54</td>
<td>82</td>
<td>34</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>47.6</td>
<td>3.6 → 4.7</td>
<td>$\geq$1.5</td>
<td>225</td>
<td>257</td>
<td>74</td>
<td>263</td>
<td>280</td>
<td>152</td>
</tr>
<tr>
<td>$\delta$</td>
<td>48.3</td>
<td>4.1 → 6.1</td>
<td>~0.5</td>
<td>15</td>
<td>24</td>
<td>102</td>
<td>89</td>
<td>66</td>
<td>118</td>
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<tr>
<td>$\epsilon$</td>
<td>51.1</td>
<td>19.7 → 96.4</td>
<td>0.5 → 2.3</td>
<td>2750</td>
<td>2870</td>
<td>532</td>
<td>3670</td>
<td>3790</td>
<td>635</td>
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<tr>
<td>6 + 5 + 4</td>
<td>42.3</td>
<td></td>
<td></td>
<td>115</td>
<td>134</td>
<td>82</td>
<td>144</td>
<td>186</td>
<td>68</td>
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<td>342</td>
<td>337</td>
<td>271</td>
<td>459</td>
<td>407</td>
<td>286</td>
</tr>
<tr>
<td>$\eta + \gamma + \delta$</td>
<td>47.8</td>
<td></td>
<td></td>
<td>367</td>
<td>344</td>
<td>204</td>
<td>406</td>
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</table>


$^b$ Note that Method 3 determined the EW at the longitude of the $\epsilon$ ring’s periapse, while Methods 1 and 2 used its apoapse.
FIG. 10. (a, b) Model fits through the radial ring profiles at apoapse; these profiles were taken from the original images (i.e., before any cleaning algorithm was applied): (a) best fit through the N6 filter data, (b) best fit through the N5 filter data. The model fit (dotted line) is superposed on the data (solid line). The dashed line is the PSF for the ring profile. The lower solid line is the residual, after subtracting the model from the data. Largest residuals are at the location of the ε ring. (c) A slice through the N6 images of the 2-D model fit (dotted line) and data (solid line). These slices are taken after subtraction of the convolved images from the original images (see text).

The δ, γ, η, β, α, and combined 456 rings. Each ring is modeled as a 1-pixel-wide ellipse with a single brightness (I/F value), at its known location. The brightness of each pixel is scaled by the fraction of the pixel that would be occupied by the ring ellipse. We further modeled Uranus as a disk whose brightness and brightness gradient were determined by the minimization procedure (results are fairly insensitive to these parameters since only the portion of the rings away from the planet was modeled; the presence of the planet is only required in the attempt to remove scattered light as discussed below). This planet + ring model must be convolved with the PSF before comparison with the data. As discussed above, the real PSF for these observations is unknown, but we do have evidence from images of Uranus’s moons taken in August 2000 that the PSF exhibits a double-lobed structure. Therefore we have constructed a theoretical PSF with two lobes, each of which is assumed to have the same shape as Uranus’s moon Miranda. We characterize the PSF by three parameters: the brightness ratio between the two lobes, the distance between the centers of the lobes, and the orientation angle of the lobes. We thus have a total of 13 independent variables, which we determined via an iterative fitting routine based on AMOEBA in IDL.

As in the 1-D analyses, scattered light from the planet presents a problem and had to be removed before we could fit a model to the data. To remove the scattered light of Uranus from the ring system, we convolved the model and data with a median function with a width of 30 pixels and subtracted these images from the originals. This method is analogous to that used to create the images on the right-hand side of Fig. 2 and enhances the contrast of small and/or narrow features. As in the 1-D analysis, we determined a ring profile by averaging over 30° in azimuth.
3.2.4. Discussion

The equivalent $I/F$ width as listed in Table V varies substantially for individual rings depending on which method is used. This is not too surprising, since the $I/F$s of adjacent rings are not independent due to the extent of the PSF. Hence variations in one ring’s $I/F$ does influence other rings. This is in particular true for ringlets in the three clusters: [4, 5, 6], [$\alpha, \beta$], and [$\delta, \gamma, \eta$]. As shown, the total EW for each cluster of rings is much better behaved. Note that analyses I and II were performed on the north (bright) side of the rings, while method III was used for the south (dim) side. Because the uncertainties in the EW of the individual rings are quite large, we will focus the following discussion on the $\epsilon$ rings and the three groups of combined rings.

To facilitate comparison between our own numbers (north and south side of the rings) and with other data, we next calculate the ring particle reflectivities. The width and normal optical depth ($\tau$) of the rings as measured by Voyager were summarized in columns 3 and 4 of Table V (Yoder 1995). In analogy to spectral lines, Elliot et al. (1984) introduced equivalent widths (E; not to be confused with our equivalent $I/F$ width EW) and equivalent depths for the rings based upon occultation profiles. French et al. (1986) derived a relation between the radial width of a ring and its equivalent width E for each ring. This parameter does not vary with ring inclination angle (Elliot et al. 1984), and we used French et al.’s values as the true width of the rings, i.e., the width of a square-well model to each ring’s occultation profile. These numbers (in kilometers) are listed in column 3 of Table VI. Dividing our measured EW by E results in the particle reflectivity, $A_v$. These numbers are listed in columns 4 and 5 of Table VI. The numbers obtained via the individual methods were averaged (method 3 was given double weight), and the error is based upon the spread between the results. We also included a 10% photometric error in the quoted uncertainty.

Our reflectivities are close to those derived by Karkoschka (2001a) from HST data at 0.9 $\mu$m at a similar phase angle (column 6 in Table VI). In general the ring particle reflectivities are quite similar from ring to ring, although the particles in the inner rings may be slightly less reflective. These rings, however, are influenced the most by Uranus’s scattered light, which may bias the ring reflectivities. Although our ring reflectivities might be slightly higher at 2 $\mu$m compared to a 1.6-$\mu$m wavelength, when including the individual error bars and comparing with Karkoschka’s 0.9-$\mu$m results, we conclude that the spectra of the ring particles are quite flat over the range of 0.9–2 $\mu$m.

4. CONCLUSIONS

We presented adaptive optics images of Uranus and its rings at an angular resolution of $\sim0.06^\prime$ in $H$ band and $\sim0.09^\prime$ in the combined $H + K$ band. We identified eight small cloud features, all of which had also been seen by HST just prior to our observations. Hammel et al. (2001) derived an accurate wind profile for Uranus’s atmosphere by combining the HST and Keck data. Continued observations of these and other such features are important for studies of atmospheric dynamics. It would be highly valuable to monitor the planet over time scales of weeks—months to derive an accurate wind profile as a function of latitude, study its stability over time, and determine the longevity of cloud features. Are the clouds detected in the northern hemisphere short-lived temporary features, or are the same features visible over many weeks? Karkoschka (1998) saw cloud features at the same locations over a 100-day time period, but we cannot exclude the possibility that features disappeared and re-formed later. Our data show that these features did disappear over year-long time scales. The northern hemisphere clouds are located at higher altitudes (between 1 and 0.5 bar) than the south polar haze (1.1–1.2 bar) and southern hemisphere clouds. Why are these high altitude features only visible in the northern hemisphere? Will they continue to exist even after these regions have been exposed to sunlight for many years? With continued observations we will be able to address questions regarding the similarity and differences between the two hemispheres as the north polar cap rotates into view: will the northern hemisphere be covered by a methane cloud/haze just like the south pole? Why/why not?
We derived equivalent $I/F$ widths and ring particle albedos for the rings. Overall our derived reflectivities (0.04–0.05) agree well with the albedos derived from HST data at 0.9 $\mu$m at a similar phase angle. Our results suggest the particles to be gray, since the spectra appear quite flat. There also does not appear to be any significant variation in color between rings. While the planet’s viewing geometry changes, our view of the rings will change as well. The changes in relative brightness of the rings contain information on ring properties, such as particle sizes and relative filling factor of the rings. Karkoschka (2001b) presented models of the rings with predictions of how the brightness of the rings will vary over the next few years, until the rings are viewed edge-on in 2007. He predicted, for example, that the broad (54 km) low brightness companion of the $\gamma$ ring will be the second brightest ring (the $\epsilon$ ring remains the brightest) near edge-on viewing. Perhaps the low brightness sheet of material discovered by Voyager interior to ring 6, as well as the sheets of micrometer-sized dust seen by Voyager only in forward-scattered light (e.g., French et al. 1991), may become visible when viewed nearly edge-on. Hence continued observations of the uranusian ring system will provide a wealth of information on this system.

Uranus may represent the largest object that a typical Shack–Hartmann AO system can use as a reference, particularly a system with $2 \times 2$ pixels per subaperture such as the Keck system. A better understanding of the effects of noncommon path and calibration errors in this large object case will improve our ability to determine the PSF. With the arrival of a new wide-field camera (NIRC2) for the Keck II AO system, AO observations of the uranusian system will become easier, since the entire system can be viewed at once and the image quality/sensitivity will improve. Application of newly developed deconvolution algorithms, such as MISTRAL (Conan et al. 2000), will improve our ability to extract ring particle albedos from the data. The data presented in this paper are just a first step in this new field of high resolution imaging of Uranus and its ring system. Based upon these data, we expect future observations to yield important information on both Uranus’s atmosphere and ring system.

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