the experimental package during descent.

Figure 1B shows a 4-km frame of ClO data with 0.08-second time resolution from the 2 October flight, synchronized with the programmed flow of added NO. In addition to demonstrating the structure in the data, Fig. 1B shows that the detector count rate is independent of NO at flow rates between 8 and 50 standard cubic centimeters (scc) per second; the two flows were chosen to verify complete conversion of ClO to Cl, while avoiding Cl depletion by the reaction

$$Cl + NO + M \rightarrow NOCl + M$$

where M is a third body.

Figure 2A gives the Cl and ClO densities determined on the three flights, showing (i) marked local structure in each of the ClO profiles, the Cl densities being too small to provide spatial detail, and (ii) significant variation in the average concentrations of Cl and ClO observed in the July, October, and December experiments. Experimental uncertainties for the measurements are listed in Fig. 2A and are based primarily on uncertainties in (i) absolute calibration in the laboratory (±20 percent), (ii) convolution of the lamp resonance line and the atomic absorption cross section as a function of lamp body temperature (±20 percent), and (iii) absolute flux measurements during flight (±10 percent). The instruments were calibrated before and after each flight and the hardware, interference filters, and key optical components were identical for all flights.

Figure 2B shows a comparison between the data of Fig. 2A averaged over 1-km intervals and four theoretical predictions of the Cl and ClO densities (*8*) for summer midday conditions at 30°N, corresponding to the maximum predicted Cl and ClO concentrations for the geographic position of the measurement. The chlorine mixing ratio, defined as the total number of chlorine atoms, bound and free, per unit volume divided by the total atmospheric number density, is indicated for each model and represents the opinion of the respective author.

Three points, apparent from inspection of Fig. 2, deserve emphasis. First, the Cl and ClO concentrations observed in the July and October flights were equal to or greater than those predicted by any of the four models (which were selected to encompass the full range of predicted chlorine radical concentrations). Together with the results of laboratory studies of the rate constants for reactions 1 to 3 and measurements of atomic oxygen and ozone in the stratosphere (*9*), this demonstrates that chlorine compounds can, under certain conditions, contribute an important component to the photochemical budget of stratospheric ozone. Second, a marked decrease in both Cl and ClO is apparent in the December data. The observed change cannot be explained by a simple photochemical dependence on solar zenith angle (*10*) but may be related to large-scale atmospheric circulation. Third, there is approximate agreement between the observed and predicted Cl/ClO ratios. This suggests that reactions 1 to 3, which are the chlorine reactions believed to be involved directly in the homogeneous gas-phase catalytic destruction of ozone, constitute the dominant reaction sequence that establishes a photochemical steady state between Cl and ClO in the stratosphere.

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Uranus: The Rings Are Black

Abstract. *An upper limit of 0.05 is established for the geometric albedo of the newly discovered rings of Uranus. In view of this very low albedo, the particles of the rings cannot be ice-covered as are those of rings A and B of Saturn.*

The recent discovery of at least five rings about Uranus (*1*) during the occultation of star SAO 158687 raises the question of possible earlier observations of the rings. During the 1972 and 1974 oppositions of Uranus, I photographed Uranus and its environs (*2*), using an 888-nm interference filter and a Varo image-intensifying tube in the method suggested by Kuiper (*3*) for recording possible faint inner satellites of the major planets. No new satellites were found on these plates to the limit of magnitude 17 at Roche's limit of 2.4 radii of Uranus. The region inside of Roche's limit (where the ring system lies) was overexposed in all of the 1-hour plates taken in the search for new satellites. One plate (Fig. 1) had an exposure of 5 minutes and shows the satellites Ariel, Umbriel, Titania, and Oberon. It shows only a possible trace of the ring system.

Four of the five rings (α, β, γ, and δ) have widths of 14 km (approximate width of each ring) in their plane and individually would not have been photographed even if they reflected all of the incident sunlight. The outermost, ring ϵ, is of variable width, but the average of the widths given by all four groups of observers (*1*) was 100 km in its plane. The attenuation of the star's light was nearly complete (60 to 90 percent) for ring ϵ but only about 20 to 40 percent for rings α, β, γ, and δ. In my photograph the maximum separation from ring α to ring ϵ would have been 0.5 arc sec at their ansae, less than the seeing disk. I will consider the rings in two ways, (i) all five rings together and (ii) ring ϵ alone, in determining an upper limit to the geometric albedo of the rings.

The limiting magnitude m_1 of the plate may be estimated as 15.5 from the recording of Umbriel at magnitude 15.3 at mean opposition (*4*). The seeing at the time of the exposure may be estimated as 1 arc sec (5×10^{-6} rad) from the apparent sizes of the satellite images. We may estimate the amount of light contained in a segment of a hypothetical image of the ring as proportional to its geometric albedo p_r, its width w, and its length ($\ell = 5 \times 10^{-6} R$) that contributes to its seeing-blurred image, where R is the distance from Earth (approximately 26×10^8 km). We can set up a proportion, using the magnitude of Uranus ($m_U = 5.5$ at mean opposition) and its geometric albedo ($p_U = 0.56$) to yield the ratio of light in the segment of the ring to the light from Uranus:

$$r = \mathrm{dex}[(m_U - m_1)/2.5] \geqslant w \ell p_r / \pi \rho^2 p_U$$

where ρ is the radius (*5*) of Uranus (25,900 km). For case (i) the average geometric albedo p_r of the rings is less than or equal to 0.05. For case (ii) the albedo of ring ϵ is $p_\epsilon \leqslant 0.08$. Since it is known that during the occultation 75 percent of the light was blocked by the particles of the ring, the average albedo of the particles is less than or equal to 0.1. The upper limit for the average particle albedo of the five rings is 0.08 (*6*).

These low values for the particle albedos are in strong contrast to the high albedo that is found for the particles in the rings of Saturn (greater than 0.9) (*7*). The particles of Saturn's rings are covered with water frost (*8*), consistent with the high albedo. A number of other objects in the solar system have been similarly found to be covered with frosts of water or methane (*9*). We may conclude that the particles of the Uranus rings are not frost-covered and may be similar to the nonfrosty surfaces of the satellites Oberon and Titania (*10*).

Table 1. Stratoscope II observations compared to the computed position of the rings of Uranus. The tilt data are my measurements of figures 4 and 8 of (*5*). The observed distance is based on measurements of a photographic print of Uranus from the senior author of (*5*) and for which a scale was given. The computed distance is a weighted average of the five rings and their shadows, which takes into account their widths and slant opacities. I judged the observed contrast from figure 10 of (*5*) with a point spread function (PSF) of 0.2 arc sec. The computed contrast represents the peak contrast computed with 0.2 PSF and a weighted average of the five rings and shadows. I assumed that the rings have negligible thickness.

Value	Tilt measured from photo edge (deg)	Distance from center of disk (arc sec)	Contrast (percent estimated)
Observed	26 ± 1	1.38 ± 0.1	4 ± 2
Computed	25.1	1.33	2.9

I now raise the question of whether the reported sightings of belts (*11*) on the disk of Uranus were in fact the rings seen in silhouette, together with their shadows. The best photographs that have been taken (*5*) showed "no distinct surface markings with the possible exception of some faint belts parallel to the rotation equator." The most prominent of these, and the only one I have been able to discern in the published photographs, lies close to the east limb of the planet in the deconvolved pictures, and is close to the expected position for the rings and their shadows (*12*). Table 1 compares the inclination, the distance from the center of the image, and the estimated intensity with that expected for the known rings and their shadows.

In view of the very low estimate for the contrast of the rings seen against the disk, it is doubtful that the earlier visual observers have seen the rings. It does appear, however, that the Stratoscope II photographs recorded the projection of the rings on the disk of Uranus.

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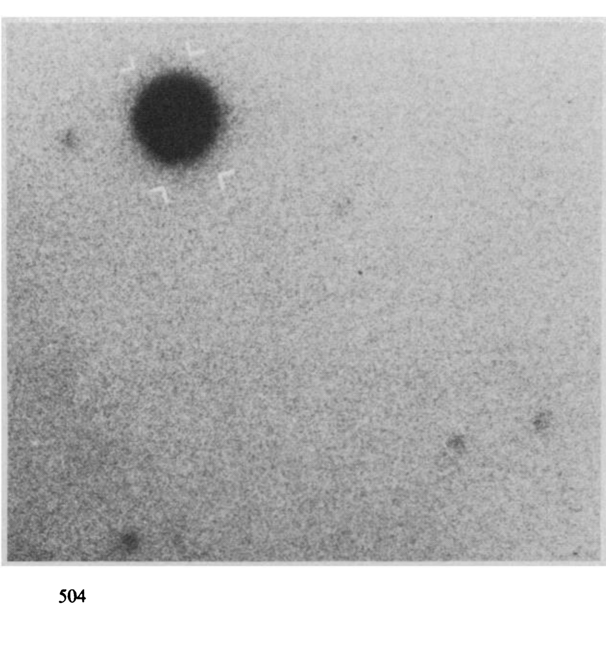

Fig. 1. Negative print of plate KD 115, taken with the 224-cm telescope at Mauna Kea Observatory. Titania is at the lower left, Oberon is close to the right edge, Ariel is next to Uranus at the left edge, and Umbriel is to the right and below Uranus. The object closest to Oberon is a spurious image. The corners of the rectangle that circumscribes the ellipse of ring ϵ are indicated in white, Midexposure was 8:08, 16 March 1972 (U.T.). North is at the top.

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13. Supported by NASA grant NGR 12-001-057.

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