THE ASTRONOMICAL JOURNAL VOLUME 90, NUMBER 12 DECEMBER 1985

THE 1983 JUNE 15 OCCULTATION BY NEPTUNE. I. LIMITS ON A POSSIBLE RING SYSTEM

J. L. ELLIOT
Department of Earth, Atmospheric, and Planetary Sciences, and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

RICHARD L. BARON, EDWARD W. DUNHAM, RICHARD G. FRENCH, KAREN J. MEECH,[a] AND DOUGLAS J. MINK[b]
Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

DAVID A. ALLEN
Anglo-Australian Observatory, P. O. Box 296, Epping, New South Wales, 2121, Australia

MICHAEL C. B. ASHLEY AND KENNETH C. FREEMAN
Mount Stromlo and Siding Spring Observatories, Research School of Physical Sciences, Australian National University, Canberra, ACT 2606, Australia

EDWIN F. ERICKSON
Ames Research Center, Moffett Field, Mountain View, California 94035

JAY GOGUEN AND H. B. HAMMEL
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, Hawaii 96822
Received 17 May 1985; revised 19 August 1985

ABSTRACT

Observations on 15 June 1983 of an occultation of a star by Neptune from Mauna Kea, Mount Stromlo, Siding Spring, and the *Kuiper Airborne Observatory* show no evidence for equatorial rings between 25 300 and 200 000 km ($R_N = 25\,269$ km, from Paper II). Within most of this region, the upper limit on the optical depth along the line of sight, for rings broader than 6 km, is 0.04, which corresponds to a normal optical depth of 0.016. These results rule out a Neptunian ring system similar to that of Saturn or Uranus, but not a system of low optical depth similar to the Jovian rings. Our data show no features that appear likely to have been caused by material in the equatorial plane of Neptune near the Roche limit.

I. INTRODUCTION

The 15 June 1983 stellar occultation involved the brightest star at optical wavelengths known to be occulted by Neptune since 1968 (Kovalesky and Link 1969; Taylor 1970; Freeman and Lyngå 1970). In addition to the high-quality data that could be obtained with the bright star, Mink *et al.* (1981) had predicted that the geometry of this event would afford the possibility of searching for rings around Neptune, from very large radii down to the top of Neptune's atmosphere. This opportunity for an extensive ring search and for probing the upper atmosphere of Neptune with unusually good signal-to-noise ratio prompted us to organize a network of large telescopes in the western Pacific Ocean, where the occultation would be visible. In this paper, we describe the observations and the limits that we have been able to place on a possible ring system around Neptune. In Paper II (French *et al.* 1985), we use these observations to obtain the equatorial radius and oblateness of Neptune, as well as temperature profiles of Neptune's upper atmosphere.

II. OBSERVATIONS

The observations are summarized in Table I, where we have listed the telescope aperture, focal-plane aperture, filter parameters, integration time, observation interval, and observers for each set of data. Observations were also attempted from Java by G. Aldering, J. Pasachoff, and their colleagues, but these were clouded out. At the Siding Spring 1.0 m telescope, the data were obtained with the GPS system and recorded with the "G" program. The photometer and data-recording system described by Baron *et al.* (1983) were used on the Mount Stromlo 1.9 m telescope. A second MIT data-recording system was used at the NASA Infrared Telescope Facility (IRTF) with the RC2 Dewar (InSb detector). The measurements were recorded simultaneously with the IRTF fast photometry program GRABBER, which was synchronized externally with the National Bureau of Standards satellite clock. The infrared system described by Barton and Allen (1980) was used on the Anglo-Australian Telescope (AAT). For the *Kuiper Airborne Observatory* (*KAO*), we used our three-channel photometer (Elliot *et al.* 1975a) with a beam splitter placed ahead of the optical channels, which routed the infrared radiation to an InSb detector in a Dewar that was mounted in place of the Erfle eyepiece. Following the investigation of Aldering (1983), we optimized our observations for the ring search by using only two broadband channels prior to Neptune's occultation of the star. While the star was behind the planet, we rearranged the filters to optimize the emersion observations for obtaining the helium abundance of Neptune's upper atmosphere, using the method of spike delays described by Elliot *et al.* (1974).

Although the telescope in the *KAO* has a smaller aperture than the others, its mobility allowed us to reserve our commitment to a particular observing strategy until the final occultation prediction became available. Three strategies for deployment of the *KAO* were considered: (i) go far north, in order to establish the longest possible north-south distribu-

---
[a] Guest Observer, Infrared Telescope Facility.
[b] Now at Smithsonian Astrophysical Observatory, Cambridge, Massachusetts 02138.

 0004-6256/85/122615-09$00.90

TABLE. I. Observations.

Station[a]	Telescope Aperture (m)	Focal Plane Aperture (arcsec)	Center Wavelength (μm)	Band-Pass (fwhm, μm)	Integration Time (sec)	Observation Interval (UTC on 15 June 1983)	Observers
Kuiper Airborne Obs.	0.9	90	0.50[b]	0.07	0.01	12:52:00-15:15:30	E.W. Dunham
			0.73[b]	0.09			J.L. Elliot
			0.78[c]	0.20			D.J. Mink
			0.83[b]	0.07			
		35	2.2	0.4			
Mauna Kea U. of Hawaii	2.2	23	0.86	0.08	0.1	13:22:32-15:24:02	J.D. Goguen H.B. Hammel
IRTF	3.0	12	2.2	0.4	0.01[d]	13:45:01-15:00:27	K.J. Meech
Mount Stromlo	1.9		0.55 0.85	0.10 0.10	0.01	14:05:00-15:20:00	R.L. Baron
Siding Spring ANU	1.0	30	0.55 0.85	0.10 0.10	0.02	12:41:15-16:47:15	M.C.B. Ashley K.C. Freeman
AAT	3.9	14	2.2	0.4	0.01	12:59:15-15:50:00	D.A. Allen

[a]The coordinates of the fixed observatories are given in Table II of Paper II. The KAO followed a course that allowed tracking on Neptune, which placed it at the coordinates (151°41'50".1 E, 16°36'18".0 N, 12.99 km) when data recording began and coordinates (148°22'50".1 E, 17°20'07".3 N, 13.69 km) when it ended.

[b]This filter installed while the star was behind Neptune.

[c]Used for immersion.

[d]The signal was chopped at 30 Hz, with the reference beam 22" away. The signal was passed through a lock-in amplifier that had a double pole filter with a time constant $\tau = (25 \pm 2) \times 10^{-3}$ sec.

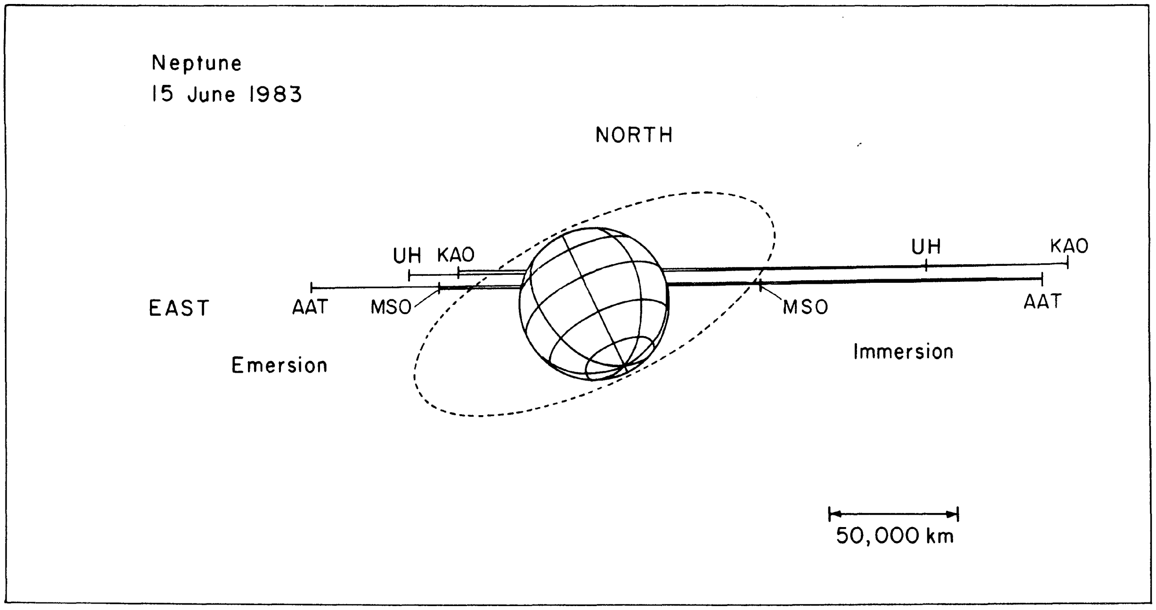


FIG. 1. Regions probed for rings. The apparent paths of the stars relative to Neptune for the present observations have been plotted in the sky plane. The chords begin and end at points corresponding to when the data recording began and ended at each station, and the placement of the chords was derived from the geometrical solution given in Paper II. The dashed ellipse shows the location of the outer accretion limit for material of density 1.0 g cm^{-3}.

tion of chords, which should provide the most accurate determination of Neptune's oblateness (assuming some southern observations would be successful); (ii) go to a location where the central flash would be visible, in order to establish the extinction of Neptune's upper atmosphere (Elliot *et al.* 1977); or (iii) go to a location where the occultation by the star would occur at the intersection of Neptune's equator and its limb, which would allow probing down to the top of Neptune's atmosphere for equatorial rings. We chose the last option, since our main goal for this occultation was probing for rings. Although the original prediction called for the optimum ring-search location to be near Australia (Mink *et al.* 1981), the final prediction (Mink and Klemola 1983) shifted Neptune's track northward, so that the *KAO* was deployed from Andersen Air Force Base in Guam.

III. ANALYSIS

A sky-plane view of the apparent paths of the star relative to Neptune for the observations described in this paper is shown in Fig. 1, where geometry was derived from Paper II (Neptune's equatorial radius $R_N = 25\,269$ km). The short-dashed ellipse indicates the outer accretion limit (66 500 km, Elliot *et al.* 1981) for material of density 1.0 g cm^{-3}. Outside of this limit, particles would tend to coalesce, since the gravitational attraction between two spherical particles of any relative size exceeds the disruptive tidal force from Neptune (Smoluchowski 1979).

In order to relate the sky-plane paths in Fig. 1 to the equatorial radii probed for rings, we have calculated the equatorial radius corresponding to each sky-plane path as a function of time and have plotted these results in Fig. 2, again using the geometrical solution given in Paper II. The dashed portions of the figure indicate when the star was occulted by Neptune. The minimum projected equatorial distances from the center of Neptune probed from each observatory were (corrected for refraction and general relativistic bending of starlight, and rounded to the nearest 50 km): Mauna Kea, 25 350 km; the *KAO*, 25 500 km; Siding Spring, 26 450 km; and Mount Stromlo, 26 550 km. A maximum projected

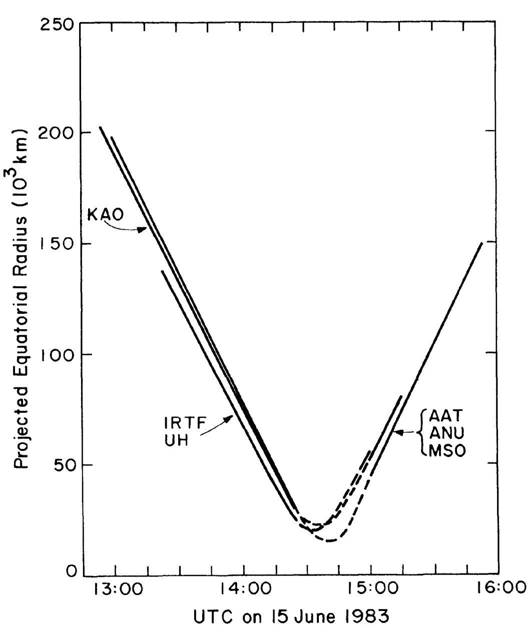


FIG. 2. Equatorial distance probed for rings. The projected equatorial distance from the center of Neptune is plotted as a function of time. The dashed portions of the lines indicate when the star was occulted by Neptune.

equatorial distance of about 200 000 km was probed by the *KAO* prior to immersion.

The limiting spatial resolution of our data was determined by the stellar diameter and diffraction. According to visual and infrared photometry of the occulted star (see Table II), its angular diameter was about 0.000 25 arcsec (Meech and Elliot 1983). From the widths of the narrowest spikes recorded during the atmospheric occultation (see Paper II), Meech (1984) found an angular diameter of $0.000\,253 \pm 0.000\,002$ arcsec. This corresponds to a FWHM (full width at half-maximum) "beam size" of 3.5 km at the distance of Neptune. The FWHM of a diffraction-limited beam is about $1.5\sqrt{\lambda D}$, where λ is the wavelength used for the observations and D is the distance between the Earth and Neptune. This beam size equals 4.7 km for $\lambda = 2.2\ \mu$m and 2.9 km for $\lambda = 0.85\ \mu$m. Quadratic addition of the diffraction (at 2.2 μm) and star diameter widths yields about 6 km. From these considerations and a typical sky-plane velocity of 22 km s,$^{-1}$ we chose an averaging time of 0.2 s as being that which would best show up the narrow rings. This averaging time was used for all data plots that follow, except those for the *KAO*. Here we used an averaging time of 1.0 s—that of the backup data-recording system—since we had problems with the primary data-recording system during some portions of the interval. These could be corrected for the regions of interest for Paper II.

We have plotted the light curves versus universal time for Siding Spring (the ANU 1.0 m) and Mount Stromlo in Fig. 3. Both the raw data from the 0.85 μm channel and that corrected for variable absorption by clouds (using the 0.55 μm channel; see Elliot *et al.* 1975b and Paper II) have been plotted. The reference times for the beginning of these plots are 14:07:05 UTC for Mount Stromlo and 14:07:07 for Siding Spring. The upper scale on the horizontal axis corresponds to the distance in the equatorial plane from the center of Neptune (see Fig. 2). Figures 4 and 5 show the data obtained from Mauna Kea, Siding Spring (the AAT), and the *Kuiper Airborne Observatory* plotted in a similar format as Fig. 3. In Figs. 4(a), 4(b), and 5(a) the data plots have been offset from each other, but normalized to a common scale of the stellar flux.

The light curves of Figs. 3–5 have various dips, most of which have known causes that are not ring occultations, and none of which correspond for two different stations. For example, the prominent slow fall and abrupt recovery of the IRTF data near 14:20 UTC is due to a telescope guiding error and its subsequent correction. At Siding Spring, scattered clouds caused dips in the data from both telescopes. The data obtained with the ANU telescope could be corrected for cloud extinctions, as described earlier. The largest dips in stellar flux observed in the AAT data in Figs. 4 and 5 are zero-level calibrations, while the smaller dips near the beginning and end of the graph were probably caused by clouds—since they occur at about the time when similar dips were recorded with the ANU telescope. The telescopes lie about 680 m apart, and one would not expect the cloud extinctions to be precisely correlated.

To summarize our limits on rings around Neptune, each station achieved different limits of stringency in the phase space of possible configurations of ring material. For equatorial rings, the data from the *KAO* and Mauna Kea probe closest to the planet; when not interrupted by clouds, the AAT data had the greatest signal-to-noise ratio. During the central portion of the data plot, none of the dips go below

TABLE II. Magnitudes of MKE 30 and Neptune.

Object	Photometric Band[1]								
	U	B	V	R	I	J	H	K	L
MKE 30	13.64±0.05	12.01±0.03	10.48±0.02	9.67±0.01	9.01±0.02	7.75±0.01	7.07±0.01	6.86±0.01	6.68±0.02
Neptune[2]	8.5	8.6	8.2	8.7	9.8	10.4	10.3	11.1	10.3

[1] The UBVRI filters are in the Johnson system.

[2] The magnitudes for Neptune are approximate and are given for comparison with the stellar magnitude.

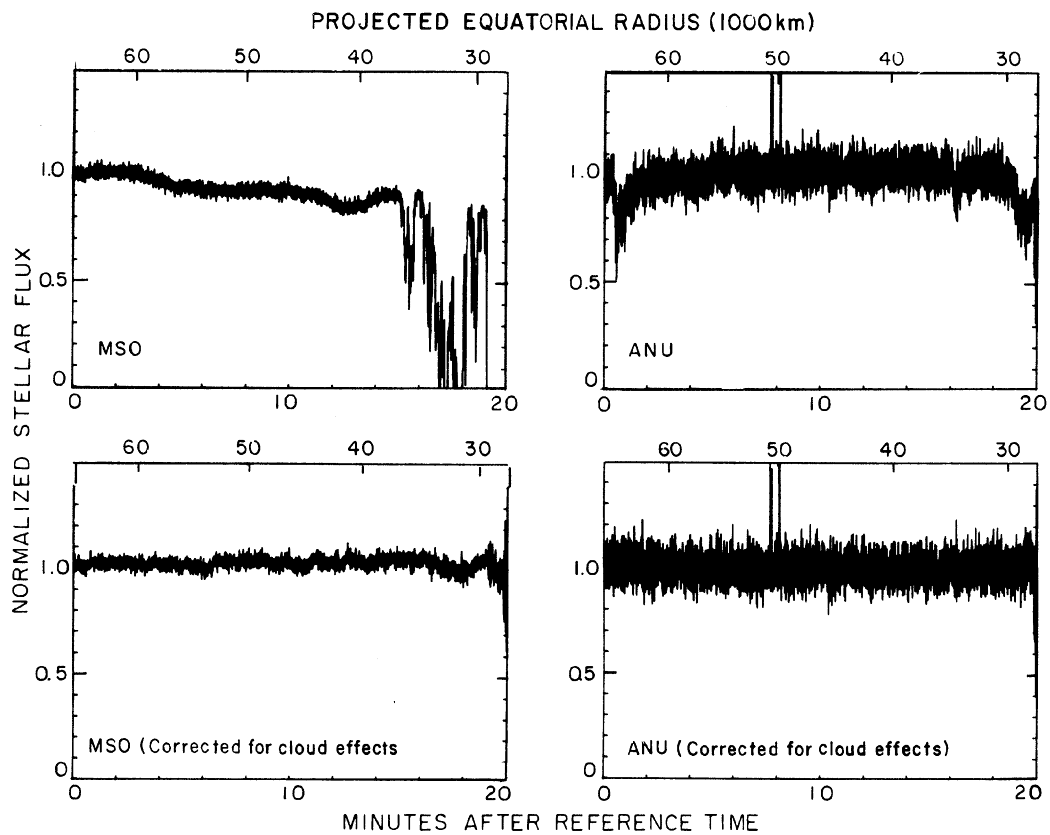


FIG. 3. Light curves from Mount Stromlo and Siding Spring. The upper frames are the raw data from the 1.9 m telescope at Mount Stromlo and the 1.0 m ANU telescope at Siding Spring. Most of the variations are due to the effects of clouds. The lower frames show the data after the effects of clouds have been removed by the method described in Paper II. The time resolution of all four graphs is 0.2 s.

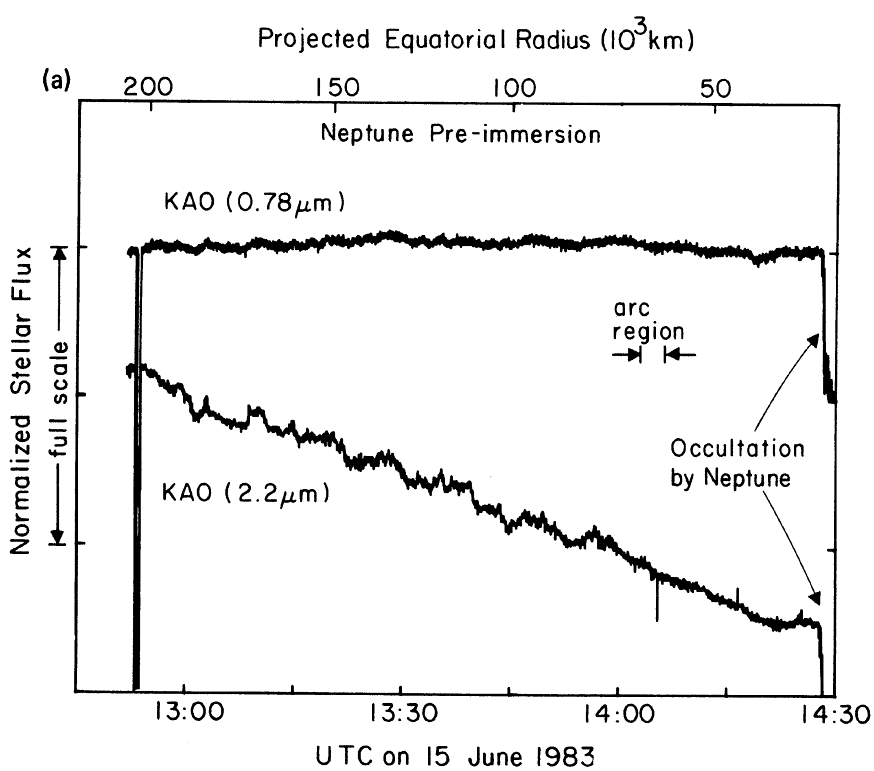
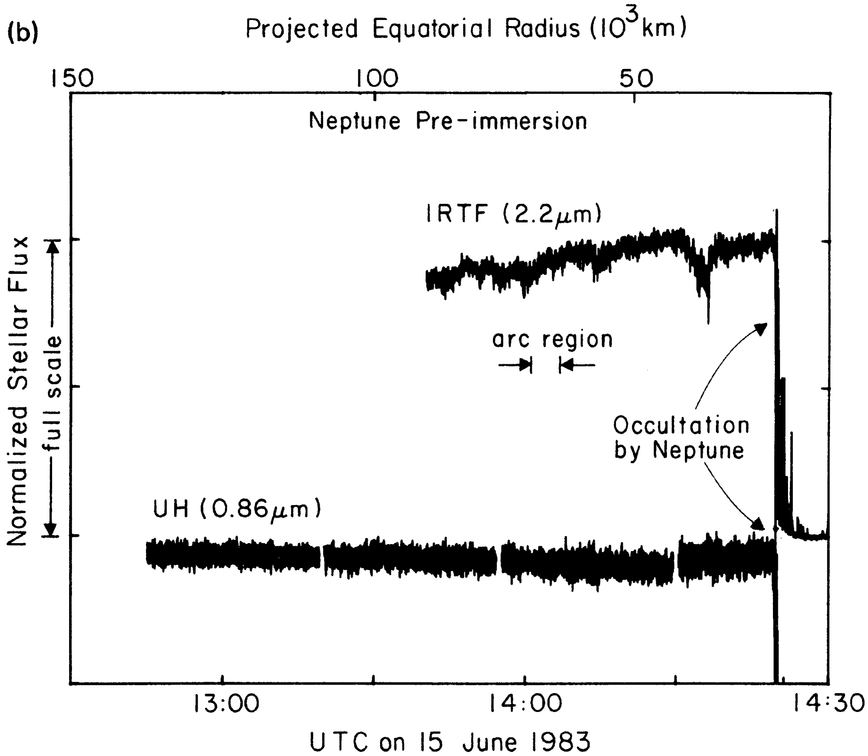


FIG. 4. Pre-immersion light curves from (a) the *Kuiper Airborne Observatory*, (b) Mauna Kea, and (c) the Anglo-Australian Telescope. The signals recorded from the star are plotted versus time and projected equatorial radius. Each graph has the full scale level for the unocculted star shown at the left and the region corresponding to the "arc" (Brahic *et al.* 1985) has been indicated also. The downward slope in the 2.2 μm data from the *KAO* is due to drift, since the system was operated unchopped. The abrupt dip that occurred near the arc region in the *KAO* 2 μm data could not have been caused by material near Neptune, since it does not appear in the other *KAO* channel. None of the other data sets show any significant features near the arc region.



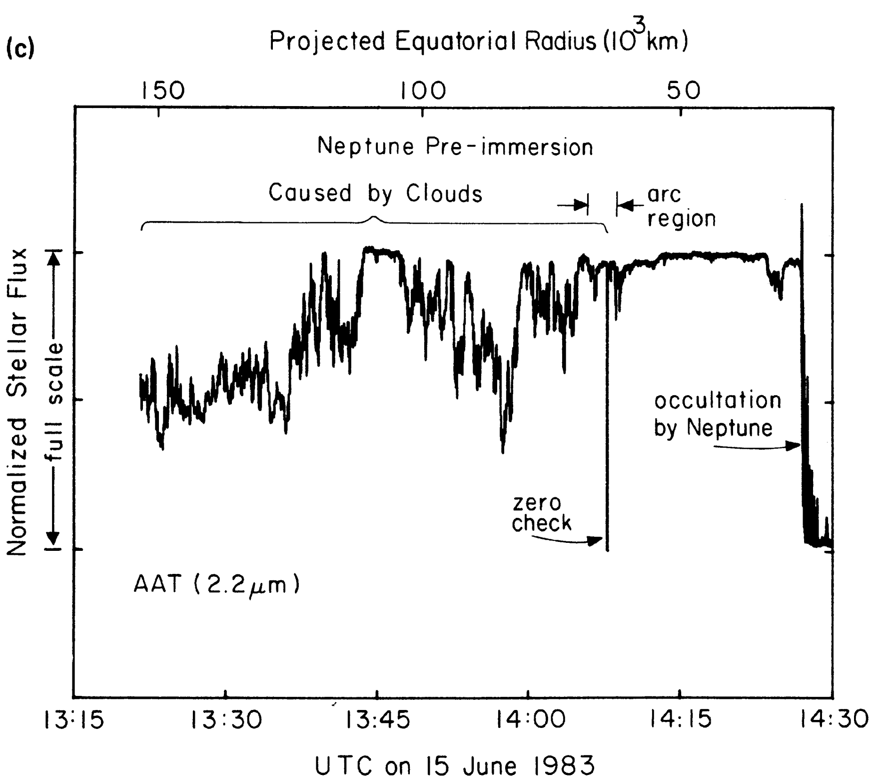


FIG. 4. (continued)

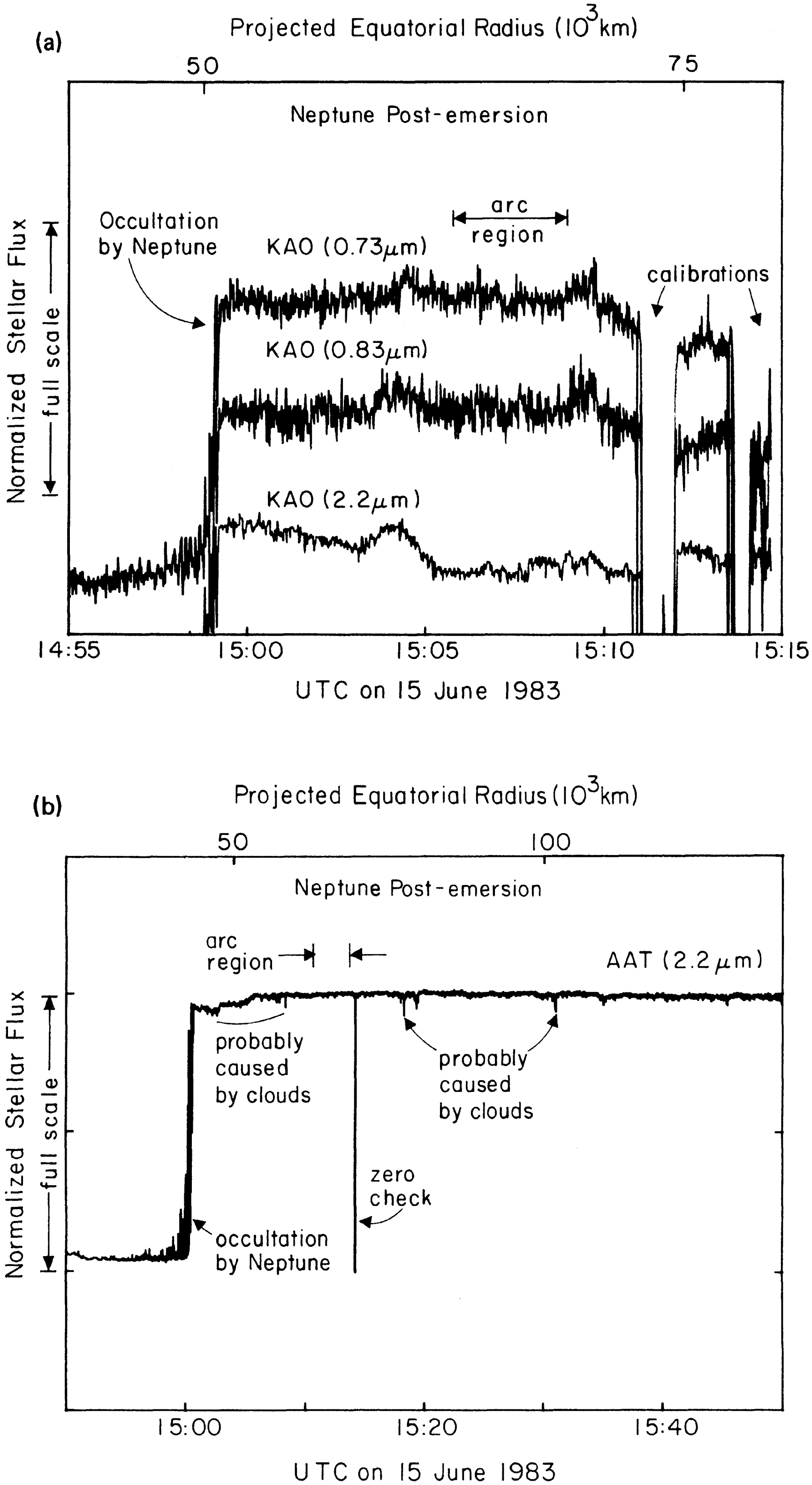


FIG. 5. Post-emersion light curves from (a) the *Kuiper Airborne Observatory* and (b) the Anglo-Australian Telescope. The signals recorded from the star are plotted versus time and projected equatorial radius. Each graph has the full scale level for the unocculted star shown at the left and the region corresponding to the "arc" (Brahic *et al.* 1985) has been indicated also. The noticeable dips in the AAT data were probably caused by clouds.

0.04, which we can place as an upper limit on the line-of-sight optical depth for rings broader than our resolution limit of 6 km. If we account for the projection angle of Neptune at the time of the observations, we can use Eq. (2) of Elliot *et al.* (1984) to interpret our limit for the normal optical depth of equatorial rings as 0.016.

IV. MATERIAL NEAR THE ROCHE LIMIT?

During the drafting of this paper, Hubbard (1984) presented strong confirming evidence for an earlier report by Manfroid (1984) and his colleagues, who observed a 35% drop in their signal (lasting for less than 2 s), while observing the 22 July 1984 appulse of Neptune to SAO 186001 from two telescopes at ESO. Hubbard's team, observing from Cerro Tololo, found a dip of similar depth and duration that occurred within 1 s of the ESO event. If interpreted as being caused by material in Neptune's equatorial plane, the observed dips correspond to a distance of about 67 000 km from the center of Neptune (Brahic *et al.* 1985). This equatorial distance is near the upper accretion limit that is traced by the dashed ellipse in Fig. 1. Since no planetary occultation was observed when the arc was detected, Brahic *et al.* could not establish its distance from Neptune precisely, but have assigned its likely location to lie within the range between 63 000 and 69 000 km. This region has been indicated in Figs. 4 and 5. Further evidence for material near this equatorial distance comes from observations made by Reitsema *et al.* (1981).

Our pre-immersion coverage of the arc region is better than our post-emersion coverage, when Neptune had nearly set as seen from Mauna Kea. Furthermore, on emersion, the *KAO* data have a lower signal-to-noise ratio, since the filters had been changed to the set optimized for our studies of Neptune's atmosphere, and we were interrupting these data for calibration observations in preparation for concluding our work for the night.

In Fig. 4(a) we see a dip at the inner edge of the arc region in the 2.2 μm channel of the *KAO*. This feature has a depth of 35% and an expanded plot of this feature shows its width to be about 1 s. This structure is similar to the arc reported by Brahic *et al.* (1985). However, its absence in the 0.78 μm channel means that it must not have been caused by occulting material near Neptune—even a bizarre distribution of particle sizes probably could not account for such an extreme difference in extinction at two wavelengths differing by a factor of only 2.8. We have no explanation for the dip.

In Fig. 4(b) we see some activity in the IRTF data, which is probably due to guiding problems, since no corresponding variations occur in the UH data recorded at the same site. Variations due to clouds affected the AAT data displayed in Fig. 4(c), but within the arc region no dip greater than 25% occurred (other than the zero check). The *KAO* data displayed in Fig. 5(a) for post-emersion is noisier than that displayed in Fig. 4(a) because of the change in filters. From the 2.2 μm data, a limit of about 10% can be placed on any short time scale dip occurring within the arc region. In Fig. 5(b) we see a series of dips in the AAT data near 47 000 km and another dip at 100 000 km, all of which we have attributed to passing clouds. The data from the *KAO* and the ANU telescopes are either absent or too noisy to have recorded these dips.

The present data give five geometrically independent probes—to varying degrees of precision—of the region near the Roche limit and show no evidence for the arc.

V. CONCLUSIONS

We have detected no ring material in this search to a normal optical-depth limit of 0.016 outside of a radius of 25 350 km for equatorial rings broader than 6 km. This limit, combined with results of other searches for rings (Elliot *et al.* 1981; Hubbard *et al.* 1984), allows us to rule out the ring system suspected by Guinan *et al.* (1982). We conclude that if Neptune has a ring system, it must be considerably less extensive than those of Saturn and Uranus—although a low optical-depth ring, such as the Jovian ring (Dunham *et al.* 1982), cannot be ruled out from our data. Furthermore, five probes of the equatorial region near the Roche limit show no obvious evidence for the arc detected by Brahic *et al.* (1985).

The greater angular resolution of the Space Telescope will allow a more sensitive imaging search for rings than has been possible from the ground (Allen 1983), and the Voyager encounter during August 1989, if the spacecraft continues to operate well, will provide the greatest imaging sensitivity that will be possible for the foreseeable future. More sensitive occultation searches for rings will become possible (i) from the ground when brighter stars are occulted and/or when telescopes with larger apertures become available, and (ii) from space, with the more powerful capability of the Space Telescope for occultations, due to its superior resolution and potential for greater photometric accuracy than ground-based observations.

We thank the *Kuiper Airborne Observatory* staff and the support staff of the UH 2.2 m telescope for their invaluable assistance. This work was supported, in part, by NASA Grants Nos. NSG-2342, NGL 12-001-0056, and NAG-7526; NSF Grant No. AST-8209825; and a grant from the National Geographic Society.

REFERENCES

Alden, H. L. (1943). Astron. J. **50**, 110.

Aldering, G. S. (1983). S. B. thesis, Massachusetts Institute of Technology.

Allen, D. A. (1983). Sky Telesc. **65**, 110.

Baron, R. L., Dunham, E. W., and Elliot, J. L. (1983). Publ. Astron. Soc. Pac. **95**, 925.

Barton, J. R., and Allen, D. A. (1980). Publ. Astron. Soc. Pac. **50**, 110.

Brahic, A., Hubbard, W. B., Bouchet, P., Elicer, L.-R., Häfner, R., Manfroid, J., Roques, F., Sicardy, B., and Vilas, F. (1985). Nature (submitted).

Dunham, E., Elliot, J. L., Mink, D. J., and Klemola, A. R. (1982). Astron. J. **87**, 1423.

Elliot, J. L., French, R. G., Dunham, E., Gierasch, P. J., Veverka, J., Church, C., and Sagan, C. (1977). Astrophys. J. **217**, 661.

Elliot, J. L., French, R. G., Meech, K. J., and Elias, J. H. (1984). Astron. J. **89**, 1587.

Elliot, J. L., Mink, D. J., Elias, J. H., Baron, R. L., Dunham, E., Pingree, J. E., French, R. G., Liller, W., Nicholson, P. D., Jones, T. J., and Franz, O. G. (1981). Nature **294**, 526.

Elliot, J. L., Veverka, J., and Goguen, J. (1975a). Icarus **26**, 387.

Elliot, J. L., Wasserman, L. H., Veverka, J., Sagan, C. and Liller, W. (1974). Astrophys. J. **190**, 719.

Elliot, J. L. Wasserman, L. H., Veverka, J., Sagan, C., and Liller, W. L. (1975b). Astron. J. **80**, 323.

Freeman, K. C., and Lyngå, G. (1970). Astrophys. J. **160**, 767.
French, R. G., Melroy, P. A., Allen, D. A., Ashley, M., Baron, R. L., Dunham, E. W., Elliot, J. L., Erickson, E. F., Freeman, K. C., Goguen, J., Hammel, H. B., Meech, K. J., and Mink, D. J. (1985). Astron. J. **90**, 2624 (Paper II).
Guinan, E. F., Harris, C. C., and Maloney, F. P. (1982). Bull. Am. Astron. Soc. **14**, 658.
Harris, A. W. (1984). Proceedings of the Uranus and Neptune Workshop, Pasadena, CA, February 6–8, 1984.
Hubbard, W. B. (1984). IAU Contrib. No. 4022.
Hubbard, W. B., Frecker, J. E., Gehrels, J. A., Gehrels, T., Hunten, D. M., Lebofsky, L. A., Smith, B. A., Tholen, D. J., Vilas, F., Zellner, B., Avey, H. P., Mottram, K., Murphy, T., Varnes, B., Carter, B., Nielsen, A., Page, A. A., Fu, H. H., Wu, H. H., Kennedy, H. D., Waterworth, M. D., and Reitsema, H. J. (1985). Astron. J. **90**, 655.
Kovalevsky, J., and Link, F. (1969). Astron. Astrophys. **2**, 398.
Manfroid, J. (1984). IAU Contrib. No. 3962.
Meech, K. J. (1984). "Stellar Diameters from Planetary Occultations," private circulation.
Meech, K. J., and Elliot, J. L. (1983). Bull. Am. Astron. Soc. **15**, 817.
Mink, D. J., and Klemola, A. R. (1983). IAU Contrib. No. 3818.
Mink, D. J., Klemola, A. R., and Elliot, J. L. (1981). Astron. J. **86**, 135.
Smoluchowski, R. (1979). Nature **280**, 377.
Taylor, G. E. (1970). Mon. Not. R. Astron. Soc. **147**, 27.