EXTENDED RING SYSTEM OF URANUS

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Abstract. Two photoelectric records of the occultation event on 10 March, 1977, obtained by two 102-cm-aperture telescopes, spaced 1500 km apart, are critically analysed and indications of a complex structure of distribution of occulting material surrounding the planet are obtained. The results confirm the existence of a very shallow broad ring system with local condensation lanes of narrow and intermediate widths. A system of numerous thin rings are also present around the planet in the equatorial plane.

1. Introduction

The occultation of SAO 158687 by Uranus on March 10, 1977, was a widely observed phenomenon by numerous teams operating from ground-based stations as well as an airborne observatory over the southern Indian Ocean. Three of these teams promptly and independently recognized the unexpected occultations evidenced by sudden diminutions in the otherwise constant light curve of the star, as caused by small bodies in orbit around the planet (Bhattacharyya and Kuppuswamy, 1977; Elliot; Dunham and Mink, 1977; Millis, Birch and Trout, 1977). Confirmation of these features were forthcoming subsequently from records of the events made at several locations, Cape Town (Churms, 1977), Western Australia (Hubbard *et al.*, 1977), Naini Tal (Mahra and Gupta, 1977), Tokyo (Tomita, 1977), Peking (New Scientist, 1977). These events have led to the recognition of a system of narrow rings (Elliot, Dunham and Mink, 1977) α, β, γ, δ, ϵ of occulting material. This principal ring system has been observed again when occultations by the planet took place, of BD-15°3969 on December 23, 1977, (Millis and Wasserman) and of a star of magnitude 11.6 on April 10 1978 (Nicholson *et al.*, 1978).

A detailed examination of the Kavalur record of the March 10, 1977, event revealed several additional features (Bhattacharyya and Bappu 1977), incompletely described in the discovery communication to the Central Bureau of Astronomical Telegrams (IAU Circ. No. 3048). Many sharp decreases in light that appeared as spikes of short duration were identified. In addition the diminution of the light of SAO 158687 by 0.046 magnitude reported in IAU Circ. 3048 was ascribed to the presence of occulting material distributed around the planet, and which forms an extended ring system about Uranus, similar to that of Saturn.

A complete recording of the March 10, 1977, event was made at Naini Tal and provided

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confirmation of the rings (Mahra and Gupta, 1977). Both the Kavalur and Naini Tal records were obtained with almost identical equipment; the telescopes were of 102-cm aperture and the procedure of photoelectric recording similar, with Uranus high up in the sky. These two telescopes separated by 1500 km had clear observing conditions. These telescopes were also the largest light collectors used for the observation of the event and with the low value of zenith distance of the planet at the time of observation, both records have a high signal-to-noise ratio. A similarity of light changes, consistent with the geometry at the two locations, would thus be proof of the reality of the condensation spikes and extended ring system discovered on the Kavalur record. In this study, we subject the Naini Tal tracing to detailed analysis, similar to that done earlier on the Kavalur tracing, and report on our findings.

2. A Simple Planetocentric Model

The light curves obtained at the two locations are shown in Figure 1. A similarity between the two curves is apparent. Because of the difference in location, there are systematic time differences between appearances of similar features in the two records. For a more critical comparison we have computed planetocentric distances of these features from the times of occurrences at these two places; for this purpose we have assumed a model of the ring system lying in the equatorial plane of the planet with circular symmetry. The coordinates of the star and Uranus were taken with the corrections determined by Franz and Wasserman and by Seidelman (Marsden, 1977), respectively. We have based our computations on the assumption that planetocentric distances of the major occultation features due to the prominent rings, as calculated from the two records, should be equal. For exact matching of the times of the events however, a further correction of $+0\overset{''}{.}15$ in declination had to be applied to the position of the star with respect to the planet. The adopted model satisfactorily explains the times of occultations not only at Naini Tal and Kavalur but at all stations where these are recorded. Figure 2 is a plot that shows computed curves of planetocentric distance of the occulting region versus time for all these locations, during the March 10 event. The times of occultation by major features of the Uranus ring system as reported by the observatories at Cape Town and Perth (Marsden, 1977; Hubbard *et al.*, 1977), Tokyo (Tomita, 1977), Peking (Chen-Dao-Han *et al.*, 1978) as well as from the Kuiper Airborne Observatory (KAO) (Elliot *et al.*, 1977) are plotted on these curves. It may be seen that the distances of the four major rings and a few other spikes are satisfactorily explained by this model with circular symmetry. For the ϵ ring and the several other minor features reported in the present communication the model has to assume a more complex form. The disagreements cannot be minimized by adjustment of relative star and planet positions or by simple reorientation of the ring plane. This is suggestive of a complex geometry of the distribution of occulting material around the planet.

With this model as a basis, the observation times are converted to distances from the planet centre and the shallow occultation features reported earlier (Bhattacharyya and

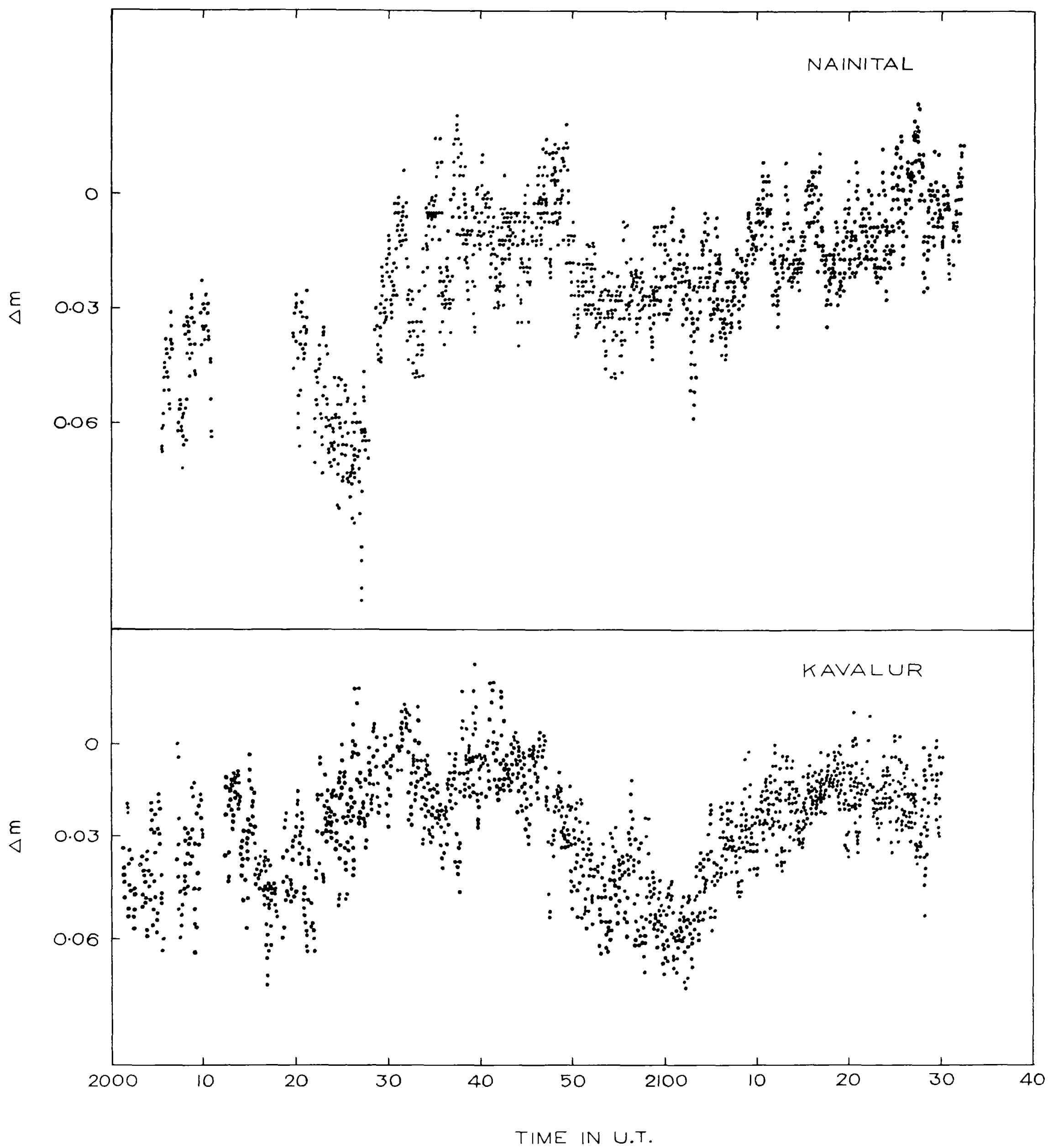

Fig. 1. Light curves of the occultation of SAO 158687 by Uranus, obtained on March 10, 1977, at Kavalur and Naini Tal.

Bappu, 1977) compared with those recorded at the other station. We find that both records contain indications of occultations by a shallow near-concentric ring system surrounding the planet Uranus. The detailed comparison reveals the existence of additional structures of intermediate dimensions and opacities in this zone.

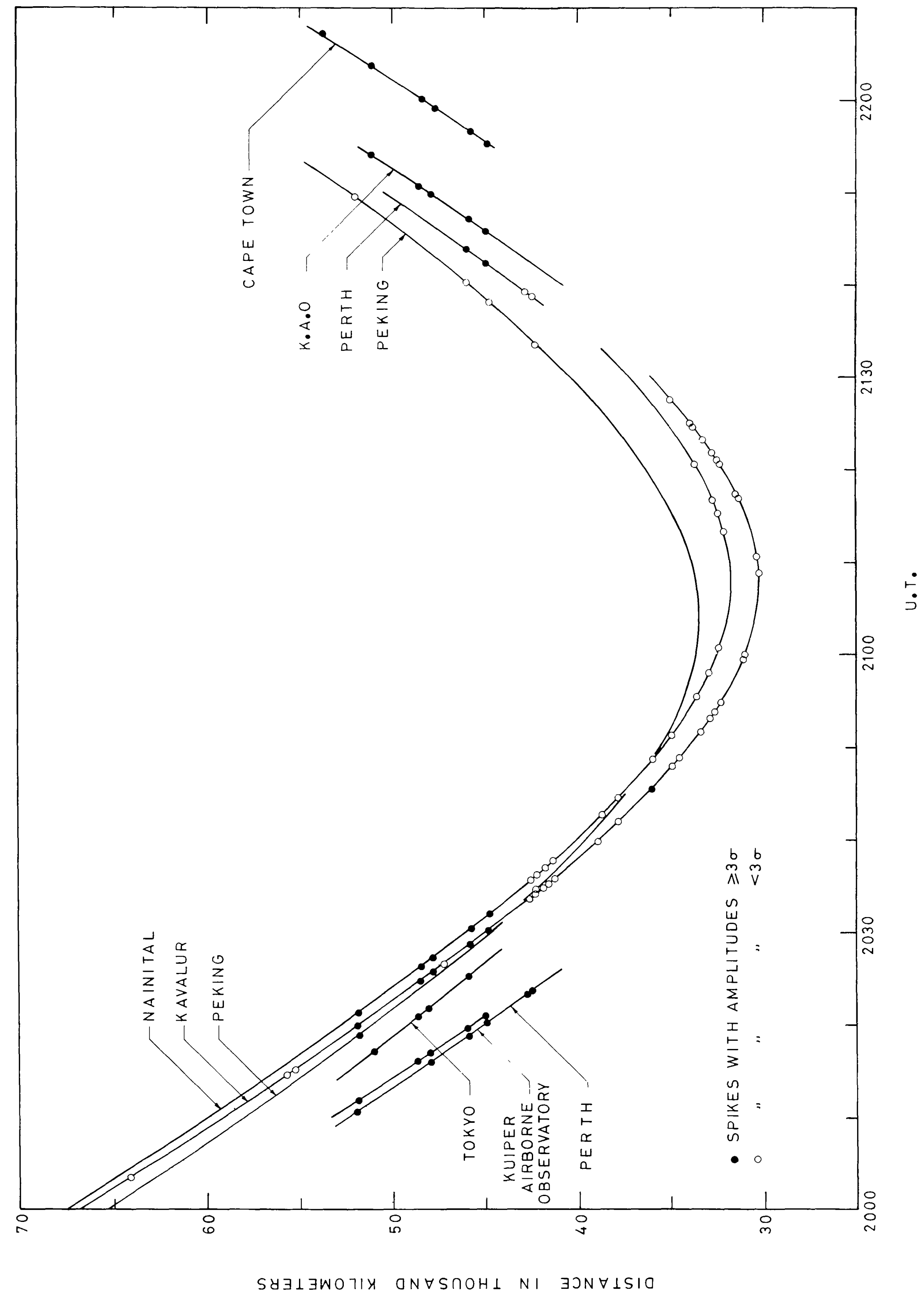

Fig. 2. Planetocentric distances of the condensation spikes based on a simple model. The different times of observation of the same feature from different locations may be seen.

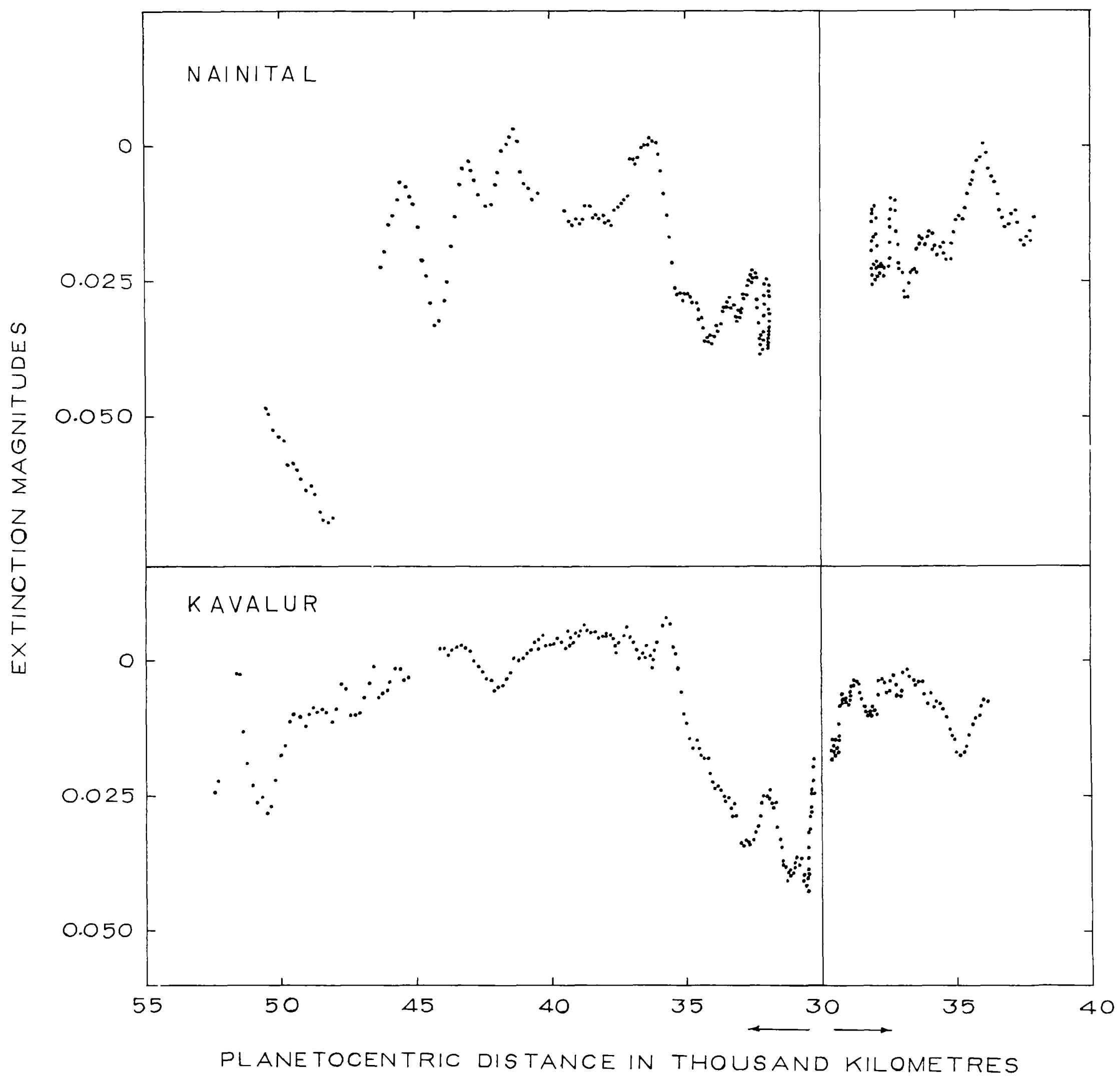

Fig. 3. The broad zones as observed at Naini Tal and Kavalur.

2.1. The broad zones

The broad features termed A, B, C and D (Bhattacharyya and Bappu, 1977) are characterised by consistent extinction of star light extending over durations covering minutes; to bring out these features a two-minute integration around each point has been employed. Moving averages of this duration are calculated and plotted against the mean planetocentric distances for the two stations. These plots are shown in Figure 3. The two plots, although very similar, show some differences at places. It does not appear possible to explain all these differences in extinction values and times of occurrence by any simple model. While variations caused by the experimental arrangement may probably be a minor contributor, a major share must, however, be ascribed to departure from uniformity of the opacity of the ring system. The shape of the light curves do not match exactly in the two records and are neither perfectly symmetrical, but a closer inspection reveals much agreement.

The occultation due to zone C can be clearly noticed. This feature is most prominent with an estimated width of 3000 km and having a maximum extinction of 0.040 magnitudes in the observation band which is around 7500 Å. The computed values of outer and inner boundaries are 36 000 km and 33 000 km from the planet centre. The extinction effect due to this feature is noticed on both records. A symmetry exists in times of occurrence of changes in the value of gradient but there is an asymmetry in the value of extinction by the ring material particularly as seen on the Kavalur record. The Naini Tal record shows a better symmetry in this respect.

Zone B, as can be judged from the comparative study of the two records, appears larger than that reported earlier (Bhattacharyya and Bappu, 1977), with an irregular structure having a longitudinal scale length that is small compared to the separation between the two stations. The section of the Kavalur extinction curve on which the earlier estimation was based has a very minor feature at corresponding positions on the Naini Tal record. If all these features are attributed to the distribution of the occulting material in this zone, the structure of this area should be very irregular. From these two records, this zone may be estimated to lie between 44 000 and 36 000 km from the planet centre. Maximum extinction in this zone as estimated from the Naini Tal record is $0^{m}.025$; it is lower on the Kavalur record.

Zone A is not well depicted in either of the two records. The principal reason for this could be due to the frequent adjustments and breaks for calibration employed during the early phases of observation, in preparation for an occultation event. The extinction in this zone is comparable to that in Zone C but the confidence is considerably diluted with the deterioration of the quality of the record for this period. The inner limit of this zone is estimated as 40 000 km on the preoccultation side.

Zone D probably lies between 30 000–32 000 km from the planet centre; the curve showing extinction versus distance appears to indicate this both on the pre-occultation and post-occultation sides in the Kavalur records. According to our model, the light from SAO 158687 as seen from Naini Tal, did not pass through this zone. A considerable variation of extinction over this zone is noticed, which may indicate a gradient in the longitudinal direction. In Table I we summarize the estimated properties of the broad zone.

It is interesting to note that the Chinese observers (Chen Dao-Han *et al.*, 1978) have also noticed this feature as a drop in luminosity of 0.05 magnitude for a duration of about 14 min centering at 2101 U.T.

2.2. The Intermediate Features

Besides the two features of a shallow extended ring system and another of sharp rings like α, β, γ, δ, a third type of condensation lanes is also seen in both the records (Figure 1). These last on the light curves for a few tens of seconds suggesting widths of a few hundred kilometers, and density of occulting material comparable to those in the shallow zones. These features are noticed prominently in the C zone and are remarkably similar in appearance on both records. When the times are converted to planetocentric distances a very close correspondence between the two records is noticed; the implication that the features

TABLE I

Estimated properties of the broad zone

Zone Nomenclature	Estimated Boundaries		Maximum Extinction magnitude		Remarks
	Outer	Inner	Kavalur	Naini Tal	
A	–	44 000	0.050	0.060	Signal-to-noise ratio poor Frequent breaks in record
B	44 000	36 000	0.010	0.025	Structure irregular
C	36 000	33 000	0.040	0.030	Well defined
D	32 000	30 000	0.045	–	–

are concentric with the planet and hence form a part of the ring system, appears more than a reasonable guess. The extinction effects due to such features are illustrated in Figure 4. The horizontal scale is many times magnified here to bring out the similarity of fine features in the two records.

2.3. THE CONDENSATION SPIKES

Several sharp spikes lasting for a second or less have been reported earlier (Bhattacharyya and Bappu, 1977). These were selected primarily on the basis of their amplitudes having values significantly higher than what the statistical probabilities in a normal gaussian distribution suggest. A number of them have been found in more records, besides the two for which results are presented here, at instants which can be explained as being due to a family of thin circular rings. Some of these have also been found in a subsequent occultation event (Marsden, 1978) and their radii estimated. Planetocentric distances calculated on the basis of our model give distances for spike numbers 4, 5, 6 and 7 as reported by Bhattacharyya and Bappu (1977), of 47 300, 42 700, 42 400 and 41 900 km, respectively. We may compare these with the Marsden values for the April 10, 1978, occultation of 47 290, 42 660, 42 394 and 42 029 km, respectively. It is clear that spike numbers 4, 5, 6 and 7 seen on the Kavalur tracing of the 1977 event are the same as η, θ, ι and κ events seen in 1978 (Marsden nomenclature) and η, 4, 5 and 6 designated by Elliot *et al.* (1978). There can hardly be better confirmation of the existence of the weak spikes that we have reported earlier.

We have re-examined the presence of these spikes from the dual consideration of statistically significant amplitude and occurrence at expected instants, and find that the list of spikes given earlier (Bhattacharyya and Bappu, 1977) can be augmented by a few more. These extra spikes are noticed prominently on any one record and a corresponding search confirmed their existence in the other, although generally with much smaller

TABLE II

Data relating to condensation spikes (see Figure 2)

S1 No.	Distance Km	Kavalur Time of Occurrence	Kavalur Amplitude in	Naini Tal Time of Occurrence	Naini Tal Amplitude in	Remarks	Other Nomenclature	Reference
1	64 100	20 03 28	2.87	–	–	No record at Naini Tal	Spike 1	1
2	55 700	14 37	2.87	–	–	No record at Naini Tal	Spike 2	1
3	55 300	15 10	2.69	–	–	No record at Naini Tal	Spike 3	1
4	51 900	19 51	7.85	20 21 19	–	Time estimated from interrupted record for Naini Tal	Ring ϵ	1, 1, 2, 7
5	48 500	24 41	5.30	26 15	5.00		Ring δ	1, 2, 4
6	47 800	25 41	3.64	27 19	3.03		Ring γ	1, 2, 4, 7
7	47 300	26 21	2.98	–	–	No record at Naini Tal	Spike $4/\eta$	1, 3, 6
8	45 800	28 40	4.47	30 25	5.09		Ring β	1, 2, 4, 7
9	44 800	30 11	6.00	32 01	7.58		Ring α	1, 2, 4, 5, 6, 7
10	42 700	33 40	2.26	35 41	1.97		Spike $5/\theta$	1, 5, 6, 7, 8
11	42 400	34 08	2.68	36 10	2.76		Spike $6/\iota$	1, 5, 6, 7
12	41 900	34 47	2.31	36 52	2.58		Spike $7/\kappa$	1, 6, 7
13	41 700	35 15	2.55	–	–	No corresponding spike	Spike 8	1
14	41 400	35 48	2.61	37 47	2.12		Spike 9	1
15	39 000	39 49	2.33	–	–	No corresponding spike	–	
16	38 800	–	–	42 41	2.42	No corresponding spike	–	
17	37 900	42 03	2.33	44 27	2.12			
18	36 100	45 31	2.33	48 47	1.97			
19	35 000	47 56	3.67	51 13	2.12	Naini Tal record shows double spike	Spike 10	1
20	34 600	48 51	2.96	–	–	No corresponding spike	Spike 11	1
21	33 600	51 40	2.32	55 28	2.07	A difference of 200 km as estimated from the two records		
22	33 000	53 10	2.50	58 07	2.12			
23	32 700	53 52	2.93	–	–	No corresponding spike	Spike 12	1

Table II continued

24	32 400	54 53	2.60	21 00 49	2.42		Spike 13	1
25	31 200	59 33	2.10	–	–	Beyond range covered by Naini Tal		
26	31 100	21 00 01	2.10	–	–	Beyond range covered by Naini Tal		
27	30 400	08 45	2.34	–	–	Beyond range covered by Naini Tal	Spike 14	1
28	30 500	10 40	2.34	–	–		Spike 15	1
29	31 400	16 58	2.30	–	–	Beyond range covered by Naini Tal	Spike 16	1
30	31 500	17 20	2.22	–	–	Beyond range covered by Naini Tal		
31	32 400	20 37	1.89	13 22	2.07			
32	32 600	21 03	2.20	15 19	2.07			
33	32 800	21 50	2.20	16 43	2.07			
34	33 400	23 12	2.04	–	–	No corresponding spike	Spike 17	1
35	33 900	24 42	1.90	20 37	2.12			
36	34 000	25 08	2.08	–	–	No corresponding spike	Spike 18	1
37	35 100	27 37	2.43	–	–	No corresponding spike	Spike 19	1

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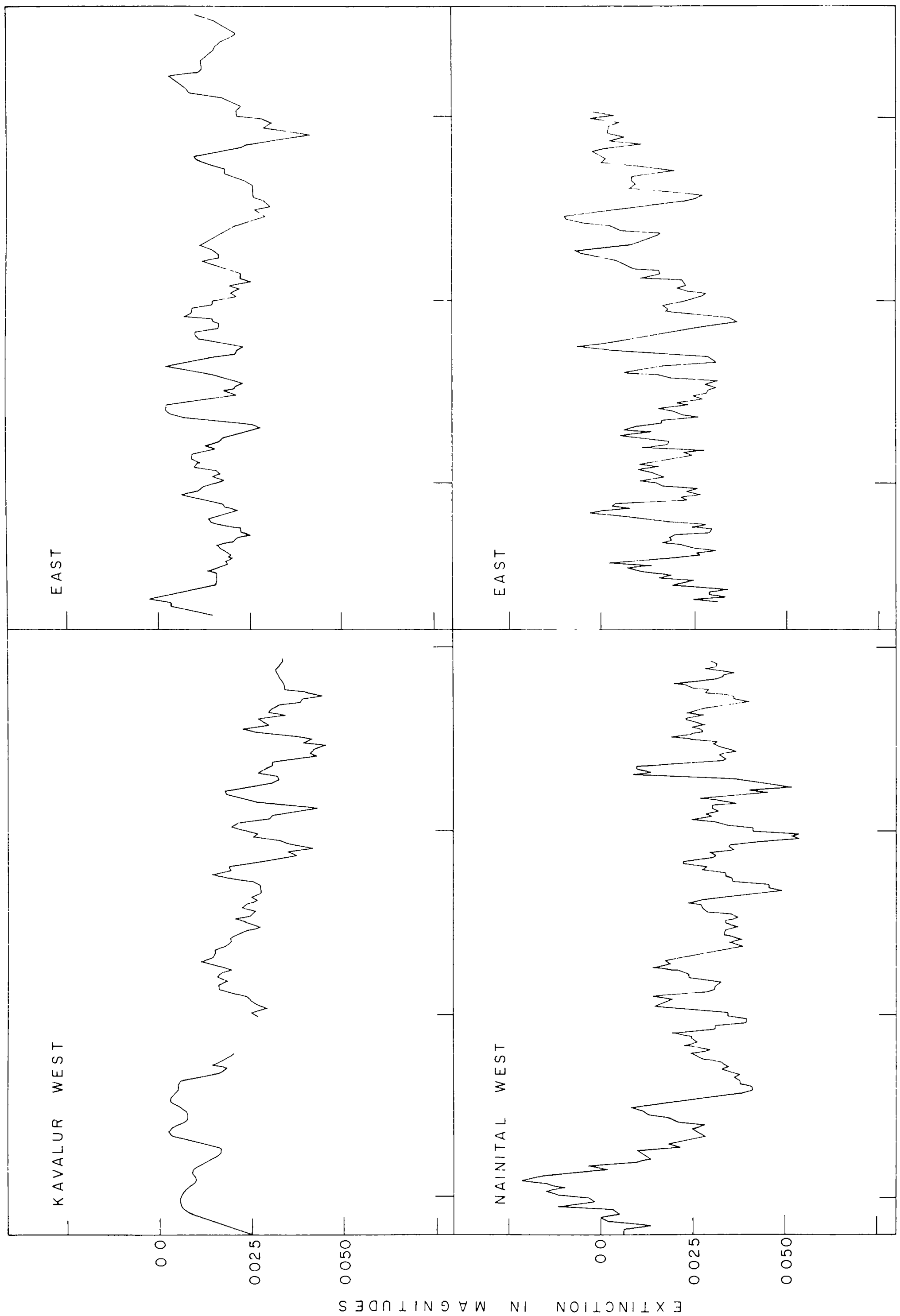

Fig. 4. Intermediate features of the occulting material seen on the Kavalur and Naini Tal records.

TABLE III
Relative Amplitudes of prominent sharp spikes

	Kavalur	Naini Tal	Kao I	Kao II
β/α	0.75	0.67	0.75	0.64
γ/α	0.61	0.40	0.73	0.72
δ/α	0.88	0.66	0.91	0.83

amplitudes. Figure 2 displays the positions of all these spikes; their times of occurrences, amplitudes and computed distances being listed in detail in Table II.

The amplitudes of these spikes have been determined directly from the records. The adjacent portions of the records have been used to estimate the standard deviation of the random fluctuations recorded. The amplitudes of all these spikes in Table II are given in units of the standard deviation of the noise in the record. In the plot the spikes with amplitude 3σ have been shown as filled circles and those less than this value with open circles.

Although the detection of the ϵ ring was not reported by the Naini Tal observers in their preliminary report, a portion of it, mixed up with a calibration break is clearly seen at an instant which agrees very well with the adopted model. This and the other four rings α through δ are also included in this list of detected spikes, and shown in Figure 2. One interesting point which may be noticed is the variation of relative amplitude of the spikes α through δ as obtained from different locations. This is shown in Table III where the relative strength of these spikes as observed from Kavalur and Naini Tal have been compared. Similar figures for the KAO estimated from their published results (Elliot *et al.*, 1977) are also shown alongside. A variation in amplitudes of spikes between Perth and Kavalur were noticed earlier (Bhattacharyya and Bappu, 1977) and are also seen in the present analysis.

The fact that corresponding spikes appear in the records of two observing locations 1500 km apart eliminates the possibility of these being produced by small individual satellite bodies, and suggests their origin as due to narrow lanes of occulting material. The contention is further strengthened by the fact that some of the spikes seen in records obtained at Peking (Chen Dao-Han *et al.*, 1978) and near Perth by the University of Arizona team (Hubbard *et al.*, 1977) on the post-occultation side occur at instants supporting a circular structure of the rings. The extinction effected by these are greater than $0^{m}.16$ and show values as high as $1^{m}.40$ in parts of the ϵ ring condensation. Some of the spikes are seen to be accompanied by prominent wings suggesting gradient in the density of occulting material in the lanes. The width of the features are lower than the resolution limit of the observing equipment, but the wings wherever present last for a few seconds, suggesting widths of tens of kilometers.

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