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INTERPRETATION OF SURFACE FEATURES OF EUROPA
OBTAINED FROM OCCULTATIONS BY IO

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Abstract

Light curves of occultations of Europa by Io have been used to generate a crude map of albedo features on Europa. The best values currently available for the impact parameters and magnitude ratios for each event have been imposed on our model. Residuals between the observed and computed light curves are interpreted as albedo features on Europa. In order to improve the fit between the observations and the model it became necessary to impose a general polar brightening. The effects of additional albedo features and alternate models are discussed.

Introduction

A concentrated effort was made to obtain observations of as many of the mutual events of the Galilean satellites as possible. During the period from 10 June 1973 to 14 April 1974 a total of 11 events were obtained from a possible 38 predicted by Aksnes (1973) and 36 by Brinkmann (1973). From this series six occultations of Europa by Io were selected to be analyzed as a self-consistent set. Since a portion of the data was obtained under less than ideal conditions, the approach to this study has been to apply simple models and adjust the parameters of the model to obtain the most consistent fit. All of our data has been released in digitized form to the Lowell Observatory data bank.

Observations

The observations used in this analysis are tabulated in Table I. The first two events were observed from the Blue Mesa Station of New Mexico State University Observatory and the other four observations were made at the Tortugas Mountain Station. The Blue Mesa data were obtained with a 61 cm f/15 reflector equipped with an uncooled EMI-9502 photomultiplier. The data were displayed on a digital voltmeter that integrated for one second and displayed the data for one second. At the Tortugas station a 40.6 cm f/34 Gregorian reflector was equipped with an RCA 1P-21 which was used uncooled. The data on this system were recorded on a chart recorder. During an event the system was run in DC mode so that a continuous light curve was generated. All observations were made in the V band of the standard UBV system. Since both systems were single channel it was not possible to simultaneously monitor the sky background and the event. Sky readings were therefore taken at the beginning and at the end of the observation except for the event on 17 June 1973. During this event the sky was monitored several times because of the rapid change in background due to sunrise.

The observed light curves with sky brightness subtracted are given in Fig. 1 in chronological order. The flux is normalized for the combined deflection from Io and Europa observed before and after an event. Sky brightness was derived by fitting a linear sky background between the sky brightness observed at the beginning and end of an event except for the event of 17 June 1973 where a second order fit was required. The

TABLE I

MUTUAL OCCULTATIONS OF EUROPA BY IO

OBSERVED AT NMSU

Event	Date	First Contact UT ± 05^s	Last Contact UT ± 05^s	Depth (ΔV mag)	Quality
NMSU-1	10 Jun 73	$9^h08^m20^s$	$9^h11^m34^s$	0.09	Good
NMSU-2	17 Jun 73	11 13 54	11 18 00	0.18	Fair (sunrise)
NMSU-3	12 Jul 73	6 26 30	6 32 04	0.39	Bad seeing
NMSU-4	13 Aug 73	3 44 51	3 51 09	0.52	Fair to good
NMSU-7	27 Aug 73	8 03 49	8 11 49	0.56	Good
NMSU-8	14 Sep 73	1 51 19	2 02 00	0.58	Very poor (sunset and clouds)

figure also gives the time elapsed since T_m, the midpoint of the event; as well as a phase scale giving the phases of the event, phase 0.0 starting at first contact and phase 1.0 being last contact. The observed data have been smoothed by the use of a five-point mean.

Inspection of these light curves gives an indication of the seeing conditions for each event. The size of the seeing fluctuations has been used to evaluate the quality of each observation. Events NMSU-3 and NMSU-8 were both obtained under less than ideal observing conditions. In the case of NMSU-8 the seeing was deteriorating rapidly during the second half of the event.

Comparison with Models

The computed light curve was modeled by generating two matrix arrays which represented the brightness distribution for each satellite. The values assigned to the elements of the arrays $\beta_I(I,J)$ and $\beta_E(I,J)$ represented the relative surface brightness per unit area with the constraint that:

$$R = \frac{\sum_{I}^{N} \sum_{J}^{N} \beta_E(I,J)}{B_I} \tag{1}$$

where R is the brightness ratio outside the occultation and B_I is the integrated surface brightness of Io.

The radii were set to 1830 km for Io and 1550 km for Europa. The value for the radius of Io was taken from G. E. Taylor, et al (1971) and is based on the 14 May 1971 occultation of Beta Scorpii C, while the radius of Europa is by Brinkmann (1973). These values lead to 101 matrix elements across the diameter of Io and 85 across Europa's diameter to yield an effective resolution of 36 km per matrix element.

The occultation was simulated by passing the Io array in front of the Europa array in a manner specified by the impact parameter. The instantaneous brightness was computed by numerical integration over the Europa array where the brightness at time t is given by

$$B(t) = B_I + \sum_I \sum_J \beta_E(I,J) \tag{2}$$

where I and J are summed over all values of $\beta_E(I,J)$ which are not occulted by Io.

The parameters for the model are the impact parameter for the event, the relative magnitudes of the satallites at the onset of the occultation, and the distribution of albedo features on Europa. The basic data for the generation of the model are given in Table II. The magnitudes are taken from Fig. 1 and Fig. 2 of the paper by Morrison et al (1974). The error in interpolating each figure may be as large as 0.01 magnitudes, resulting in a possible error of ±0.02 magnitudes. Impact parameters were first treated as a free parameter of the model. A set of best fit impact parameters for our observations was determined. These best fit values were found to be in good agreement with the values which may be obtained from

$$d = R_{Io} + R_{Eu} - 2R_{Eu} \cdot \mathrm{Mag} \tag{3}$$

where Mag is the predicted magnitude of the event tabulated by Aksnes

TABLE II

Event	Date	$(UT)_m$	α	θ_I	θ_{II}	V_I	V_{II}	Impact Parameter km
NMSU-1	10 Jun 73	$9^h09^m57^s$	9°05′	229°5	330°6	5.21	5.46	-2915
NMSU-2	17 Jun 73	11 15 57	8 09	232.2	329.5	5.18	5.45	-2450
NMSU-3	12 Jul 73	6 29 17	3 51	241.3	325.8	5.11	5.43	-1365
NMSU-4	13 Aug 73	3 48 00	2 55	254.6	322.1	5.12	5.41	-807
NMSU-7	27 Aug 73	8 07 49	5 42	261.8	321.1	5.17	5.45	-590
NMSU-8	14 Sep 73	1 56 39	8 31	273.2	320.6	5.24	5.47	-156

$(UT)_m$ = Universal Time at midevent (±05 seconds)

α = Solar phase angle

θ_I = orbital phase angle for Io

θ_{II} = orbital phase angle for Europa

V_I = V magnitude for Io ±.02 mag.

V_{II} = V magnitude for Europa ±.02 mag.

(1974). For the analysis of albedo features, the impact parameters were fixed at the values given by Eq.(3).

A series of models with increasingly complex albedo features is displayed in Fig. 2, with the observed minus calculated residuals plotted as a function of the phase of the event. Since the values of the impact parameters are established by Eq.(3), additional adjustment of the calculated curves must be obtained from albedo features. Figure 2a shows the residuals for all six events when the albedo model for Europa was assumed to be a uniform disk. Inspection of the earliest events suggests that a bright polar cap being occulted could account for the depth of the observed events.

Following the suggestion of a bright polar cap, a second series of models was computed, varying the size and general albedo of the polar cap. A typical case is illustrated in Fig. 2b, where the albedo of the polar cap relative to the rest of the disk is 2.5 and the cap covers the region from +35° to +90° in latitude. From these models it was found that the residuals of NMSU-1 were sensitive to the assumed brightness of the pole while NMSU-2 is very sensitive to the southern limit of the pole as can be seen by the reversal of the sense of the residuals for NMSU-2 from Fig. 2a to Fig. 2b. Raising the southern limit of the pole to +40° produces the desired improvement in the residuals for this event. A light curve from the occultation of 13 June 1973 would be extremely useful in establishing the limits of the pole.

The residuals of NMSU-3, 4 and 7 suggest albedo features on the leading and following edges. Several trial models were tested; however, the small number of observed events allows a large degree of freedom in the assumed latitudinal dependence. The longitudinal dependence is even more difficult to determine since it depends critically on the quality of the photometry. Any albedo features south of the pole must be determined from the events NMSU-3, 4, 7, and 8. Unfortunately, both NMSU-3 and 8 were observed under non-photometric conditions and must therefore be given low weight.

Figure 2c, our final model, has been adjusted so as to reduce the residuals of NMSU-4 and 7 as much as possible without introducing new residual features in the remaining events. The most dominant feature of the model is the bright north polar cap which is 2.3 times as bright as the average brightness of Europa. Starting 40 degrees east and west of the central meridian and extending to the limb are two more bright features. The brightnesses of the eastern and western features are 1.16 and 1.01 respectively. The remainder of the disk has an average brightness of 0.63 with a slight gradient from 0.61 at the eastern extremity to 0.65 in the west. The model is shown in Fig. 3.

A slight improvement over the residuals observed in Fig. 2c may be produced by reducing some of the impact parameters slightly from Aksnes' values; however, the quality of the photometry does not justify this. The residuals for NMSU-4 could be improved by adjusting the assumed brightness ratio, but for consistency a model based on published impact parameters and magnitudes has been imposed. In the last two events the sense of the residuals from phase 0.78 to 1.0 is reversed; therefore, any attempt to improve one residual produces the opposite effect on the other.

An albedo map of Europa has been published by Vermilion et al (1974). This map was produced by a technique similar to ours; however, some of their photometry was obtained under better observing conditions. On the other hand, their map is constrained by only four events. Two of their events are common with our data. Figure 4 shows the residuals between their model and our observations. Impact parameters and brightness ratios have been kept the same as in our model 2c. The best residuals are for NMSU-7, one of the events common to both investigations. The main source of the large residuals are the differences in the assumed impact parameters and brightness ratios.

Conclusion

The most important feature which must be included in all models is the bright polar region in which the albedo has been increased by a factor of 2.3 over the average value. The brightness of the pole and its extent are well determined from NMSU-1 and 2. In this respect, the NMSU data is more sensitive than the four events used by Vermilion (1974). The other two albedo features in our model are not as well determined due to the lack of sensitivity of the data to the exact extent of the boundaries.

Two general trends in the albedo distribution on Europa are indicated by the results. First, there is a general darkening of the disk from north to south, starting from the large bright pole cap and possibly extending to the relatively dark south pole. One source of the large residuals with Vermilion's model is the bright southwestern quadrant of his model. The second trend of our model is that while both limbs are bright relative to the disk as a whole, the leading limb is uniformly brighter than the trailing limb.

The final question which must be addressed is the uniqueness of the solution. There are two interrelated parameters in this problem, first the extent of the various albedo regions and second the relative brightness which must be assigned to each region.

In the case of the bright leading and trailing limb, the solution is by no means unique. The size of each of these regions can be varied considerably if care is taken to adjust the brightness so that the fraction of the total light originating from the area is constant. This implies that these regions can be replaced by somewhat smaller, but brighter, zones without noticeably affecting the residuals.

In the case of the polar regions, NMSU-2 is extremely sensitive to the size of the polar cap, while the brightness of the polar region is determined by both NMSU-1 and 2 and the value of the brightness ratio for these two events. Since the assumed brightness ratios have an effect on the brightness of the polar cap, and since this quantity is variable due to the stronger opposition effect for Io, it should not be treated as a constant. The available data and the constraints of our model lead to a unique solution as far as the polar regions are concerned.

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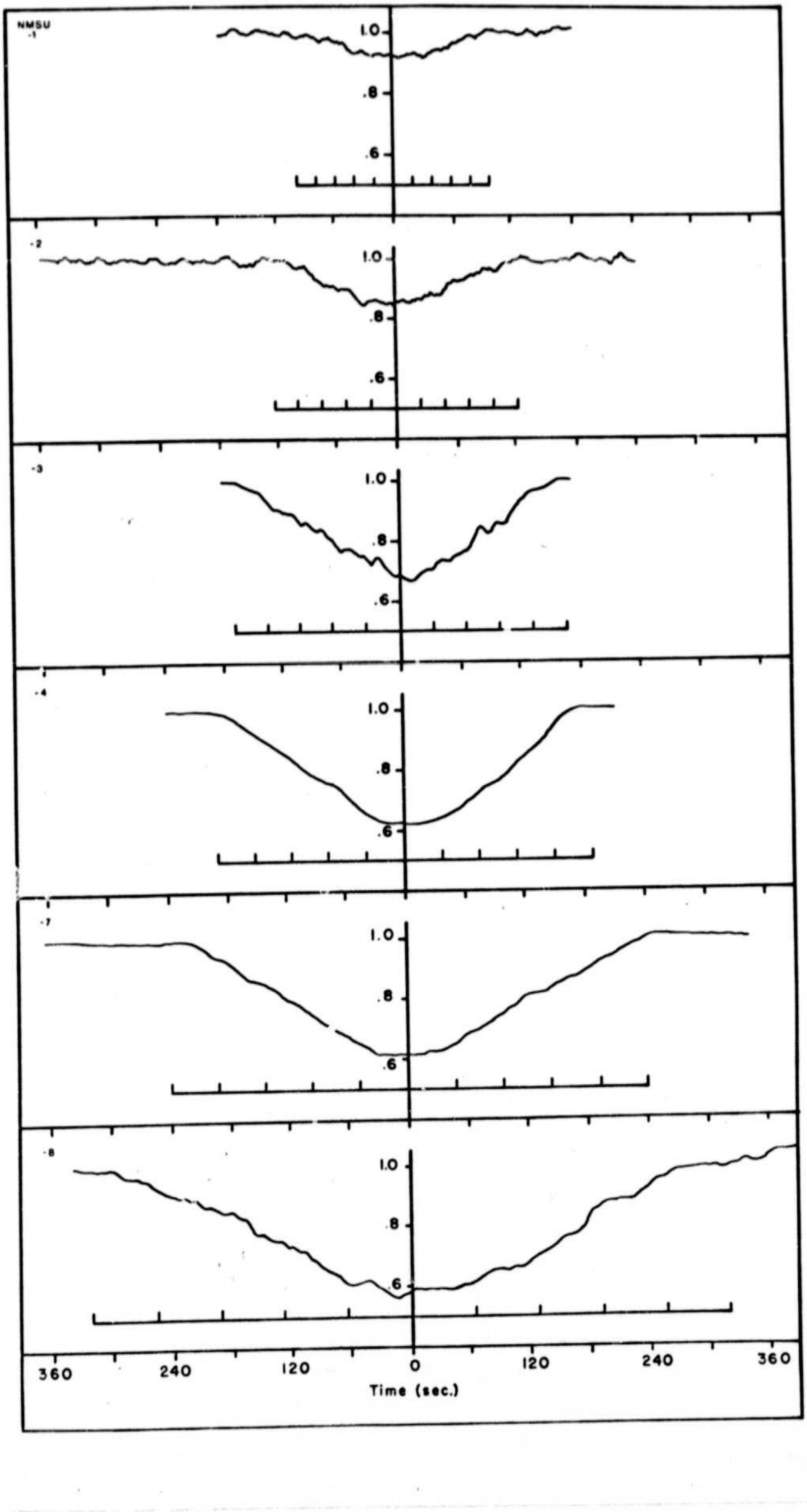
Figure Captions

Figure 1. Observed light curves minus sky brightness. All flux values are normalized to the combined flux of Io and Europa. Universal Time (±05 sec), tabulated relative to the midpoint of the event is as follows: NMSU-1, 10 June 1973, $9^h09^m57^s$; NMSU-2, 17 June 1973, $11^h15^m57^s$; NMSU-3, 12 July 1973, $6^h29^m17^s$, NMSU-4, 13 August 1973, $3^h48^m00^s$; NMSU-7, 27 August 1973, $8^h07^m49^s$; NMSU-8, 14 September 1973, $1^h56^m39^s$. The horizontal scale represents a phase scale with first contact at 0 and last contact at 1.

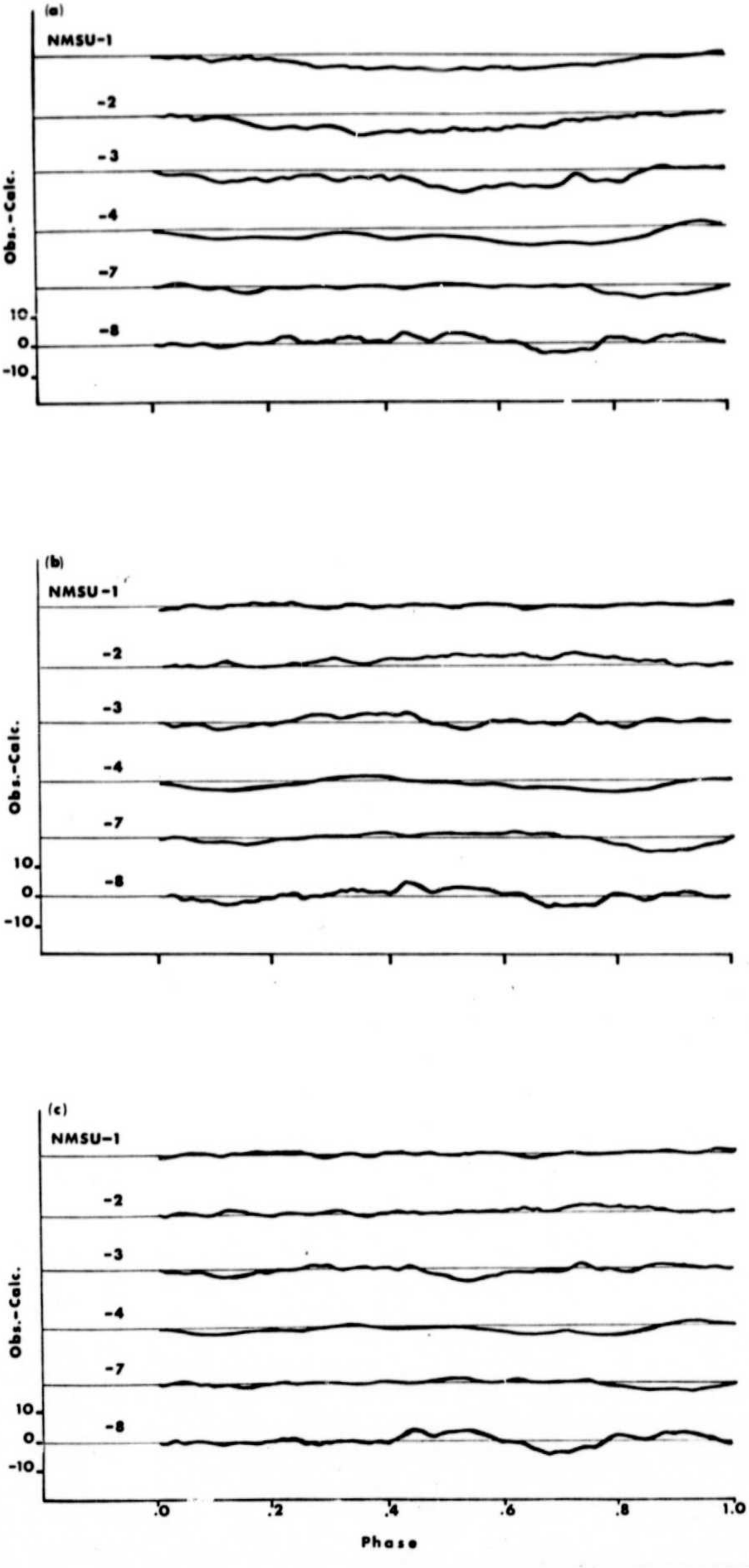
Figure 2. A comparison of computed models with observed values. The residuals displayed in the figure represent the observed minus calculated values of normalized fluxes. Figure 2a represents Europa as a uniform disk, 2b includes a bright polar cap and 2c is the result of a detailed albedo model described in the text. The vertical scale is constant for all events where the units for the residuals are percent of the normalized flux which in the range 0 to 10 are roughly comparable to units of .01 magnitude.

Figure 3. The 2c model albedo map of Europa centered on 325°W longitude. Implicit in this map is the assumption of synchronous rotation for the Galilean satellites. The numbers indicate the relative brightness of each region in terms of the average brightness for the entire disk. Astronomical north and east are indicated by "N" and "E", while "d" is the relative direction of motion of Europa relative to Io. "n" is the normal to the orbital plane.

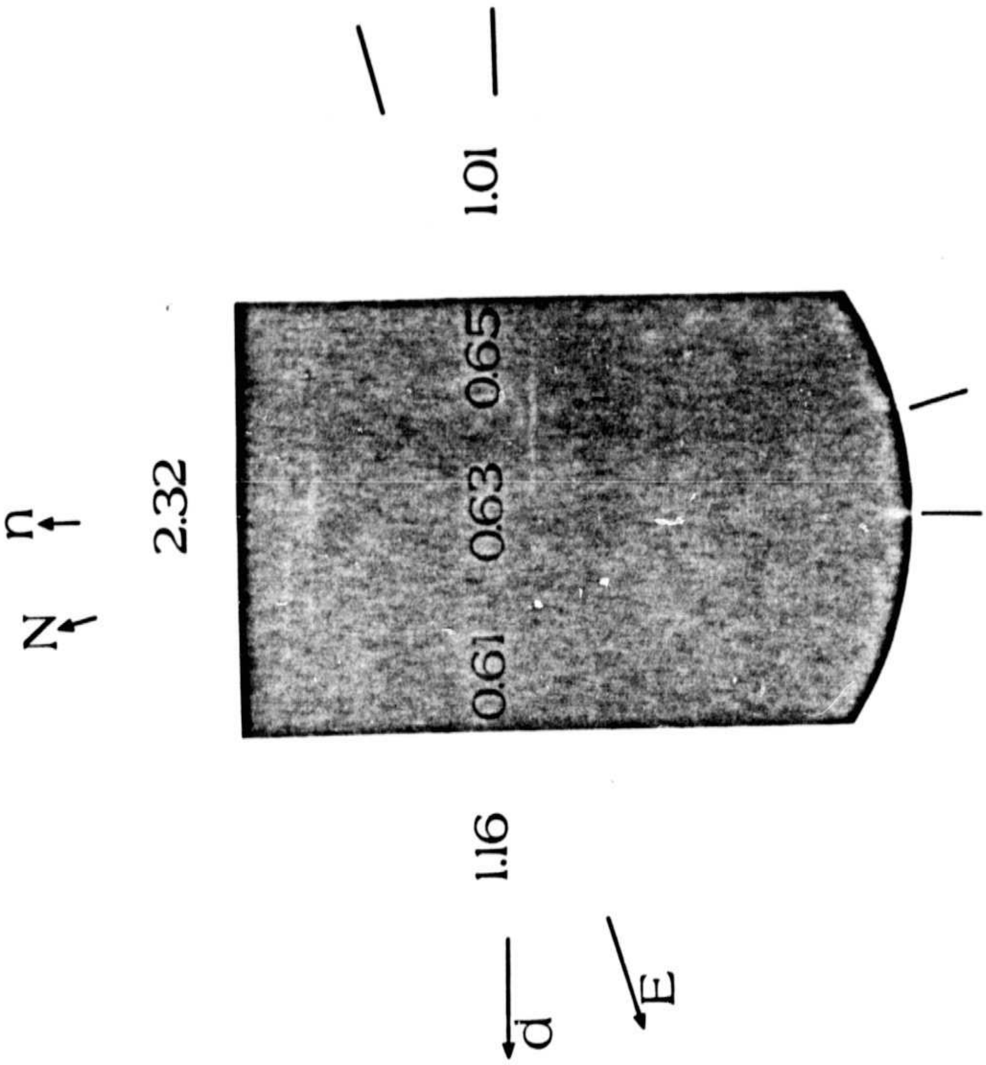
Figure 4. A comparison of the Vermilion et al model (1974) with the NMSU observations. Impact parameters and magnitudes for the event are as tabulated in Table II.



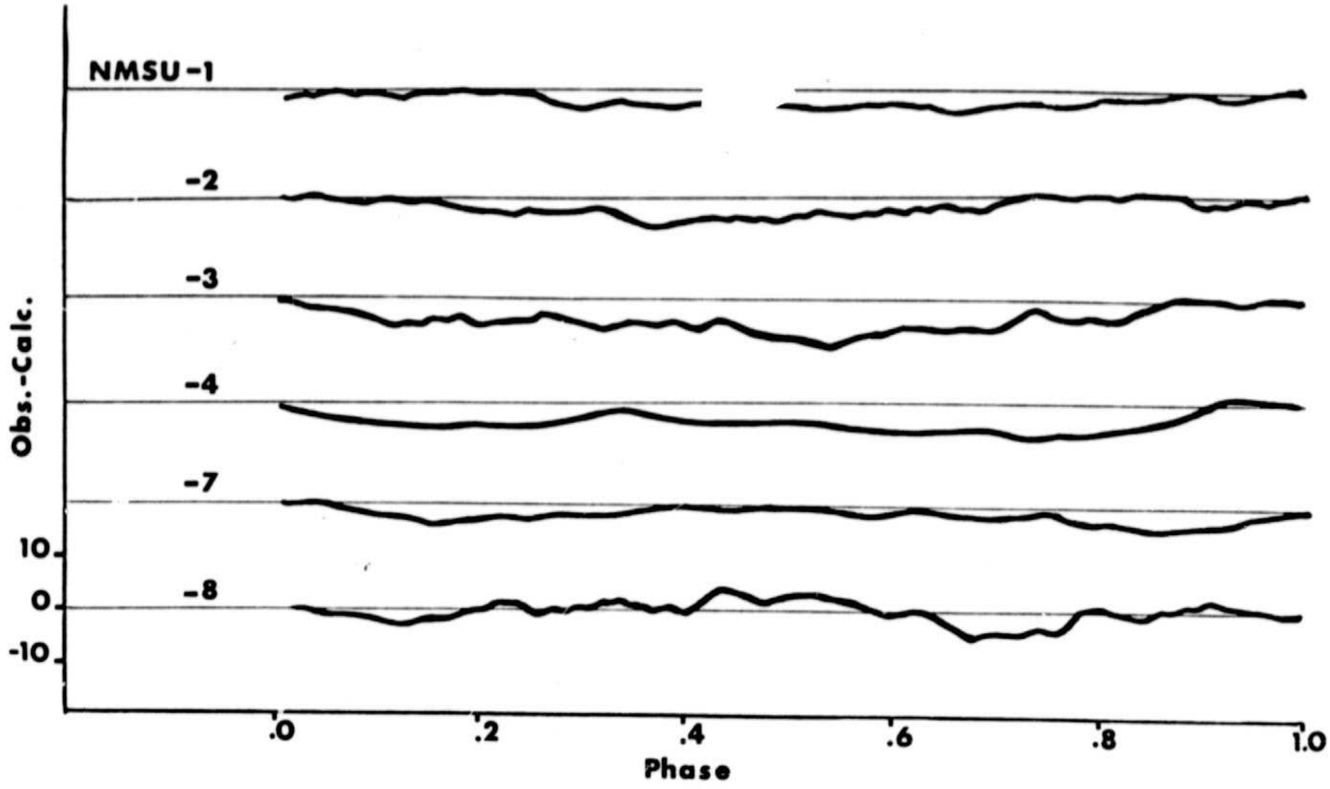
HERZOG AND BEEBE - Fig. 1



HERZOG AND BEEBE - Fig. 2



HERZOG AND BEEBE - Fig. 3



HERZOG AND BEEBE - Fig. 4