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A Modeling Analysis Program for the JPL Table Mountain Io Sodium Cloud Data

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16. Abstract

A detailed review of 110 of the 263 Region B/C images of the 1981 data set is undertaken and a preliminary assessment of 39 images of the 1976-79 data set is presented. The basic spatial characteristics of these images are discussed. Modeling analysis of these images after further data processing will provide useful information about Io and the planetary magnetosphere. Plans for data processing and modeling analysis are outlined. Results of very preliminary modeling activities are presented.

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I. Summary of Research Performed in the Second Quarter

Research activities in the second quarter have focused upon (1) a review of Region B/C images from the 1981 data, (2) a preliminary assessment of the 1976-79 image data, (3) formulation of areas for specific data processing and modeling analysis, and (4) initiation of modeling activities.

1. Review of 1981 Region B/C Images

A more thorough review of the 263 Region B/C images of the 1981 JPL data set was undertaken this quarter to expand information acquired in the preliminary assessment reported last quarter. This review was greatly facilitated by the September 19-22 visit to AER of Bruce Goldberg. The geometric phase angles and System III magnetic longitudes of Io covered during the 14 nights of observations in 1981 are shown in Figure 1. Although most of the 263 images in the 1981 data set have been processed only preliminarily to remove background signal, images on May 4, 5, 12 and 13 and on June 4 have undergone further processing to remove the instrumental response function and to normalize the image intensity. The images acquired on May 4, 5, 12 and 13 were chosen as the basis of the more thorough review undertaken in the second quarter and provide a representative sample (42% or 110 images) of the complete 1981 Region B/C image data set.

The spatial morphology of the Region B/C sodium cloud images of 1981 may for discussion purposes be divided into two main components: (1) the bright forward cloud that precedes Io and is located primarily inside of the satellite orbit, and (2) the dimmer directional feature that trails behind Io and is located primarily outside of the satellite orbit. Review comments will be mostly limited to discussing these two components of the cloud. Some background information will, however, first be given to set the larger context for the more detailed discussion.

As Io moves about Jupiter on its circular orbit which appears only as a thin ellipse from the Earth, the forward cloud swings through the line of sight once prior to eastern elongation (i.e., between 0° and 90° Io phase angle) and once prior to western elongation (i.e., between 180° and 270° Io phase angle). At these two critical phase angles, the spatial brightness distribution appears fairly symmetric east and west of Io. These two critical phase angles depend primarily upon the inward inclination of the forward cloud as measured from a line drawn through Io and tangent to the satellite's orbit. These two critical phase angles, as noted first by Goldberg et al. (1978, 1980) from the 1976-79 image data, do not occur at diametrically opposite phase angles and hence measure an east-west orbital asymmetry in the cloud morphology. This east-west orbital asymmetry was attributed by Smyth (1979, 1983) to the effects of solar radiation pressure on the sodium cloud. These two critical angles were recently evaluated by Goldberg, Garneau and LaVoie (1984) using information extracted from the 1976-79 data set and the May 4, 5, 12 and 13 images of the 1981 data set. Their results in Figure 2 indicate an eastern critical phase angle that ranges from about 60° to 80° and a western critical phase angle rather tightly confined at 235°. This implies that the eastern cloud is inclined inside of Io's orbit by an amount varying between 10° and 30° whereas the western cloud is inclined inside of Io's orbit by about 35°.

Directional features for the Io sodium cloud were first discovered by Pilcher [see Hartline (1980)]. These directional features have since been discussed and analyzed by Pilcher et al. (1984). Their analysis concentrated on regularly appearing directional features that trailed Io and were located primarily outside of the satellite orbit. They showed that changes in the north-south orientation of these directional features relative to the satellite plane were correlated with the System III magnetic longitude of Io. Their correlation, shown in Figure 3, indicates that the directional features generally appear inclined to the north for System III magnetic longitudes of Io between about 160° and 340° and to the south for the complementary angular region. Their analysis showed that features can result from a source of high velocity sodium (~20 km sec^{-1}) combined with the oscillating neutral sodium sink provided by the plasma torus. The phase relationship between the feature's directions and Io's magnetic longitude can be understood if escaping sodium is initially directed at near right angles to Io's orbital motion. The initial directions and speeds of sodium atoms escaping Io to form the directional features can be understood in terms of a magnetospheric-wind-driven escape mechanism.

The more detailed discussion of the spatial brightness morphology of the 1981 sodium cloud images will begin with the May 12 data. On that evening, 23 images were obtained, each with an effective integration time between 18 and 47 minutes. These 23 images were produced by adding three consecutive images initially recorded with an integration time of about 10 minutes. As can be seen from Figure 1, these 23 images cover an Io phase angle range from about 45° to 90°. For phase angles between 45° and 50°, the forward cloud, seen primarily to the left of Io, diminishes in length, and for phase angles between 50° and 60° swings through the line of sight. For larger phase angles, the forward cloud can be seen to the right of Io, and a well-developed north-inclined directional feature can be seen to the left of Io. A representative image at a 75° phase angle, indicated by the symbol A in Figure 1, is shown in Figure 4. The north-inclination of the directional feature is consistent with the correlation of Figure 3.

On the following night, May 13, there are 25 images in the data set, each with an effective integration time between 31 and 49 minutes. These images were produced by adding three consecutive images initially recorded with an integration time of about 10 minutes. These 25 images span an Io phase angle range from about 255° to nearly 300°. Since the forward cloud swings through the line of sight at about 235° (see Figure 2), the forward cloud is always distinct and to the left of Io for this phase angle coverage. A south directional feature is also well developed and appears to the right of Io at the beginning of this observational sequence, as denoted by the symbol B in Figure 1 and is illustrated in Figure 4. The inclination of the south directional feature decreases to near zero degrees as Io approaches a System III magnetic longitude of about 160°-170° and then has a northern inclination for larger angles of System III magnetic longtitude of Io. This orientation of the directional feature is consistent with the correlation in Figure 3. One such image at a System III magnetic longitude of Io of 168°, denoted by the symbol C in Figure 1, is shown in Figure 4.

The data of May 5 consist of 31 images, each with an effective integration time between 25 and 36 minutes, which were produced by adding three consecutive images initially recorded with about a 10 minute integration time. The May 5 data, taken a week before the May 12 data, cover a similar set of Io phase angles and System III magnetic longitude angles as can be seen in Figure 1. For phase angles between 60° and 70°, the images appear to be somewhat symmetric about Io as the forward cloud swings through the line of sight and establishes itself to the right of Io. A north-inclined directional feature is also evident for larger Io phase angles and is similar to the directional feature shown earlier for the May 12 data. The directional feature in the May 5 data becomes less inclined to the north as expected (see Figure 3) by the end of this observational sequence.

For the May 4 data, there are 31 images, each with an effective integration time between 30 and 40 minutes. These images were produced by adding three consecutive images initially recorded with about 10 minute integration times. These images cover an Io phase angle range from about 215° to 270°. As projected on the sky plane, the forward cloud appears to the right of Io for phase angles less than about 230° and to the left of Io for phase angles greater than about 240° as expected from Figure 2. For Io at phase angles larger than 240°, the projection of the trailing cloud on the sky plane can begin to be unambiguously identified to the right of Io and appears as a directional feature inclined slightly southward. This south inclination is not consistent with the general correlation of Figure 3. Spatial distortions introduced in the cloud near Io that have yet to be properly removed by improved subtraction of the continuum scattered light of Io could, however, change the north-south orientation of the directional feature in the corrected image. If the corrected orientation of the directional feature is not to the north, the data on May 4 may provide a counter case to the general correlation of Figure 3 similar to the March 10 data of Pilcher et al. (1984) also recorded in 1981 (see Figure 3).

2. Preliminary Assessment of the 1976-79 Region B/C Images

Of the 46 two-dimensional images recorded in the 1976-79 data set, there were 39 usable Region B/C images. Each image was recorded with an integration time of about 2 to 3 hours and hence provides a time-averaged picture of the sodium cloud over an Io phase angle interval of about 17° to 25° and a System III magnetic longitude of Io angle interval of about 56° to 83°. The UT dates and time intervals for these 39 observations are given in Table 1. Also in Table 1 are the values of the geometric phase angle and System III magnetic longitude of Io for the start and end time of each image. This angular information is also presented in graphical form in Figure 5.

In Figure 5, the angular coverage in system III magnetic longitude of Io is excellent, especially near eastern elongation. The angular coverage in Io geocentric phase angle is only deficient near 0° and 180° where observational conditions are poor because of the high background light levels reflected by

Jupiter's disk. As can be seen in Figure 5, there is one pair of images where the coverage in both angles is essentially identical and there are many pairs of images that have nearly the same angular range. Intercomparison of these images and additional comparison with images in the 1981 data set will help to establish the stability or variability of the sodium cloud over time scales of days, weeks, months and even one to four years. Two of the images were obtained on the encounter day (5 March 1979) of the Voyager 1 spacecraft with Jupiter, and several additional images were obtained within a week of this encounter date.

Seven of the 1976-79 images were presented earlier in a paper by Goldberg et al. (1980). In this paper, a comparison was made between the first image recorded on March 5, 1979 and the second image recorded on December 5, 1977 (see Table 1). Both of these images have an Io phase angle at their recorded midpoints of 256°. In this comparison, the forward clouds were similar in length and brightness, but the trailing clouds were distinctly different and were not understood in the modeling analysis presented in the paper. The first image recorded on March 5 has a more developed trailing cloud which is distributed south of the orbit plane, while the second image on December 5 contained less sodium and has a trailing cloud that is distributed symmetrically about the orbit plane. From Figure 5, the explanation is now obvious, since it can be seen that the March 5 cloud is centered at a System III magnetic longitude of Io of 34.8° (i.e., in the south directional feature domain of Figure 3), while the December 5 cloud is centered at a System III magnetic longitude of Io of 142°(i.e., near the transition angle that separates the north and south directional features in Figure 3). This realization indicates that although the integration times of the 1976-79 images were long compared to the 1981 images, the earlier time-averaged images still have significant diagnostic value in understanding the structure and time variability or stability of the sodium cloud.

3. Data Processing and Modeling Analysis

As a result of our more thorough review of the 1981 Region B/C images and the preliminary assessment of the 1976-79 images this quarter, data processing and modeling analysis priorities have been more specifically formulated. The three major data processing priorities are summarized in Table 2. The first two priorities will be initiated in the third quarter. The first priority is important in modeling studies of the spatial brightness morphology of the cloud such as the east-west orbital asymmetry, the directional features and other structural features that appear in some images. The second priority is important in determining the absolute flux of sodium escaping Io, in studying the east-west intensity asymmetry of the cloud, and in understanding the temporal variability/stability of the cloud over the 1976-1981 time interval.

The six main modeling analysis priorities are summarized in Table 3. The first listed priority was accomplished in the past quarter and is discussed in the following section. The remaining five priorities represent different studies of the data that will provide useful insights into the nature of Io's local atmosphere, the manner in which material escapes Io and provides a plasma source for the planetary magnetosphere, and the properties of the Io plasma torus. These studies will use the images prepared in the third data processing priority listed in Table 2.

4. Preliminary Modeling Studies

A modified D_2 brightness image was incorporated this quarter in the model output to properly include north-south distortions produced in the image data by the doppler motion of the sodium atoms along the Earth-Jupiter line of sight. These distortions occur because the spectral dispersion direction is along the north-south image direction on the two-dimensional image recording plane. These vertical distortions are small relative to Io's location if the differences in the line of sight velocities of the cloud atoms and Io are small (i.e., a few km/sec) but may be significant if these velocity differences are large ($\gtrsim$20 km/sec). These distortions may in fact be helpful in understanding the velocity dispersion in the cloud.

Preliminary model calculations were performed this quarter and compared with 1981 Region B/C images. Although the detail comparison must be postponed until further data processing is applied to these images, the initial comparison suggests a sodium source rate for the forward cloud (Region B) of between 1-2 x 10^{26} atoms sec^{-1} and a sodium source rate of approximately one half this value for the directional features outside of Io's orbit. These values are similar to the sodium source rates determined by Pilcher et al. (1984).

II. Program for the Third Quarter

Data processing priorities 1 and 2 of Table 2 will be initiated in the third quarter at the MIPL facility at JPL and will be supervised by Bruce A. Goldberg. The lifetime information for sodium in the Io plasma torus will also be improved in the AER sodium cloud model using new electron density and temperature information obtained recently from reanalysis of the Voyager 1 UVS data by Shemansky (1984) and the Voyager 1 PLS data by Sittler (1984) and Bagenal (1984). Modeling studies outlined in Table 3 will be initiated as new processed images become available in the third quarter.

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Table 1
1976-79 Io Sodium Cloud Image Data of Goldberg

	Date (UT)	UT Start	Io Phase	Io Sys III Mag. Longitude	UT End	Io Phase	Io Sys III Mag. Longitude
1976	29 November	9:37	35.3	336.2	11:52	54.4	38.7
	3 December	2:58	73.5	299.3	6:28	103.4	36.4
	16 December	5:42	224.1	45.9	8:42	249.4	129.4
	18 December	6:58	281.6	335.5	9:58	306.8	59.1
1977	18 February	3:07	263.5	182.3	5:17	281.7	242.6
	19 February	2:25	101.4	109.3	5:25	127.0	192.5
	26 February	2:30	85.6	100.5	5:10	108.3	174.5
	22 March	2:50	287.3	278.3	4:50	304.2	333.9
	4 December	8:10	35.0	142.6	11:10	60.3	226.1
	5 December	5:23	215.7	11.6	8:23	241.2	94.9
	5 December	8:35	242.9	100.4	11:35	268.4	183.8
	6 December	7:50	79.3	27.6	10:50	104.8	110.9
	11 December	9:23	30.6	165.9	12:23	56.0	249.4
	13 December	5:32	45.1	313.1	8:32	70.5	36.5
1978	22 January	4:40	262.9	329.5	7:10	284.0	39.2
	22 January	7:20	285.4	43.8	8:50	298.0	85.6
	23 January	2:25	86.7	214.7	4:55	108.1	284.0
	17 February	2:45	138.2	338.4	4:45	155.3	33.9
	19 February	4:50	203.1	290.0	6:20	215.8	331.7
	19 February	6:25	216.5	334.1	7:55	229.2	15.8
	22 February	2:00	68.7	53.0	3:30	81.5	94.6
	22 February	4:09	87.1	112.7	6:09	104.1	168.1
	22 February	6:15	105.0	170.9	8:15	122.1	226.3
	24 February	2:03	116.4	308.0	4:03	133.5	3.5
	24 February	4:13	134.9	8.1	6:13	152.0	63.6
	15 December	9:30	203.2	67.8	12:30	228.8	150.9
	16 December	7:56	33.5	331.3	10:26	54.5	41.0
	16 December	10:34	55.6	44.7	13:04	76.7	114.3
1979	26 February	3:00	251.5	341.3	5:30	272.7	50.8
	26 February	6:10	278.4	69.3	8:40	299.5	138.9
	26 February	8:50	300.9	143.6	11:20	321.9	213.2
	4 March	5:30	53.2	93.7	8:30	78.6	177.1
	5 March	4:04	245.5	360.0	6:34	266.6	69.5
	5 March	6:40	267.5	72.3	9:20	290.0	146.5
	6 March	3:03	79.5	279.6	4:13	89.4	312.0
	6 March	4:15	89.7	313.0	6:30	108.8	15.4
	7 March	4:34	296.6	268.0	7:04	317.7	337.7
	12 March	4:33	234.3	2.4	7:03	255.5	71.9
	12 March	9:00	271.9	126.1	11:30	293.0	195.7

Table 2

Data Processing Priorities

1. Improve Techniques to Remove Distortion in the Brightness Distribution of Images

    a. Implement improved background subtraction techniques for images.

    b. Improve techniques for removal of image distortion near Io produced by continuum light scattered by Io.

2. Determine the Absolute Brightness Calibration for the Images

    a. Analyze 1981 1-D slit data on Io's disk and Region A image data to establish an absolute brightness calibration for the 1981 data.

    b. Analyze 1976-79 1-D slit data on Io's disk to establish a brightness calibration for the 1976-79 data.

3. Prepare Images for Modeling Analysis

    a. Using improved techniques in 1 above, remove brightness morphology distortions in a selected subset of images.

    b. Using the information in 2 above, absolutely calibrate this selected subset of images.

Table 3

Modeling Analysis Priorities

1. Include the north-south spatial distortions in the model calculated D_2 images introduced by the instrument because of the doppler motion of the sodium atoms along the line of sight.

2. Study the spatial characteristics of the sodium directional features in the 1981 data.

3. Study the east-west differences in the cloud morphology and relate them to solar radiation pressure, sodium source characteristics, and sodium sink characteristics.

4. Study east-west intensity differences in the 1981 cloud data and relate them to solar radiation pressure, sodium source characteristics, and sodium sink characteristics.

5. Study the temporal variability/stability of the cloud images having similar Io phase and/or System III magnetic longitudes of Io.

6. Study "other structural features" identified in the images.

Figure Captions

Figure 1. Observing Parameters for 1981 Io Sodium Cloud Images. The angular coverage for the Io geocentric phase angle and the System III magnetic longitude of Io over which Region B/C images were recorded in the JPL Table Mountain Data Set is indicated for all 14 nights of observations. Three particular images denoted by A, B and C are discussed in the text and shown in Figure 4.

Figure 2. Ratios of Sodium Brightness East and West of Io as a Function both of Time and Io's Orbital Phase Measured from Superior Geocentric Conjunction. These ratios were derived from the brightness averaged in two rectangular 3 x 8 arcsecond areas located 9 arcseconds on either side of Io and centered on the orbital plane. Triangles represent data obtained with multislits, while all other data points were derived from two-dimensional images. Horizontal bars indicate the extent of orbital integration during the multi-hour exposures required before 1980. A common optical system was used for all observations represented here.

Figure 3. Classification of Directional Features of Pilcher et al. (1984) as a Function of Io's Magnetic Longitude at the Time of the Observations. Observed northward features are plotted at the top, southward features at the bottom, and null observations (no feature) in the center. Observations at overlapping longitudes have been displaced vertically for clarity. Observations from 1980 are plotted above those from 1981. Solid lines connect data points corresponding to a continuous series of observations on a single night. A dashed line connects the points corresponding to two observations obtained ~3 hours apart on March 11 UT, 1981. The dotted line partially used for the data of April 13 UT, 1981, is meant only to call attention to the fact that during these observations Io passed through 0° magnetic longitude, and the plotted points therefore appear separated in the figure, as do the points for March 11 UT, 1981.

Figure 4. 1981 Region B/C Images of the Io Sodium Cloud. The three images identified by A, B, C are part of the larger data set of images obtained from the Table Mountain Observatory. The observing parameters of these three images are indicated in Figure 1.

Figure 5. Observing Parameters for the 1976-79 Io Sodium Cloud Images. The angular coverage for the Io geocentric phase angle and the System III magnetic longitude of Io over which each Region B/C image was recorded in the JPL Table Mountain Data Set is indicated.

1981 IO SODIUM CLOUD DATA FROM TABLE MOUNTAIN OBSERVATORY

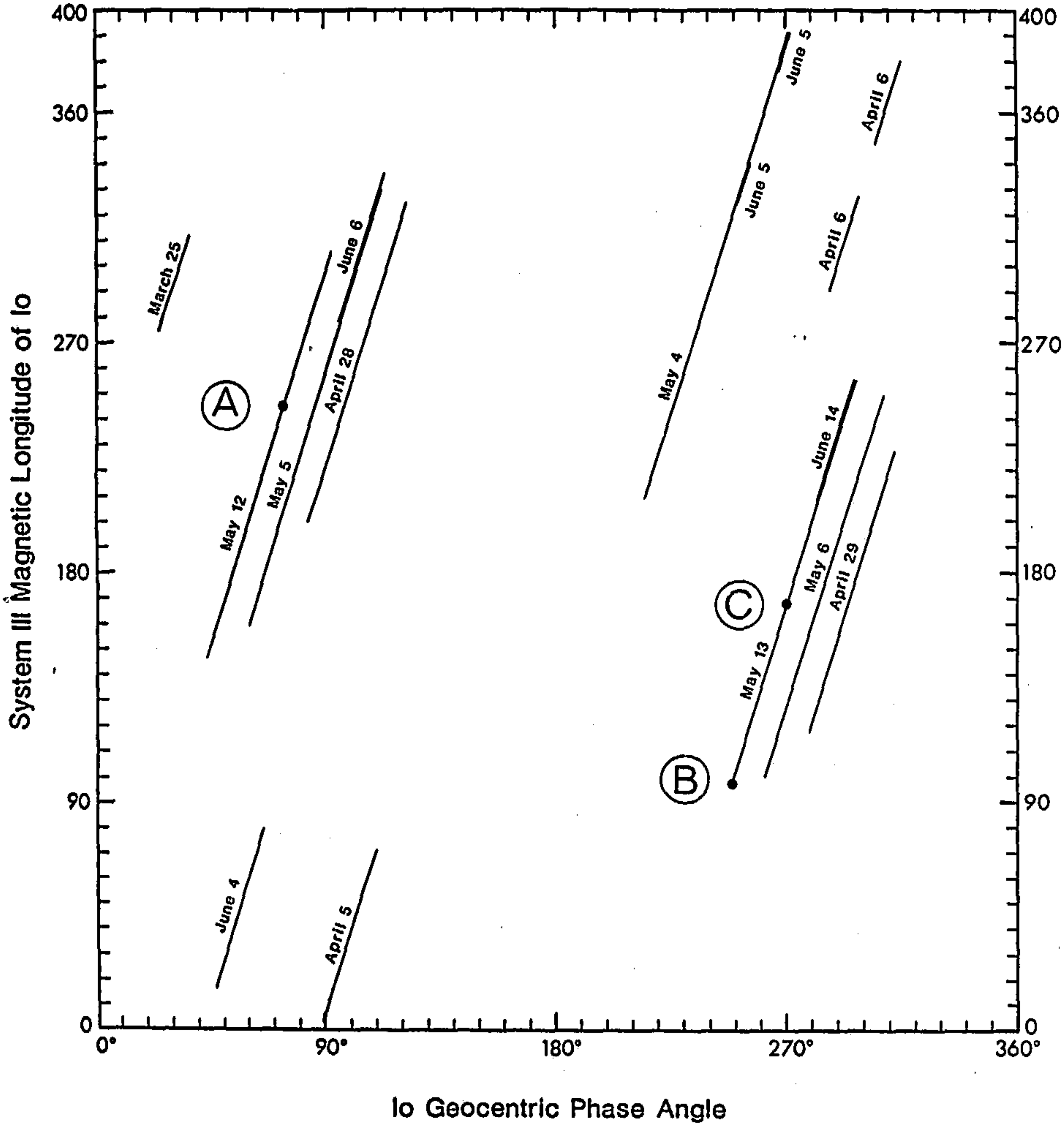


Figure 1

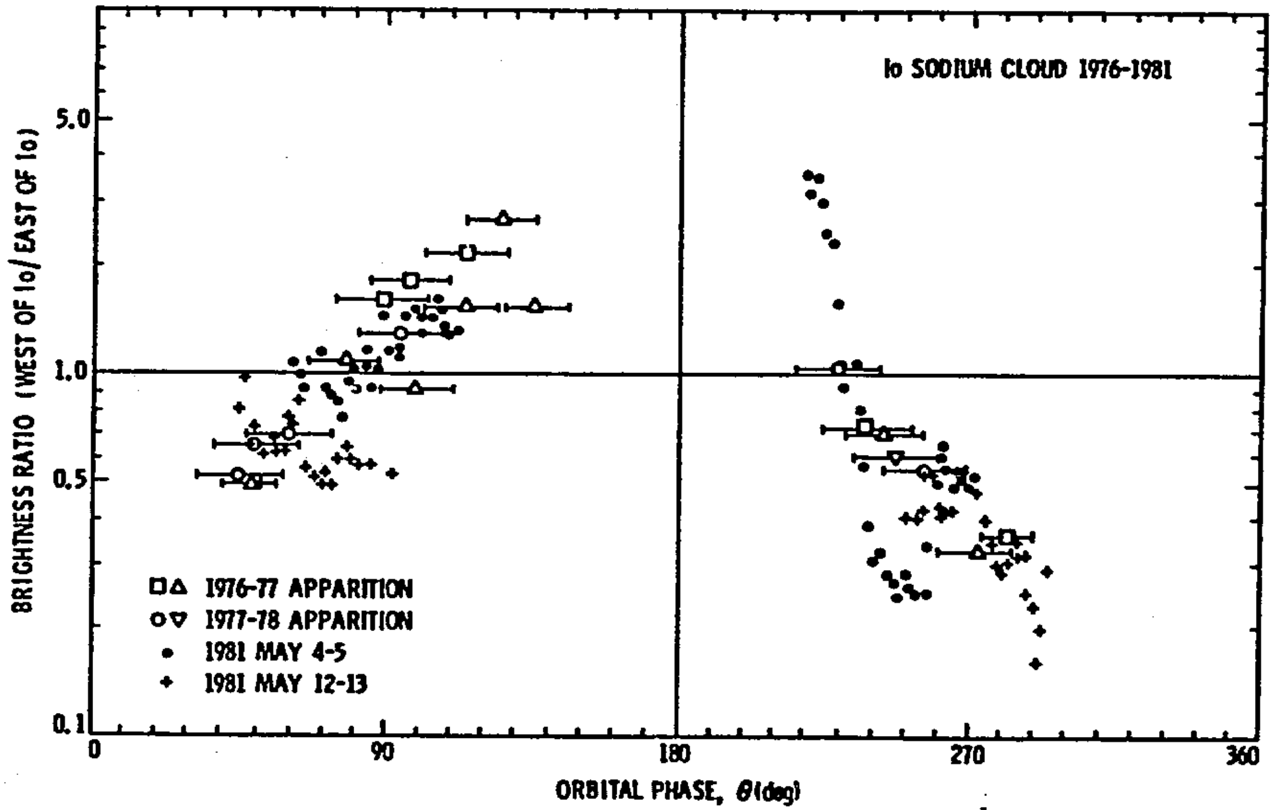
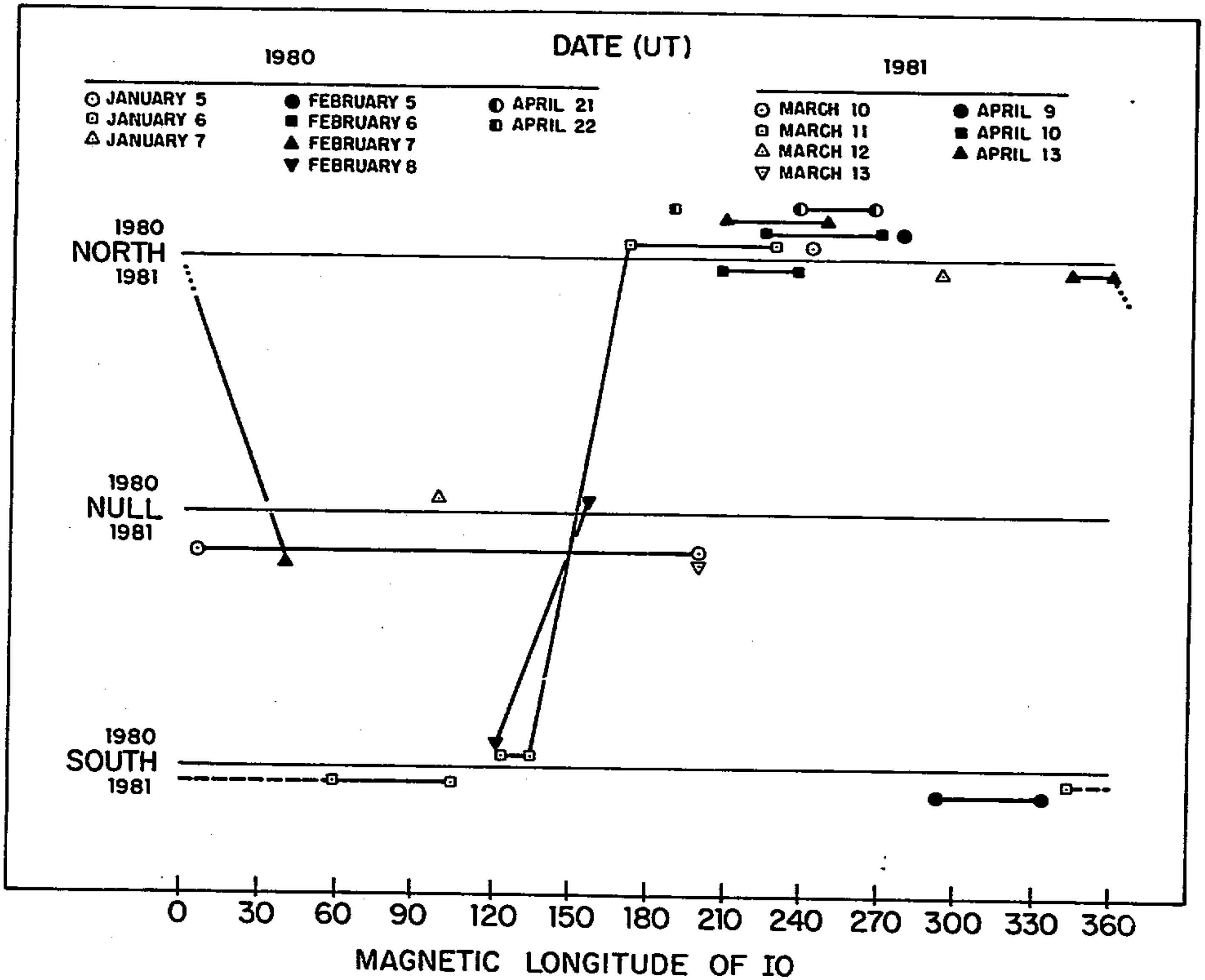

Io SODIUM CLOUD 1976-1981
BRIGHTNESS RATIO (WEST OF Io/ EAST OF Io)
5.0
1.0
0.5
0.1
0
90
180
270
360
ORBITAL PHASE, θ(deg)
1976-77 APPARITION
1977-78 APPARITION
1981 MAY 4-5
1981 MAY 12-13

Figure 2



DATE (UT)
1980
JANUARY 5
JANUARY 6
JANUARY 7
FEBRUARY 5
FEBRUARY 6
FEBRUARY 7
FEBRUARY 8
APRIL 21
APRIL 22
1981
MARCH 10
MARCH 11
MARCH 12
MARCH 13
APRIL 9
APRIL 10
APRIL 13
1980
NORTH
1981
1980
NULL
1981
1980
SOUTH
1981
0
30
60
90
120
150
180
210
240
270
300
330
360
MAGNETIC LONGITUDE OF IO

Figure 3

IO SODIUM CLOUD 1981

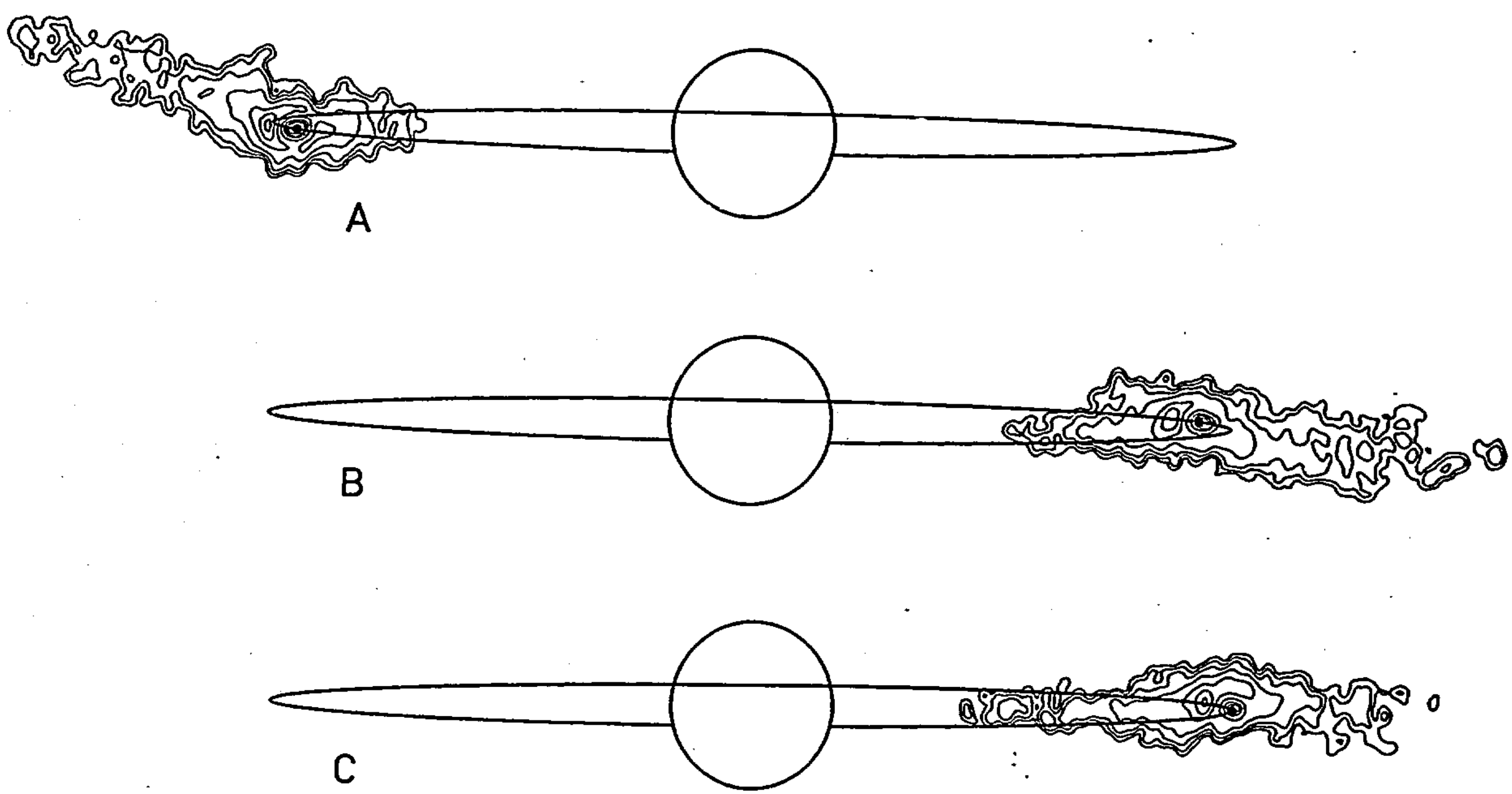


Figure 4

1976-1979 IO SODIUM CLOUD DATA FROM TABLE MOUNTAIN OBSERVATORY

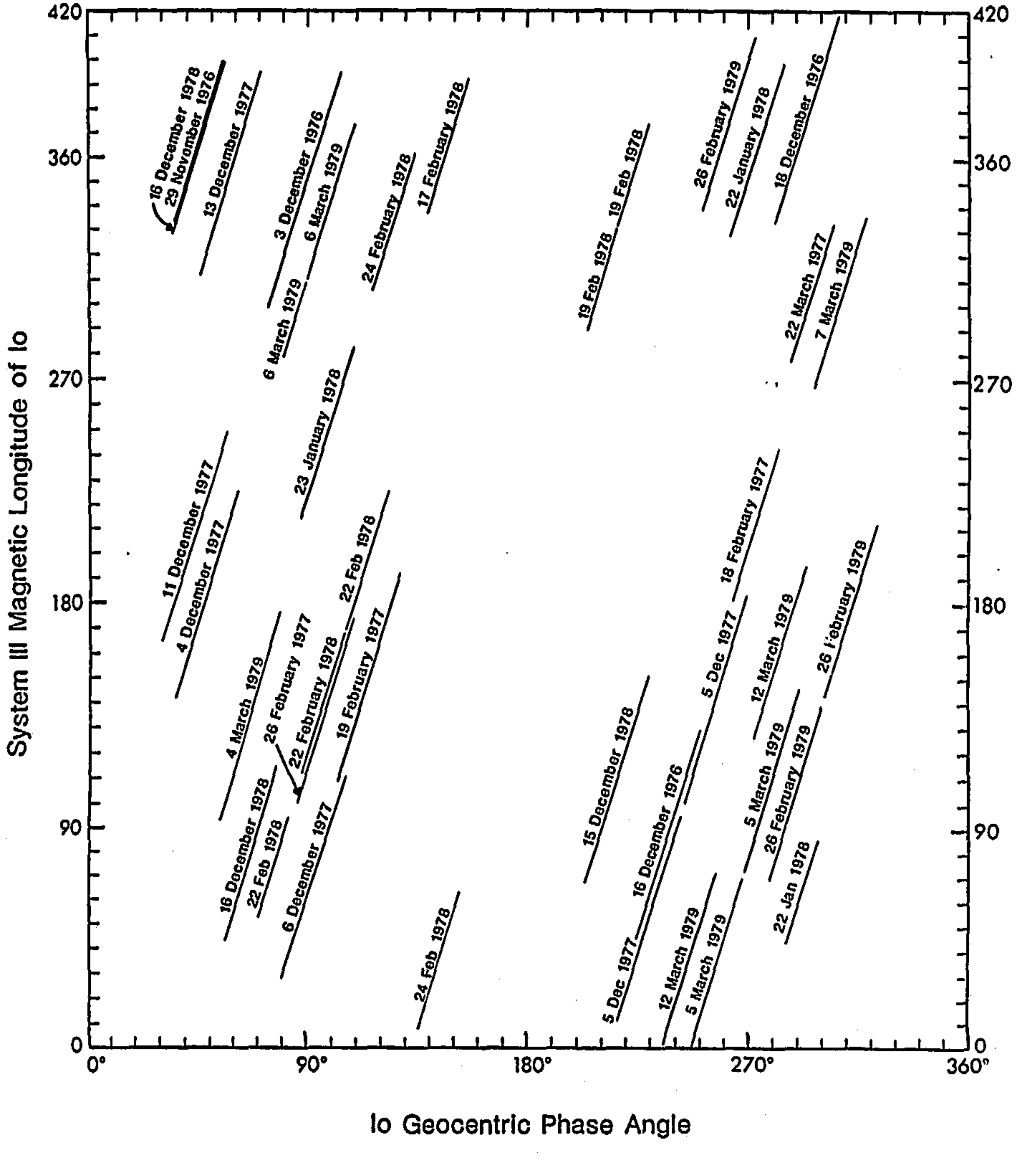


Figure 5