MEASUREMENT ON THE LUNAR SURFACE OF IMPACT-PRODUCED PLASMA CLOUDS

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MEASUREMENT ON THE LUNAR SURFACE OF IMPACT-PRODUCED PLASMA CLOUDS

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September, 1971

ABSTRACT

Simultaneous enhancements of low-energy ions and negative particle fluxes due to the impact of the Apollo 14 Lunar Module were observed by the lunar-based Charged Particle Lunar Environment Experiment (CPLEE). The impact occurred 66 kilometers distant from CPLEE, and the time delay between impact and flux onset was approximate 1 minute. It is argued that the observed charged particles could not have been energized at the instant of impact, but rather that the impact produced expanding gas clouds, and that constituents of these clouds were ionized and accelerated by some continuously active acceleration mechanism. It is further shown that the acceleration mechanism could not have been a static electric field, but rather is possibly a consequence of interaction between the solar wind and the gas cloud.

The Apollo 14 Lunar Module Antares ascent stage impacted on the lunar surface on February 7, 1971 at 00 hours, 45 minutes, 24 seconds GMT. Shortly after the impact, a lunar-based charged particle detector based 66 km distant detected fluxes of low-energy positive ions and negative particles with intensities a factor of 10 greater than the ambient fluxes. The ion and electron enhancements exhibited near-perfect temporal simultaneity, and we report here preliminary studies of these impact-produced plasma clouds.

The measurements were made with the Charged Particle Lunar Environment Experiment (CPLEE) deployed as part of the Apollo 14 ALSEP instrument array at Fra Mauro. The CPLEE instrument is conceptually similar to the device code-named SPECS, described in detail by O'Brien, et al. (1967). Two identical particle analyzers are housed in the unit. One, labeled Analyzer A, is pointed toward the local vertical and the other, labeled Analyzer B, is pointed 60° from vertical toward lunar West.

We refer the reader to O'Brien, et al. (1967) for a detailed description of the particle analyzers and report here a few salient features of the instrument relevant to this report. Charged particles are deflected by a set of electrostatic deflection plates according to energy and charge sign into the apertures of an array of 6 channel electron multipliers, and at a given deflection plate voltage an analyzer makes measurements of fluxes of particles of one charge sign (e.g. electrons) in five energy ranges and particles of the opposite charge sign (e.g. ions) in a single energy range. Normally the instrument steps through a series of 6 deflection voltages plus two background steps every 19.2 seconds. However, the automatic sequence can be halted by ground command and the deflection voltage stepped to any one of the eight levels, with a consequent reduction of the sampling interval to 2.4 seconds. The decision was reached prior to the impact to operate the instrument in the manual mode at a deflection voltage where the instrument was sensitive to negative particles in five energy ranges centered at 40 ev, 50 ev, 65 ev, 95 ev, and 200 ev respectively, and sensitive to positive ions in a single energy range centered at 70 ev. As shall be seen, this decision proved extremely fortuitous.

The Antares impact occurred at lunar coordinates 3.42° South latitude and 19.67° West longitude, a point 66 km West of CPLEE, at 00 hours, 45 minutes, 24 seconds GMT on February 7, 1971. The terminal mass and velocity were 2303 kilograms and 1.68 km/sec. respectively, resulting in an impact energy of 3.25×10^{11} joules (Latham, private communication). The LM contained approximately 180 kg of volatile propellants, primarily dimethyl hydrazine fuel ($CH_3NHNHCH_3$) and nitrogen tetroxide oxidizer (N_2O_4).

In Figure 1 are shown the counting rates of channel 6 of Analyzer A, measuring positive ions with energies of 50 ev to 150 ev per unit charge and channel 3 of the same analyzer, measuring negative particles with energies of 61 to 68 ev for the period 00/44/53 GMT to 00.48/55 GMT on February 7, 1971.

As can be seen from Figure 1, the counting rates prior to and during Antares impact were reasonable constant, and in fact examination of subsequent data have shown that these fluxes represent an ambient population of photoelectrons which are present whenever the lunar surface in the vicinity of CPLEE is illuminated. (We note as proof of this assertion that these ambient fluxes disappeared entirely during the total lunar eclipse occurring a few days later on February 10, 1971). However, beginning at T + 48 seconds a series of pronounced increases in both the ion and negative particle fluxes was observed, with the data dominated by two major enhancements centered at T + 58 seconds and T + 74 seconds, respectively. As the enhancements were observed simultaneously in particles of both charge types, we refer to these events as plasma clouds.

Figure 2 shows the same data for Analyzer B oriented 60° from vertical toward lunar West (i.e. toward the impact point). From comparison of Figures 1 and 2 one can note that the flux enhancements were essentially simultaneous in the two directions, but the ion flux measured by Analyzer A was 5 times higher than the flux measured in Analyzer B. The geometric factors of the corresponding sensors in Analyzers A and B are essentially identical, and hence the relative flux magnitudes can be directly compared by comparing the relative counting rate enhancements above the background level. On the other hand, the negative particle flux measured by Analyzer A was only 1/3 as great as the negative particle flux measured by Analyzer B.

The detailed characteristics of the two dominant plasma clouds are shown in Figure 3, a plot on an expanded time scale of the negative particle fluxes in five energy ranges and ion flux in a single energy range measured by Analyzer A. The plot shows clearly that the negative particle enhancement was confined to energies less than 100 ev, as the 200 ev flux remained essentially constant throughout the event. The figure also shows that to the enhancements of all the particles measured were simultaneous to within the temporal resolution of the instrument (2.4 seconds).

The negative particle spectrum is seen (Figure 3) to vary throughout the event both in the magnitude of the fluxes and the shape of the spectrum. Figure 4 shows a comparison of the pre-impact negative particle spectrum and the spectrum during the enhancements. The first spectrum was measured at 00/42/38, or during the period of stable, ambient fluxes some 3 minutes prior to impact. The second spectrum was measured at 00/46/21, or during the first enhancement. The differing spectral shapes are clearly seen in this figure.

It might well be questioned whether the flux enhancements at T + 58 and T + 74 seconds were actually initiated by the Antares impact. Indeed, in the time period of approximately 2 days following the impact event, when CPLEE was in the magnetosheath, several rapid enhancements in the low-energy electron fluxes by up to a factor of 50 were observed. However, these other enhancements were not correlated with positive ion flux increases, and in fact the event referred to here is the only such example of such perfectly correlated low energy ion and negative particle enhancements seen to date. In addition, careful monitoring prior to the impact revealed that the fluxes were relatively stable, constant to within a factor of 2 over time periods of a few minutes. This lends credence to the belief that we have here a valid case of cause and effect.

Further confidence in our interpretation that the flux enhancements were artificially impact-produced rather than of natural origin is gained by noting that although no such plasma clouds have previously been detected resulting from impact events, Freeman et. al. (1971) have reported detection of positive ion clouds with the Apollo 12 Suprathermal Ion Detection Experiment (SIDE) which they concluded resulted from the Apollo 13 and 14 Saturn IV-B stage impacts. Furthermore, the positive ion component of the plasma clouds reported here were also detected by the SIDE. (Freeman, private communication).

It is concluded therefore that the impact of the Apollo 14 Lunar Module ascent stage was responsible for the positive and negative particle fluxes observed by CPLEE, and these fluxes are referred to as plasma clouds. The salient features of the event are the time delay between the impact and the flux enhancements ($\sim$ 60 seconds) and the simultaneous appearance of positive and negative particles.

There are two possible interpretations of these data in a gross sense, in that it can be assumed that the particles were created and energized at the instant of impact, or that the impact created an expanding neutral gas cloud, and the components of the neutral cloud were ionized and accelerated by mechanisms which were more or less continuously active and independent of the impact itself.

It is assumed that the particles were energized at the instant and point of impact by some unknown mechanism, it is necessary to explain the subsequent behavior of the plasma clouds.

According to this hypothesis, the plasma clouds had an average travel velocity of $\sim$ 1 km/sec and horizontal dimensions of 14 and 7 km respectively for the first and second clouds. Noting that the positive and negative particles appeared simultaneously, a mechanism must be found to explain both the cloud containment and the relatively slow propogation velocity. It can be postulated that the positive ion directed velocity was on the order of the inferred plasma cloud propogation velocity ($\sim$ 1 km/sec), and then one can appeal to ambipolar diffusion to contain the negative particle component, if it is assumed that the negative particles observed were electrons. In Table 1 are listed several calculated parameters of 50 ev charged particles of various masses, and it is seen from this Table that in order to fit the foregoing hypothesis the ion mass would have to be on the order of 1000 AMU. Since the gas released at impact probably consists mainly of vaporized LM propellants and lunar surface materials, we would estimate ion masses in the range 25-100 AMU, but it is difficult to see how mass 1000 ions could have been created. Indeed, this assumption is borne out by the observation of the Apollo 13 Saturn IV-B impact ion cloud by Freeman et. al., (1971) with the Apollo 12 SIDE instrument. The mass analyzer portion of the instrument showed peak ion fluxes in the range 66-90 AMU/unit charge.

Rejecting the hypothesis that the particles travelled in straight line paths between the impact point and CPLEE, there still exists the possibility that the particles could have been energized at the instant of impact and the trajectories influenced by a local magnetic field or that the plasma cloud could be magnetically confined. The measurements of the lunar surface magnetic field by the Apollo 12 Lunar Surface

Magnetometer (Dyal, et. al., 1970) showed a steady field of 36 ± 5 gammas, while the Apollo 14 Lunar Portable Magnetometer indicated fields in the vicinity of CPLEE ranging up to a factor of 3 higher (Dyal, et. al., 1971). By contrast, magnetic field measurements by the lunar-orbiting Explorer 35 spacecraft showed values of 10-12 gammas 800 kilometers above the lunar surface (Ness, et. al., 1967). From these data we might postulate that the plasma clouds were magnetically confined in the enhanced magnetic field close to the surface. However, recalling that according to the hypothesis the dimensions of the two clouds were 14 and 7 kilometers, and arguing that the cyclotron radii of the particles can be no larger than the cloud dimensions, it is seen from Table 1 that the ions would have to be predominately of small masses (i.e. protons). We have argued above, however, that the ions most likely have masses in the range 25-100 AMU, and these ions would have cyclotron radii (see Table 1) too large ay a factor of at least 5 to fit the observed data.

Therefore it appears that it is impossible to reconcile the observed data with the hypothesis that the charged particles were energized at the instant of impact and then propogated in some manner to the location of CPLEE. The time delay between impact and observation by CPLEE and the relatively short duration of the enhancements were seen to require, depending upon which mode of propogation was chosen, either extremely large (~ 1000 AMU) or extremely small (~ 1 AMU) ionic masses and it was argued that such extreme values are highly unlikely.

An alternate hypothesis is that the Lunar Module impact produced expanding gas clouds, and the components of the gas cloud were then ionized by solar photons or other mechanisms and subsequently energized by a continuously or erractically active acceleration mechanism. The fluxes were observed by CPLEE only when the expanding, annular gas cloud was in the vicinity of the instrument. Thus, according to this hypothesis, the velocity of 1 km/sec deduced from the impact - CPLEE distance and the delay time is a characteristic velocity of the gas cloud expansion. The fact that there were two large enhancements, and by inference two gas clouds, can be explained by noting that the LM impact trajectory was at a low ($\sim 10^{\circ}$) elevation angle which could of course lead to secondary impacts following the primary impact.

We can only speculate as to the mechanism responsible for energization of the charged particles. We note that the solar magnetospheric coordinates of CPLEE at the time of impact were $Y_{SM} = 34\ R_E$ and $Z_{SM} = 21\ R_E$, and the solar elevation angle was 30°. Examination of the complete CPLEE data records prior to and after the impact show that the impact occurred just prior to the instrument crossing from the interplanetary medium into the magnetosheath. Therefore, the solar wind had direct access to the lunar surface at the time of the impact event.

Manka and Michel (1970) have calculated the trajectories of ions created near the lunar surface and accelerated by the $\vec{V} \times \vec{B}$ electric field of the solar wind. Although their calculated electric field values (2-4 volts/km) are certainly of sufficient magnitude to produce the observed particle energies, there are two observational features of these impact data which cause the hypothesis of acceleration in a static electric field to be rejected immediately. The first is that energetic particles of both charge signs appeared simultaneously, and the second is that positive ions resulting from the impact were detected both by CPLEE located east of the impact site and by the Apollo 12 SIDE located west of the impact site. (Freeman, private communication)

The solar wind energy density is $\sim 80 \times 10^{-10}$ ergs/cm^3, and comparing this value with the range of plasma cloud energy densities calculated from the measured flux (see Table 1), it is seen that the solar wind is energetically capable of being the energy source. Whether or not interaction between the solar wind and a gas cloud can actually accelerate particles to the observed energies and fluxes is unknown, although Alfven (1954) and Lehnert (1970) have pointed out that strong interactions may occur between magnetized plasmas and neutral gases.

In summary, these Lunar Module impact data indicate a situation of interaction between a neutral gas cloud, the solar wind, and possibly local lunar magnetic fields, offering a unique problem in plasma physics.

TABLE 1

PLASMA CLOUD PARAMETERS

PARTICLE ENERGY	CHARGE SIGN	MASS (AMU)	VELOCITY (km/sec)	ENERGY DENSITY (ergs/cm^3)	CYCLOTRON RADIUS 36 γ FIELD	CYCLOTRON RADIUS 100 γ FIELD
50 ev	+	1	100.0	5.6×10^{-10}	30 km	10 km
50 ev	+	25	20.0	28.0×10^{-10}	150 km	50 km
50 ev	+	100 1000	10.0	56×10^{-10}	300 km	100 km
50 ev	+	m_e	1.0	560×10^{-10}	3000 km	1000 km
50 ev	-		4300	-	.7 km	.23 km

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ACKNOWLEDGEMENTS

This work was supported by NASA Contract NAS9-5884 and analysis was assisted in part by the Science Foundation in Physics at the University of Sydney, Sydney, Australia.

FIGURE CAPTIONS

1. The counting rates of channel 3 and channel 6 of Analyzer A at -35 volts, measuring 65 ev negative particles and 70 ev ions respectively, showing the particle fluxes resulting from the LM impact.

2. Same as Figure 2, except showing data from Analyzer B.

3. An expanded view of the data of Figure 2, showing details of the two prominent peaks. In this figure are shown fluxes computed from 5 negative particle energy ranges and a single ion energy range.

4. Electron spectra measured by Analyzer A for two periods. The first is a few minutes prior to impact and the second is the time at the height of the first large peak in Figure 2.

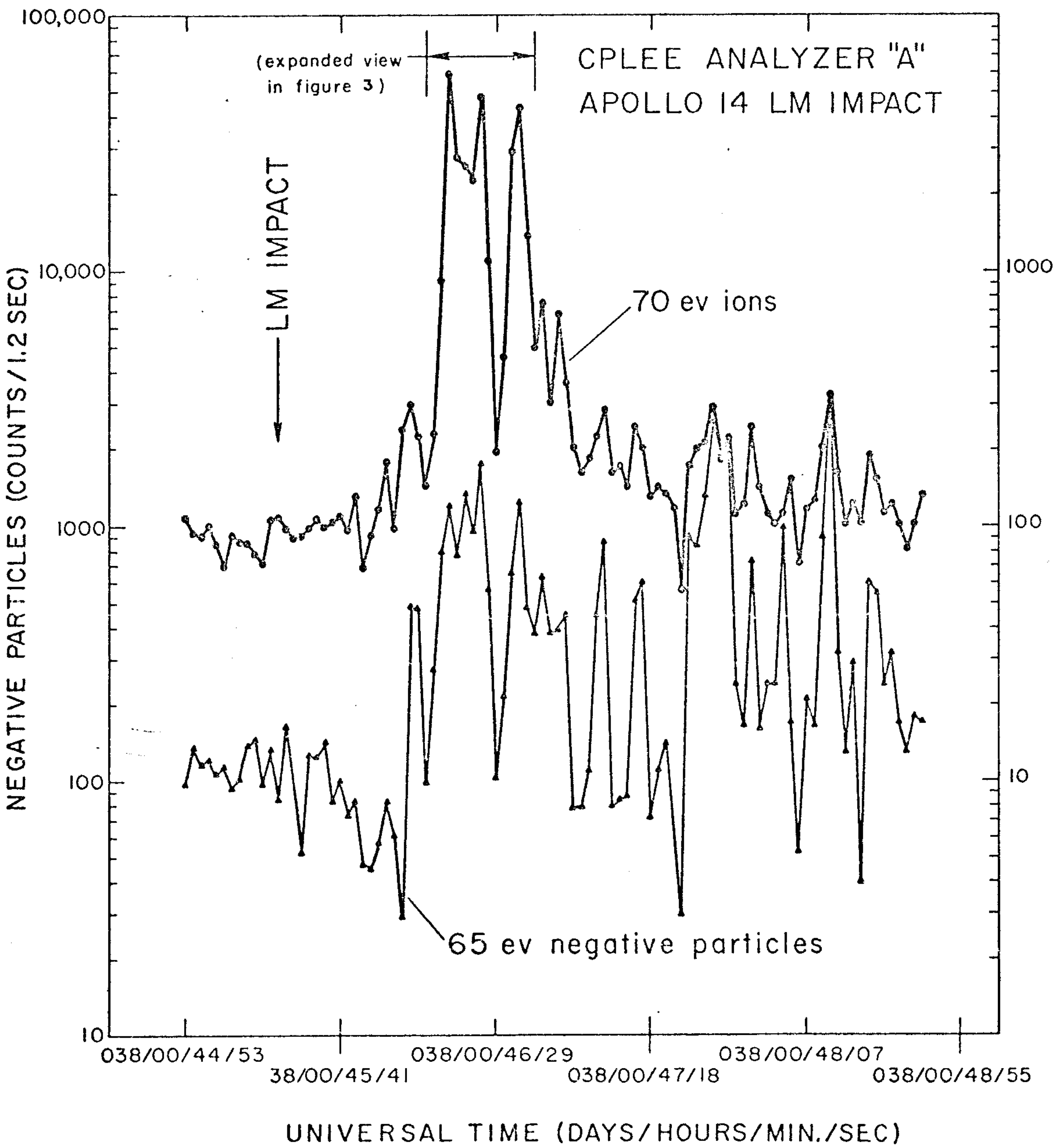
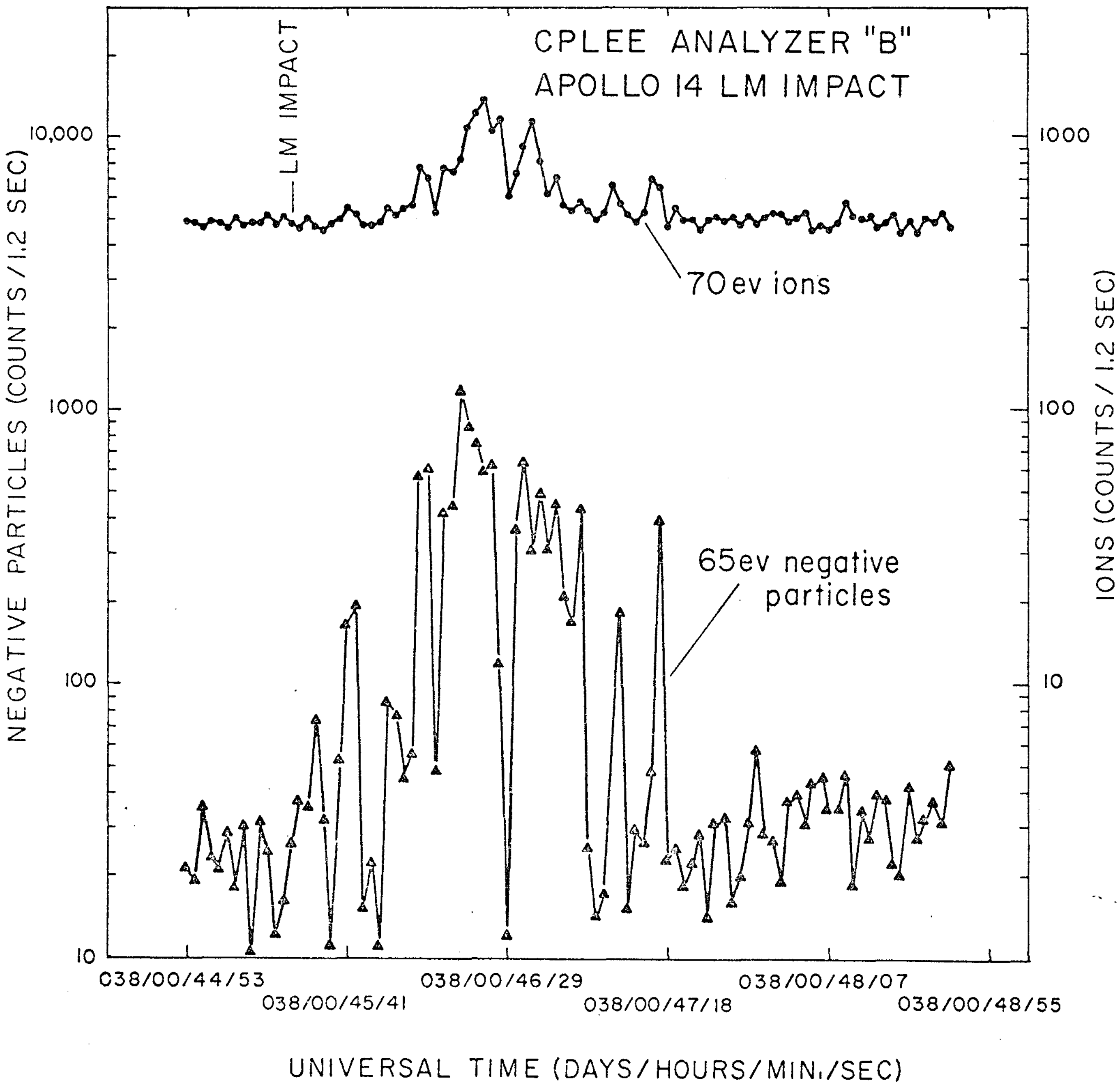

100,000
10,000
1000
100
10
1000
100
10
NEGATIVE PARTICLES (COUNTS/1.2 SEC)
IONS (COUNTS/1.2 SEC)
(expanded view in figure 3)
CPLEE ANALYZER "A"
APOLLO 14 LM IMPACT
LM IMPACT
70 ev ions
65 ev negative particles
038/00/44/53
38/00/45/41
038/00/46/29
038/00/47/18
038/00/48/07
038/00/48/55
UNIVERSAL TIME (DAYS/HOURS/MIN./SEC)

Figure 1



CPLEE ANALYZER "B"
APOLLO 14 LM IMPACT
LM IMPACT
70ev ions
65ev negative particles
NEGATIVE PARTICLES (COUNTS / 1.2 SEC)
IONS (COUNTS / 1.2 SEC)
10,000
1000
100
10
1000
100
10
038/00/44/53
038/00/45/41
038/00/46/29
038/00/47/18
038/00/48/07
038/00/48/55
UNIVERSAL TIME (DAYS/ HOURS/ MIN./SEC)

Figure 2

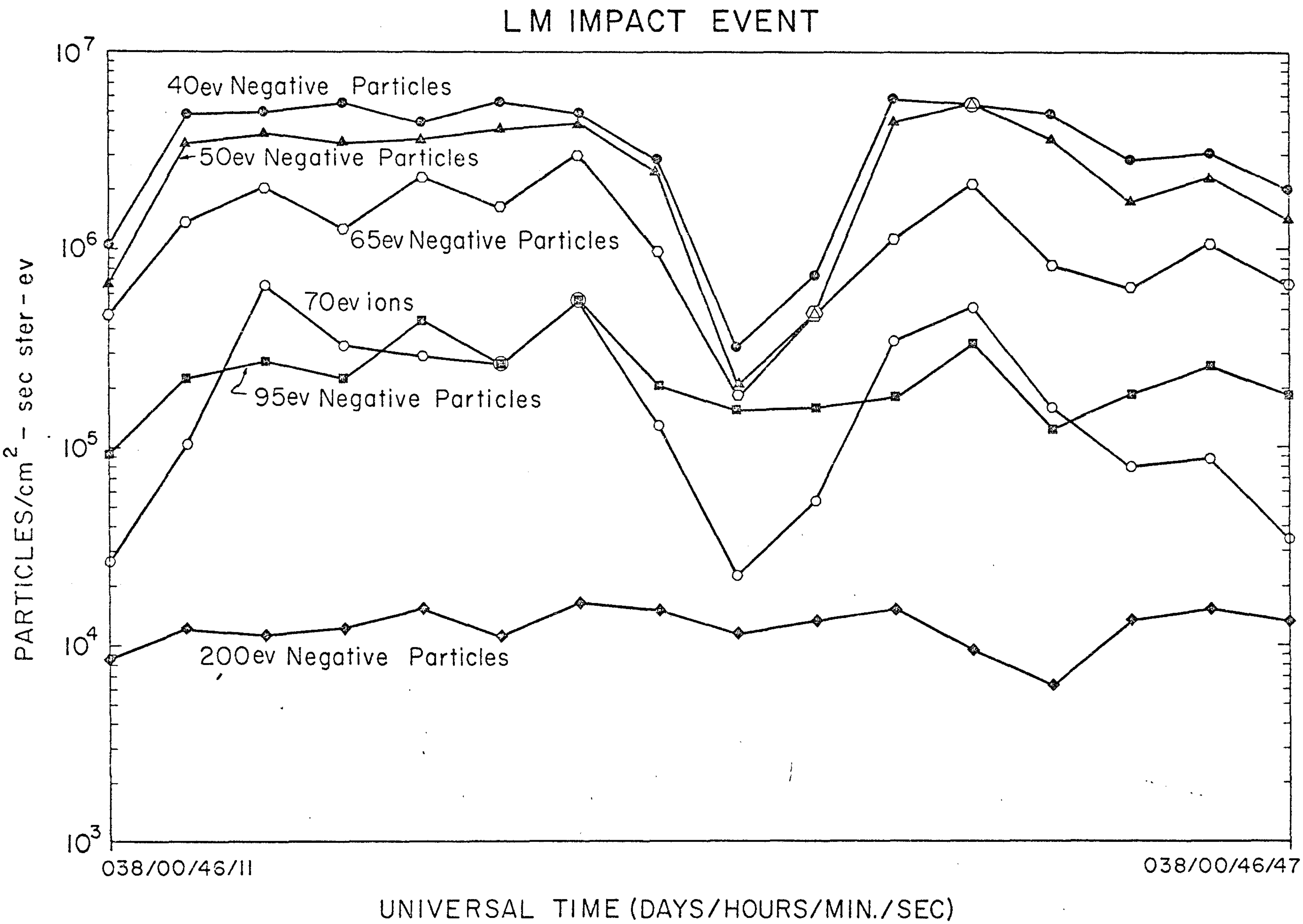
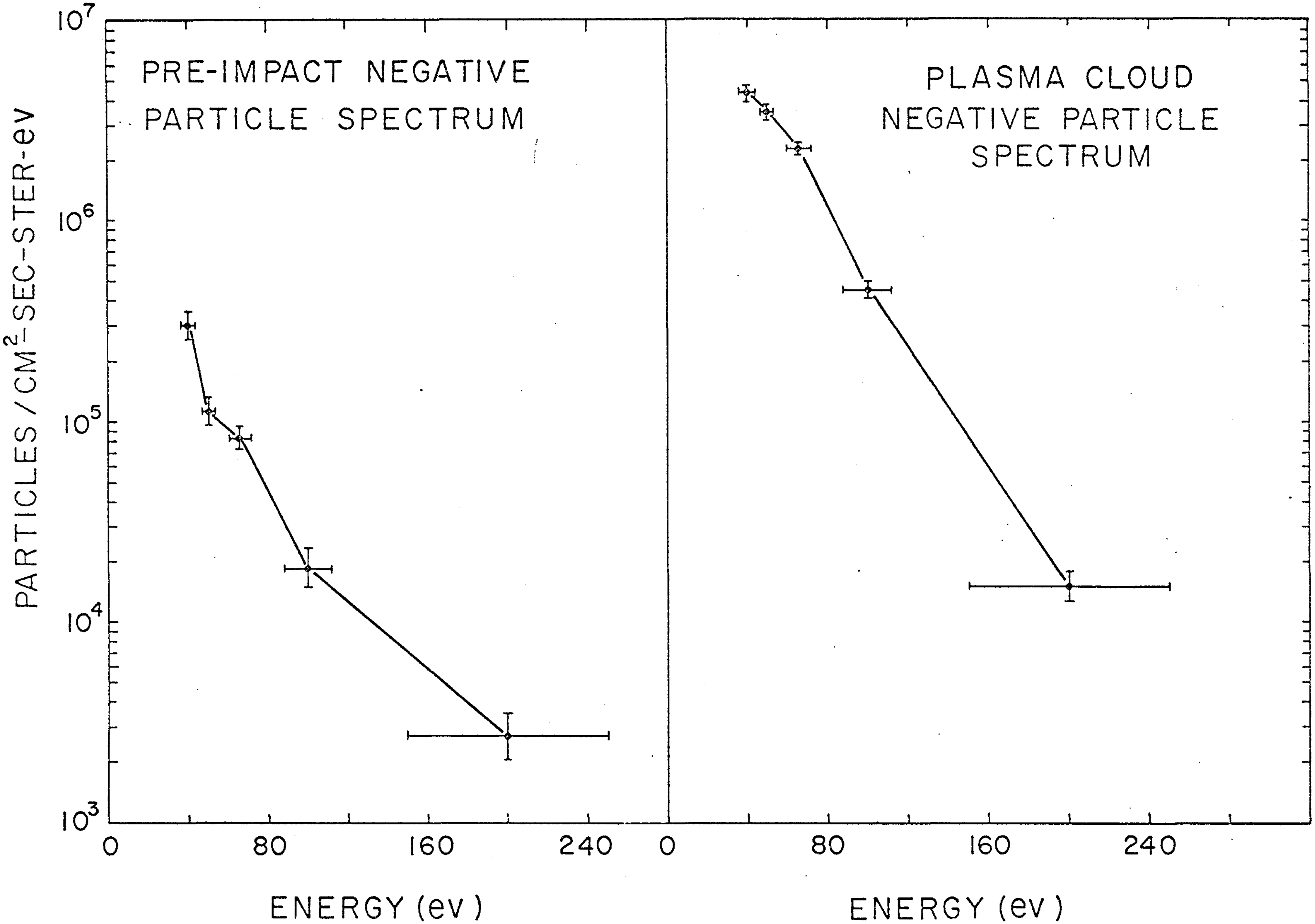

LM IMPACT EVENT
10^7
10^6
10^5
10^4
10^3
PARTICLES/cm^2 - sec ster - ev
40ev Negative Particles
50ev Negative Particles
65ev Negative Particles
70ev ions
95ev Negative Particles
200ev Negative Particles
038/00/46/11
038/00/46/47
UNIVERSAL TIME (DAYS/HOURS/MIN./SEC)

Figure 3



PRE-IMPACT NEGATIVE PARTICLE SPECTRUM
PLASMA CLOUD NEGATIVE PARTICLE SPECTRUM
PARTICLES / CM2-SEC-STER-eV
10^7
10^6
10^5
10^4
10^3
0
80
160
240
ENERGY (ev)
ENERGY (ev)

Figure 4