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FINAL REPORT

SKYLAB CONTAMINATION RESULTS: S052 PARTICLE ANALYSIS AND T025 ANALYSIS

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ABSTRACT

The size and velocity distributions of 500 contaminant particles in the near environs of Skylab are determined from video tape data obtained by the High Altitude Observatory's White Light Coronagraph (experiment number SO52). A complete listing of derived particle parameters, their frequency distributions, and their behavior as a function of time are presented. A correlation between particle size and velocity is noted, and at least two prominent directions of the particle spacecraft origins are identified.

I. INTRODUCTION

In a "Preliminary Study of Contaminant Particulates around Skylab" (Schuerman and Weinberg, 1976), it was demonstrated that data from the High Altitude Observatory's White Light Coronagraph (experiment number S052) contained reducible information on the particulate environment of Skylab. In particular, for particles within two hundred meters or so of the spacecraft, their size and velocity distributions could be determined. In this study, we have analyzed 500 particles which appear on the S052 video tape on day 220 between GMT 17:34:02 and 17:37:10. This section of the video tape was chosen because it is the only section of data to which we have access that can provide enough particles to establish a reasonable set of statistics.

Figure 1 shows the number of particles in the field-of-view as a function of time for the six minute portion of the video tape used in this study. All particles within the shaded region of the plot were studied in detail. It was felt that any time dependence in the particle parameters could best be identified if the whole population (500 particles) was both complete and contiguous in time. The ticks at the top of the graph refer to particles studied earlier by Schuerman and Weinberg (1976).

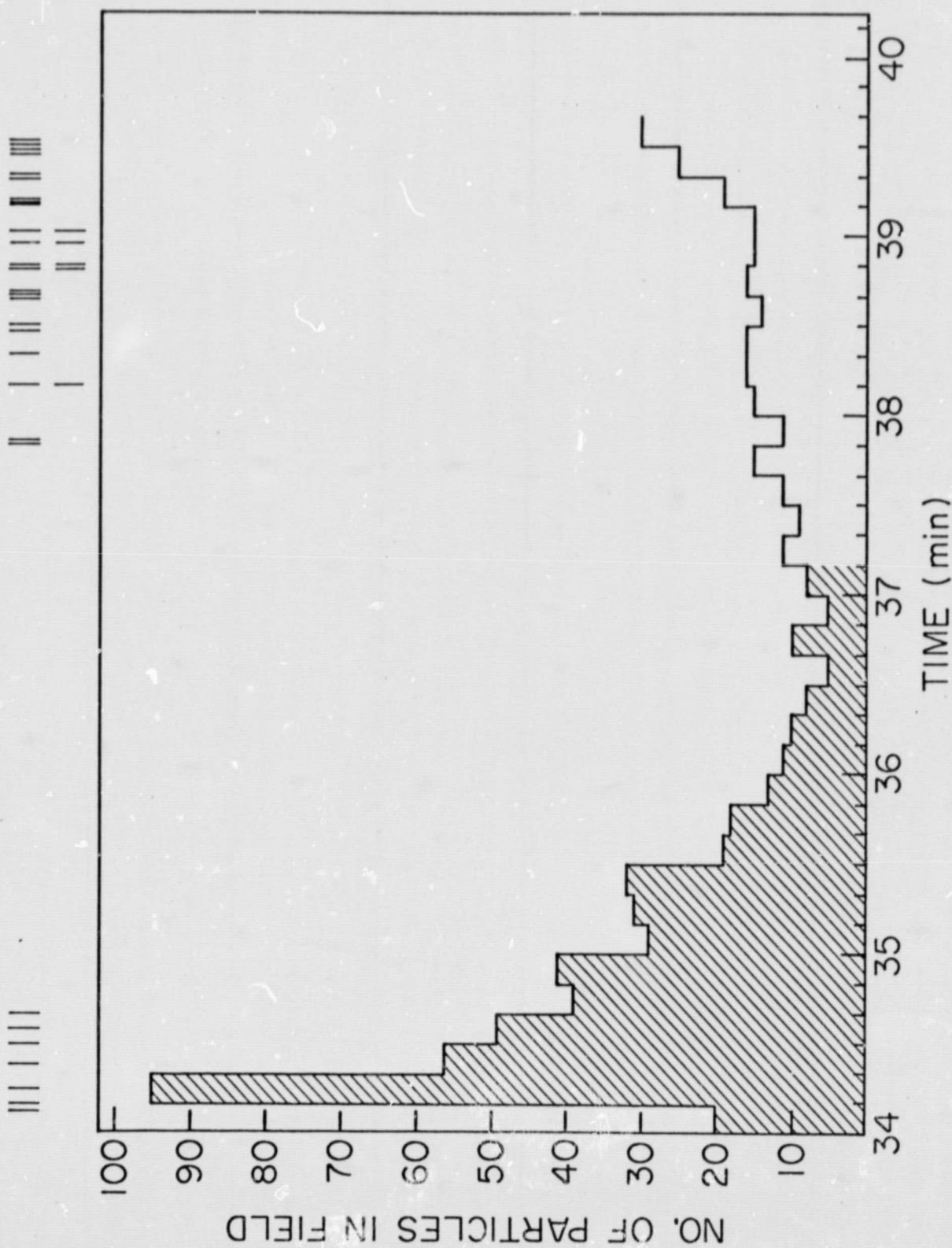


Fig. 1. The number of particles in the S052 field of view as a function of time for the six minute portion of video tape beginning on day 220 (1973), GMT 17:34. The shaded area refers to those particles analyzed in this report, while the marks at the top of the graph designate the 34 particles analyzed in our earlier study.

II. THE METHOD

The theoretical development necessary to extract the radial velocity, the transverse velocity and direction, the distance from the spacecraft, and the size of an individual particle from an S052 photograph is given by Schuerman et al. (1977, hereafter called Paper I; equations and figures cited from that article will be preceded by the Roman numeral I), a reprint of which is appended to this report. The reduction of the video data differs from that of the photographic data in two important respects. First, the particles that can be fully investigated are not limited to the extent that they were in the photographic method, where the particle had to both start and stop on the film. In the video method, we only require that the image speed be small enough so that the image itself registers as circular within any individual frame. In effect, about 95% of all particles observable on the tape fulfill this criteria. Second, the theory developed in Paper I needs certain modifications. In particular, the "effective" exposure time (eq. I-6) is no longer a defined quantity, and Δt , defined by equation (I-3) for the photographic method, is just the time interval between consecutive measurements for the video data. When equations (I-7) and (I-8) are redeveloped with τ being replaced by T , the frame exposure time, equation (I-10) becomes

$$W = \frac{4q \Omega_0}{\pi A^2} \quad (1)$$

W , as defined in Paper I, is the brightness of the particle above background in units of the brightness of the solar image. With these modifications, the theory of Paper I can be applied to the video data without restriction.

IIa. Parameters obtained from the video tape.

The exposure time of the video system is $1/60$ sec, so that, at any instant, most particle images are not tracks as on the photographs, but rather well-defined circles-of-confusion. The diameter of the circle (a) the x and y video positions, the brightness/area (h) and the time were all measured at three points along the path of the particle's image. In practice, the y coordinate and the width (a) of the particle's image were obtained by counting the TV scanning lines. The line through the center of the occulting disc was designated as the origin. The occulting disc itself was known from the photographic study to have an angular extent of $.752^\circ$, and it was found to span 76 TV scanning lines. This established the conversion from number of lines to arc degrees for the y measurements. By using this method to also obtain the width (a) of the particle image, we were able to resolve circles-of-confusion as small as 1 line or $\sim 0.01^\circ$. This corresponds to a particle being 180 meters from the coronagraph.

The x and h measurements were read from an oscilloscope monitoring the video signal; possible non-linearities in the monitor sweep were thus avoided. By suitable delaying techniques, the single line of interest was displayed. The x position was recorded as the time (in μsec) from the start of line to the center of the image. The width of the occulting disc was found to be $22 \mu\text{sec}$ so that $1 \mu\text{sec}$ corresponds to 0.034° , and the center of disc was found to reside at $27 \mu\text{sec}$. The brightness (h) of the image above background was read, in arbitrary units, from the scope display of brightness vs. time. The range of h was from .2 (for low background) to 4.0 for saturation. For h less than about 3.8, h responded in a linear fashion to the gray scale provided with the video tape.

To obtain W (in units of the solar image) from h , the image of Saturn, which was in the field-of-view on day 166, was used. For Saturn, $h = 1.51$. W and h are related by

$$W = \frac{K h}{V(\theta)} \quad (2)$$

where K is a calibration constant and V is the vignetting function (Fig. I-3). Saturn was assumed to have a visual magnitude of +0.3 or 1.47×10^{-11} times the solar flux. Its image spanned two TV lines. The image of the sun would span $76 \times 0.533^\circ / 0.752^\circ = 53.87$ lines. Therefore the brightness of Saturn (W) in terms of the sun's image is

$$W = 1.47 \times 10^{-11} \cdot (53.87/2)^2 = 1.066 \times 10^{-8}. \quad (3)$$

Furthermore, Saturn was measured to be $\theta = 1.18^\circ$ from the center of the disc which corresponds to a value of $V(\theta)$ of 0.867. Equation (2) then yields the value of $K = 6.123 \times 10^{-9} E_\odot / h$ unit. Combining equations (1) and (2), we find that

$$Q \equiv \log q = 4.84 + \log h - \log V(\theta). \quad (4).$$

Finally, the time corresponding to the particles' instantaneous position was recorded. Since a 1 second interval display was provided on the video tape, one could resolve time to $1/60$ of a second by counting the number of frames elapsed (up to 60) before the time display changed by 1 second.

The following parameters for 500 consecutive particle images were recorded at 3 different times along the trajectory of each particle:

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Quantity	Symbol (i=1,2,3)	Units	How obtained
time	t_i	sec	from time display and counting frames (60/sec)
video x position	x_i	arc deg.	oscilloscope time axis; 22 msec = 0.752°
video y position	y_i	arc deg.	counting of TV scan lines 76 lines = 0.752°
width of particle image	a_i	arc deg.	counting of TV scan lines
scattering angle	θ_i	arc deg.	$\theta = \sqrt{x^2 + y^2}$
vignetting	$V_i (\theta_i)$	dimensionless	instrumental vignetting function, see Fig I-3.
the surface brightness of the particle image	h_i	solar image surface brightness	video level from oscilloscope + calibration using Saturn.
logarithm of scattering cross-section	Q_i	log cm ²	equation (4)

IIB. Computation of distance, velocity, and size.

The distance (L) of the particle from the S052 entrance aperture is found from equation (I-1). Knowing the width (a) of the particle,

$$\begin{aligned} L (\text{meters}) &= A(\text{meters}) \frac{f(\text{mm})}{a(\text{mm})} \\ &= \frac{A(\text{meters})}{a(\text{radians})} = \frac{A(\text{meters}) \cdot 180^\circ}{a(\text{deg}) \pi} \quad (5) \\ &= \frac{.03123 \cdot 180^\circ}{a(\text{deg}) \pi} . \end{aligned}$$

For each particle, the distance L_i is calculated for 3 points on the particle's trajectory; $i=1,2,3$. The minimum and maximum values of L are tabulated in Section III.

The radial velocity (VR_i) is trivially calculated from the changes in L with respect to the corresponding changes in time. Three values of VR_i were calculated for each particle:

$$\begin{aligned} VR_1 &= (L_1 - L_2) / (t_1 - t_2) \\ VR_2 &= (L_2 - L_3) / (t_2 - t_3) \\ VR_3 &= (L_1 - L_3) / (t_1 - t_3) . \end{aligned} \quad (6)$$

The average value of VR was then taken as

$$VR = .25VR_1 + .25VR_2 + .50VR_3 .$$

VR_3 was doubly weighted because its increments are larger and thus are probably determined more accurately. The random error (1 standard deviation) in the determination of VR was calculated according to

$$VR \text{ error} = \pm \sqrt{\frac{3}{2} \left[\frac{(VR_1)^2}{4} + \frac{(VR_2)^2}{4} + \frac{(VR_3)^2}{2} - (VR)^2 \right]} . \quad (7)$$

VR for each particle, along with its associated error, is presented in the next section.

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In order to compute the transverse velocities, the X and Y space coordinates are needed. These were calculated from equations (I-1) and (I-2):

$$X_i = Ax_i/a_i; Y_i = Ay_i/a_i; i=1,2,3 \text{ for each particle.}$$

VT was then computed according to

$$\begin{aligned} VT_1 &= \sqrt{\frac{(X_1 - X_2)^2 + (Y_1 - Y_2)^2}{(t_1 - t_2)^2}} \\ VT_2 &= \sqrt{\frac{(X_2 - X_3)^2 + (Y_2 - Y_3)^2}{(t_2 - t_3)^2}} \\ VT_3 &= \sqrt{\frac{(X_1 - X_3)^2 + (Y_1 - Y_3)^2}{(t_1 - t_3)^2}} \end{aligned} \quad (8)$$

The average VT and its associated error were determined in exactly the same manner as VR (equations 6 and 7) and are listed for each particle in Section III.

The angle ϕ is the direction of the particle motion across the field of view. When $\phi = 0^\circ$, the particle is traveling from left to right as viewed on the TV monitor; $\phi = 90^\circ$ corresponds to particle motion from bottom to top of the screen (see inset in Fig I-5). For the one recognizable "dump" on our copy of the video tape, all particles had $\phi = 90^\circ$. That portion of the tape (day 240, 10 hrs, 37 min.) was not analyzed in this report. ϕ was calculated by

$$\tan \phi = \frac{y_3 - y_1}{x_3 - x_1}$$

with due regard for quadrants; $0^\circ \leq \phi < 360^\circ$. The value of ϕ for each particle is listed in the next section.

Finally, the size of each particle was determined using the values of Q_i (equation 4) and θ_i for each particle. This procedure is described in detail in Paper I; the same Q vs θ diagram (Fig I-2) was used to determine the minimum, maximum, and best estimate of the particle radius, ρ in μm . Results are tabulated in Section III.

III. RESULTS

The following ten pages contain the results of this study in tabular form. The time column represents the reading of the GMT display when the first measurements were made of the particle. In general, the numbering of particles (1 through 500) is monotonic in time. The other column headings are self-explanatory.

IIIa. Table averages

average radial velocity (VR)	:	$25 \pm 25 \text{ m sec}^{-1}$.
average error (1σ) in VR	:	$70 \pm 71 \text{ m sec}^{-1}$.
average minimum distance (L min)	:	$43 \pm 1 \text{ m}$.
average maximum distance (L max)	:	$58 \pm 2 \text{ m}$.
average tranverse velocity (VT)	:	$2.17 \pm .13 \text{ m sec}^{-1}$.
average error (1σ) in VT	:	$1.24 \pm .11 \text{ m sec}^{-1}$.
average minimum radius (ρ min)	:	$14.6 \pm .58 \text{ } \mu\text{m}$.
average "best guess" radius (ρ best)	:	$24.9 \pm 1.0 \text{ } \mu\text{m}$.
average maximum radius (ρ max)	:	$48.1 \pm 3.2 \text{ } \mu\text{m}$.

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TIME MIN:SEC	VT (L/SEC)		L (M)	VR (M/SEC)		PHI (DEG)	RHO (MICRONETERS)		
							MIN	BEST	MAX
1 34:02	.0±	.0	180-180	.750±	.069	152	13.0	20.0	23.0
2 34:03	.0±	.0	45- 45	4.090±	.033	173	10.0	15.0	20.0
3 34:03	235.9±	156.8	60-180	4.706±	3.071	219	11.0	25.0	25.0
4 34:03	137.7±	94.9	60-180	1.545±	.359	204	12.0	13.0	14.0
5 34:04	8.0±	72.6	25- 45	1.830±	.270	147	12.0	23.0	25.0
6 34:04	.0±	.0	36- 36	.799±	.061	231	30.0	36.0	40.0
7 34:05	-3.9±	81.5	16- 25	1.977±	.807	171	15.0	30.0	40.0
8 34:05	70.3±	57.7	30- 60	1.277±	.706	181	20.0	30.0	70.0
9 34:05	.0±	.0	22- 22	1.069±	.057	163	19.0	24.0	30.0
10 34:05	26.3±	70.3	22- 36	2.044±	.812	184	13.0	30.0	60.0
11 34:05	25.0±	5.1	25- 45	.975±	.227	102	14.0	21.0	22.0
12 34:05	.0±	.0	25- 25	.927±	.132	176	12.0	30.0	50.0
13 34:06	32.3±	23.0	25- 45	.768±	.370	169	15.0	30.0	60.0
14 34:07	5.6±	4.9	11- 12	.602±	.205	149	30.0	45.0	48.0
15 34:06	9.0±	7.8	36- 45	.306±	.127	215	13.0	19.0	30.0
16 34:07	-131.6±	100.2	30- 45	7.401±	2.039	167	8.0	9.0	9.5
17 34:07	18.4±	16.7	22- 25	1.912±	.368	157	9.0	30.0	40.0
18 34:08	-5.9±	4.7	22- 25	.791±	.054	116	6.2	7.0	8.5
19 34:09	.3±	156.8	60- 90	2.387±	1.701	30	9.0	10.0	13.0
20 34:11	270.7±	234.4	90-180	10.487±	8.859	164	9.0	12.0	15.0
21 34:12	.0±	.0	18- 18	.652±	.552	178	75.0	80.0	85.0
22 34:13	.0±	.0	30- 30	.217±	.001	180	30.0	48.0	70.0
23 34:14	58.2±	3.5	25- 45	1.275±	.771	184	30.0	35.0	55.0
24 34:14	-.1±	31.4	30- 36	1.341±	.646	171	8.0	38.0	55.0
25 34:14	36.1±	31.3	18- 30	2.267±	.843	65	6.7	9.0	30.0
26 34:15	.0±	22.4	25- 30	.910±	.641	104	9.5	30.0	250.0
27 34:09	-16.6±	13.2	26- 45	.755±	.111	86	8.5	10.0	15.0
28 34:10	95.4±	147.0	60- 90	1.823±	.624	192	10.0	12.0	14.0
29 34:11	213.5±	67.0	30- 90	3.755±	1.377	183	15.0	20.0	30.0
30 34:11	-8.6±	46.0	18- 22	2.237±	.820	166	12.0	16.0	35.0
31 34:11	47.1±	14.4	22- 30	.631±	.082	241	30.0	48.0	55.0
32 34:11	-3.7±	2.6	13- 15	1.339±	.021	279	30.0	50.0	75.0
33 34:12	75.3±	65.3	22- 30	3.468±	.337	171	8.5	15.0	26.0
34 34:12	-37.7±	201.1	45- 60	5.413±	2.486	183	9.0	12.0	30.0
35 34:12	20.9±	51.6	20- 25	2.382±	.539	163	9.0	20.0	40.0
36 34:12	385.3±	160.0	36- 90	2.872±	.955	169	9.2	10.0	11.0
37 34:12	-37.7±	37.9	25- 30	3.616±	1.356	169	8.5	20.0	47.0
38 34:12	.0±	.0	25- 25	1.069±	.308	210	7.7	8.0	8.3
39 34:12	1.3±	155.9	30- 36	7.233±	.947	182	7.7	10.0	12.0
40 34:12	.0±	.0	60- 60	4.418±	2.145	269	6.5	6.7	7.0
41 34:12	36.1±	91.9	25- 36	1.851±	.262	183	9.0	17.0	40.0
42 34:12	98.0±	40.2	22- 36	1.177±	.131	158	7.5	20.0	40.0
43 34:13	.0±	.0	45- 45	3.380±	.719	182	9.5	11.0	13.0
44 34:13	251.0±	180.6	30- 60	3.679±	3.472	164	12.0	25.0	130.0
45 34:13	37.7±	40.2	18- 22	1.656±	.299	169	16.0	48.0	60.0
46 34:13	45.2±	55.4	30- 36	2.115±	.773	163	8.0	25.0	80.0
47 34:13	.0±	.0	45- 45	1.009±	.065	191	8.5	35.0	50.0
48 34:13	52.7±	166.6	22- 36	3.112±	.946	178	16.0	37.0	40.0
49 34:13	47.5±	3.3	25- 45	.845±	.012	166	14.0	15.0	500.0
50 34:13	67.8±	120.7	11- 22	2.336±	1.024	167	16.0	48.0	70.0

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#	TIME MIN:SEC	VT (M/SEC)		L (M)	VR (M/SEC)		PHI (DEG)	RHO (MICROMETERS)		
								MIN	BEST	MAX
51	34:13	43.8±	31.3	25- 45	1.196±	.306	183	14.0	18.0	19.0
52	34:14	.0±	.0	90- 90	1.337±	.247	172	8.5	10.0	11.0
53	34:14	19.6±	14.2	30- 36	1.401±	1.179	167	13.0	40.0	60.0
54	34:14	75.3±	65.3	45- 60	1.341±	1.017	192	9.0	12.0	20.0
55	34:14	251.2±	268.2	30- 60	3.820±	3.976	150	10.0	25.0	45.0
56	34:14	301.4±	783.1	30- 90	14.346±	9.521	171	6.5	9.0	23.0
57	34:14	125.6±	134.1	45- 60	3.762±	.761	171	7.5	18.0	25.0
58	34:14	35.2±	26.8	30- 36	.816±	.487	193	23.0	30.0	45.0
59	34:14	150.7±	553.7	45- 90	7.768±	5.942	180	9.0	22.0	24.0
60	34:14	45.2±	39.2	36- 45	1.597±	.157	61	9.0	25.0	60.0
61	34:14	51.7±	7.5	25- 36	1.449±	.176	71	10.5	11.0	15.0
62	34:14	.0±	.0	60- 60	2.766±	.321	156	7.2	7.2	7.2
63	34:15	-18.1±	15.7	30- 36	1.352±	1.058	10	50.0	100.0	300.0
64	34:14	.0±	.0	90- 90	1.003±	.906	188	9.0	17.0	27.0
65	34:14	83.6±	53.4	25- 45	.933±	.672	176	50.0	125.0	400.0
66	34:15	150.7±	130.5	60- 90	3.708±	2.759	157	8.0	9.0	10.0
67	34:15	51.1±	15.7	16- 30	.579±	.177	175	35.0	90.0	120.0
68	34:15	.0±	.0	60- 60	1.868±	.906	165	6.5	7.0	8.3
69	34:15	-45.2±	39.2	36- 45	2.442±	1.193	183	8.0	17.0	27.0
70	34:15	.0±	.0	90- 90	2.529±	.413	223	8.0	18.0	21.0
71	34:15	229.6±	349.8	60-180	9.032±	5.264	216	11.0	18.0	27.0
72	34:15	30.1±	16.1	30- 36	.740±	.407	182	70.0	70.0	70.0
73	34:15	180.8±	208.8	15- 36	6.671±	5.036	102	6.5	7.0	8.0
74	34:15	45.2±	39.2	36- 45	1.142±	.415	183	11.0	12.0	30.0
75	34:15	.0±	.0	45- 45	.425±	.101	164	17.0	35.0	40.0
76	34:15	-25.1±	21.8	20- 22	1.663±	.408	182	9.0	30.0	45.0
77	34:15	.0±	.0	36- 36	.990±	.017	69	13.0	14.0	16.0
78	34:15	160.3±	164.9	15- 22	3.068±	3.604	128	8.7	10.0	11.0
79	34:15	62.3±	18.6	20- 30	.645±	.234	169	35.0	48.0	90.0
80	34:15	.0±	.0	36- 36	1.058±	.182	184	10.5	28.0	35.0
81	34:15	.0±	.0	30- 30	.955±	.352	221	9.0	9.5	30.0
82	34:15	17.3±	6.1	7- 9	2.337±	.681	289	12.0	37.0	50.0
83	34:16	51.7±	44.7	25- 36	1.042±	.596	189	17.0	28.0	45.0
84	34:16	.0±	130.5	45- 60	3.000±	2.070	96	6.5	7.0	7.5
85	34:16	.0±	.0	45- 45	1.290±	.061	245	7.0	14.0	30.0
86	34:16	140.5±	137.0	25- 36	2.089±	2.027	173	12.0	100.0	290.0
87	34:16	.0±	.0	15- 15	1.375±	.031	75	10.0	25.0	26.0
88	34:16	15.8±	11.5	12- 25	1.018±	.270	167	9.5	11.0	15.0
89	34:16	-25.5±	103.0	18- 25	2.103±	.844	176	10.5	11.0	13.0
90	34:16	753.5±	804.5	90-180	21.959±	23.176	210	6.7	7.0	7.3
91	34:16	86.3±	75.3	20- 25	2.393±	1.292	215	14.0	100.0	180.0
92	34:16	76.4±	73.8	20- 25	2.271±	1.856	146	12.0	23.0	28.0
93	34:16	.0±	.0	25- 25	1.870±	.316	178	10.4	60.0	150.0
94	34:16	35.5±	325.3	45- 60	6.261±	6.482	154	9.0	10.0	30.0
95	34:16	14.7±	11.2	20- 22	.297±	.175	161	45.0	50.0	53.0
96	34:16	.0±	.0	60- 60	.729±	.000	90	7.5	20.0	21.0
97	34:17	.0±	261.0	45- 60	3.448±	3.379	90	9.0	13.0	24.0
98	34:17	45.2±	39.2	36- 45	.774±	.369	203	10.0	12.0	35.0
99	34:17	90.4±	78.3	36- 45	1.817±	1.153	203	25.0	25.0	26.0
100	34:17	21.5±	70.8	25- 36	2.245±	.880	182	9.0	17.0	30.0

#	TIME MIN:SEC	VT (M/SEC)		L (°)	VR (M/SEC)		PHI (DEG)	RHO (MICROMETERS)		
								MIN	BEST	MAX
101	34:17	16.7±	17.9	18- 20	.683±	.322	162	30.0	32.0	45.0
102	34:17	150.7±	391.5	20- 60	6.668±	5.777	186	8.0	10.0	11.0
103	34:17	.0±	37.3	25- 30	.963±	.585	236	12.0	16.0	40.0
104	34:18	118.4±	136.4	60- 90	2.775±	2.226	184	8.0	12.0	20.0
105	34:18	.0±	.0	90- 90	.346±	.048	201	8.0	3.5	9.0
106	34:18	5.0±	18.5	15- 18	.801±	.108	265	35.0	100.0	225.0
107	34:18	.0±	.0	45- 45	.371±	.017	90	9.0	17.0	40.0
108	34:18	-226.0±	276.9	30- 90	6.623±	7.473	238	8.5	9.0	9.8
109	34:18	115.2±	21.5	20- 30	2.019±	1.367	121	7.0	9.0	11.0
110	34:18	.0±	.0	60- 60	1.516±	.364	198	16.0	15.0	45.0
111	34:19	2.1±	6.7	9- 10	1.636±	.057	289	8.0	13.0	26.0
112	34:19	.0±	.0	60- 60	.779±	.178	228	22.0	25.0	35.0
113	34:19	44.0±	33.5	45- 60	1.138±	.474	150	7.0	7.5	7.8
114	34:19	226.0±	402.3	60-180	10.276±	4.338	164	8.0	9.0	24.0
115	34:19	.0±	.0	45- 45	.437±	.024	219	17.0	17.0	40.0
116	34:20	75.3±	65.3	60- 90	1.826±	1.161	196	8.0	23.0	26.0
117	34:20	75.3±	65.3	60- 90	1.649±	1.224	127	6.5	8.0	24.0
118	34:20	.0±	11.9	15- 16	1.200±	.117	250	48.0	49.0	50.0
119	34:20	30.3±	29.3	10- 12	1.827±	.285	198	30.0	50.0	80.0
120	34:20	19.4±	10.8	25- 30	.434±	.126	215	10.0	22.0	23.0
121	34:21	.0±	37.3	25- 30	1.166±	.772	200	6.5	13.0	20.0
122	34:21	.0±	.0	45- 45	.588±	.000	157	6.5	7.0	7.2
123	34:21	.0±	.0	45- 45	.596±	.163	164	8.5	17.0	20.0
124	34:21	22.6±	120.7	36- 45	2.700±	1.223	206	35.0	45.0	95.0
125	34:21	-7.5±	6.5	11- 12	.899±	.108	133	35.0	43.0	45.0
126	34:21	12.6±	47.9	20- 25	1.359±	.340	65	9.0	13.0	28.0
127	34:21	.0±	.0	30- 30	.843±	.233	243	10.0	60.0	75.0
128	34:21	90.4±	70.3	36- 45	1.527±	.773	200	22.0	23.0	24.0
129	34:22	-75.3±	65.3	45- 60	2.551±	1.435	253	14.0	37.0	40.0
130	34:22	10.0±	22.9	16- 20	.784±	.369	139	7.0	18.0	21.0
131	34:22	.0±	.0	36- 36	.876±	.054	150	7.8	8.6	9.2
132	34:22	.0±	.0	60- 60	.736±	.314	192	17.0	42.0	45.0
133	34:22	133.0±	115.2	18- 22	2.276±	1.813	186	35.0	150.0	480.0
134	34:22	.0±	.0	20- 20	1.346±	.018	234	28.0	45.0	48.0
135	34:22	.0±	.0	90- 90	.492±	.108	251	6.5	6.5	6.5
136	34:23	.0±	.0	60- 60	.369±	.007	138	6.5	15.0	23.0
137	34:23	.0±	.0	36- 36	.402±	.034	214	7.0	25.0	40.0
138	34:23	25.9±	51.9	15- 18	1.194±	.596	182	10.0	70.0	350.0
139	34:23	110.5±	87.9	60- 90	3.187±	.432	233	9.0	11.0	14.0
140	34:23	21.0±	10.1	10- 12	.764±	.277	218	80.0	95.0	300.0
141	34:23	.0±	.0	22- 22	.848±	.085	241	70.0	75.0	80.0
142	34:24	75.3±	92.3	60- 90	2.149±	1.539	195	5.2	6.0	6.8
143	34:24	-150.7±	130.5	60- 90	5.347±	3.715	180	6.5	6.5	6.8
144	34:24	.0±	.0	90- 90	1.297±	.313	227	6.0	6.5	7.2
145	34:24	39.7±	100.6	9- 18	1.272±	1.072	107	16.0	45.0	180.0
146	34:24	.0±	.0	90- 90	.963±	.157	182	7.0	8.0	8.3
147	34:25	12.6±	9.6	25- 30	.363±	.033	207	60.0	70.0	80.0
148	34:25	193.8±	11.2	25- 45	2.727±	.709	177	10.2	28.0	40.0
149	34:25	17.9±	19.2	25- 30	.402±	.171	230	18.0	30.0	43.0
150	34:25	.0±	.0	36- 36	.874±	.022	227	50.0	60.0	75.0

ORIGINAL PAGE IS
OF POOR QUALITY

#	TIME MIN:SEC	VT (M/SEC)		L (M)	VR (M/SEC)		PHI (DEG)	RHO (MICROMETERS)		
								MIN	BEST	MAX
151	34:26	.0±	.0	25- 25	.307±	.078	217	48.0	48.0	60.0
152	34:26	.0±	65.3	45- 60	1.537±	.976	142	15.0	15.0	17.0
153	34:26	.0±	.0	60- 60	1.205±	.089	253	6.7	9.0	11.0
154	34:26	10.8±	9.3	25- 30	.316±	.115	188	12.0	35.0	40.0
155	34:26	33.9±	15.4	22- 36	1.137±	.325	14	75.0	125.0	250.0
156	34:26	60.3±	52.2	36- 60	.997±	.900	161	10.0	22.0	30.0
157	34:27	-90.4±	78.3	36- 45	2.805±	.902	129	7.8	15.0	21.0
158	34:27	904.2±	783.1	90-180	19.997±	16.025	208	9.0	10.0	12.0
159	34:27	21.5±	70.8	25- 36	1.695±	1.004	77	7.5	7.7	7.8
160	34:28	25.8±	22.4	25- 36	.538±	.381	162	9.0	15.0	30.0
161	34:28	.0±	.0	60- 60	1.105±	.298	203	9.0	11.0	15.0
162	34:28	.0±	.0	18- 18	1.344±	.323	49	6.0	6.5	7.0
163	34:28	.0±	.0	36- 36	.838±	.023	239	35.0	43.0	45.0
164	34:28	.0±	2.6	7- 7	.277±	.011	120	45.0	49.0	55.0
165	34:28	-43.1±	37.3	25- 30	2.415±	1.134	212	12.0	70.0	450.0
166	34:28	263.7±	201.1	90-180	6.886±	3.813	152	8.0	8.4	8.9
167	34:28	60.3±	13.1	36- 60	1.162±	.311	244	9.0	15.0	35.0
168	34:28	25.8±	22.4	25- 36	1.065±	.300	45	27.0	33.0	52.0
169	34:29	.0±	.0	90- 90	.563±	.131	224	15.0	15.0	35.0
170	34:29	.0±	.0	36- 36	.435±	.039	284	14.0	30.0	45.0
171	34:29	12.6±	109.8	60- 90	1.679±	1.822	229	14.0	33.0	47.0
172	34:30	.0±	.0	90- 90	.830±	.051	218	25.0	26.0	27.0
173	34:30	9.7±	20.9	12- 13	.963±	.108	293	50.0	60.0	100.0
174	34:30	.0±	.0	30- 30	.585±	.028	159	35.0	48.0	55.0
175	34:30	37.7±	6.5	30- 45	.490±	.100	142	17.0	35.0	40.0
176	34:30	.0±	.0	45- 45	.519±	.010	231	47.0	55.0	60.0
177	34:30	.0±	.0	180-180	1.374±	.665	187	8.5	9.5	10.0
178	34:31	178.6±	206.9	45- 60	5.767±	1.495	173	8.0	11.0	15.0
179	34:31	21.9±	22.1	20- 22	3.071±	.641	177	9.0	23.0	25.0
180	34:32	-21.5±	18.6	25- 30	1.303±	.691	242	12.0	13.0	23.0
181	34:32	75.3±	02.5	25- 45	1.960±	1.380	185	7.0	8.0	9.0
182	34:32	.0±	.0	45- 45	1.298±	.247	276	12.0	13.0	15.0
183	34:32	-45.2±	39.2	36- 45	3.141±	1.405	171	15.0	18.0	40.0
184	34:32	.0±	.0	16- 16	1.828±	.100	231	9.5	10.5	11.0
185	34:32	15.1±	52.2	15- 22	1.314±	.759	168	15.0	15.0	35.0
186	34:33	-37.7±	40.2	36- 45	1.756±	.924	246	35.0	47.0	60.0
187	34:33	.0±	.0	90- 90	.770±	.092	235	9.0	9.0	22.0
188	34:33	-452.1±	652.5	30- 90	12.746±	8.640	68	25.0	30.0	150.0
189	34:33	22.6±	19.6	36- 45	.760±	.371	260	25.0	30.0	150.0
190	34:34	63.6±	69.6	20- 45	1.156±	1.303	186	50.0	90.0	100.0
191	34:34	-37.7±	32.6	45- 60	1.416±	.571	284	35.0	48.0	60.0
192	34:34	.0±	4.6	6- 7	.424±	.042	68	12.0	14.0	30.0
193	34:34	103.0±	13.4	30- 45	2.280±	.220	177	12.0	32.0	37.0
194	34:35	.0±	.0	30- 30	1.055±	.076	70	20.0	26.0	30.0
195	34:35	132.5±	116.6	25- 30	2.202±	1.890	187	15.0	50.0	150.0
196	34:35	.0±	.0	45- 45	.703±	.000	270	45.0	53.0	60.0
197	34:35	.0±	.0	36- 36	.942±	.069	257	45.0	51.0	55.0
198	34:35	14.1±	14.6	6- 10	.269±	.235	180	75.0	200.0	400.0
199	34:36	17.1±	7.4	15- 20	1.449±	.087	269	10.0	11.0	25.0
200	34:36	51.7±	44.7	25- 36	1.029±	.692	156	15.0	15.0	35.0

#	TIME MIN:SEC	VT (M/SEC)		L (M)	VP (M/SEC)		PHI (DEG)	RHO (MICROMETERS)		
								MIN	BEST	MAX
201	34:36	96.9±	83.9	12- 22	2.085±	1.331	244	8.0	21.0	25.0
202	34:36	8.5±	31.1	22- 30	.789±	.602	243	25.0	60.0	100.0
203	34:36	-44.0±	33.5	60- 90	1.018±	.360	284	15.0	17.0	50.0
204	34:36	-12.6±	30.5	11- 12	1.503±	.558	294	9.0	10.0	25.0
205	34:36	-37.7±	32.6	45- 60	1.479±	.495	241	15.0	17.0	50.0
206	34:37	-11.7±	14.3	9- 10	1.811±	.393	230	10.0	12.0	30.0
207	34:37	.0±	.0	60- 60	1.959±	.042	248	9.0	27.0	30.0
208	34:37	96.9±	46.6	25- 45	1.327±	.899	177	12.0	50.0	200.0
209	34:37	.0±	.0	60- 60	.364±	.009	221	12.0	26.0	27.0
210	34:37	22.6±	2.2	18- 22	.857±	.229	300	50.0	100.0	300.0
211	34:37	43.1±	7.3	16- 30	.614±	.188	182	11.0	30.0	200.0
212	34:37	150.7±	130.5	45- 60	3.160±	2.129	208	12.0	21.0	40.0
213	34:38	45.2±	39.2	36- 45	1.234±	.298	185	10.0	23.0	25.0
214	34:38	.0±	.0	90- 90	1.854±	.075	219	7.0	8.0	9.0
215	34:38	33.9±	21.9	5- 9	.512±	.516	151	15.0	48.0	100.0
216	34:38	.0±	.0	90- 90	.220±	.039	180	9.0	21.0	25.0
217	34:38	-75.3±	65.3	60- 90	3.317±	2.135	248	9.0	12.0	30.0
218	34:39	9.8±	7.1	15- 18	1.213±	.027	68	11.0	27.0	50.0
219	34:39	.0±	.0	36- 36	1.336±	.036	246	15.0	47.0	100.0
220	34:39	.0±	.0	60- 60	1.174±	.034	67	8.0	8.5	9.0
221	34:40	.0±	.0	36- 36	1.058±	.095	152	8.0	47.0	100.0
222	34:40	.0±	.0	45- 45	1.266±	.106	237	11.0	46.0	100.0
223	34:40	18.8±	16.3	22- 30	.394±	.152	165	9.0	10.3	11.0
224	34:40	.0±	.0	45- 45	.429±	.063	270	15.0	35.0	50.0
225	34:40	-45.2±	39.2	36- 45	1.983±	.958	250	8.0	9.0	11.0
226	34:41	.0±	.0	60- 60	.122±	.086	296	13.0	38.0	40.0
227	34:41	24.2±	19.8	25- 45	.412±	.228	178	25.0	27.0	35.0
228	34:41	30.1±	46.2	13- 18	1.422±	.242	295	7.0	18.0	20.0
229	34:42	.0±	.0	45- 45	.791±	.073	200	40.0	48.0	50.0
230	34:42	60.3±	13.1	36- 60	1.369±	.225	141	10.0	23.0	30.0
231	34:42	75.3±	65.3	22- 30	2.249±	.671	166	6.5	33.0	45.0
232	34:43	21.5±	26.4	20- 25	.826±	.155	173	35.0	55.0	65.0
233	34:43	16.1±	19.8	25- 30	.794±	.308	119	11.5	13.0	16.0
234	34:43	1.9±	1.6	11- 12	.339±	.145	107	50.0	75.0	100.0
235	34:43	.0±	.0	45- 45	.498±	.049	237	9.0	15.0	15.0
236	34:44	.0±	.0	25- 25	1.724±	.027	316	11.0	26.0	30.0
237	34:44	3.4±	33.8	20- 30	.872±	.440	168	35.0	43.0	60.0
238	34:44	.0±	.0	22- 22	.195±	.040	135	40.0	60.0	100.0
239	34:44	44.0±	102.5	16- 22	1.926±	.643	172	40.0	58.0	90.0
240	34:44	.0±	.0	60- 60	.676±	.082	205	15.0	28.0	30.0
241	34:44	-332.7±	433.3	36- 60	4.116±	1.159	8	14.0	18.0	27.0
242	34:45	12.1±	5.5	10- 12	.786±	.111	171	25.0	30.0	40.0
243	34:46	-74.2±	151.9	36- 60	4.241±	2.537	259	14.0	17.0	40.0
244	34:46	33.0±	30.0	20- 25	1.321±	.089	273	20.0	28.0	55.0
245	34:46	30.4±	37.0	15- 16	.888±	.248	180	8.0	8.7	9.5
246	34:46	.0±	.0	90- 90	.751±	.364	270	8.8	9.0	9.2
247	34:46	.0±	.0	60- 60	4.372±	2.738	175	7.2	18.0	20.0
248	34:46	563.4±	414.6	90-180	10.106±	6.368	202	6.5	6.8	7.1
249	34:47	60.3±	173.1	45- 60	2.226±	3.133	328	12.0	18.0	30.0
250	34:47	-203.9±	287.0	60- 90	5.135±	5.292	270	8.0	22.0	25.0

ORIGINAL PAGE IS
OF POOR QUALITY

#	TIME MIN:SEC	VT (M/SEC)		L (M)	VR (M/SEC)		PHI (DEG)	RHO (MICROMETERS)		
								MIN	BEST	MAX
251	34:48	77.9±	17.7	30- 60	.901±	.801	195	20.0	26.0	30.0
252	34:48	372.3±	393.6	45- 60	7.725±	8.019	203	14.0	85.0	90.0
253	34:48	-6.7±	779.4	60- 90	13.766±	13.557	214	8.5	9.5	10.3
254	34:48	39.2±	169.3	36- 45	3.069±	2.675	210	20.0	28.0	60.0
255	34:48	-27.5±	21.9	20- 22	1.088±	.552	164	20.0	27.0	60.0
256	34:48	401.0±	387.3	60- 90	11.574±	10.988	270	11.0	25.0	25.0
257	34:49	35.8±	41.4	30- 36	.956±	1.090	111	15.0	17.0	22.0
258	34:49	-67.5±	119.8	30- 45	2.799±	3.252	180	20.0	28.0	40.0
259	34:49	308.5±	263.3	25- 36	6.707±	5.063	180	9.5	10.0	11.0
260	34:50	-37.8±	29.0	25- 30	4.017±	.650	182	24.0	28.0	40.0
261	34:51	-19.0±	191.6	60- 90	2.175±	2.075	352	11.0	11.5	28.0
262	34:51	-13.8±	11.0	10- 11	1.447±	.077	238	45.0	90.0	110.0
263	34:51	-66.0±	52.7	30- 36	5.727±	.523	176	9.0	9.5	12.0
264	34:51	-49.3±	39.6	45- 60	1.729±	.994	113	7.7	8.2	8.3
265	34:52	-30.0±	31.9	30- 36	1.199±	.218	177	6.5	8.0	9.8
266	34:52	.0±	.0	90- 90	.592±	.217	300	8.4	8.6	8.8
267	34:52	1.5±	86.4	16- 18	4.730±	.203	178	5.7	7.5	7.9
268	34:52	34.9±	2.5	20- 25	.662±	.192	188	35.0	35.0	50.0
269	34:52	160.1±	573.0	30- 45	9.122±	6.113	183	7.1	7.4	7.6
270	34:53	67.8±	53.0	60- 90	1.571±	.841	202	7.3	7.8	9.0
271	34:53	37.4±	26.5	60- 90	1.469±	.118	178	9.0	10.3	11.0
272	34:53	7.5±	6.5	9- 10	.315±	.211	240	12.0	15.0	20.0
273	34:53	35.0±	29.3	36- 45	.864±	.500	190	15.0	17.0	20.0
274	34:53	.2±	12.6	9- 10	.511±	.147	256	22.0	23.0	40.0
275	34:53	126.6±	109.7	25- 30	1.161±	.868	188	9.0	13.0	20.0
276	34:53	-441.6±	859.1	36- 60	20.855±	14.273	176	7.8	7.9	8.1
277	34:54	-33.7±	81.7	12- 15	2.956±	1.043	188	23.0	30.0	60.0
278	34:54	72.8±	37.6	18- 25	2.028±	.663	196	27.0	28.0	80.0
279	34:54	.0±	.0	18- 18	1.697±	.250	164	25.0	29.0	30.0
280	34:54	-6.1±	36.4	5- 6	1.370±	.833	254	45.0	75.0	80.0
281	34:54	27.3±	13.0	6- 6	.921±	.058	201	9.5	20.0	30.0
282	34:54	-20.1±	15.2	13- 15	1.508±	.700	174	20.0	22.0	40.0
283	34:55	-9.2±	17.6	13- 15	.589±	1.105	174	12.0	18.0	40.0
284	34:55	.0±	.0	36- 36	3.290±	.641	177	8.7	10.5	11.5
285	34:56	.0±	.0	30- 30	2.532±	.536	170	5.8	6.5	6.8
286	34:56	29.2±	26.1	45- 60	.808±	.251	171	6.0	7.0	8.0
287	34:56	-11.8±	2.3	10- 12	.992±	.197	140	11.0	28.0	40.0
288	34:56	.0±	.0	90- 90	.227±	.135	16	7.5	7.8	8.0
289	34:56	.0±	.0	90- 90	.390±	.023	180	8.0	8.3	9.0
290	34:57	55.1±	101.7	30- 45	2.837±	1.970	118	6.0	7.0	7.8
291	34:57	36.1±	91.9	25- 36	1.452±	1.443	166	12.0	26.0	60.0
292	34:58	.0±	.0	90- 90	.531±	.044	251	9.0	27.0	30.0
293	34:58	9.8±	7.4	30- 36	.755±	.146	209	8.0	35.0	40.0
294	34:58	9.8±	7.4	30- 36	.755±	.146	209	8.0	35.0	40.0
295	34:58	-25.1±	56.6	18- 22	1.981±	1.226	170	6.5	10.0	20.0
296	34:58	5.3±	46.9	25- 30	.748±	.447	298	20.0	35.0	50.0
297	34:59	25.5±	18.5	36- 60	.956±	.310	87	7.5	8.7	10.0
298	34:59	-67.8±	40.4	30- 90	3.072±	1.553	237	7.0	9.5	14.0
299	34:59	22.0±	22.1	20- 22	.415±	.189	148	9.0	10.0	12.0
300	34:59	13.6±	10.6	18- 20	.456±	.054	142	9.0	11.0	13.0

#	TIME MIN:SEC	VT (M/SEC)		L (M)	VR (M/SEC)		PHI (DEG)	RHO (MICROMETERS)		
								MIN	BEST	MAX
301	35:00	-25.3±	21.9	13- 16	1.687±	.037	220	45.0	60.0	300.0
302	35:00	12.1±	9.8	36- 45	.326±	.200	206	25.0	45.0	50.0
303	35:00	38.2±	.6	20- 25	1.465±	.312	224	7.5	8.0	8.2
304	35:00	61.0±	24.1	25- 60	.617±	.180	135	8.0	11.0	15.0
305	35:00	9.7±	8.2	20- 22	.491±	.099	72	30.0	45.0	80.0
306	35:00	44.3±	5.1	11- 16	.309±	.241	212	40.0	51.0	60.0
307	35:01	31.3±	30.1	25- 36	1.376±	.168	174	5.5	7.0	9.0
308	35:01	8.0±	6.1	25- 30	.868±	.044	212	11.0	14.5	30.0
309	35:01	32.2±	124.7	60- 90	2.262±	1.974	196	6.0	6.5	7.0
310	35:01	-126.4±	99.4	60- 90	4.301±	3.305	210	7.0	10.0	20.0
311	35:01	-34.1±	258.8	60- 90	4.446±	5.463	330	7.0	7.8	8.0
312	35:02	8.6±	7.8	18- 22	.661±	.043	172	7.5	17.0	60.0
313	35:03	27.8±	23.5	36- 45	.478±	.327	206	6.2	7.5	8.8
314	35:04	.0±	.0	90- 90	.646±	.002	244	15.0	30.0	70.0
315	35:04	.0±	.0	90- 90	.451±	.086	240	7.8	8.0	8.1
316	35:04	.0±	.0	36- 36	1.348±	.017	218	11.0	19.0	20.0
317	35:05	80.4±	90.4	60- 90	3.250±	.729	314	15.0	40.0	50.0
318	35:05	16.9±	51.1	10- 22	.807±	.466	216	13.0	27.0	60.0
319	35:05	.0±	.0	90- 90	.958±	.021	235	5.7	6.0	6.2
320	35:06	-197.9±	146.0	90-180	6.431±	1.798	270	8.0	13.0	30.0
321	35:06	-15.6±	68.0	60- 90	1.281±	1.062	306	12.0	15.0	40.0
322	35:06	42.3±	35.3	10- 16	.680±	.499	127	7.8	70.0	170.0
323	35:07	.0±	162.1	90-180	2.732±	2.671	193	6.7	8.0	10.0
324	35:07	.0±	.0	180-180	1.074±	.260	264	7.0	7.7	8.5
325	35:08	-22.9±	22.8	25- 30	1.855±	.388	250	15.0	17.0	220.0
326	35:08	-39.0±	45.1	12- 18	1.274±	.780	153	5.8	6.3	7.0
327	35:08	47.0±	41.3	60- 90	1.590±	.400	261	7.8	12.0	18.0
328	35:09	.0±	.0	45- 45	.502±	.031	204	6.0	7.0	8.0
329	35:09	.0±	.0	90- 90	1.466±	.519	242	7.7	7.9	8.0
330	35:11	.0±	.0	60- 60	.856±	.130	285	5.5	6.1	7.0
331	35:11	27.9±	23.6	36- 45	.919±	.338	102	6.5	6.8	7.2
332	35:11	293.8±	261.2	90-180	6.762±	5.869	210	7.0	8.0	8.2
333	35:11	-159.5±	18.4	36- 60	.409±	.014	58	9.5	10.5	11.5
334	35:11	-112.3±	49.7	25- 36	4.069±	1.925	113	7.0	11.0	27.0
335	35:12	-164.9±	189.2	90-180	3.712±	3.338	270	7.7	9.0	10.0
336	35:12	131.8±	98.1	90-180	3.728±	2.293	270	6.5	7.7	8.7
337	35:12	.0±	.0	45- 45	.249±	.056	79	7.5	8.0	8.8
338	35:12	166.1±	131.9	60- 90	2.771±	1.390	173	15.0	21.0	300.0
339	35:13	70.6±	51.3	20- 60	.837±	.954	177	12.0	75.0	250.0
340	35:13	9.4±	14.1	12- 20	.455±	.119	249	35.0	60.0	120.0
341	35:13	-39.9±	74.9	12- 60	1.532±	.492	256	6.2	11.0	23.0
342	35:13	131.9±	100.6	90-180	4.004±	3.003	330	5.6	5.8	6.2
343	35:13	-2.4±	82.9	45- 60	1.059±	.654	264	7.8	9.0	23.0
344	35:14	-75.3±	57.3	60- 90	3.161±	1.076	260	6.8	8.5	9.5
345	35:15	-223.3±	191.9	30- 45	11.459±	2.176	177	9.0	12.0	30.0
346	35:15	-35.6±	176.8	25- 30	8.772±	3.043	178	5.7	6.6	7.2
347	35:15	58.5±	246.8	18- 36	3.830±	2.245	181	12.0	40.0	120.0
348	35:16	.0±	.0	180-180	.374±	.147	305	5.5	5.7	5.8
349	35:16	-113.3±	98.1	60- 90	3.634±	2.148	254	8.5	21.0	23.0
350	35:17	54.8±	27.6	36- 60	.935±	.507	178	11.0	23.0	32.0

ORIGINAL PAGE IS
OF POOR QUALITY

#	TIME MIN:SEC	VT (M/SEC)		L (M)	VR (M/SEC)		PHI (DEG)	RHO (MICROMETERS)		
								MIN	BEST	MAX
351	35:17	.0±	.0	90- 90	1.110±	.679	203	9.0	9.5	22.0
352	35:17	35.3±	41.2	45- 60	1.287±	1.124	319	8.5	21.0	22.0
353	35:17	84.9±	22.6	36- 90	1.749±	.196	247	8.5	23.0	30.0
354	35:17	44.0±	44.2	20- 30	.818±	.780	170	35.0	40.0	130.0
355	35:17	.9±	20.2	20- 22	.477±	.365	224	26.0	30.0	40.0
356	35:17	63.2±	24.3	13- 18	.393±	.270	187	11.0	70.0	150.0
357	35:18	.0±	.0	60- 60	.069±	.035	311	11.0	30.0	30.0
358	35:18	99.7±	79.1	36- 45	2.285±	1.274	164	6.0	8.0	11.0
359	35:19	-14.2±	140.6	20- 36	2.604±	2.347	178	11.5	22.0	60.0
360	35:19	.0±	.0	90- 90	4.098±	.813	188	6.3	7.7	7.8
361	35:20	-16.9±	12.7	45- 60	.770±	.035	270	9.0	11.0	25.0
362	35:20	.0±	.0	20- 20	.789±	.525	164	16.0	26.0	30.0
363	35:20	28.6±	83.0	12- 30	1.402±	1.616	174	24.0	24.0	70.0
364	35:20	99.1±	47.8	18- 30	1.423±	1.021	210	17.0	13.0	300.0
365	35:21	36.4±	29.2	60- 90	.770±	.150	202	10.0	11.0	15.0
366	35:21	10.3±	8.0	22- 30	.318±	.035	290	12.0	27.0	35.0
367	35:21	14.5±	133.1	16- 22	3.078±	1.865	135	6.2	6.8	7.1
368	35:22	135.0±	115.2	18- 22	2.178±	1.766	166	11.0	28.0	30.0
369	35:22	110.8±	87.9	20- 30	2.350±	1.368	172	12.0	27.0	30.0
370	35:22	.0±	.0	90- 90	.333±	.024	164	11.0	13.0	14.0
371	35:22	.0±	.0	90- 90	.394±	.054	270	8.3	10.0	30.0
372	35:22	146.9±	240.0	18- 25	4.212±	4.650	170	6.3	8.0	20.0
373	35:22	.0±	.0	45- 45	1.141±	.050	253	11.0	25.0	25.0
374	35:22	10.4±	29.2	10- 16	1.133±	.301	94	8.5	21.0	300.0
375	35:23	-24.1±	174.7	90-180	2.832±	3.433	153	8.0	11.0	12.1
376	35:23	3.3±	131.0	18- 36	2.188±	1.417	182	9.0	26.0	30.0
377	35:23	.0±	.0	60- 60	.313±	.078	229	12.0	14.0	26.0
378	35:23	38.4±	44.3	22- 25	.785±	.914	131	8.0	17.0	30.0
379	35:24	106.8±	33.9	18- 60	.505±	.249	175	11.0	13.0	14.0
380	35:24	.0±	.0	36- 36	.240±	.038	229	14.0	22.0	55.0
381	35:25	8.6±	7.3	20- 22	.552±	.107	258	45.0	60.0	280.0
382	35:25	.0±	.0	60- 60	.965±	.260	251	9.0	17.0	30.0
383	35:25	13.3±	76.9	45- 60	1.480±	.722	180	11.5	21.0	130.0
384	35:25	-65.7±	216.3	60- 90	2.223±	3.107	192	6.5	6.9	7.1
385	35:26	.0±	.0	60- 60	.732±	.039	224	21.0	27.0	45.0
386	35:26	-86.1±	47.9	22- 36	3.317±	1.342	216	11.5	35.0	80.0
387	35:27	-43.9±	42.8	22- 25	.523±	.435	49	24.0	26.0	27.0
388	35:27	-10.0±	8.1	36- 45	.628±	.183	224	8.5	17.0	45.0
389	35:27	-44.4±	157.7	60- 90	2.526±	3.731	172	12.0	26.0	27.0
390	35:27	264.0±	139.1	11- 20	4.234±	3.250	167	10.0	28.0	30.0
391	35:29	87.6±	23.5	30- 60	1.219±	.134	185	8.5	11.0	13.0
392	35:29	8.7±	60.4	25- 30	1.387±	.629	249	10.0	26.0	30.0
393	35:30	100.1±	253.7	45- 60	3.841±	2.693	180	8.0	8.5	9.0
394	35:30	119.7±	857.8	45-180	12.508±	13.684	64	6.9	7.5	11.0
395	35:31	100.7±	84.1	90-180	3.019±	2.270	150	7.5	7.7	8.0
396	35:32	6.8±	5.3	22- 25	.353±	.043	252	35.0	40.0	45.0
397	35:33	.0±	.0	25- 25	1.049±	.013	261	8.8	19.0	27.0
398	35:33	11.4±	10.2	36- 45	.631±	.093	299	13.0	29.0	40.0
399	35:33	202.4±	21.3	30- 60	2.228±	.077	167	7.8	9.0	11.0
400	35:34	.0±	116.9	36- 45	3.569±	2.790	209	9.8	13.0	30.0

#	TIME MIN:SEC	VT (M/SEC)		L (M)	VR (M/SEC)		PHI (DEG)	RHO (MICROMETERS)		
								MIN	BEST	MAX
401	35:34	270.0±	230.4	36- 45	7.086±	5.259	210	15.0	15.0	40.0
402	35:35	8.3±	6.6	30- 36	.231±	.090	196	12.0	27.0	90.0
403	35:35	140.3±	131.1	45- 60	1.575±	1.076	16	45.0	46.0	50.0
404	35:36	.0±	.0	90- 90	1.333±	.795	258	8.8	28.0	55.0
405	35:37	30.1±	91.4	22- 36	1.579±	1.028	224	15.0	35.0	90.0
406	35:37	4.0±	21.5	22- 25	1.496±	.154	249	7.5	10.0	11.0
407	35:38	.0±	.0	60- 60	.279±	.001	90	11.8	20.0	30.0
408	35:38	7.7±	6.3	16- 20	.209±	.017	196	12.0	35.0	45.0
409	35:38	-11.9±	0.5	11- 15	1.027±	.435	355	11.0	24.0	25.0
410	35:39	-3.6±	50.0	45- 60	2.124±	.644	346	9.8	30.0	80.0
411	35:39	-143.0±	117.6	90-180	4.617±	3.537	237	7.0	8.0	9.8
412	35:40	-31.8±	23.9	60- 90	1.137±	.110	265	8.0	22.0	25.0
413	35:40	55.7±	497.9	60-180	10.277±	9.446	287	6.4	6.8	7.1
414	35:40	.0±	.0	60- 60	.237±	.035	270	9.0	19.0	30.0
415	35:40	.0±	.0	180-180	1.991±	1.473	337	6.8	6.9	7.1
416	35:40	296.3±	110.5	60-180	4.970±	1.467	261	9.1	10.2	11.8
417	35:40	-36.0±	27.1	36- 45	2.653±	.715	196	12.0	15.0	200.0
418	35:42	-2.4±	29.2	8- 12	.633±	.393	118	8.8	21.0	32.0
419	35:42	72.9±	17.7	12- 22	1.494±	.326	318	15.0	16.0	40.0
420	35:43	.0±	.0	60- 60	.082±	.024	240	13.0	30.0	40.0
421	35:43	.0±	.0	60- 60	.373±	.155	14	7.8	9.0	23.0
422	35:43	3.3±	21.0	18- 20	.377±	.179	127	8.2	15.0	22.0
423	35:44	-.1±	7.9	25- 30	.148±	.122	154	40.0	40.0	40.0
424	35:45	.0±	27.0	45- 60	.540±	.297	204	9.9	16.0	25.0
425	35:46	.0±	.0	90- 90	.075±	.008	270	9.0	9.4	9.8
426	35:46	.0±	.0	30- 30	.232±	.015	22	17.0	30.0	105.0
427	35:47	.0±	54.0	60- 90	.252±	.235	30	8.5	9.1	9.8
428	35:48	.0±	.0	90- 90	.283±	.005	259	8.8	20.0	25.0
429	35:49	.0±	.0	90- 90	2.728±	.882	196	7.8	12.0	20.0
430	35:50	2.4±	17.5	36- 45	.223±	.074	302	15.0	15.0	28.0
431	35:50	-.8±	15.7	15- 18	.434±	.185	211	48.0	50.0	53.0
432	35:51	.0±	.0	90- 90	.511±	.008	270	6.0	7.0	8.0
433	35:52	9.1±	158.7	60- 90	3.267±	2.304	243	6.6	8.5	10.2
434	35:53	8.2±	24.1	9- 12	.896±	.060	297	10.0	32.0	80.0
435	35:53	6.8±	6.0	22- 25	.147±	.107	172	35.0	53.0	60.0
436	35:53	-32.2±	29.8	18- 22	1.255±	.316	67	6.1	21.0	28.0
437	35:55	.0±	.0	45- 45	.667±	.083	292	16.0	38.0	40.0
438	35:56	183.2±	31.0	12- 22	4.325±	.043	43	7.8	8.0	20.0
439	35:56	.0±	.0	90- 90	1.376±	.223	149	6.3	6.5	6.8
440	35:57	6.3±	11.9	16- 25	.375±	.249	160	23.0	65.0	100.0
441	35:57	14.5±	13.1	30- 36	1.264±	.169	245	7.0	8.0	9.5
442	35:59	.0±	.0	60- 60	.273±	.022	66	15.0	15.0	40.0
443	36:00	31.1±	30.4	30- 45	1.021±	.662	300	35.0	38.0	48.0
444	36:01	27.0±	101.4	60- 90	2.290±	1.370	341	7.0	11.0	14.0
445	36:01	.0±	.0	90- 90	1.263±	.064	355	6.9	7.2	10.0
446	36:02	169.2±	170.5	25- 45	5.830±	4.167	60	6.8	8.0	9.5
447	36:02	34.6±	28.1	60- 90	1.131±	.404	270	5.5	7.9	8.0
448	36:03	8.1±	6.6	30- 36	.475±	.023	226	11.0	43.0	50.0
449	36:05	.0±	.0	90- 90	.209±	.018	270	9.0	21.0	22.0
450	36:06	-93.6±	81.1	90-180	3.128±	2.287	246	7.0	7.7	8.0

ORIGINAL PAGE IS
OF POOR QUALITY

#	TIME MIN:SEC	VT (M/SEC)		L (N)	VR (M/SEC)		PHI (DEG)	RHO (MICROMETERS)		
								MIN	BEST	MAX
451	36:05	.0±	.0	90- 90	.487±	.015	203	5.0	14.0	25.0
452	36:06	-38.2±	50.4	36- 45	.554±	.761	270	5.5	5.5	6.1
453	36:08	.0±	.0	90- 90	2.186±	.595	133	7.0	10.0	14.0
454	36:10	-111.9±	97.9	90-180	2.642±	2.094	305	7.2	7.6	8.0
455	36:11	.0±	.0	180-180	2.255±	.079	300	8.0	10.0	14.0
456	36:11	.0±	.0	25- 25	.433±	.013	121	6.0	7.8	8.0
457	36:11	.0±	.0	180-180	.099±	.090	270	6.2	6.6	6.9
458	36:12	42.5±	44.5	60- 90	1.722±	.775	248	6.0	7.2	8.5
459	36:13	.0±	16.2	36- 45	.338±	.172	263	14.0	35.0	48.0
460	36:15	31.2±	27.0	60- 90	.500±	.308	299	9.5	23.0	27.0
461	36:16	-42.1±	35.6	60- 90	1.948±	.891	236	8.0	9.0	15.0
462	36:18	-98.6±	83.9	90-180	3.276±	2.236	207	9.0	30.0	210.0
463	36:18	-34.1±	30.2	60- 90	1.259±	.807	99	6.8	7.9	8.0
464	36:20	-11.8±	92.7	60- 90	1.771±	1.660	229	8.5	11.0	25.0
465	36:21	.0±	.0	30- 30	.079±	.002	200	40.0	45.0	47.0
466	36:23	.0±	.0	60- 60	.373±	.054	235	8.5	15.0	22.0
467	36:25	-93.6±	81.1	90-180	3.073±	2.350	205	7.3	7.8	8.2
468	36:27	-305.9±	462.4	60-180	12.881±	7.891	243	7.2	9.5	13.0
469	36:27	320.7±	262.1	90-180	9.256±	6.573	255	6.2	6.4	7.6
470	36:27	.0±	.0	60- 60	1.814±	.000	248	7.2	28.0	50.0
471	36:27	90.8±	78.6	45- 60	2.218±	1.192	297	8.5	21.0	28.0
472	36:32	1.1±	8.9	25- 30	.177±	.165	203	6.6	7.2	7.8
473	36:33	-13.3±	448.9	90-180	7.425±	8.377	224	9.0	10.0	11.0
474	36:36	.0±	.0	45- 45	1.987±	.283	238	8.5	9.0	9.5
475	36:37	-286.6±	408.8	60-180	10.316±	9.473	256	5.8	9.0	11.5
476	36:38	32.0±	147.7	45- 60	2.143±	1.531	247	14.0	30.0	65.0
477	36:43	-55.8±	80.5	18- 25	1.538±	1.180	42	11.0	32.0	90.0
478	36:43	-43.2±	39.3	60- 90	1.471±	1.107	229	8.0	8.7	9.6
479	36:44	96.0±	83.8	90-180	1.363±	.847	279	9.3	10.5	13.0
480	36:44	.0±	.0	180-180	1.512±	.180	334	7.0	9.0	11.0
481	36:45	-6.4±	6.7	25- 30	.056±	.019	307	12.0	14.0	35.0
482	36:45	-18.2±	24.2	30- 36	1.735±	.494	275	9.0	24.0	25.0
483	36:46	45.4±	5.6	22- 30	.383±	.116	211	11.0	13.0	35.0
484	36:47	.0±	.0	90- 90	3.245±	.013	3	5.0	5.8	6.5
485	36:47	.0±	.0	180-180	4.201±	2.055	174	8.0	10.0	12.0
486	36:47	73.4±	1063.1	90-180	19.762±	21.895	229	7.0	7.4	8.0
487	36:54	1.5±	23.5	16- 20	.863±	.377	61	45.0	90.0	200.0
488	36:54	.0±	.0	180-180	1.229±	.047	140	7.0	40.0	105.0
489	36:54	-253.4±	235.4	90-180	8.188±	7.301	131	5.6	6.3	6.9
490	36:59	-6.7±	57.1	60- 90	.973±	1.042	116	9.6	9.9	10.1
491	36:59	1.0±	41.0	36- 45	.821±	.719	224	16.0	45.0	48.0
492	37:05	15.1±	287.7	90-180	4.293±	4.600	237	6.9	8.0	10.0
493	37:05	139.9±	131.2	90-180	4.093±	3.480	255	6.2	6.9	7.5
494	37:06	.0±	.0	90- 90	1.364±	.277	7	6.2	7.5	9.0
495	37:06	-44.2±	37.3	60- 90	1.154±	.275	277	7.0	7.4	8.0
496	37:07	.0±	.0	60- 60	1.559±	.092	263	6.8	8.2	8.3
497	37:08	405.0±	345.5	22- 36	7.900±	6.038	169	8.9	9.2	13.5
498	37:09	.0±	.0	36- 36	.572±	.077	281	17.0	42.0	48.0
499	37:09	66.0±	50.4	60- 90	.801±	.212	265	9.0	11.0	12.0
500	37:11	-6.3±	83.6	16- 30	1.680±	.866	185	40.0	52.0	90.0

IV. DISCUSSION

In this section the results of this study are presented in graphic form. The first three plots (Figs. 2, 3, 4) show $\log VT$, ϕ , and $\log \rho$, respectively, plotted against particle number. The particle number itself is a monotonic function of time so that any trends apparent in these plots can be interpreted as functions of time. In general, the particle parameters do not appear to be strongly time dependent.

Figure 5 is a plot of $\log VT$ vs $\log \rho$. A definite correlation between velocity and size is apparent; the smaller the particle, the faster is its transverse space velocity.

The final three graphs show the frequency distributions of $\log VT$, $\log \rho$, and ϕ (Figures 6, 7, and 8, respectively). The $\log VT$ distribution (Figure 6) appears to be Gaussian-like. This distribution is not limited to any great extent by instrument detectability; it represents the true velocity distribution of the particles. The particle size distribution (Figure 7), on the other hand, is limited by the detectability of the instrument. The minimum size particle that can be detected is about $5 \mu\text{m}$ in radius (for a detailed examination of detectability limits, see Schuerman and Weinberg, 1976). Finally, the frequency distribution of ϕ is shown in Figure 8. The two strong peaks near 180° and 270° suggest the anti-direction of at least two strong sources for the contaminants.

IVa. Suggestions for future study.

Beside providing directly the size and velocity distributions of the contaminant particles, this study illuminates other relationships which could be expanded to determine the origin and solution to eliminating the contaminant particles. Figure 5 implies a relationship between size and velocity; the larger particles travel more slowly. This would be true if the source from which the particles came needed a certain threshold energy (i.e. vibrational, thermal, etc.) to dislodge them. If all particles from a given source were dislodged with the

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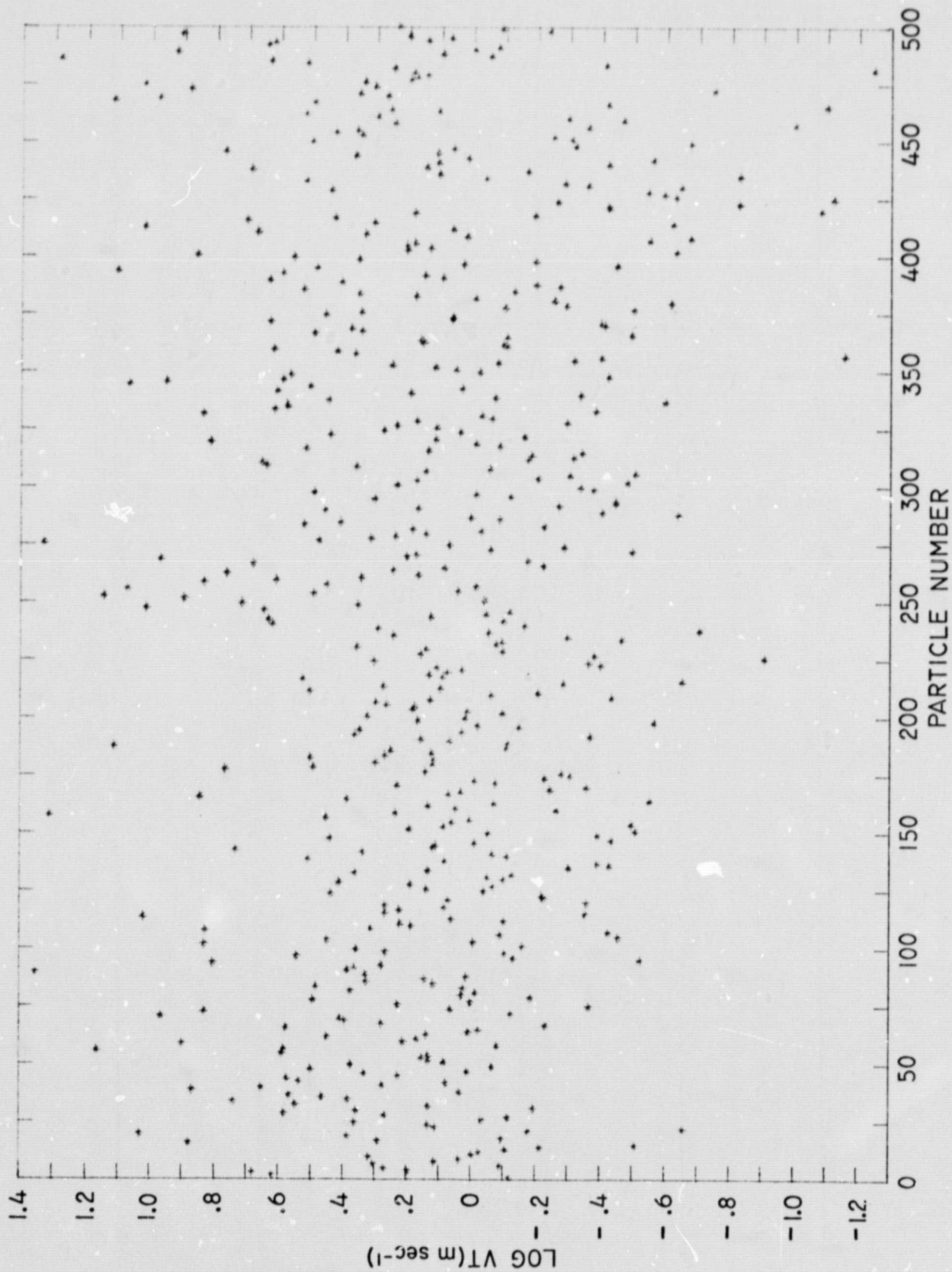


Fig. 2. Transverse space velocity as a function of particle number. The particles were selected in chronological order, and therefore the abscissa is a measure of time. A very slight decrease in particle transverse velocity with respect to time is discernable.

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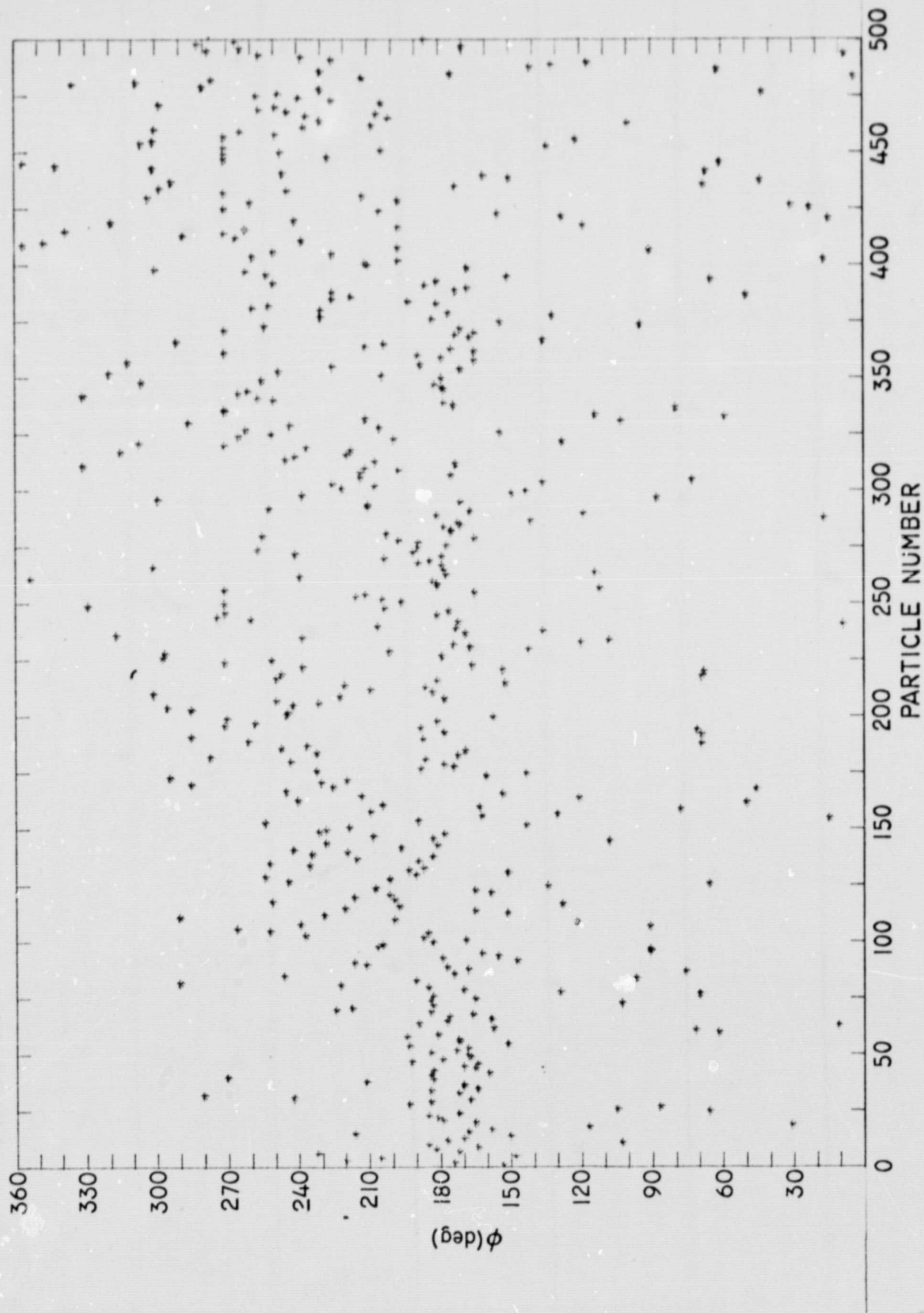


Fig. 3. The direction of transverse particle motion vs. particle number (time). The direction $\phi = 180^\circ$ predominates initially, and then a second direction, $\phi = 270^\circ$, becomes prominent. The graph seems to indicate at least two major (and time dependent) particle origins.

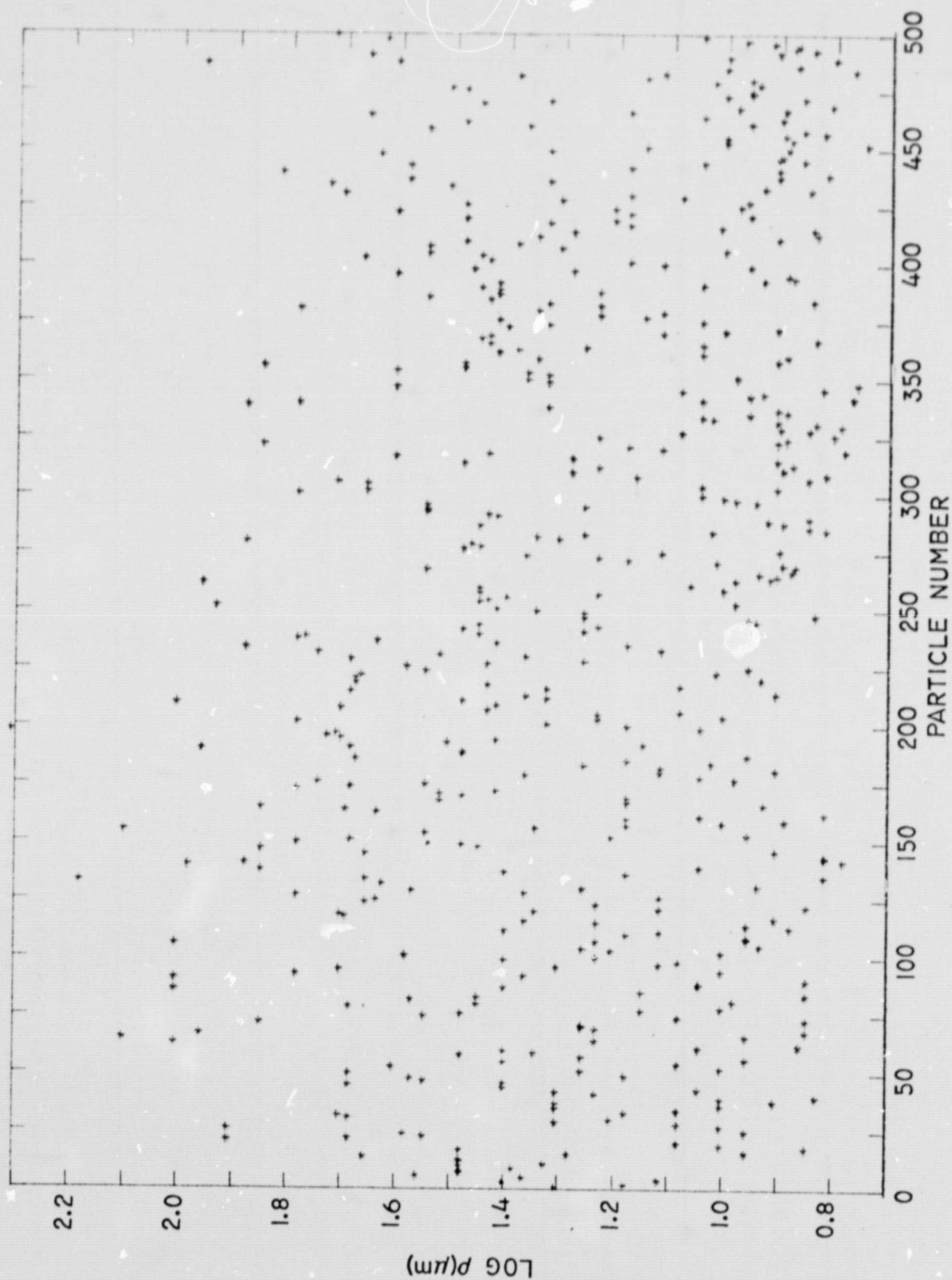


Fig. 4. Logarithm of the particle radius vs. particle number (time). A slight decrease in particle size with respect to time is discernable.

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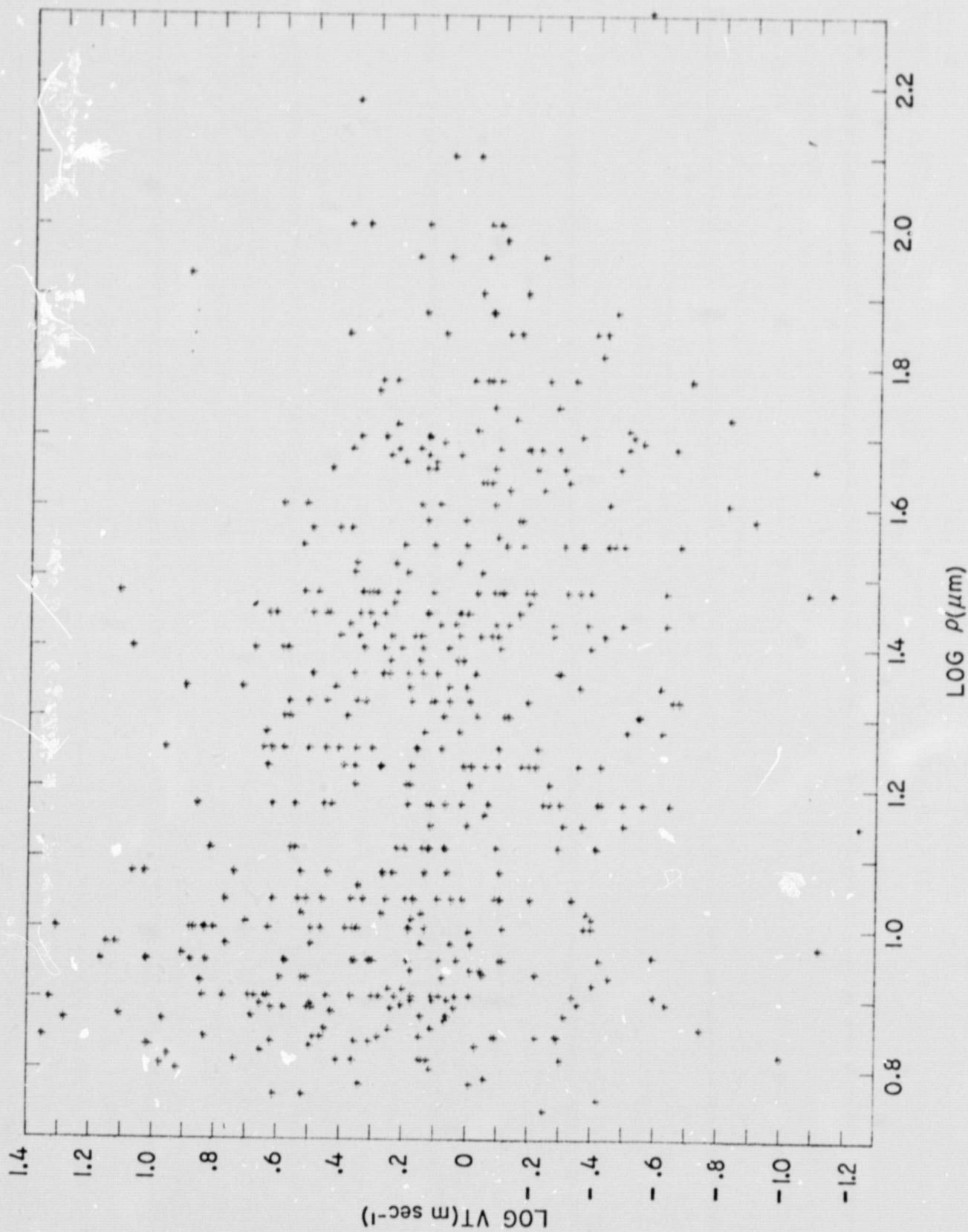


Fig. 5. The correlation of transverse velocity with particle size (radius). A definite relationship exists in the sense that smaller particles have larger velocities.

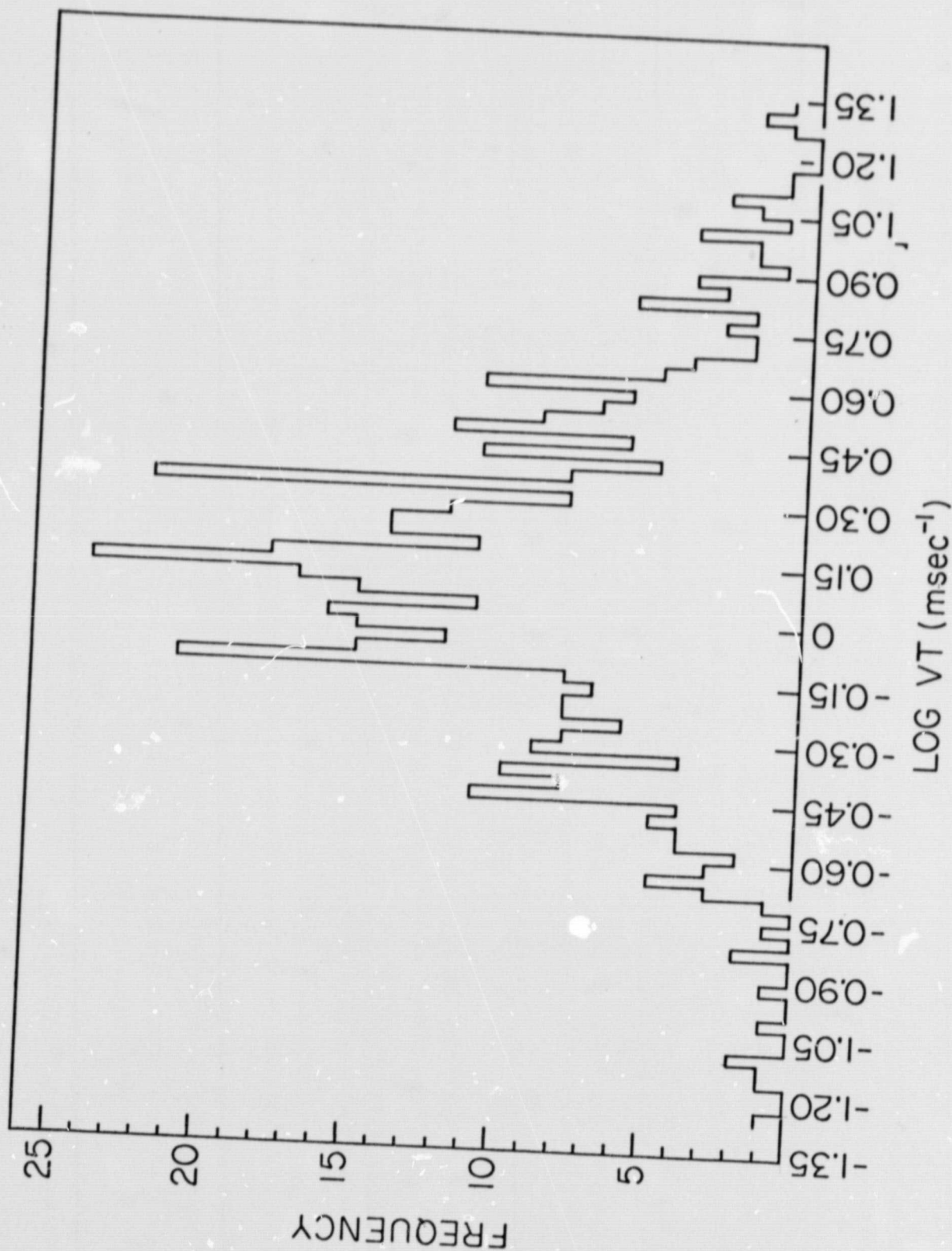


Fig. 6. The distribution of transverse velocities. The histogram suggests a Gaussian (normal) distribution in log VT.

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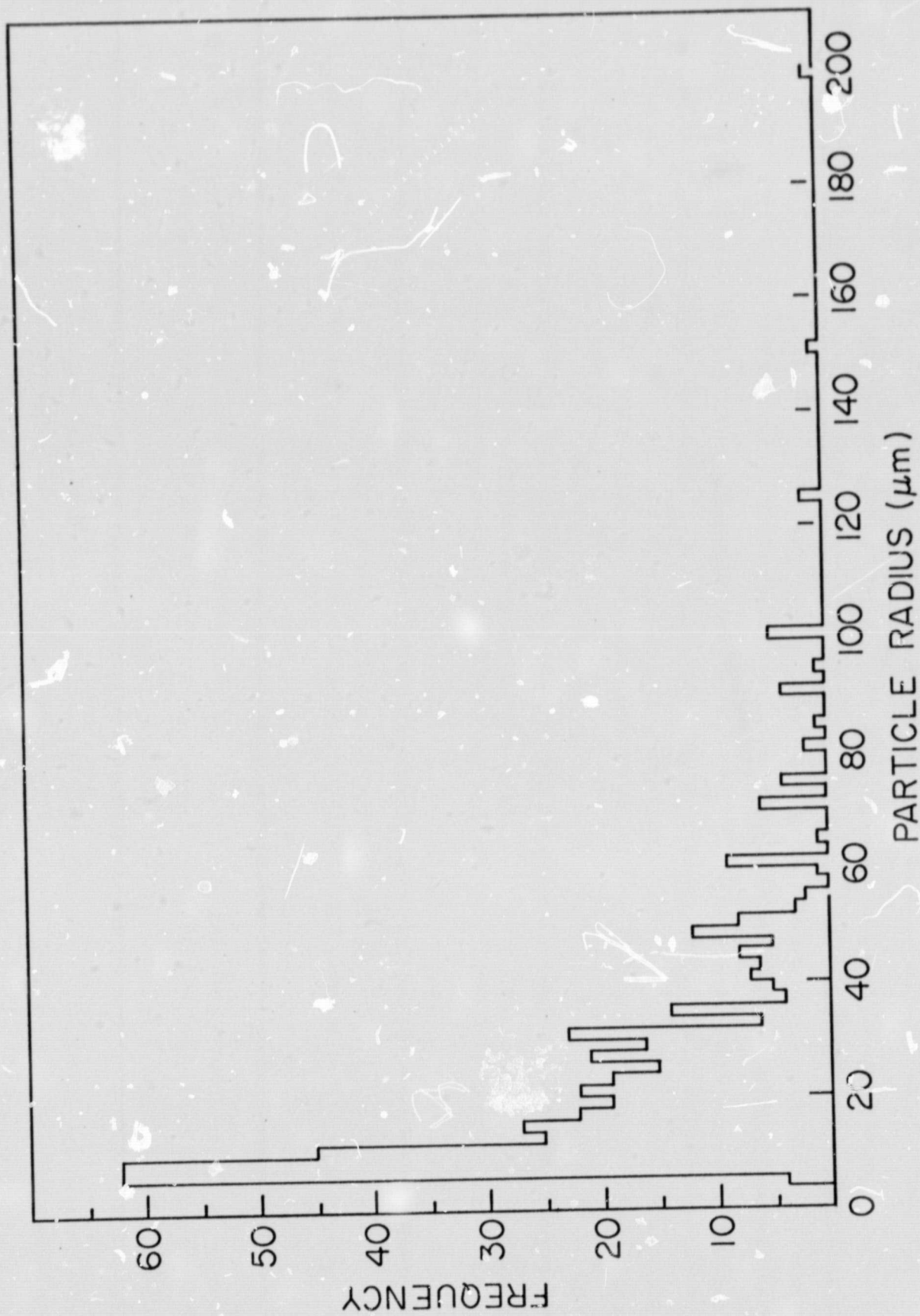


Fig. 7. The distribution of particle sizes. The lower cutoff at $5\text{ }\mu\text{m}$ is due to the sensitivity of the S052 coronagraph; the true distribution apparently continues (in an unknown manner) for particles smaller than $5\text{ }\mu\text{m}$.

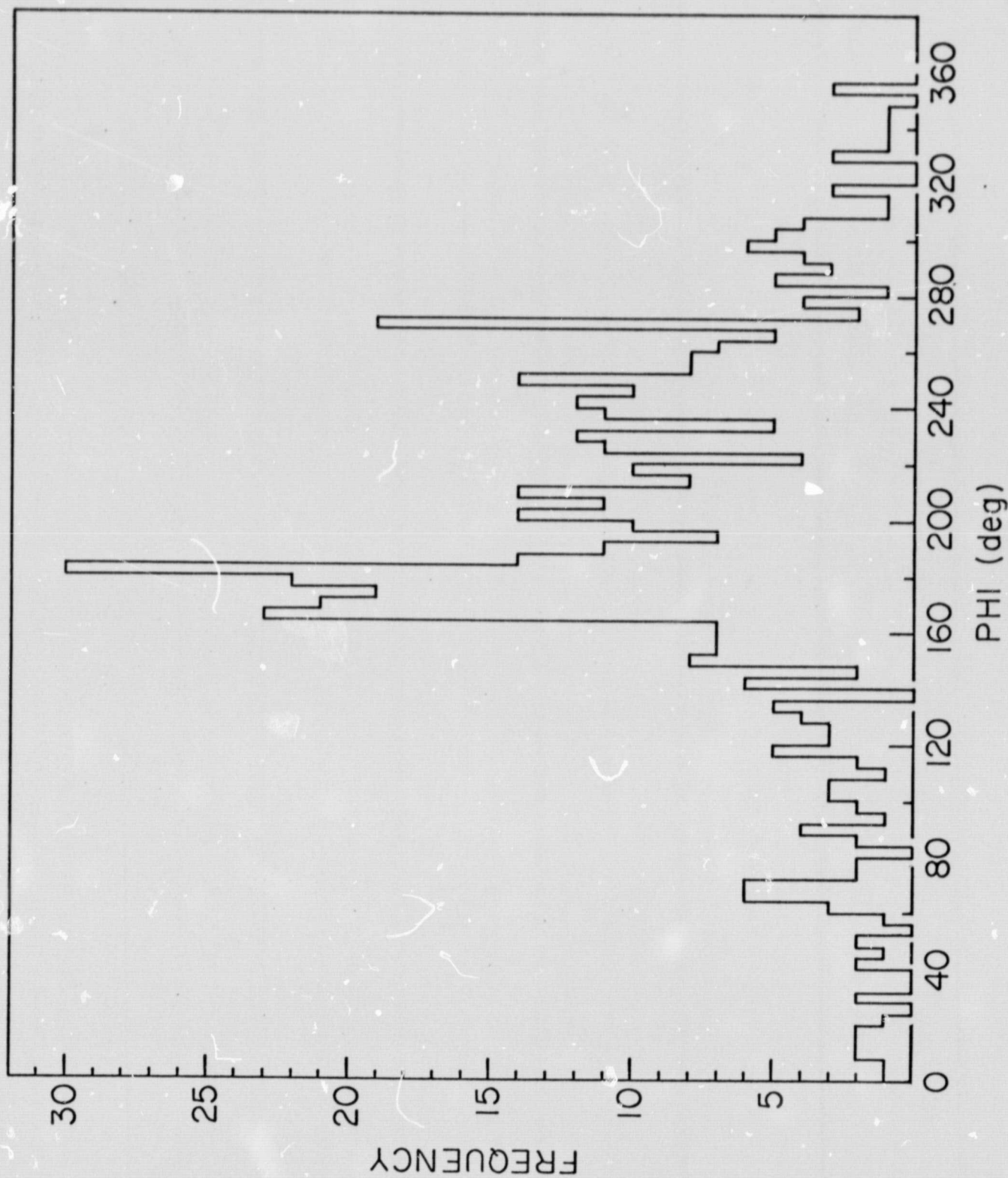


Fig. 8. The distribution of transverse particle directions. $\phi = 0^\circ$ corresponds to the particle moving from left to right across the TV monitor; $\phi = 90^\circ$ corresponds to motion from bottom to top of screen. The anti-directions of at least two sources are evident: $\phi \approx 180^\circ$ and $\phi \approx 270^\circ$.

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same kinetic energy, the more massive particles would move more slowly. Also, it would be of great interest to attempt to geometrically locate the region of the source of these particles on the spacecraft surface. Such a study was previously proposed to be incorporated into this work, but it was not funded. If the source regions were identified, it would be interesting to apply the energy concept mentioned above to see if the source regions had the same or different threshold energies.

V. REFERENCES

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Coronagraphic technique to infer the nature of the Skylab particulate environment

Donald W. Schuerman, David E. Beeson, and Frank Giovane

Photographs taken with the High Altitude Observatory's White Light Coronagraph (Skylab experiment S052) are shown to contain information on the sizes and velocities of contaminant particulates around Skylab. Sizes as small as $5\text{ }\mu\text{m}$ (radius) are derived for particles as far away as 200 m from the spacecraft. The random error in the size derivation is about 30%, and no particle larger than $120\text{ }\mu\text{m}$ was observed. Transverse velocities are determined to within 0.08 m sec^{-1} and radial velocities to within 9 m sec^{-1} . The S052 data bank contains about 3500 contaminated frames from which the nature of the Skylab environment can be inferred.

I. Introduction

The nature of the self-induced particulate environment of spacecraft is not well known due to a previous lack of reducible, optical data. With the advent of numerous Shuttle missions, it is imperative that the size range, number density, sources, and sinks of these particles be understood because they may be the limiting factor for optical and ir experiments.

The High Altitude Observatory's White Light Coronagraph on Skylab (experiment number S052) produced over 35,000 photographs of the solar corona. Approximately 10% of these frames contain evidence of particulates in the environs of the spacecraft. The contaminated frames now represent the only existing large body of optical data relevant to the problem. This investigation attempts (1) to define the S052 limits of particle detectability, (2) to enumerate which particulate parameters can be inferred, and (3) to note the accuracy with which these parameters can be found in practice.

The S052 coronagraph was designed to observe the *K*- and *F*-coronal components over the angular range of $0.5\text{--}1.6^\circ$ from sun center. A series of three external disks and an internal Lyot disk was employed to achieve a rejection factor (ratio of scattered light to the intensity of the sun's surface) of almost 10^{-10} . The resulting vignetting characteristics of the optical design were used to advantage to suppress the extreme radial gradient of the coronal light to a net dynamic range of a factor of 16. The plate scale is $482 \pm 3\text{ sec of arc mm}^{-1}$, so the focal

length f is 428 mm; the diameter A of the objective is 31.23 mm. A more complete description of the system is presented by MacQueen *et al.*¹

The actual film used in this pilot study is a first generation copy of eleven sequential S052 frames containing particle tracks. This film, along with pertinent instrumental data, have been provided by MacQueen, the principal investigator of the S052 experiment. This photographic sequence, initiated on day of year 159 (1973) at 0200 GMT, was selected only on the basis that it is representative of the contamination data.

II. Theory

A nearby particle moving within the field of view of the S052 white light coronagraph registers as a track of width a and length l on the film. The width of the track is defined by the circle-of-confusion (here assumed uniform) resulting from an out-of-focus point source and is a measure of the particle's distance L from the instrument. Since the coronagraph is focused at infinity, a and L are related by

$$a = (A/f)L \text{ for } a \geq e, \quad (1)$$

where e is the resolution of the system. When L is less than about 200 m, a is larger than e , and the particle's distance can be obtained directly from the film. The two other space coordinates of the particle (X, Y) can be found from the particle's film coordinates (x, y):

$$X/L = x/f \text{ and } Y/L = y/f. \quad (2)$$

The particle's space velocity (except for sign) can only be obtained if the track under consideration is entirely contained within a single photograph. Then the length l of the track is known. Consider any two points on the track separated by a distance on the film of Δl . The time Δt required for the particle image to traverse Δl is related to the frame exposure time T by

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$$\Delta t = \frac{\Delta L}{l}, \text{ provided } \frac{\frac{\Delta X}{\Delta L} \left(\frac{x}{l}\right) + \frac{\Delta Y}{\Delta L} \left(\frac{y}{l}\right)}{\left(\frac{\Delta X}{\Delta L}\right)^2 + \left(\frac{\Delta Y}{\Delta L}\right)^2} \ll 1 \quad (3)$$

for both points on the track. The inequality holds except for those few particles whose motion is mostly along the line of sight. The radial and transverse space velocities are then found by

$$V_r = \frac{\Delta L}{\Delta t} \text{ and } V_t = \left(\frac{(\Delta X)^2 + (\Delta Y)^2}{(\Delta t)^2} \right)^{1/2} \quad (4)$$

The transverse space velocity, in turn, is related to the rate of image motion v across the film by

$$v = \frac{fV_t}{L} \quad (5)$$

It is this image motion which determines an effective particle exposure time τ . At the center of the track an elemental area of the film is exposed to the moving circle-of-confusion of diameter a for a time

$$\tau = \frac{a}{v} = \frac{aL}{fV_t} = \frac{A}{V_t} \quad (6)$$

The film density of the particle track thus depends on τ ; the film background depends on the frame exposure time T .

Photometric measurements of the particle track can be used to derive the actual size of the particle. The energy/area incident on the film in the center of a track can be calculated if the spectral sensitivity of the system is known. The wavelength response of the S052 coronagraph is shown in Fig. 1. The monochromatic energy response of the film due to an out-of-focus particle image is then given by

$$E_p(\lambda) = \text{const} \cdot O(\lambda) \cdot F(\lambda) \cdot I_p(\lambda) \cdot \pi(A/2)^2 \cdot \tau / \pi(a/2)^2, \quad (7)$$

where $O(\lambda)$ and $F(\lambda)$ are defined in Fig. 1, and $I_p(\lambda)$ is the particle irradiance. If Eq. (7) is integrated over wavelength and normalized to the solar image through the same instrument, it becomes

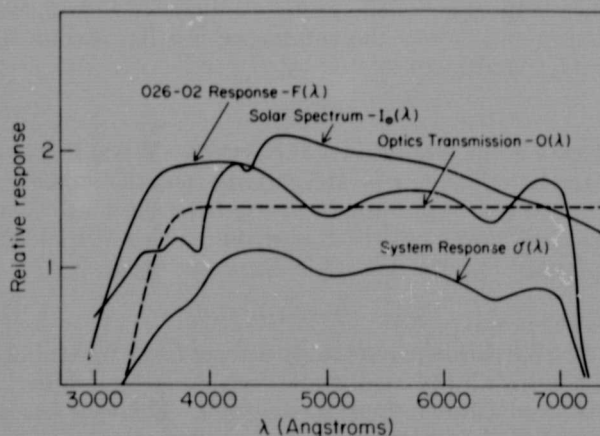


Fig. 1. The spectral responses associated with the S052 White Light Coronagraph. $F(\lambda)$ is the film (026-02) sensitivity; $\sigma(\lambda)$ results from $F(\lambda) \cdot I_{\odot}(\lambda) \cdot O(\lambda)$.

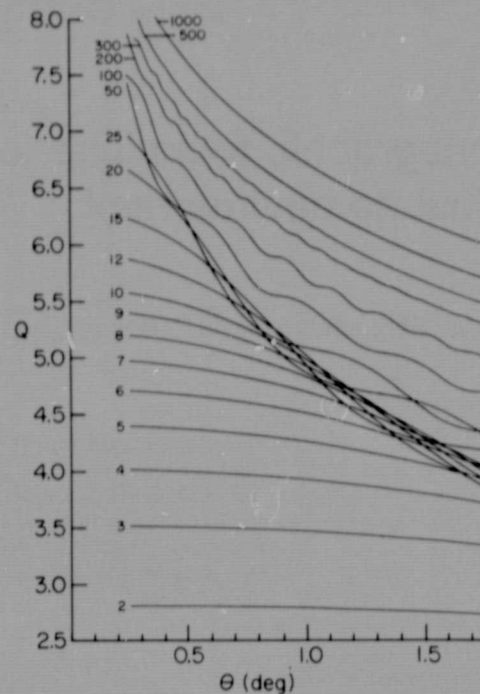


Fig. 2. The functions $Q = \log(q)$ vs scattering angle parameterized by particle radius for $2 \mu\text{m} \leq \rho \leq 1000 \mu\text{m}$. The scattering cross section q (μm^2) has been calculated from diffraction theory and averaged over the system wavelength response.

$$W = \frac{E_p}{E_{\odot}} = \frac{\int I_p(\lambda) O(\lambda) F(\lambda) d\lambda}{\int I_{\odot}(\lambda) O(\lambda) F(\lambda) d\lambda} \frac{4f^2 A \Omega_{\odot}}{\pi a^2 T V_t} \quad (8)$$

The results presented in the next section confirm that the particle irradiance $I_p(\lambda)$ is due to the scattering of sunlight by particles larger than a few microns in radius. For particles of this size and larger, the scattering process is well approximated by diffraction theory (Van de Hulst²):

$$I_p(\lambda) = I_{\odot}(\lambda) \frac{\rho^2 J_1^2 \left(\frac{2\pi\rho}{\lambda} \sin \theta \right)}{L^2 \sin^2 \theta}, \quad (9)$$

where ρ is the radius of the particle, θ is the scattering angle, and J_1 is the first-order Bessel function. Combining Eqs. (1), (8), and (9), we find

$$W = \frac{q 4 \Omega_{\odot}}{\pi T A V_t}, \quad (10)$$

where q is the system-weighted average,

$$q(\rho, \theta) = \frac{\int \frac{\rho^2}{\sin^2 \theta} J_1^2 \left(\frac{2\pi\rho}{\lambda} \sin \theta \right) \sigma(\lambda) d\lambda}{\int \sigma(\lambda) d\lambda}, \quad (11)$$

and $\sigma(\lambda)$ is the system response shown in Fig. 1.

The function $Q = \log_{10}(q)$ is plotted in Fig. 2 for various values of the particle radius ρ (μm). Since estimates of W and V_t can be made from the film at several values of θ along a given track, $q(\rho, \theta)$ is also determined experimentally. By matching $\log_{10}(q)$ with the curves in Fig. 2, a particle size can be estimated.

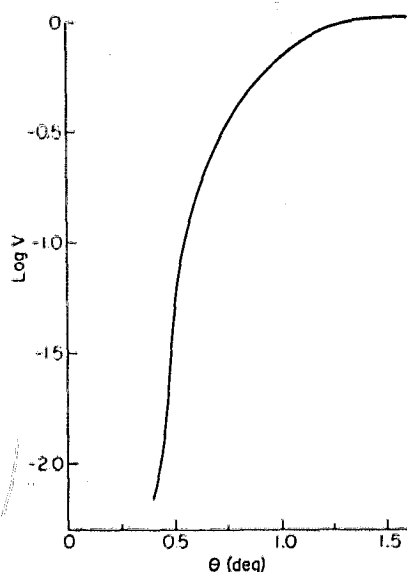


Fig. 3. The radial vignetting function. V , the effective transmission of the optical system as function of angular distance from sun center, must be included in the determination of the brightness of each particle track [Eq. (12)].

There exists a region of overlap in Fig. 2 in which the exact interpretation of particle size is difficult for a track which covers a narrow range of θ . The angular dependence of this effect is such that for $\theta \approx 1^\circ$, the photographic response from a $\rho = 10 \mu\text{m}$ particle is approximately equivalent to one with $\rho = 22 \mu\text{m}$, while for a smaller scattering angle of say, 0.5° , this degeneracy is well removed. The region of overlap shown in Fig. 2 is the vestige of the oscillations of J_1^2 in the integrand of Eq. (11) and, because of the weight factor $\sigma(\lambda)$, is unique to the S052 coronagraph. Since the coronagraph has such a large bandpass, the averaging process [Eq. (11)] keeps the region of overlap to a minimum. For a narrowband instrument the region of overlap would be much larger, and the oscillations in the individual curves of Fig. 2 would be much more pronounced. It should also be noted that since only diffraction theory is employed, no information concerning the chemical composition of the particle can be obtained. On the other hand, the function Q is very sensitive to the projected geometrical cross section of the particle, which, for ease of interpretation, is considered a circle of radius ρ .

III. Photographic Observations and Their Reduction

The sequence of eleven photos examined in this study contains four 3-sec frames, four 9-sec frames, and three 27-sec frames. It was found that no tracks both started and stopped on the 27-sec exposures. Those frames were not considered further, since the locations of the track end-points are crucial to size and velocity determinations. From the eight remaining photographs, sixty-one tracks were selected for analysis.

A Mann measuring engine was used to determine the track length l . A scanning densitometer was employed to obtain values of the track width a , the densities of

both the backgrounds and central regions of the image at several positions along the track, and a scan of the calibration wedge located in the center of each frame. The calibration of the step wedge in units of the sun's surface brightness (Poland *et al.*³) allowed us to construct density D vs $\log(E/E_\odot)$ curves for both the 3-sec and 9-sec exposures; $E_\odot$ is the energy per unit film surface which results from an image of the sun. The D - $\log(E/E_\odot)$ curves do not take into account the severe radial vignetting function V shown in Fig. 3. Any photometric measurement made within the annular field of view of the coronagraph must be corrected for this effect. Therefore, the quantity W , the midtrack particle energy used in Eqs. (8) and (10), is observationally determined by

$$W = \frac{E/E_\odot(\text{track} + \text{background}) - E/E_\odot(\text{background})}{V(\theta)} \quad (12)$$

once the $E/E_\odot$'s are obtained from the corresponding density measurements and the D - $\log(E/E_\odot)$ curves (see Schuerman and Weinberg⁴ for specific examples).

With a and W known on at least two portions of the track and the length of the track known as well, the theory of Sec. II applies, and the following quantities can be determined from a single track:

- (1) particle radius— ρ ;
- (2) characteristic distance of particle from spacecraft— L ;
- (3) transverse space velocity— $V_t = (V_x^2 + V_y^2)^{1/2}$ (without sign);
- (4) azimuthal angle of transverse velocity— $\phi = \tan^{-1}(V_y/V_x)$;
- (5) radial space velocity— V_r (without sign).

An indication of the random uncertainties in the above determinations can be found in most cases because any particular quantity has been overdetermined. For example, scans of the track at two points are sufficient to determine V_t and V_r . In fact, if the width of the track does not noticeably change along its length, only one scan is needed to determine V_t , and V_r is assumed to be zero. In many cases, three scans of a single track are used to determine V_t . Once V_t is established, the same three scans are used to determine three values of W , so a triplet of points is located on the scattering diagram of Fig. 2. The extent to which this triplet lies along a curve of constant ρ is indicative of the uncertainty in particle radius. The measurements from any one track thus yield two or three values of V_t and ρ . The spread in these numbers, when seen in the context of a large number of particle tracks, indicates the precision with which ρ and V_t can be determined. The same method is used for determining the uncertainties in V_r and L .

The ρ , V_t plane makes a convenient format for the discussion and presentation of the results for each track. Not only can ρ and V_t and their associated errors be plotted in this plane, but the limit of particle detectability can also be represented by this scheme. This is because $q(\rho, \theta)$ is proportional to WV_t , as shown in Eq. (10). At a fixed value of θ , the quantity WT has a minimum value $(WT)_{\min}$, below which no track can be distinguished. This minimum value is influenced by

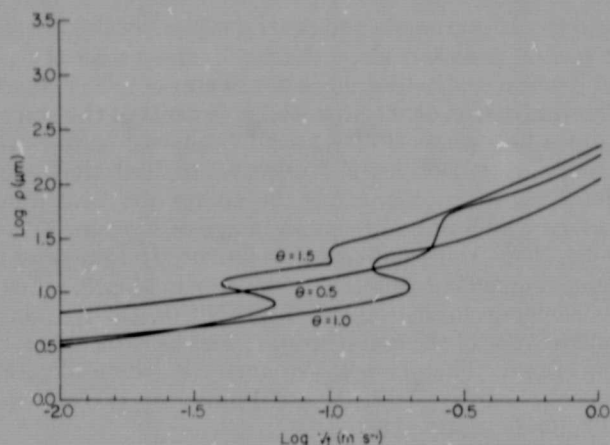


Fig. 4. The detectability limits for three scattering angles. Any particle below the curves in the $\log \rho$, $\log V_t$ plane will not be detected by the system.



Fig. 5. A typical S052 photograph showing contamination tracks. The support boom obscures part of the field of view on the left side of the frame; the step wedge is inset in the center of the occulting disk. The matrix of white dots at the right are LEMs, which code the housekeeping data. The nine contamination tracks analyzed in this photograph are labeled A through I.

the vignetting function via Eq. (12) and, therefore, depends on the radial position θ . We found the minimum value of WT to be about the same for both the 3-sec and 9-sec exposures: $(WT)_{\min} \approx 9 \times 10^{-10}/V(\theta)$. The value of $E/E_{\odot}$ (track background) $- E/E_{\odot}$ (background) associated with $(WT)_{\min}$ was 3.2×10^{-10} at a background level of 1.8×10^{-9} for the 3-sec exposure. Thus a track could be distinguished if its surface energy was 18% greater than the background at a film density of 0.73. By setting $WT = (WT)_{\min}$ in Eq. (10), detectability limits can be established in the ρ , V_t plane for fixed values of the scattering angle. These limits, parameterized by θ , are shown in Fig. 4. We define the system limit to be the bottom envelope of these curves.

One of the eight frames selected for study is shown in Fig. 5. It is a 3-sec exposure, the fourth frame of the

eleven-exposure sequence. The occulting disk, with the step wedge inset, subtends about 1.5 solar diameters. The disk support is to the left and obscures part of the corona. The matrix of bright spots on the right is due to light-emitting diodes in the instrument which code the housekeeping data. The nine particle tracks selected for study are labeled A through I. The scattering diagram associated with this frame is shown in Fig. 6. Three points on tracks E and G were measured; only two points were measured on the others. Each measurement, labeled 1, 2, or 3 after the track letter designation, is represented by a point in this diagram. Lines connect the points belonging to the same track. The estimate of particle size is made by associating the line(s) of a given track with the theoretical curves parameterized by particle radius.

The results of all eight photographs are shown in the $\log \rho$, $\log V_t$ plane of Fig. 7, along with the system limit. It is evident that the bottom of the distribution of points is interrupted by the system limit. The distribution itself undoubtedly continues downward to include particles smaller than the system can detect. On the other hand, if particles larger than 120 μm truly are present, they should be observable. Therefore, we interpret the upper cutoff of particle sizes to be a real effect and representative of the spacecraft environment at the time the pictures were taken. The upper bound

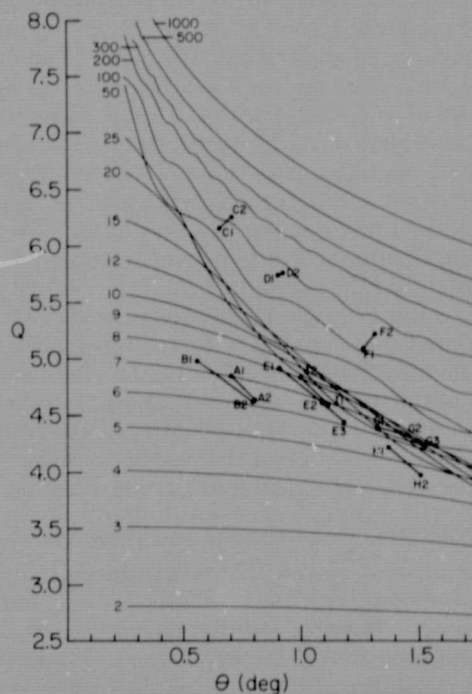


Fig. 6. The scattering diagram associated with the photograph of Fig. 5 for interpreting particle size. Each set of connected points are derived from photometric measurements of the nine particle tracks A through I. The extent to which any set falls on a curve of constant radius (μm) is a measure of the uncertainty in the size of the particle.

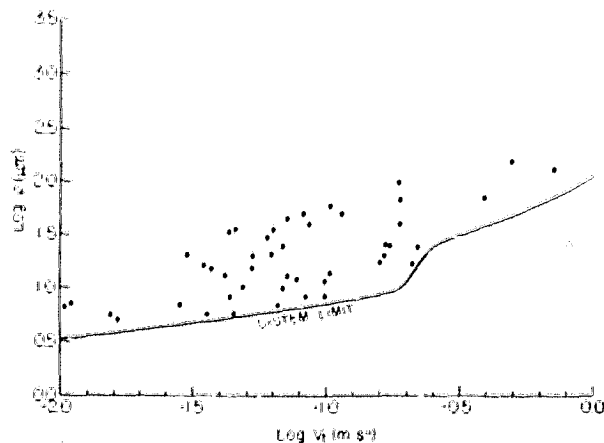


Fig. 7. Plot of photographic results. All particles that were analyzed are shown in the $\log \mu$, $\log V_t$ plane along with the system limit.

on V_t , on the other hand, arises because of the restriction that a particle image must both start and stop on the frame. It does not represent the true velocity limit of the contamination cloud.

A summary of all the derived parameters is presented in Table I. In some cases, either a densitometer scan was positioned incorrectly on the track, or the track was not distinguishable above the background so some of the parameters could not be determined. These cases are represented by dashes in the appropriate columns of Table I. In that table the frames are presented in chronological order along with the track designation. The average radial velocity V_r of each particle is shown along with its standard deviation if two or more determinations of V_r were made. The column labeled L contains the range of particle distances as determined from measurements of the track width. The next two columns specify the transverse velocity. The one marked V_t gives the magnitude and its standard deviation (where possible), and the column labeled ϕ gives the track direction as seen on the photograph. The reference direction for ϕ is shown by the inset in Fig. 5. In that figure we have measured, for example, the angle ϕ to be 88° or 268° for track F . Since it cannot be determined whether the particle was moving up or down the track, we arbitrarily limit the range of angle to $0^\circ \leq \phi < 180^\circ$.

The last three columns include the best estimate of upper and lower bounds to the particle size. These are inferred from the scattering diagrams associated with each frame. The average particle size as determined from the best estimate column is $27 \mu\text{m}$. Since the sample is biased at least by the system limit, this number represents only an upper limit on the average of the true distribution.

The standard deviations in the V_t and V_r columns do not appear to be proportional to their velocity values, so the precision of the velocity determination should be expressed in absolute units. The average of the standard deviations of each of these two columns is used to define a mean error associated with the reduction

method. In this sense, the mean error in the determination of V_t is 0.08 m sec^{-1} , and for V_r it is 8.9 m sec^{-1} . The average of the lower and upper limit columns compared with the average of the best estimate column suggests that the precision in determining particle size is about 30%.

IV. Conclusions and Summary

From the S052 photographic data the following parameters are derived: the transverse space velocity to within 0.08 m sec^{-1} ; the radial velocity to within 9 m sec^{-1} ; and the particle size to within 30% for those particles closer than 200 m from the spacecraft. Since the coronagraph cannot detect particles smaller than $5 \mu\text{m}$ in radius, the size average of the true particle distribution must be smaller than the $27\text{-}\mu\text{m}$ average found in this study. But the upper limit of $120 \mu\text{m}$ seems to be a characteristic of the true size distribution.

We have used techniques similar to those developed here to investigate the S052 video data. Video data exist for periods prior to actual picture taking; the TV monitor was used to ensure that solar conditions warranted and that spacecraft contamination permitted photography. The video contamination data, which do not have the step wedge calibration or the spatial resolution of the photographic data, have the advantage that the restriction of a track starting and stopping on a given frame does not apply. The particle's velocity is determined from the video framing rate. The video study¹ shows that the average transverse space velocity is 1.2 msec^{-1} , compared with the 0.1 msec^{-1} found here. The photographic analysis, therefore, is limited to the slower particles.

Although in this paper we have not considered the origin of the particles, the angles ϕ of the particle tracks with respect to the instrument could be used in conjunction with spacecraft attitude data and particle velocity to identify the location(s) of the contamination source and thus to infer the chemical composition of the particulates. It is the size distribution and chemical makeup which determine whether spacecraft contamination poses serious threats to the sophisticated scientific experiments (particularly those operating in the ir) planned for future manned missions. The application of the techniques developed here to a much larger sample of the S052 data, along with the source determination discussed above, would be a major step in understanding the spacecraft environment.

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Table I. Photographic Results

Frame	Track	V_r	L	V_t	ϕ	ρ		
		Radial velocity (m sec ⁻¹)	Distance (m)	Transverse velocity (m sec ⁻¹)	Track angle in deg	Lower limit	Best estimate	Upper limit
1-3	A	4.5 ± 5.2	30-40	0.133 ± 0.023	141	8	12	18
1-9	D	0.8 ± —	16-24	0.051 ± —	143	—	—	—
	C	0.7 ± 0.5	23-28	0.015 ± 0.011	91	5	6	6
	F	1.7 ± 1.5	19-31	0.028 ± 0.011	155	6	7	8
	G	2.3 ± 6.0	37-49	0.080 ± 0.022	105	6	8	10
	H	0.6 ± 3.3	21-30	0.053 ± 0.048	150	8	15	25
	I	0.6 ± —	21-25	0.037 ± —	141	9	15	17
	L	1.7 ± 4.7	35-42	0.077 ± 0.051	120	7	12	17
	J	0.8 ± 1.5	23-35	0.045 ± 0.038	90	—	6	—
2-3	A	2.6 ± —	31-36	0.007 ± —	109	6	7	7
	B	4.4 ± —	40-62	0.011 ± —	92	6	7	8
	C	19.6 ± —	64-90	0.188 ± —	137	70	100	130
	D	25.6 ± —	84-126	0.392 ± —	62	60	70	80
	E	0.9 ± 0.8	32-35	0.069 ± 0.012	134	6	10	20
	F	7.4 ± —	34-44	0.192 ± —	88	50	65	80
	G	1.3 ± 1.3	19-22	0.048 ± 0.009	17	6	10	15
	H	0.9 ± —	22-24	0.016 ± —	165	5	5	6
	I	1.5 ± —	58-60	0.101 ± —	50	7	12	20
2-9	J	2.2 ± 3.8	69-85	0.065 ± 0.025	50	6	7	12
	M	0.4 ± —	43-45	0.035 ± —	87	10	16	27
	L	5.0 ± 13.0	105-136	0.166 ± 0.042	45	13	20	26
	N	0.0 ± —	^a 246-247	^a 0.220 ± —	46	23	25	30
	O	1.4 ± —	38-46	0.043 ± —	65	8	8	8
	Q	1.2 ± —	27-33	0.010 ± —	88	6	7	7
	T	5.2 ± 1.4	25-57	0.043 ± 0.018	154	25	35	45
	P	7.3 ± 18.0	39-98	0.062 ± 0.073	72	13	21	35
	R	1.4 ± 13.0	35-113	0.116 ± 0.065	68	40	50	55
	U	11.3 ± 13.0	42-128	0.190 ± 0.127	66	35	40	45
	V	1.7 ± 9.7	56-118	0.162 ± 0.033	55	12	18	25
	W	4.8 ± 4.6	75-115	0.173 ± 0.088	46	15	25	35
	Z	31.0 ± 89.0	78-140	0.717 ± 1.080	43	—	130	—
	BB	—	96	0.101 ± —	37	—	—	—
	AA	3.3 ± —	121-151	0.317 ± —	61	—	—	—
	X	3.2 ± 8.5	53-88	0.072 ± 0.018	49	7	13	20
	Y	1.4 ± 4.8	29-44	0.071 ± 0.049	69	35	45	55
3-3	B	—	50	—	52	10	15	21
	C	8.4 ± —	119-131	0.146 ± —	45	50	60	70
	A	1.4 ± 4.0	17-20	0.063 ± 0.024	139	30	35	40
	D	—	44	—	50	12	17	25
	E	21.1 ± —	38-41	0.035 ± —	61	5	6	6
	G	—	89	—	51	7	15	20
3-3	F	—	63	—	55	—	23	—
3-9	K	0.3 ± —	88-91	0.063 ± —	68	—	—	—
	H	0.5 ± —	72-74	0.045 ± —	54	30	35	40
	J	5.3 ± 0.2	68-101	0.086 ± 0.006	53	12	40	50
	I	1.0 ± —	113-119	0.053 ± —	51	10	20	25
	L	0.7 ± 0.4	67-71	0.030 ± 0.011	45	8	20	25
	M	2.2 ± 5.4	25-39	0.069 ± 0.000	53	20	25	25
	N	0.2 ± 4.0	29-47	0.042 ± 0.006	48	7	13	18
	O	—	258	0.344 ± —	43	—	—	—
	P	5.0 ± —	36-82	0.232 ± —	40	—	—	—
	Q	7.5 ± —	133-201	0.202 ± —	41	—	—	—
	R	5.9 ± —	153-184	0.098 ± —	42	5	8	22
	T	—	^a 225	^a 0.162 ± —	51	—	—	—
	S	0.3 ± 5.0	30-50	0.082 ± 0.061	54	25	50	75
4-3	D	—	70	—	56	—	6	—
	C	5.1 ± —	92-100	0.171 ± —	44	23	28	30
	A	5.2 ± 6.5	37-50	0.213 ± 0.118	23	10	17	25
4-9	F	—	90	0.059 ± —	43	—	30	—
	E	0.5 ± 20.0	54-163	0.488 ± 0.177	54	120	120	200
	G	—	74	0.058 ± —	43	—	—	—
Average		4.5		0.122		19	27	34
Average of the standard deviations		8.9		0.083				

^aProbably a lower limit.

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