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HIGH SPATIAL AND TEMPORAL RESOLUTION OPTICAL SEARCH FOR EVIDENCE OF METEOROID FRAGMENTATION

R. L. HAWKES
Physics Department, Mount Allison University, Sackville, NB, Canada E4L 1E6
(E-mail: rhawkes@mta.ca)

P. G. BROWN and N. R. KAISER
Physics and Astronomy Department, University of Western Ontario, London, ON, Canada N6A 3K7

A. J. FALOON, K. A. HILL and L. A. ROGERS
Physics Department, Mount Allison University, Sackville, NB, Canada E4L 1E6

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Abstract. A digital image intensified CCD camera with an electronically gated image intensifier was used to produce very short duration images of meteors. The observational system employed a 0.40 m F/4.5 Newtonian telescope to obtain high spatial resolution. A second intensified CCD camera was used to yield height information using parallax. At a typical meteor height one pixel (for the vertically oriented system) corresponded to about 1.1 m. A sampling of 59 mainly sporadic meteors was analyzed. There is clear variability from meteor to meteor, with many meteors (nearly 50%) showing only a small amount of wake, while some meteors (approximately 20%) have the off segments completely filled in.

Keywords: Ablation, fragmentation, high resolution, meteor, structure, wake

1. Introduction

The classical papers on wake (the degree to which the instantaneous light production region of a meteor is not a point source) have considered both photochemical (Halliday, 1958) and fragmentation and lag (McCrosky, 1958) mechanisms. The quantitative dustball model (Hawkes and Jones, 1975) predicts that cometary meteoroids should cluster into constituent grains during or prior to atmospheric ablation. Unless the size distribution of these grains is uniform, differential aerodynamic drag would be expected to produce wake (Fisher et al., 2000). Observational evidence of wake in faint meteors has proven to be elusive however, with most studies indicating only a small percentage of faint meteors with detectable wake (Robertson and Hawkes,

Current address: L. A. Rogers, Department of Physics, University of Ottawa, Canada
Current address: N. R. Kaiser, Department of Geology and Geophysics, University of Calgary, Canada

1992; Shadbolt and Hawkes, 1995; Fisher et al., 2000). In this study we used significantly improved spatial resolution accompanied with very short duration exposures to search for wake in faint meteors.

2. Equipment

A digital image intensified CCD camera (Intensified Retiga) with an electronically gated image intensifier was coupled to a 0.40 m F/4.5 Newtonian telescope to obtain high spatial and temporal resolution. The intensifier was gated in a mode with the gate on for exactly 1/5 of the exposure and off for 4/5 of the exposure time, and the repetition rate was 375 Hz. Therefore, the effective length of each exposure was 0.53 ms. The P43 phosphor used in the image intensifier has persistence of approximately 10% after 1.2 ms (however, because of the gating mode used in the intensifier the persistence is not really an issue in any case). The image covered 24.8 $\times$ 19.0 arc minutes (and in the mode used 676×518 pixels) so that at a typical meteor altitude one pixel (for the vertically oriented system) would correspond to about 1.1 m. A nongated video rate intensified CCD camera was mounted at a second location to yield height information for coincident events using parallax (Kaiser et al., 2005). Corrected meteor magnitudes were generally in the range from $+8$ to $+10$ magnitude (Kaiser et al., 2005) while apparent stellar limiting magnitude was $+13$ to $+14$ over the observing period. Samples of observed meteors are shown in Figure 1.

3. Analysis and Results

A sampling of 59 mainly sporadic meteors from September and October 2003 and May 2004 were analyzed (see Tables I and II). Sky conditions were

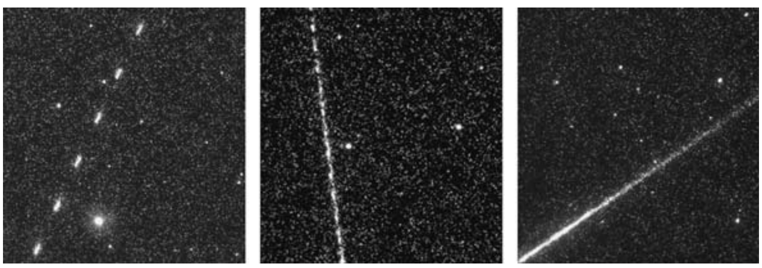

Figure 1. Classification system used for the data. A meteors have clear on and off segments as shown in the left image. W-meteors have the off segments totally filled in with wake as pictured on the right. P-meteors, shown in the middle, have variable degrees of fill in the images.

excellent on the nights used for these observations. The companion paper by Kaiser et al. (2005) provides full width half maximum (FWHM) values for stars observed with the system, which typically are 2 to 3 pixels. Since the effective exposure of the meteor is so short (0.53 ms), a time short compared with most of the atmospheric induced scintillation, we would expect that image blooming due to the seeing for meteors will be even less.

As a first stage of analysis we classified each meteor into the following categories: A, all segments have clear on and off features; P, portions of the trail have the segments filled in while some indication of the gating is still visible; and W, full wake with all off segments filled in on the meteor images. In the overall sample, 30 meteors were of type A, 19 of type P and 10 of type W.

For each A-type meteor we obtained a luminous intensity plot using the full width of the meteor trail. Nearby regions were used to calculate a mean local background intensity and standard deviation. We defined regions with at least two successive values two standard deviations above the mean local background as on. We calculated a duty cycle fraction (f) for each light curve segment, defined as the fraction of each cycle which was on. The results are shown in Figure 2, with the length of each line representing $\pm 1\sigma$ values. A point source meteor would produce a value of 0.2. It is obvious that almost none of even the A meteors are consistent with a point-source hypothesis.

In order to obtain a measure of the minimum possible wake we used the following relationship (1 pixel corresponds to 1.1 m resolution at a height of 100 km):

$$w_{\min} = \frac{1.1\tau_{\mathrm{p}}h}{100}(f - \sigma_f - 0.2) \tag{1}$$

Here $w_{\min}$ is the minimum wake component perpendicular to the line of sight, τ_{p} is the number of pixels in one cycle, h is the height (in km) of the meteor, f is the mean fraction of the cycle which is luminous averaged over all segments of the meteor, and σ_f is the standard deviation in f. We show in the last columns of the tables the minimum wake values for the A-class meteors.

It is not possible to give photometric masses or peak luminosity absolute magnitudes for these meteors since they are observed for only a small portion of the total light curve. The companion study by Kaiser et al. (2005) suggests that the absolute meteor magnitudes fall in the range from about $+8$ to $+10$. We do provide in Tables I and II the peak brightness of each meteor (averaged transverse to the trail) on an arbitrary scale with higher numbers corresponding to brighter meteors. This provides the reader with some indication of the relative intensity.

TABLE I

Data for 2003 telescopic gated observations

Date	UT	Type	f	ω	τ_p	h (km)	I	w_{min}(m)
9/30/03	5:36:02	A	0.43 ± 0.08	5.0 ± 0.6	21.90	90.0	140	3.3
9/30/03	5:37:03	A	0.37 ± 0.09	17.9 ± 3.1	78.00	90.0	62	6.2
9/30/03	5:47:04	A	0.34 ± 0.04	5.9 ± 0.4	25.67	90.0	118	2.5
9/30/03	5:55:07	W						
9/30/03	6:05:22	P						
9/30/03	6:35:24	A	0.31 ± 0.05	29.6 ± 2.1	129.00	75.0 ± 3.3	98	6.4
9/30/03	6:43:22	P						
9/30/03	6:53:30	P						
9/30/03	7:31:30	P				88.0 ± 3.1		
9/30/03	7:37:07	W				104.4 ± 6.6		
9/30/03	7:45:05	A	0.32 ± 0.05	16.9 ± 1.3	73.60	111.7 ± 11.1	97	6.3
9/30/03	7:50:06	A	0.34 ± 0.07	8.8 ± 1.0	38.56	83.5 ± 2.6	122	2.5
9/30/03	7:50:37	W						
9/30/03	8:08:50	P						
9/30/03	8:13:09	P				110.9 ± 3.9		
9/30/03	8:17:53	A	0.29 ± 0.02	19.9 ± 1.1	87.00	70.4 ± 1.2	142	4.7
9/30/03	8:41:40	A	0.35 ± 0.05	9.4 ± 0.8	40.82	93.0 ± 5.0	93	4.2
9/30/03	8:46:54	A	0.29 ± 0.06	28.7 ± 3.7	125.00	90.0	80	3.7
9/30/03	8:59:24	A	0.25 ± 0.03	3.4 ± 0.3	14.62	90.0	74	0.3
9/30/03	9:04:42	W						
9/30/03	9:11:29	A	0.38 ± 0.05	8.6 ± 0.8	37.54	80.9 ± 2.7	150	4.3
9/30/03	9:13:29	A	0.33 ± 0.04	29.0 ± 1.4	126.50	90.0	119	11.3
9/30/03	9:18:20	A	0.34 ± 0.10	9.1 ± 1.9	39.67	90.0	97	1.6
9/30/03	9:23:53	A	0.29 ± 0.03	6.7 ± 0.2	29.08	90.0	105	1.7
9/30/03	9:24:23	A	0.48 ± 0.11	12.8 ± 1.8	56.00	107.9 ± 8.2	160	11.3
9/30/03	10:07:39	A	0.29 ± 0.06	30.5 ± 3.5	133.00	90.0	112	4.0
10/1/03	5:50:16	P						
10/1/03	5:57:00	A	0.24 ± 0.05	6.6 ± 0.8	28.95	90.0	135	−0.3
10/1/03	6:40:25	A	0.51 ± 0.05	10.1 ± 0.7	44.22	80.7 ± 3.0	141	10.2
10/1/03	7:06:31	P						
10/1/03	7:06:56	A	0.43 ± 0.10	10.2 ± 1.0	44.64	90.0	116	5.7
10/1/03	7:21:43	A	0.54 ± 0.02	17.9 ± 0.5	78.20	77.4 ± 3.1	138	21.3
10/1/03	7:31:08	A	0.20 ± 0.03	36.0 ± 3.1	157.00	90.0	85	−4.7
10/1/03	7:36:45	P						
10/1/03	7:41:43	P				105.7 ± 3.9		
10/1/03	7:42:59	A	0.27 ± 0.06	19.9 ± 3.0	86.80	90.0	167	0.9
10/1/03	8:00:43	A	0.56 ± 0.26	34.2 ± 13.8	149.00	90.0	100	14.8
10/1/03	8:05:30	A	0.53 ± 0.09	20.6 ± 1.5	90.00	82.7 ± 3.0	116	19.6
10/1/03	8:26:19	A	0.35 ± 0.03	16.0 ± 0.6	69.90	81.4 ± 2.8	178	7.5
10/1/03	8:44:20	W						
10/1/03	8:51:11	P						
10/1/03	9:00:28	W						

The date and universal time, the trail classification (A, clear breaks in each cycle; P, partially filled in breaks; and W, breaks completely filled in), followed by the fraction (f) of each cycle which is luminous above background and the standard error in that fraction, the angular velocity (ω) in degrees per second and its uncertainty. This is followed by the length of one cycle of the trail in pixels (τ_p), the height in km (if no parallax measurement was possible a standard height of 90 km was used in the analysis) and the standard error on the height measurement. The smoothed maximum intensity (I) of the meteor (arbitrary units) is given followed by the computed minimum wake perpendicular component w_{min} in the final column, expressed in meter.

TABLE II
Data for 2004 telescopic gated observations. Columns have same meaning as in Table I

Date	UT	Type	f	ω	τ_p	h (km)	I	w_{min} (m)
5/13/04	8:22:24	W				83.0 ± 0.9		
5/17/04	4:11:05	A	0.30 ± 0.04	6.8 ± 0.7	29.76	90.0	111	1.8
5/17/04	4:24:29	P						
5/17/04	5:53:13	A	0.30 ± 0.04	4.9 ± 0.3	21.33	90.0	78	1.3
5/17/04	6:15:42	A	0.67 ± 0.08	3.3 ± 0.2	14.35	90.0	150	5.5
5/20/04	4:47:34	P	0.34 ± 0.07	20.2 ± 4.3	88.00	97.6 ± 2.8	132	6.6
5/20/04	5:01:39	P				81.5 ± 0.5		
5/20/04	5:45:33	P						
5/20/04	5:45:33	W						
5/20/04	6:46:08	P				92.4 ± 2.2		
5/20/04	8:23:57	A	0.54 ± 0.08	4.3 ± 0.3	18.65	90.0	217	4.8
5/26/04	3:05:29	W				95.8 ± 2.4		
5/26/04	3:07:18	P	0.66 ± 0.09	4.3 ± 0.4	18.55	86.6 ± 0.5	133	6.5
5/26/04	3:19:37	A	0.31 ± 0.04	8.4 ± 0.8	36.47	87.5 ± 0.6	153	2.5
5/26/04	3:38:05	W				83.4 ± 3.3		
5/27/04	5:10:42	P				78.1 ± 0.4		
5/27/04	7:35:40	P	0.62 ± 0.11	4.3 ± 0.5	18.55	90.0	67	5.7

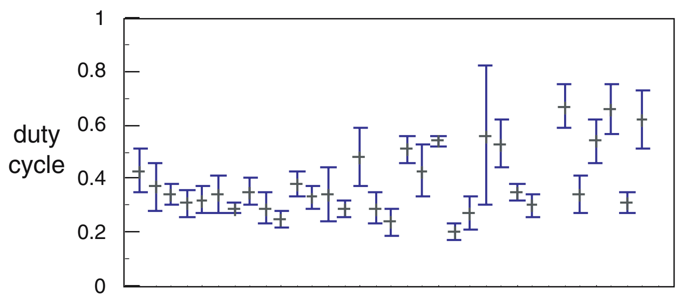

Figure 2. For A-type meteors the mean (averaged over all segments of the meteor light curve) fraction of the trail which has luminosity is plotted (the length of the line shows $\pm 1\sigma$). With our instrument a meteor with no wake would have 0.2 for the theoretical duty cycle with our equipment.

The velocity of the meteors cannot be determined, since the angle of the trail to the line of sight is not known. We plot in Tables I and II the angular velocity, ω which should be statistically related to the velocity. As shown in Figure 3, the amount of wake seems to increase with angular velocity of the meteor. This may suggest that cometary origin meteoroids, which would be expected to impact with higher geocentric velocities than meteoroids of asteroidal origin, produce larger amounts of wake.

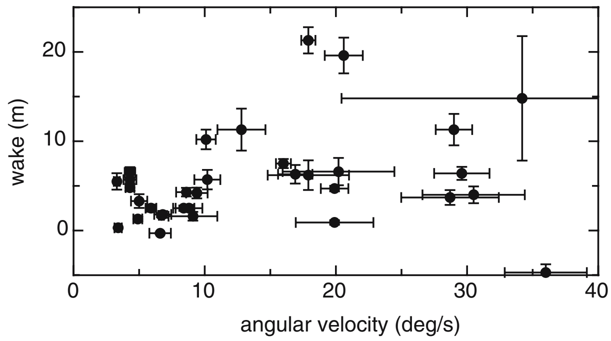

Figure 3. Plot of minimum apparent wake (in meters) versus the angular velocity (in degrees per second) for the A type meteors in this study.

4. Discussion

A powerful new tool for meteor science has been developed which permits simultaneous high spatial and temporal resolution optical studies of faint meteors. If the meteors observed here are typical, it has been shown that more than 50% of meteors in this magnitude range have spatial wakes of about 16 m or more (all of the W- and P- classified meteors, and a few from the A set), and almost all meteors have a small amount of wake which can be measured by this technique.

The most obvious question to ask is whether the wake measured here for A-type meteors is due to differential lag of dustball grains, or atomic excitation and decay over a distributed region. Monte Carlo techniques were used to model the flow field around a meteoroid by (Boyd, 2000). They found a region of elevated temperature and ablated vapor density extends much further along the longitudinal direction than transverse to the meteor trail (about 1–2 m transverse and 10–30 m longitudinal). Those results would be consistent with the wake values measured here, and with the finding of little evidence for optical trail width using the same equipment (Kaiser et al., 2005). However, it must be stressed that the masses of the meteors in the numerical simulations were more than a million times larger than the meteors studied here (the meteors in this study have masses of the order of 10^{-8} kg, although it must be stressed that with so little of the luminous path being captured photometric masses cannot be derived). Using an air beam model (Popova et al., 2000) came to somewhat similar conclusions to those of Boyd. They find that a dense vapor cloud around the meteoroid partially screens the meteoroid surface from direct impacts by air molecules. In their results while the temperature of the vapor has dropped by a factor of 2 in only a distance of 1 m, the temperature is still elevated to about 5500 K at a distance 5 m behind the meteor head. Clearly, additional work on meteor ablation theory is necessary before the nature of the wake observed in this study can be definitively attributed to vapor interactions or to differential grain deceleration. We feel that at least the P- and W-type meteors probably require differential aerodynamic lag, and therefore this research supports the view that at least half of very faint meteors have a dustball structure.

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