References

[1] Allen, H. J., "Estimation of the Forces and Moments Acting on Inclined Bodies of Revolution of High Fineness Ratio," RM A9126, Nov. 1949, NACA.

[2] Bursnall, J. and Loftin, K., "Experimental Investigation of the Pressure Distribution About a Yawed Circular Cylinder in the Critical Reynolds Number Range," TN 2463, Sept. 1951, NACA.

[3] Hoernher, S. F., *Fluid Dynamic Drag*, 1965 edition, published by the author, 148 Busteed Drive, Midland Park, N.J., 07432, pp. 3–11, 4–5, 5–3, 6–2, 3.

Artificial Simulation of Micrometeoroids

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Facilities

We possess powerful machines which are able to accelerate projectiles to meteoric velocities. The well-known light gas gun can shoot projectiles of centimeter size at velocities up to10 km/sec. Further, there is the electrostatic accelerator with an upper limit in velocity for micron-sized particles of about 70 km/sec, and the linear accelerator which, at a length of 1 km, could in principal bring a particle of 1 μ radius to a velocity of 1000 km/sec. Several circular and magnetic techniques are under discussion, as well as the laser powered accelerator which causes rocket-like propulsion by asymmetric evaporation of the particle. Finally there is the technique that uses the momentum flux of an electron beam to push a negatively charged particle forward.

Some people hope to initiate fusion reactions with the projectiles from such machines and to observe the Lorentz contraction. However, the existing facilities are rather limited. Even a velocity exceeding the escape velocity of the Earth, 11 km/sec, is difficult to achieve for a particle with a radius of 1 μ. Beyond that, a strict selection of projectile material is necessary, and additionally, the density of the projectiles must be as high as possible.

Most of the experiments described here were carried out with iron microspheres from electrostatic dust accelerators

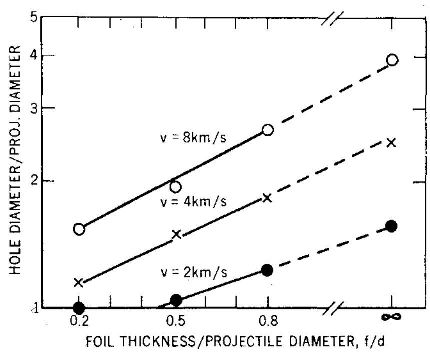

Fig. 1 Hole diameter as a function of foil thickness.

Presented as Paper 70-30 at the AIAA 8th Aerospace Sciences Meeting, New York, January 19–21, 1970; submitted April 31, 1970; revision received July 14, 1970.

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at 0.1–3 million v. The radii of the projectiles were usually of the order of 1 μ, the velocities ranging from 0.5 to 40 km/sec. A critical velocity was observed at 4 to 6 km/sec. Below 4 km/sec the impact is nonexplosive. Above 6 km/sec the impact is always explosive, and no principal difference is observed at velocities between 6 and 40 km/sec. We will mainly discuss the velocity range above 4-6 km/sec because it includes most of the meteoric velocities. Furthermore, no fundamental difference in the behaviour of different materials has been found. Therefore, we can expect that our conclusions have some general validity in spite of the restrictions which are imposed by the existing facilities.

Meteor Studies

When a meteoroid enters the atmosphere of the Earth, collisions with gas molecules cause it to radiate and to leave a trail of ions behind itself. In order to simulate the processes, Friichtenicht et al.[1] injected iron microparticles with velocities between 15 and 45 km/sec into an air target. They measured the total radiant energy in the spectral band 3400–6300 Å and found that it was nearly independent of velocity in the range 20 to 40 km/sec, namely about 0.5% of the kinetic energy of the projectile.

Further, this group[2] measured the number of ions produced by the total ablation of projectiles in air. They found that at a velocity between 20 and 45 km/sec, about 6 and 80%, respectively, of the total number of atoms of the projectile were ionized. In an argon target the ionization was a factor of 2–4 lower.

Crater Studies

A micrometeoroid produces a crater at impact on a solid material, and the process differs completely from that of a contaminating particle which sinks slowly on the same surface. The intention of a collection experiment is to determine mass, velocity, composition and number of micrometeoroids. To achieve this, a series of investigations has been accomplished with the Heidelberg dust accelerator using iron projectiles for micrometeoroid simulation.

The crater shape was studied by Rudolph[3] with an electron stereoscan. This instrument uses the secondary electron yield of the sample surface, which is a strong function of the angle of inclination, to get a stereoscopic image of the surface roughness. In the particular case of a crater, its diameter, depth, general shape, surface roughness and the width of its rim can be determined.

Rudolph found that the crater volume is proportional to the kinetic energy of the projectile. He demonstrated quantitatively the following to be valid: The amount of energy which would be necessary to heat and melt the material which has been in the crater before its formation is equal to the kinetic energy of the projectile. This explains why, under equal conditions, a crater in lead is more than a factor of 10 larger in volume than a crater in beryllium.

Further, he found that the shape of a crater is typical for each target material. In particular the ratio depth-to-diameter T/D is constant for a projectile velocity in excess of 4 km/sec. Craters are semispherical, approximately, with T/D equal to about 0.5 in most of the target materials investigated, namely Ag, Au, Cd, Ni, Pb, Pd, Ta and Ti, and cylindrical with T/D equal to 1.0 in Al and Be targets. At a velocity below 4 km/sec, the crater shape is changing with velocity. Between 0.5 and 1.0 km/sec the projectile sticks nearly unchanged in the target. The crater diameter D is equal to the projectile diameter d, while the crater depth T is increasing rapidly with velocity. Above 1.0 km/sec up to approximately 4 km/sec, the crater diameter D is increasing more rapidly with increasing velocity than the crater depth T. Thus, from the ratio T/D and from the condition of the projectile which is found in the crater, one can directly estimate the projectile velocity. Above 4 km/sec, diameter and depth of the crater are increasing at the same rate with increasing projectile velocity.

The remnants of the projectile in the crater were investigated by Neukum[4] with an electron microprobe. This instrument uses the characteristic X-ray emission of a certain element for its identification. Thus, the projectile material can be distinguished from the target material. It has been found that the projectile is successively flattened with increasing velocity and behaves similar to a liquid. Above a critical projectile velocity, which is 6.0 km/sec for an aluminum target and 3.5–4.9 km/sec for a cadmium target, the projectile breaks to pieces. At a further increase of the velocity, the number of pieces in the crater is increased, thus forming a more or less uniform layer on or mixture with the inner surface and the rim of the crater. Neukum developed an integrating method to determine the mass of projectile material in the crater and found that, within the experimental error of 20% and velocities up to 12.6 km/sec, the total projectile mass remains in the crater. Now, knowing the kinetic energy of the projectile (from the crater volume) and its mass (according to this method), it is evident that the velocity can easily be calculated.

Neukum measured the intensity of the Fe-K_α radiation to determine the mass of iron in the crater, since the projectiles consisted of pure iron. If the composition of a projectile is unknown, this kind of measurement has to be repeated with the characteristic X-rays of all elements which are expected to be found in the crater. Thus, the major nonvolatile elements of any projectile or micrometeoroid can, in principle, be determined and, as a result, its composition will be known.

Penetration Studies

A micrometeoroid produces a hole at impact in a thin foil. This effect is used more and more frequently in combination with other detection principles to get additionally a hole or an electrical signal by the same particle. A disadvantage of penetration, especially for small- and low-density particles, is the fact that the velocity is reduced and often the particle is damaged. To study penetration quantitatively, a series of experiments was carried out by Grün and Rauser[5] with the Heidelberg dust accelerator using iron projectiles for micrometeoroid simulation.

The foil materials were aluminum, gold, carbon and nitrocellulose. The results obtained with aluminum foils are typical and will be summarized here.

It has been found that the velocity loss Δv of a projectile in an aluminum foil is proportional to its initial velocity v. It is also a decreasing function of the projectile diameter and an increasing function of the foil thickness. Some typical values are given in Table 1.

It is evident that the hole diameter D cannot be larger than the diameter of a crater which would be produced by the same projectile in a thick target ($f/d = \infty$ Fig. 1). On the other hand, D cannot be smaller than the projectile diameter d, which means $D/d \geq 1$. Within these two limits, D/d is a function of the projectile velocity v and the normalized foil thickness f/d, as shown in Fig. 1 for aluminum as foil material.

During penetration, only small pieces or no material at all are stripped off the projectile as long as the foil is relatively thin. At certain thicknesses the foil causes the projectile to burst into many fragments. The experiments showed that, as a rough rule, a projectile bursts if the diameter of the hole is more than twice the projectile diameter.

Table 1 Projectile velocity loss as a function of foil thickness

Foil (Al) thickness ÷ Projectile (Fe) diameter	$\gg 2$	2	1	0.3	0.1	$\ll 0.1$
Velocity loss ÷ Initial velocity, %	100	50	20	10	5	0

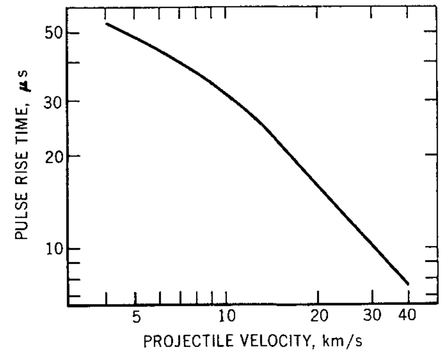

Fig. 2 Rise time of charge pulse as a function of projectile velocity.

Plasma Studies

In search of a new detection technique for micrometeoroids, the emission of positive and negative charges at high-velocity impact of iron projectiles on a tungsten plate has been investigated by Auer and Sitte[6] with the Heidelberg dust accelerator.

They found that an equal amount of positive and negative charges, a plasma, is emitted from the point of impact. The velocity of the plasma is roughly 30–50% of the projectile velocity and is independent of the projectile mass. One portion of the plasma is expanding along the target plane at a higher velocity than another portion which is expanding normal to the target plane with a lower velocity. The unequivocal relation between projectile and plasma velocities for a given geometry can be used in micrometeoroid detectors to determine the velocity of the projectile without influencing it in any way before it strikes the target. Figure 2 shows this relation, as an example, for the micrometeoroid detector to be flown on the HEOS-A2 satellite.

Knowing the velocity v of the projectile, its mass m can be determined from the total emitted charge Q according to the empirical formula

$$Q = 1.5m^{0.67}v^{2.5} \tag{1}$$

with Q = total emitted charge of ions or electrons in units of 10^{-15} coulomb, m = projectile mass in picogram, v = projectile velocity in km/sec. The sensitivity of a detection technique based on the detection of the emitted plasma is some orders of magnitude better than conventional techniques. It can easily be shown that a micrometeoroid with a mass of $m = 10^{-20}\,g$, if Eq. (1) is applicable to this mass range, and a velocity in excess of 10 km/sec is detectable by means of open electron multipliers.

The most attractive attribute of the emitted plasma, with regard to micrometeoroid detection, is its content of ions of the projectile material. At velocities of some km/sec, where energy of impacting atoms is only a few electron volts, ions of contaminating alkali metals dominate in the plasma because of their low ionization potential. At velocities exceeding 6 km/sec, which is typical for micrometeoroids, ions of the projectile material have been observed very well. According to experimental results of another group,[7] ions of the elements H, C, O, Na, K, Fe and Ta are to be observed at the impact of an iron (98%) projectile at a velocity of 40 km/sec on a tantalum target. It is expected that a mass spectrum of the elements of any projectile or micrometeoroid can be achieved, resulting in the knowledge of its composition, provided the degrees of ionization will be measured in the laboratory with good precision.

Light Flash Studies

At the impact of a high-velocity projectile on a thick target a small fraction of the kinetic energy is converted to radiant energy. The light intensity as a function of time as well as the optical spectrum can be observed. Friichtenicht[8] used iron microparticles and observed the light flash by two-color photometry. He found that the blue part of the spectrum is increasing more rapidly with velocity than the red part. He observed a narrow (typically 0.2 μsec wide) fast risetime pulse of light followed by a much wider pulse (typically 10 μsec) which decays slowly to zero intensity. These observations are quite similar to results of Rollins and Jean[9] with bigger projectiles. They were able to measure more details because of the higher light intensity available. The projectiles were aluminum of cm size and were accelerated by a light gas gun. The target material was cadmium.

The first spike is continuum radiation and only present at the impact point. It is apparently due to a fast jet of material caused by the very high initial pressures. The peak intensity and the initial rate of change of intensity of the spike are proportional to $v^8 d^\alpha$ and $v^6 d^{2.1}$, respectively, with v = projectile velocity, d = projectile diameter, α = 2.9...4.0 (exact value depending on the wavelength used), and were found to be suitable to determine both diameter and velocity of a projectile if its composition is known.

The tail of the light flash is associated with a luminous ring expanding along the target plane. This ring is radiating in spectral lines which are characteristic of both target and projectile material. By analyzing the emission spectrum it is, in prinicpal, possible to determine the composition of the projectile.

Conclusion

As we have seen, there are three independent methods to determine velocity, mass, and composition of micrometeoroids. The light flash, however, is probably too faint and the emission spectrum too complicated as to lead to a practicable analysis. In order to investigate the crater, a very narrow beam of medium energy electrons and additional complicated instruments for electron and X-ray detection are necessary: volatile elements certainly escape observation. Analysis of the plasma seems to be the only practicable technique for micrometeoroid analysis onboard a spacecraft, although much additional effort is necessary to arrive at a quantitative method.

References

[1] Friichtenicht, J. F., Slattery, J. C., and Tagliaferri, E., "A Laboratory Measurement of Meteor Luminous Efficiency," *Astrophysical Journal*, Vol. 151, No. 1, Feb. 1968, pp. 747–758.

[2] Slattery, J. C. and Friichtenicht, J. F., "Ionization Probability of Iron Particles at Meteoric Velocities," *Astrophysical Journal*, Vol. 147, No. 1, Jan. 1967, pp. 235–244.

[3] Rudolph, V., "Untersuchungen an Kratern von Mikroprojektilen im Geschwindigkeitsbereich von 0,5 bis 10 km/sec," *Zeitschrift für Naturforschung*, Vol. 24a, No. 3, March 1969, pp. 326–331, English Translation NASA TT-F-11890.

[4] Neukum, G., "Untersuchungen des Projektilmaterials in Mikrokratern," Diplomarbeit, Universität Heidelberg, 1969, English Translation, NASA TT-F-12327.

[5] Grün, E. and Rauser, P., "Penetration Studies of Iron Dust Particles in Thin Foils," *Space Research*, Vol. IX, North-Holland Publishing Co., Amsterdam, 1969, p. 147.

[6] Auer, S. and Sitte, K., "Detection Technique for Micrometeoroids Using Impact Ionization," *Earth and Planetary Science Letters*, Vol. 4, No. 2, April 1968, pp. 178–183.

[7] Hansen, D. O., "Mass Analysis of Ions Produced by Hypervelocity Impact," *Applied Physics Letters*, Vol. 13, No. 3, Aug. 1968, pp. 89–91.

[8] Friichtenicht, J. F., "Experiments on the Impact-Light-Flash at High Velocities," NASA CR-416, March 1966, TRW Systems, Redondo Beach, Calif.

[9] Rollins, T. L. and Jean, B., "Impact Flash for Micrometeoroid Detection," NASA CR-92122, May 1968, Computing Devices of Canada, Ottawa, Ontario.

Determination of the Energy Balance of a Pulsed Plasma Source

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Introduction

Design of a continuously working inductive plasma accelerator requires knowledge of the efficiency of energy exchange into the plasma. For basic information, it is sufficient to study the process of ionization, acceleration and heating of a pulsed accelerator. It is possible to obtain an approximate determination of the energy balance on the complete system by spectroscopically determining particle temperature, plasma velocity, and the damping rate of the oscillatory circuit of the system.

Measuring Instrumentation

The pulsed inductive acceleration device has been described in detail in Refs. 1 and 2. Helium gas, passing through a quick acting electromagnetic valve, enters the acceleration tube (pyrex glass) which is evacuated to a pressure lower than 10^{-5} torr. The gas is ionized and accelerated by a single-turned conical coil across which a capacitor battery (6.5 μF, 10–15 kv) is discharged a defined time Δt (here 450 μs) after opening the valve.

Spectroscopic measurements are carried out with optical interference filters. Signals are led through fiber optics to photomultipliers where they are registered on an oscilloscope screen. The optical arrangement was attached on a support which could be shifted along the acceleration tube. Thus, the arrival of the plasmoids at different positions could be observed and velocities determined. Simultaneously, the damping of the oscillating current with and without plasma generation and acceleration was measured using a pick-up coil.

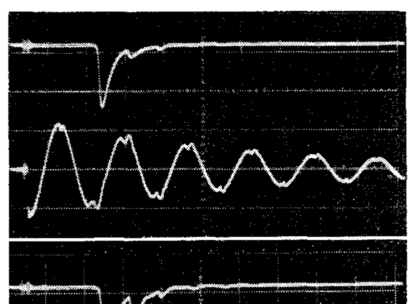

Fig. 1 Oscillograms of corresponding light intensities and pick-up voltages.

Received August 3, 1970; revision received October 13, 1970.

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