Reports

Sound from Apollo Rockets in Space

Abstract. *Low-frequency sound has been recorded on at least two occasions in Bermuda with the passage of Apollo rocket vehicles 188 kilometers aloft. The signals, which are reminiscent of N-waves from sonic booms, are (i) horizontally coherent; (ii) have extremely high (supersonic) trace velocities across the tripartite arrays; (iii) have nearly identical appearance and frequencies; (iv) have essentially identical arrival times after rocket launch; and (v) are the only coherent signals recorded over many hours. These observations seem to establish that the recorded sound comes from the rockets at high elevation. Despite this high elevation, the values of surface pressure appear to be explainable on the basis of a combination of a kinetic theory approach to shock formation in rarefied atmospheres with established gas-dynamics shock theory.*

In order to expand our knowledge of atmospheric infrasonic waves initiated by large rockets launched from Cape Kennedy, Florida (*1*), tripartite arrays of infrasonic sensors were placed in Bermuda in addition to those established at sites on the east coast of the United States. The Bermuda sensors detected sound from Apollo 12 and Apollo 13 spacecrafts on 14 November 1969 and 11 April 1970, respectively. The rockets passed eastbound at an elevation of 188 km and were 55 km south of the arrays. This elevation (essentially that of the parking orbit) is generally regarded as above the sensible atmosphere, so that only a very small drag is exerted on the vehicle. Low-frequency acoustic (infrasonic) waves coherent across the array, with a strong impulsive beginning, arrived at times appropriate to the arrival of a shock wave initiated by the rocket. Initiation and propagation of such a wave from an altitude of 188 km seem remarkable because of the extremely low atmospheric density and the long (158 m) molecular mean free path length at that altitude.

Infrasonic signals are most commonly recorded by instruments sensitive to very weak pressure changes of the type produced by the passage of acoustic waves. Fehr and Fiske acoustic transducers (*2*) and Globe capacitance microphones (*1*) were used as sensors. A major recording problem is often the reduction of noise caused by wind turbulence which may produce local variations of pressure exceeding those of the signal. To minimize this effect, the following procedures were adopted: (i) each sensor was located in a small clearing in deep woods which act as a wind screen (a difficult task in Bermuda); (ii) sensors were placed far enough apart to avoid being affected by the same wind gust; and (iii) electronic band passes of 0.5 to 10 hz for Apollo 12 and 0.3 to 10 hz for Apollo 13 were used to remove the effects of wind, which are very strong below this range.

The array spacing used for Apollo 12 was increased for Apollo 13 as indicated in Fig. 1. The sensors were close enough to record the signal simultaneously on frequency-modulation magnetic tape as well as on individual strip chart recorders. To further discriminate against a coincidental local source for Apollo 13, a fourth sensor was placed 4085 m to the northeast of the array.

The tape playbacks of the Apollo 12 and Apollo 13 signals are shown in Fig. 2. The third sensor for Apollo 13 did not operate. For Apollo 12, the only impulsive signal received coherently on all sensors during the entire recording interval of several hours arrived 16 minutes, 50 seconds after launch (16 hours, 32 minutes G.M.T.). For Apollo 13 the only coherent signal arrived 17 minutes, 7 seconds after launch (19 hours, 13 minutes G.M.T.). There is a possible uncertainty of 2 to 3 seconds in these arrival times. In addition to the matching of the travel times, the infrasonic signals from the two rocket passages are strikingly similar in frequency and wave form. Maximum signal amplitude is about 10 μb (10 dyne/cm^2).

The arrival time of the signal, 17 minutes after launch, corresponds to the expected arrival time of the rocket's Mach cone at Bermuda. The second stage of the rocket passed the Bermuda meridian 193 km slant range from the observing site at 9.2 minutes after launch. The shock wave initiated there arrived 7.8 minutes later, traveling the 193 km in 468 seconds, thus giving an average speed of 412 m/sec. This is a reasonable value for the average speed of the shock wave normal to the shock front in view of the high speed of sound in the upper atmosphere as compared with a speed at the surface of about 340 m/sec. Interestingly, the 17-second additional travel time for the Apollo 13 waves corresponds almost exactly to the 16-second delay in the time required for

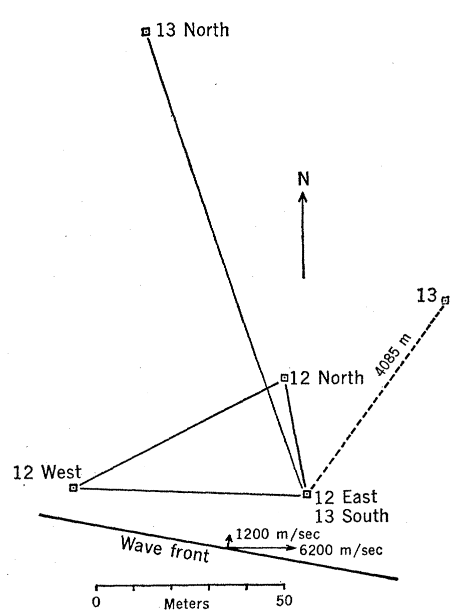

Fig. 1. Chart showing arrays of sensors in Bermuda for Apollo 12 and Apollo 13 rocket launchings. Site designations by direction correspond to similar designations on the traces of Fig. 2. The horizontal trace of the Mach cone approaching the array is also shown together with the velocity normal to the trace and the eastward velocity of the Mach cone. (The velocity in the atmosphere normal to the cone is the acoustic velocity appropriate to the ambient temperature.)

the latter rocket to cross the Bermuda meridian (541 seconds for Apollo 12 and 557 seconds for Apollo 13).

The arrival of the signal appeared to be essentially simultaneous on the Apollo 12 west and east sensors; the Apollo 12 north sensor is a different type of instrument with different response characteristics and cannot be validly compared with the other two sensors. An expected 0.007-second time delay between the east and west sensors, corresponding to the east-west velocity of the Mach cone (rocket), is too small for detection by our time resolution.

For Apollo 13 there was a time delay of 0.08 second between the arrival of the signal at the south and the north sensor. The delay expected on the basis of the eastward movement of the shock cone is 0.11 second. The single instrument 4085 m to the northeast of the tripartite array recorded a signal essentially identical to that of the tripartite array at the appropriate time. Because this record was made by a strip chart pen recorder, time resolution was too poor to permit velocity determinations to be made but the record does establish the coherence of the signal.

The signal begins with a wave form that resembles a shock or N-wave, of period about ¾ second, characteristic of sonic booms from supersonic aircraft (*3*), and is followed by a few later oscillations. The exact repetition of timing from two Saturn 5 rocket launchings precludes the possibility that the waves were initiated by supersonic aircraft. We conclude from all of the observations given that the signals described were generated by the shock waves from the Saturn rockets passing high above and slightly to the south of Bermuda.

These conclusions introduce the problem of how a sonic wave can propagate from an elevation of 188 km, where the air density ρ is 4.3×10^{-10} kg/m^3, as compared with 1.22 kg/m^3 at the ground, and the molecular mean free path length is 158 m, as compared with 6.63×10^{-8} m at the ground.

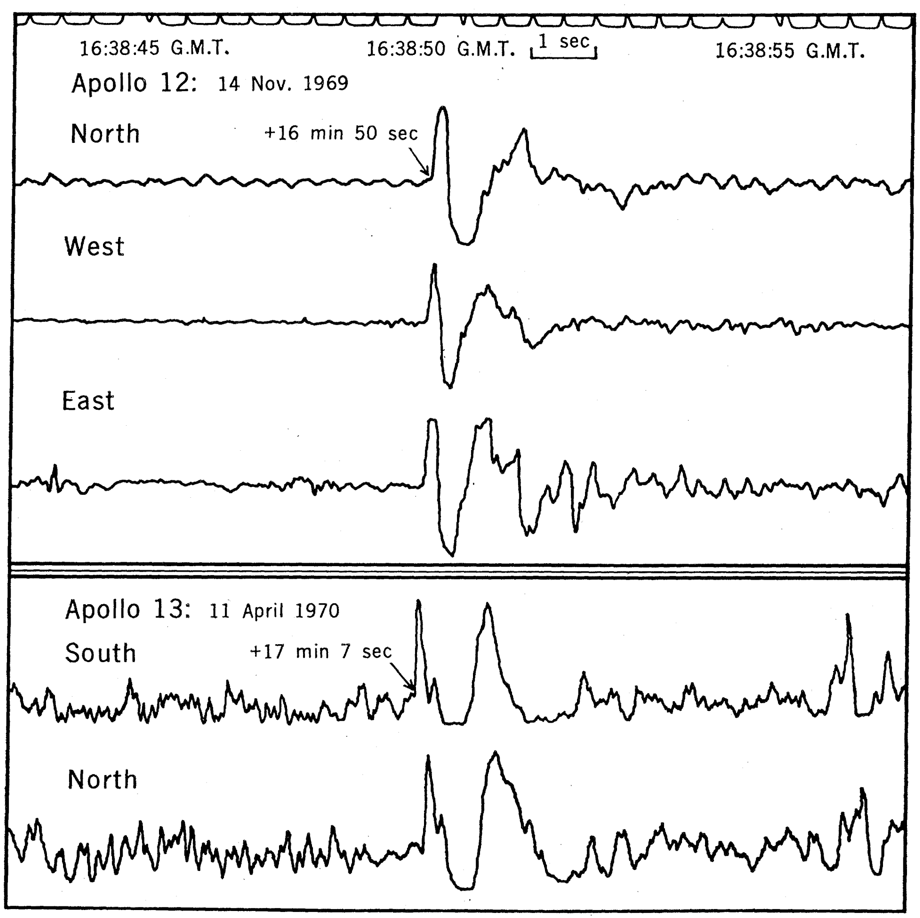

Fig. 2. Tracings of pressure variations recorded at the two arrays on Bermuda with the passage of the Apollo 12 and Apollo 13 rockets aloft. Maximum variation is about 10 μb (10 dyne/cm^2). The electronic band pass was 0.5 to 10 hz for Apollo 12 and 0.3 to 10 hz for Apollo 13. The time interval between the launch and the arrival of the initial impulse is also shown.

We are preparing a more complete analysis of the problem of generation and propagation of the signal (*4*), but a summary of the theoretical results is appropriate here. The wavelength λ at sea level is $c_0\tau$, where c_0 (the speed of sound at sea level) is 340 m/sec and the observed τ (the wave period) is ¾ second so that $\lambda = 250$ m at the ground. Because the length of a shock wave increases during propagation (*5, 6*), it should be less near the source, as should the period. Since the mean free path length and the N-wavelength in the rarefied upper atmosphere are thus not too different, sonic transmission by molecular collision seems questionable. In fact, detailed calculations show that complete absorption of a 1-hz sound wave would occur in propagation through the upper atmosphere.

Although the flow is nearly free molecule flow, Grad (*7*) has shown that, for free molecule flow at supersonic speeds, a shock front is formed asymptotically at distances several mean free path lengths away from the source. This front obeys asymptotically the shock equations as developed from continuum fluid mechanics. Thus the formation of a shock front by this supersonic (Mach 8) rocket can be expected. It has also been shown by Grad that the expected amplitude is related to the drag on the rocket.

The amplitude Δp of the pressure jump at a shock front at any level formed by a supersonic projectile or aircraft is generally calculated from some variant of a formula derived by Witham (*8*). The appropriate form of the formula, including a correction factor N_c for nonlinear propagation in a nonuniform atmosphere, is given by Pierce and Thomas (*9*) as follows:

$$\Delta p = p_h \left[N_c \frac{C_g}{\bar{C}} \left(\frac{\rho_g}{\rho_h} \right)^{1/2} \right] K_r \times (M^2 - 1)^{1/8} \left(K_s \frac{D}{L} \right) \left(\frac{1}{h} \right)^{3/4}$$

where p_h is the ambient pressure at the rocket, C_g is the sound speed at the ground, $\bar{C}$ is the sound speed averaged over the height from the ground to the rocket height h, and M is the Mach number or vehicle speed divided by the sound speed calculated for the elevation of flight.

We can solve for Δp at sea level by using for K_s, the shape factor, Witham's value of about 0.5 for a slender projectile and for K_r, the reflection coefficient, a value of 2. For the rocket dimensions, D (diameter) is 10 m, L (length) is 68.5 m, and K_sD/L is 0.073. With these values Δp is computed to be 0.1 μb (0.1 dyne/cm^2) rather than the observed signal, which is two orders of magnitude larger.

But the effective cross section of the rocket is much larger than the cross section of the rocket itself as a result of the spreading of the rocket's exhaust gas. The exhaust plume travels with the rocket and serves as a blunt body of large cross section moving at supersonic speed through the ambient air, thus generating a shock much stronger than that which would come from the rocket casing alone. The effective width (D) of the source is certainly much greater than the simple diameter of the casing, as is the case with supersonic aircraft (*6*). Reasonable values of the plume diameter can increase the value of K_sD/L to the order of 10, thus giving the observed Δp. However, the Witham formula does not include attenuation terms because prior applications of the formula have been to low-elevation supersonic objects where attenuation is relatively small. Moreover, the complete explanation involves consideration of the effect of drag.

As we noted above, during propagation through the upper atmosphere a sonic wave with a period of about 1 second would be severely attenuated. But the presence of the recorded signals and calculations of the signal strength at high elevations require that the sonic wave propagate as a shock front through the rarefied upper atmosphere. In order to explain this observation, we must assume that the nonlinear propagation of a shock front at these elevations must occur with much lower damping than for an acoustic wave. Only when the wave approaches a few tens of kilometers above the surface does its amplitude become small enough for acoustic damping to apply, but at this elevation the kinematic viscosity is sufficiently low so that the attenuation there is negligible. Thus, the recorded signals, which at first seemed unlikely, appear tractable.

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Alteration of Lunar Optical Properties: Age and Composition Effects

Abstract. *A model for lunar surface processes is presented which explains the main albedo and color contrasts and the temporal changes in these optical properties. Evidence from Apollo 11 and Apollo 12 samples and telescopic spectral reflectivity measurements indicates that the maria are similar in mineralogy on a regional scale and that the highlands are consistent with an anorthositic-gabbro composition. Bright craters and rays in both regions expose materials that are relatively crystalline compared with their backgrounds, which are richer in dark glass. With age, bright craters and rays in the maria darken in place by meteorite impact–induced vitrification and mixing with the surrounding material. Highland bright craters and rays may, however, darken primarily through regional contamination by iron- and titanium-rich mare material.*

We have previously compared the spectral reflectivity (0.35 to 2.5 μm) of the Apollo 11 surface fines with telescopic data for an area 18 km in diameter containing the landing site (*1*, *2*). The very close agreement between sample measurements and telescopic measurements implies that the Apollo 11 surface fines are representative of areas of 10-km scale or larger. It was also possible to show that the optical properties of the samples are a function of the mineralogy and the glass content.

Recently we have measured spectral-reflectivity curves for Apollo 12 samples from Oceanus Procellarum. We have compared these curves with the Apollo 11 sample data and with a variety of telescopic measurements for the near side of the moon. Comparison of the several sample curves and the telescope curves has led to new conclusions about the composition of the lunar surface as a whole and about surface processes.

Laboratory measurements were made with a Beckman DK-2A ratio-recording spectrophotometer over the spectral range of 0.35 to 2.5 μm. The instrumentation and the sample-handling techniques are discussed elsewhere (*2*).

Comparison of spectral-reflectivity curves of the Apollo 12 fines and the Apollo 11 fines reveals (*3*):

1) Two Apollo 12 samples of bulk fines (samples 12042 and 12070) and two samples from near the top of the double core tube (samples 12025,13 and 12025,6) have essentially identical reflectivity curves. These samples will be referred to as "surface fines."

2) The Apollo 12 surface fines have an integral reflectivity that is 10 percent higher than the Apollo 11 surface fines in the visible spectral region (0.4 to 0.7 μm).

3) The slope of the curve for the Apollo 11 surface fines is less steep than that for the Apollo 12 surface fines.

4) The Apollo 12 surface fines show a 6 percent deeper absorption band at 0.95 μm than does the Apollo 11 material and the Apollo 12 curve contains a second broad band at 2.0 μm that the Apollo 11 curve does not have.

5) Material that is 20 cm below the top of the Apollo 12 core tube has an integral reflectivity in the visible range that is 40 percent higher than is this value for the Apollo 12 surface fines.

6) The curve slope is less steep and the 0.95- and 2.0-μm bands are deeper for the 20-cm-deep sample from Apollo 12 than for the surface samples.