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Physics in the Missile and Satellite Fields

*By **Winston E. Kock***

SCIENTISTS in many and varied branches of physics are playing increasingly important roles in today's missile and space projects. The gamut of this activity ranges from nuclear through solid state, and includes optics, acoustics, electromagnetics, and even relativity. The demand for physicists trained in appropriate fields in college, or possessing pertinent experience in industry, has been great and is continually increasing. It is important that the physics departments of our colleges and universities be aware of this situation so that proper stress can be laid upon subjects which can effectively prepare physics students who wish to enter this field of activity.

We read much of the "electronic" devices that go into missiles and satellites. Actually, the field of electronics, once a more or less mundane branch of electrical engineering, has passed through the stage of being a field of just applied physics and now demands from its contributors a knowledge of many of the most basic physical concepts. Electronic technology in the past exploited the control of electrons in vacuum or gas-filled devices. Today physicists have uncovered the paths towards mastery of the control of electrons in solids. Missiles and space probes are major benefactors of the developments in solid-state physics which have made possible extremely compact and lightweight amplifiers, computers, and circuit elements.

In space science physicists have begun to make impressive contributions. The discovery of the great radiation belts by Van Allen and his colleagues will long stand out as a milestone in the history of scientific exploration. We know from the orbits of the Explorer and Vanguard satellites that the earth has a flatness ½% less than had previously been assumed by cartographers. The Argus experiments, in which the effects of a nuclear explosion at high altitudes were studied, yielded important added knowledge about the properties of space in the vicinity of the earth. These experiments were in a sense a scaled-up version of an experimental device from Project Sherwood, namely, the magnetic mirror machine which confines a plasma within a magnetic field. In the Argus experiment, the earth's magnetic field in outer space constituted a gigantic magnetic mirror in which electrons produced by the nuclear burst were trapped.

The list of instruments already carried or soon to be carried on satellites reads like a list of instruments in a college physics laboratory. Sputnik III carried a geiger counter, a Čerenkov counter to detect heavy cosmic particles, a fluorescent screen and photomultiplier to detect fast electrons, a flux-gate magnetometer to measure the magnetic field of the earth, special ion traps to permit only positive ions to be recorded, and a mass spectrometer to ascertain the atmospheric constituents at various altitudes. The newer Explorer satellites are equipped with albedo sensors to measure the direct solar radiation and that fraction which is reflected from the earth, cadmium sulfide photoconductors to detect the impact of tiny meteorites, an ultraviolet detector equipped with a lithium fluoride window to measure the strength of the Lyman-Alpha line of atomic hydrogen, a sensor chamber having a beryllium window to measure soft x rays, and a special ionization chamber designed to sort and count primary cosmic rays in three different ranges of particle mass.

A recent development in the field of mass spectroscopy is of interest since it made possible a small size, lightweight spectrometer, ideal for satellite instrumentation. The original mass spectrograph devised by F. W. Aston utilizes a magnetic field to deflect ions of different

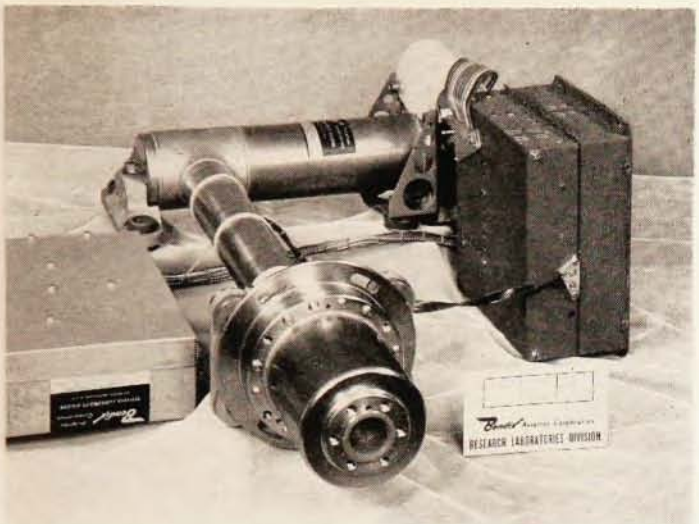

Fig. 1. Compact nonmagnetic mass spectrograph, designed for incorporation in rockets and satellites, samples 6 different constituents of the atmosphere every 120 seconds.

charge-to-mass ratio into different paths and thus resolves the various constituents of a mixture. The magnet is heavy and the spectrograph itself relatively bulky. Recently, an invention of two Bendix scientists, W. C. Wiley and I. H. McLaren, made possible a very compact time-of-flight mass spectrometer with high resolution capabilities. This spectrometer makes use of the fact that ions of different mass acquire different velocities in an electric field and the time required for them to traverse a fixed distance therefore depends upon their mass. The ion mixture to be analyzed is admitted as a short burst and the times of flight of the various constituents measured. No deflection magnet is employed and the spectrometer can be made small enough and light enough for incorporation in rockets and satellites (Fig. 1).

The mass spectrometer provides a convenient and accurate tool for determining the nature, concentration, and state of electrical charge of the various molecules and atoms present in the space environment. An interesting feature of this and other satellite sensors is that no glass envelope is required to maintain a vacuum; at the altitudes where satellites orbit, the environment *is* a vacuum.

An important component of this spectrometer is a specially designed electron multiplier, which turns out to be of interest in other measurements, particularly the Lyman-Alpha radiation. This photomultiplier tube (Fig. 2) begins to become sensitive just in the Lyman-Alpha wavelength region and it is therefore not disturbed by the longer wavelengths which contain much of the energy present in the solar spectrum. The Air Force Cambridge Research Center recently used this multiplier in conjunction with a rocket-borne vacuum ultraviolet spectrometer and obtained the best measure-

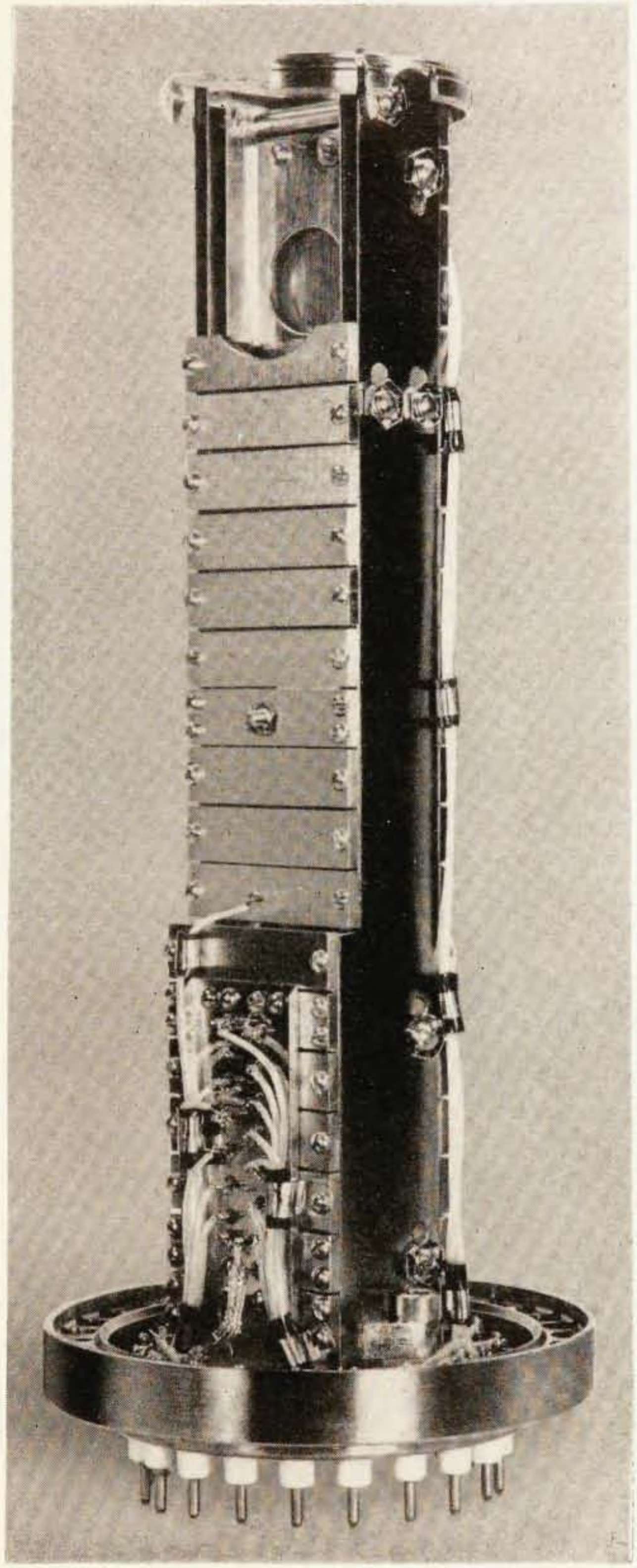

Fig. 2. This photomultiplier tube is sensitive in wavelength region from 1300 to at least 300 A. Rocket borne, and in conjunction with a spectrometer, it provided an analysis of the sun's radiation in this relatively unknown portion of its spectrum.

ments to date of the solar spectrum between 1300 and 300 angstroms.

Nuclear reactor physicists are also involved in missile and space efforts. Nuclear energy is an attractive possibility for rocket propulsion because of the relatively low weight of its fuel and because lightweight propellants such as hydrogen can be employed. The exhaust velocity of a rocket motor determines its specific impulse and both of these factors are inversely proportional to the square root of the molecular weight of the propellant. Conventional chemical propellants have molecular weights of about 20, and with hydrogen having a weight of 2, the specific impulse of a nuclear rocket can be as much as three times that of a chemical rocket.

One of the problems in a nuclear rocket is the start-up time. In an actual launching, the reactor operating time prior to the attainment of full thrust must be minimized in order to conserve the propellant. This requires an exceedingly rapid rise from no power to full power as compared with conventional power reactors. The servo-operated control equipment therefore must possess performance of a high order. Our Research Laboratories are developing such reactor controls for a series of nuclear rocket engines to be tested on Project Rover, the nuclear rocket project of the Atomic Energy Commission at Los Alamos. These controls must operate accurately in the high radiation and temperature environment of the reactor; a maladjustment could overheat or destroy the nuclear engine. I was privileged to witness the full-power ground test of the first of the Project Rover reactors in July

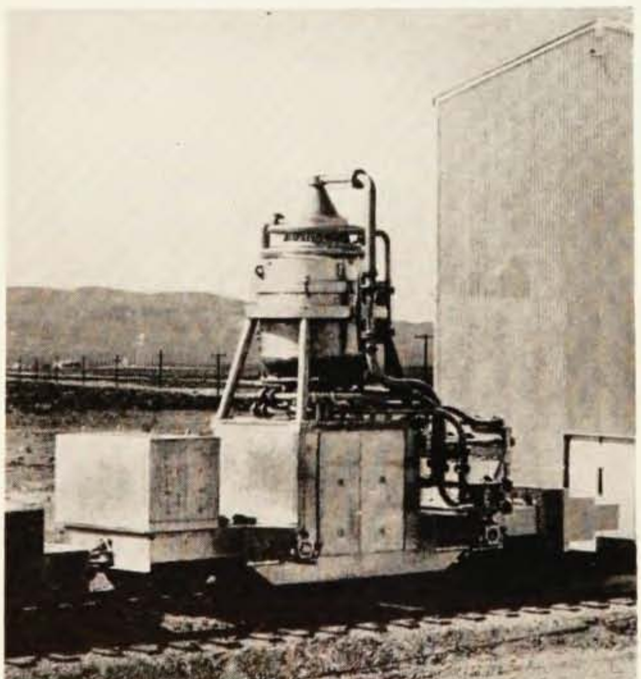

Fig. 3. Successful test of KIWI-A reactor furnished first positive indication that nuclear propulsion of rockets holds great promise.

Fig. 4. An array of underwater loudspeakers provides a useful tool for exploring the use of sound waves for communication between missile launching submarines.

(Fig. 3). Named "Kiwi-A" after the New Zealand wingless bird, it was tested at Jackass Flats, Nevada. Its success led Senator Clinton P. Anderson, Chairman of the Joint Committee on Atomic Energy to wire Norris Bradbury, Director of the Los Alamos Scientific Laboratory, the following message: "Congratulations. This is truly a milestone in the development of atomic propulsion. All involved deserve the thanks of the Nation." Which suggests that nuclear rocket propulsion may be here to stay.

The Kiwi tests will undoubtedly lend added impetus to another nuclear propulsion project in which our laboratories are also playing a part. I refer to Project Pluto, a program aimed at investigating the possibilities of nuclear ramjet propulsion. It is under the guidance of the Lawrence Radiation Laboratory of the AEC at Livermore, California. The Pluto vehicle will operate after the fashion of the V-1 buzz bombs of World War II, except that it will employ a nuclear reactor for its source of energy instead of chemical fuel. Since it will, by its nature, be an air-breathing device, it will always operate within the earth's atmosphere. With the growth of the field of application of nuclear reactor technology, many universities are recognizing the need to acquaint their students with the workings of a reactor and are acquiring for this purpose either research or training reactors.

Acousticians are also active in the missile fields. Ultrasonic transducers are used to monitor the level of liquid oxygen in some of the liquid propellant rockets. As the liquid level drops below the transducer point, the acoustic impedance seen by the transducer changes markedly and an indication is given. For the low temperatures of liquid oxygen, barium titanate, because of its transition point at 0° centigrade, is unsuitable, but a new compound of lead, zirconium, and titanium performs satisfactorily in this application. In another area, an investigation is underway to see if sound waves can be used to control the rate of burning of solid fuels in rockets. In the burning process of solid fuel rockets, the components become gases that mix in a thin layer on the surface of the solid fuel. It is believed that high-intensity sound waves can create a faster mixing of these gaseous components than would normally occur, so that the burning rate can be controlled by controlling the intensity of the sound waves. The field of underwater sound is important in the Polaris submarine-launched missile project. Fig. 4 is a photograph of an underwater sound transducer designed for our laboratories' program of long-range sound transmission studies sponsored by the Office of Naval Research and the Polaris Special Projects Group of the Bureau of Ordnance. The Polaris submarine constitutes a highly maneuverable and highly invulnerable missile launching base as long as it does not divulge its location. It must therefore remain submerged to avoid visual or radar detection, and underwater sound transmission constitutes a promising technique for navigation, communication, and for the detection of other vessels. Extensive research is also under way on sound quieting measures for the Polaris submarines so as to make them less susceptible to detection by underwater listening systems.

Rockets and satellites have opened up many new possibilities for astronomers and here optical physicists play an important part. The success of Herbert Friedmann and his colleagues at the Naval Research Laboratory in obtaining for the world the first photograph of the sun utilizing only the Lyman-Alpha radiation (Fig. 5), was in large part due to a very ingenious solar disc camera containing two focusing gratings and a diaphragm to exclude from the final photographic plate the unwanted spectrum, that is, the visible and other wavelengths. Until we had measuring instruments which could rise above the atmosphere, our knowledge of the radiations from space and the sun was limited to wavelengths longer than those absorbed by the atmosphere, namely, wavelengths longer than about 2850 angstrom units. Because the continuous emission of the sun in the visible range resembles that of a black body at 6000°K, we used to believe that it would still resemble a 6000°K source in the ultraviolet. Measurements now reveal that the sun is orders of magnitude weaker as the wavelength decreases toward 1000 angstroms. Below 1500 A, the continuum intensity becomes almost negligible and bright lines begin to appear. The Lyman-Alpha line at 1216 A stands out as the most prominent, and in the middle of the previously unknown spectrum between the Lyman-Alpha and the x-ray end of the scale, the line of ionized helium II at 304 A has been found to contain more energy than all the rest of the region combined.

Fig. 5. This is the first photograph ever taken of the sun using its Lyman-Alpha radiation alone. (*Courtesy of Herbert Friedman, Naval Research Laboratory.*)

Optics plays a part in missiles which employ star trackers for their guidance. Astronomers are devising many experiments from satellites, and because of the space limitations, special mechanisms and special designs are needed for the large aperture, long focal length optical telescopes to be employed. For the detection of nuclear explosions, satellites utilizing optical and spectroscopic techniques have been suggested. In this process, use would be made of the characteristic spectrum radiated by an atomic bomb.

Of interest to theoretical physicists is the plan to put Einstein's two theories of relativity to a test by satellites. We recall that his special theory provides that the rate at which a clock ticks as measured by a particular observer depends upon the relative motion of the clock. The clock of a space traveler, on his return to earth, would appear to have ticked slower than the earth clocks; the traveler would have become younger than his identical twin on earth.

On the other hand, the general theory of relativity maintains that gravitational fields also affect the rate at which a clock ticks, and that a space traveler, after having orbited the earth at not too large a radius, would be *older* than his identical twin on earth. It happens that these two effects cancel at a height above the earth equal to one half of the earth's radius. A clock on a satellite which is continuously orbiting the earth at that altitude would always agree with a clock on earth.

For the test of these theories, physicists have come up with very compact and lightweight atomic clocks. The measurement of the small time differences involved requires extremely stable oscillators or clocks, but both the cesium molecular beam clock and the maser solid-state oscillator appear to have sufficient frequency stability to be effective for the tests. The gravitational effect is so small, for example, that a clock, after orbiting for one hundred years, would be only one second apart from an earth clock.

Relativistic effects also plague the designers of really long space journeys. To reach the stars or even the distant planets in reasonable time periods, speeds approaching the velocity of light will be required. Large Doppler shifts are then encountered. For a speed equal to one third the speed of light, the frequency of a radio communication circuit centered originally at 250 Mc would be shifted by 70 Mc. For the rapidly receding vehicle the power received at earth is greatly reduced, with a consequent impairment of the signal-to-noise ratio at the earth receiver.

The physics of fluid flow is of course important in the rocket thrust problem. Many satellites, once they are in orbit, use small thrust controllers to prevent tumbling. Our Laboratories supplied such attitude control jets for the Discoverer series of satellites (Fig. 6). Reaction jets of this type preferably are of the proportional control variety instead of just on or off, and when completely off they must have very low leakage. Those which operate from a bottle of compressed gas are termed cold gas reaction jets, those whose gas comes from the decomposition or combustion of fuel are called hot gas jets. For long duration flights, weight considerations favor the hot gas jets. Accurate attitude control is necessary for satellites intended for photographing or televising the sun, the earth, or the heavens.

I mentioned earlier that missiles and satellites were major benefactors of the solid-state advances of the last decade. I have left solid-state physics as my last topic because it is perhaps the most important contributor to missile and satellite instrumentation. Without solar batteries and without the light-weight, low-power drain transistor, the useful life of our satellites would have been greatly reduced. Sputnik III is said to carry several thousand transistors and diodes, and the solar battery on our first Vanguard satellite has enabled it to continue to transmit signals to earth for over a year and a half. The Explorer VI paddle-wheel satellite contains 21 000 silicon solar cells.

But the transistor and solar battery were just the start of the solid-state physics dynasty which invaded the microwave, the communications, and the computer fields, and now, with great vigor, is entering the missile and satellite field. To the transistor amplifier has been added the maser and parametric amplifier, both having phenomenally low noise and hence greater signal sensitivity than comparable vacuum tube or transistor amplifiers. While the high-frequency response of the transistor was being slowly and laboriously inched upwards, these two effectively leapfrogged to extend with small effort the field of solid-state amplification into the microwave region. The narrow bandwidth of the maser amplifier furnishes the requisite for the atomic clock application mentioned earlier, whereas the wide bandwidth of the parametric amplifier is exactly what the communication circuitry of the missile or satellite needs.

Satellites and missiles all require computers for their guidance and other functions, and here, too, solid-state physicists have been large contributors. Transistorization was of course a first step in compacting the huge vacuum tube computers of the 1940's but this has turned out to be only the first step. Along one line, scientists have made greatly increased computer speeds possible by utilizing the rapid avalanche breakdown properties of solid-state materials at low temperatures. Along another, the parametric subharmonic computer technique, proposed independently by Goto in Japan and by von Neumann here, has been pushed to microwave frequencies, enabling computer pulse repetition rates to exceed 100 Mc. This is nearly a thousand times faster than many present-day computers. Parametric amplifiers were made possible through the development of solid-state diodes whose effective electrical capacity could be varied by varying the applied voltage.

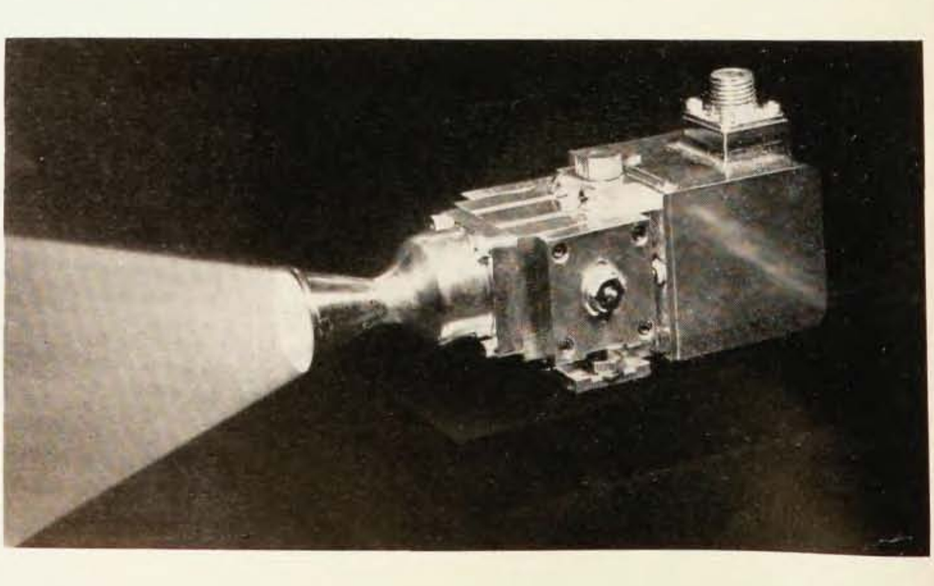

Fig. 6. The attitude of satellites (and the course of cosmic probes) is controlled by small gas jets of this type affixed to the vehicle and operated by various sensing mechanisms.

A higher frequency "pump" voltage causes amplification of signals at a subharmonic frequency. Parametric amplifiers have the advantage of very low noise, and this feature can be further improved by cooling the diode, for example by liquid nitrogen. By using several parametric amplifier stages in a distributed amplifier arrangement, extremely wide bandwidths, even approaching those obtainable with traveling wave tubes, have been achieved.

When a parametric diode is operated as an oscillator at one half the pump frequency, there are two stable oscillation modes that can occur and these two modes are 180 degrees out of phase with one another. In the digital computer applications mentioned above, these two modes are distinguishable and are made the ones and zeros of a binary arithmetic. This technique permits operation of the computer as a carrier system, where the bandwidth utilized is centered about a carrier frequency which can be very high and the bandwidth used is a modest percentage of the carrier frequency. Most computers employ a base-band system in which the pulses represent the presence or absence of a direct current. Such systems require the amplifiers to be effective from near zero frequency to the upper frequency involved. Because of the limitations in the gain-bandwidth product of amplifiers, base-band computers have been limited to about 50 Mc pulse repetition rates. This picture may change, however, with the rapid development of the high-frequency tunnel diode invented by the Japanese scientist Esaki.

The reduced noise advantage in masers and parametric amplifiers which accrues from the cooling of the device has spurred effort in the search for improved solid-state Peltier cooling substances. In a thermocouple the difference in temperature between the hot and cold junction creates a voltage difference. This is the Seebeck effect. Peltier was the first to observe the reverse effect, by which a current flow can engender a temperature difference between two junctions. Bismuth telluride and alloys of this material with bismuth selenide and antimony telluride are examples of solid-state materials with which Peltier temperature differences of many degrees centigrade have been achieved.

In satellites a solar battery can act as the power source to lower, by the Peltier effect, the temperature of a parametric diode and thus reduce its noise. Terrestrial communication circuits do not benefit appreciably from the strikingly low noise feature of masers and parametric amplifiers since the temperature of the earth and its cloud cover causes noise to appear in the first receiver amplifier which may be higher than the noise created in the amplifier itself. Satellites, however, orbit well above the earth and their receiving antennas generally "see" the low temperature of outer space. In their case the low noise of the solid-state amplifiers can effectively improve their receiver sensitivity by as much as 10 to 100 times. For communication satellites which will "talk" to one another in order to relay their information back to some ground station, the low noise solid-state amplifiers will be particularly useful.

Attempts to improve the Peltier and Seebeck efficiencies were recently encouraged by the discovery that many substances exhibit large increases in Seebeck coefficients at extremely low temperatures. The Debye and Peierls explanation of the mechanism of heat conduction involves the concept of elemental energy packets of mechanical (thermal) vibration, i.e., sound waves, which are called phonons. With decreasing temperature, the phonon density decreases so that the phonon mean free path increases and the possibility of one phonon interacting with another decreases. The temperature gradient maintained in a thermoelectric device causes an excess flow of phonons in one direction. Recently Herring at Bell Laboratories has suggested that the increased thermoelectric power observed at low temperatures can be explained by a so-called phonon drag effect. The relatively unidirectional flow of phonons at low temperatures tends to enhance the normal flow of charge carriers (electrons or holes) and thus generates an unusually high Seebeck voltage. If a similar effect could be produced at room temperatures, the applications of the Seebeck and Peltier effects would be greatly extended.

Recent solid-state developments have opened up new possibilities in the field of the infrared. Detectors previously available were generally sensitive only at the shorter infrared wavelengths, which in general are absorbed by the earth's atmosphere. Although a fairly transparent window was known to exist in the wavelength region between 8 and 14 microns, no detectors were known. Work at various laboratories with gold-doped and zinc-doped germanium has shown that when these materials are properly cooled they are highly photoconductive in this wavelength region and exhibit, as detectors, very low noise levels along with very rapid response times. They thus lend themselves to fast scanning devices for tracking satellites.

Finally, I should like to mention the possibility of solid-state gyroscopes. Spatial references for many missile guidance systems now are provided by mechanical gyroscopes. For ballistic missiles, where all of the guidance for its long flight is accomplished in the first few minutes after take off, the gyroscope need be effective for only a short time. Now under investigation in several laboratories is the possibility of using an oriented spin system in a solid substance as a free gyro. After all, nuclei *are* gyroscopes and their gyroscopic behavior has been made use of in many nuclear magnetic resonance experiments.

The basic developments in physics are the pioneering forces which mold and advance our missile and space programs. Our accomplishments here pace not only the growth of these programs but also our progress in extending our knowledge of outer space. All are basic to the military strength essential to our survival. Talented young students of physics should be made aware of the fact that in this field there lies for them opportunities for important service and opportunities for a challenging intellectual life with satisfying rewards.