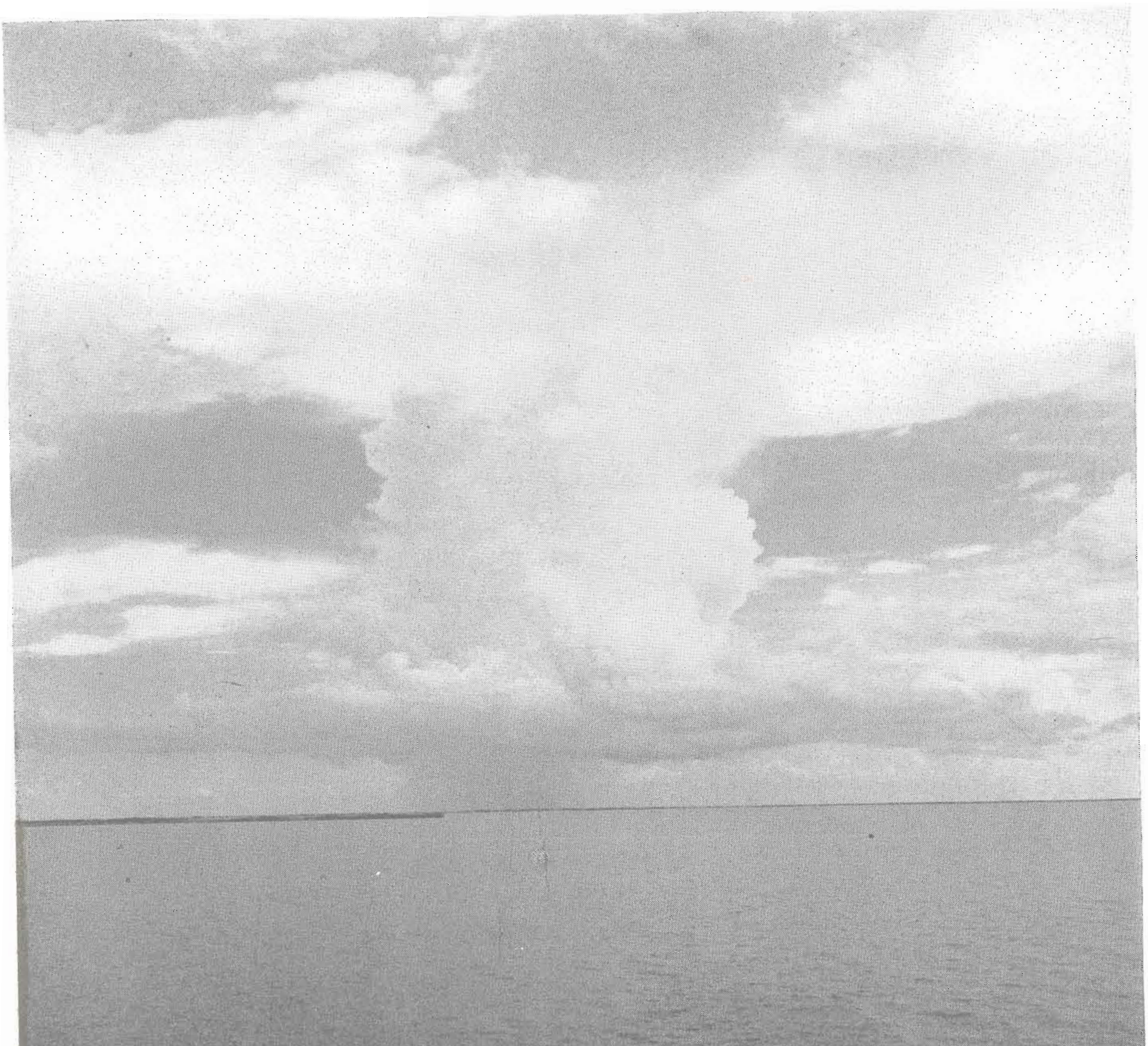
THE EARTH'S ELECTRICITY

The earth is charged with respect to the atmosphere, and the atmosphere is sufficiently ionized to be a conductor. How, then, is the earth capable of maintaining its charge?

by James E. McDonald



THUNDERSTORM over the Louisiana bayous pours rain and negative electric charge upon the earth. Towering above it is the cumulo-nimbus cloud. Later the cloud forms an "anvil" top (*see pages 34 and 35*).

IN 1887 a little-known German physicist named F. Linss raised a question which has plagued scientists for two generations. The French physicist C. A. de Coulomb had observed a century earlier that air conducts electricity away from charged objects. Linss made careful measurements of the rate of this leakage and found that it was much more rapid than had been supposed. The question then raised was: How does the earth—a charged object quite obviously exposed to the atmosphere—maintain its charge? The fact that it did so was well known.

By measurements of the natural electric field in the lowest few feet of the atmosphere, physicists had shown that the earth has a negative charge which in modern units amounts to some 400,000 coulombs. We walk about with our heads in air that is some 200 volts positive with respect to the ground under our feet. If the air conducts electricity, Linss reasoned, the earth's charge must constantly leak into the atmosphere. He calculated that the earth as a whole must be leaking charge at the prodigious rate of 1,800 amperes, and at this rate it should lose 90 per cent of its charge to the atmosphere within an hour! Yet the earth's charge persisted, and there was every reason to believe that it had not decreased appreciably since at least early geologic time.

Linss's paradox captured the interest of many physicists, and as often happens with such puzzles, a whole new branch of science was built up around efforts to resolve it. The investigations led to the discovery of cosmic rays, among other things. The story is one more instance of the way in which important developments in science often grow out of efforts to account for small discrepancies between theory and observation.

In 1899 J. Elster and H. Geitel in Germany and C. T. R. Wilson in England independently discovered ions in the atmosphere. J. J. Thomson had shown earlier that ions were responsible for gaseous conduction in the laboratory. Atmospheric ions differ slightly from those of the chemist's test tube. They consist of clusters of molecules held together by the electric field of a central charged molecule. (Such ions should not be confused with the much larger ones that form on particles of dust or other matter in the air.) Because of their high mobility, the molecular ions carry most of the atmosphere's currents.

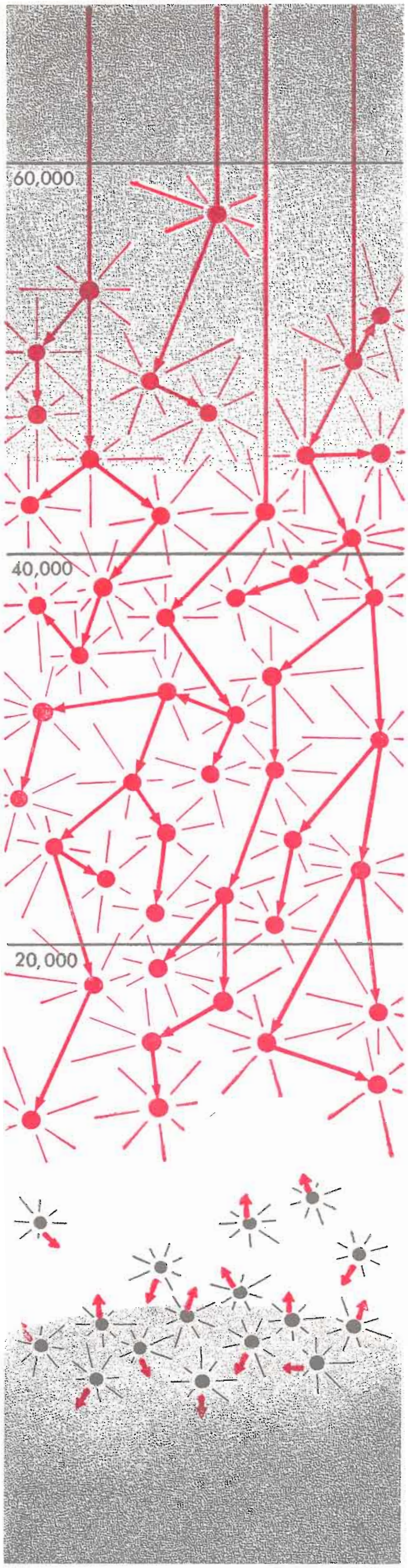
ONCE the existence of atmospheric ions had been established, the next task was to explain how the central molecules acquired their charges. Elster and Geitel at once found an answer in the then new and exciting discovery of radioactivity. Radiations from the radioactive minerals in the earth and from radioactive gases (mainly radon) in the air, they said, ionized the air molecules. Their first measurements of the average ionization rates produced by these radioactive substances seemed to bear out their suggestion.

When they went on to check the hypothesis further in the laboratory, however, they discovered something puzzling. They hoped to be able to prove that air shielded from radioactivity would show a lack of ionization. They enclosed samples of purified air in vessels so heavily shielded with lead that no known radiation, not even the very penetrating gamma rays, could enter. The conductivity of this air should have been zero. But Elster and Geitel found that the shielded air was still able to carry a current. They decided that it must have been ionized by some extraordinarily penetrating "ultragamma" radiation from an unknown mineral in the earth.

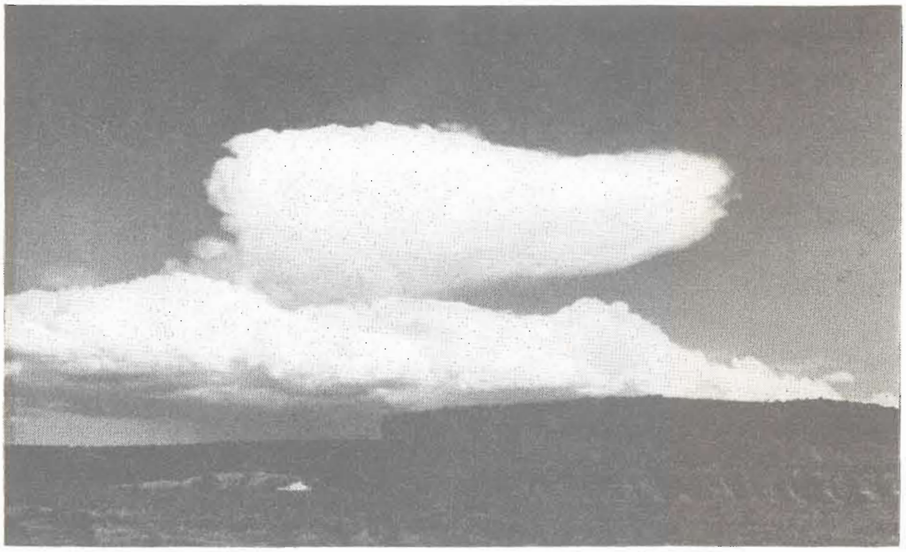
If this was true, atmospheric ionization should decrease as one went farther away from the earth. In 1911 the Viennese physicist Victor Hess went up 16,000 feet in a balloon to test the theory. He discovered that instead of decreasing, the ionization actually increased as he went to high altitudes. At the top of his flight the ionization rate was several times greater than at sea level! In short, the "ultragamma" rays that penetrated lead chambers were coming from above, not from below. They were soon named "cosmic rays" [see "Cosmic Rays," by George W. Gray; SCIENTIFIC AMERICAN, March, 1949].

Exactly where the cosmic rays were coming from was not clear then, and it is still not entirely clear today, 42 years later. But from the point of view of atmospheric electricity, Hess's discovery of cosmic rays (for which he was awarded a Nobel prize in 1936) was most stimulating. Cosmic rays were found to account for some 15 to 20 per cent of the ground-level ionization of the air over land and for almost all the ionization over the oceans, which contain little radioactive matter. Moreover, later ascents to higher altitudes showed that the atmosphere's conductivity steadily increased with height. At 60,000 feet, which was reached by a National Geographic Society balloon in 1935, the conductivity was about 100 times greater than the average at sea level.

The high ionization of the upper atmosphere might well play an important part in maintaining the earth-atmosphere electrical balance. But how? In 1920 Wilson suggested an answer which now seems almost certainly the correct one. Wilson, whose name is associated with the cloud chamber he devised to study the paths of ions, had been making careful measurements of vertical electric field intensity near the earth's surface. During fair weather, he found, the earth's negative charge was con-



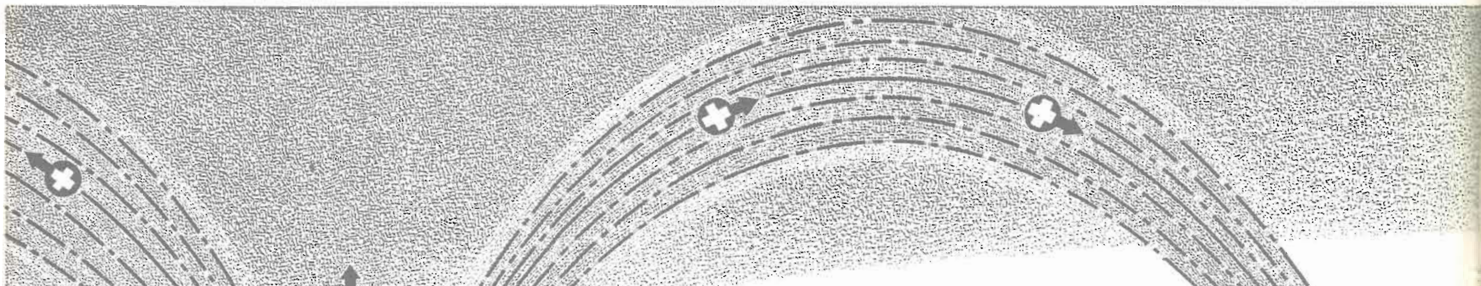
IONIZATION of the atmosphere is due to cosmic rays (*red symbols in the upper part of drawing*) and the disintegration of radioactive atoms (*red symbols at bottom*). The approximate altitudes at which these phenomena produce ions is in feet.



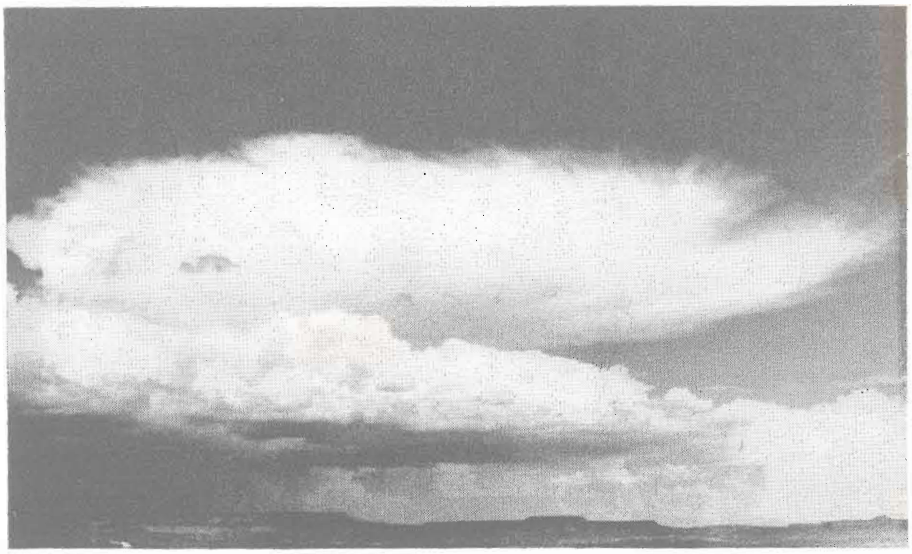
GROWTH OF THE ANVIL TOP of a cumulo-nimbus cloud is depicted in these three photographs from the collection of the U. S. Weather Bureau. This is the final stage in the development of the cloud. The anvil some-

stantly and rapidly being neutralized by a steady downward flow of positive ions —which is electrically equivalent to the upward leakage of negative charge. But Wilson noticed that during thunderstorms the field intensity fluctuated wildly and rose to very high values. More important, he showed that beneath thunderstorms the electric field was often positive instead of negative, and that large negative currents must be flowing to the earth. He suggested that lightning strokes from thunderstorms, which occur in many parts of the world every day, might supply enough negative charge to the earth to balance its loss of charge to the atmosphere in storm-free areas.

Stripped of its details (and in 1920 Wilson was unable to fill in many of these anyway) his hypothesis visualized the thunderstorms that are scattered over the globe at any one instant as a battery of many cells in parallel. Their lower poles fed negative charge downward to the earth *via* lightning and point discharge currents from trees,



FLOW OF CURRENT maintaining the earth's charge is shown in this diagram suggested by the hypothesis of C. T. R. Wilson. At the left and right are two thunderstorms, which add negative charge to the earth and pos-



times reaches phenomenal heights. The average height of summer thunderstorms observed in Ohio was 37,000 feet, with some attaining 50,000 feet. The shape of anvil indicates that its movement is from left to right.

towers and other pointed and grounded objects. Their upper poles, embedded in the highly conducting region of the high atmosphere, leaked an equivalent positive charge to that region. This upward flow was then dispersed through the region and supplied the charge for the descending currents in fair-weather areas. Pursuing the analogy further, one may say that Wilson regarded thunderstorms as cells lying in the gap between the two electrodes of a gigantic spherical condenser. The inner, negative sphere of this condenser was the earth; the somewhat leaky "nonconductor" was the atmosphere; the outer, positive sphere was assumed to be a highly conducting shell of the upper atmosphere. The existence of such a shell had already been suspected from its effects on radio transmission, and a few years after Wilson published his theory it was confirmed by experiments and named the "ionosphere."

Wilson's thunderstorm hypothesis has so far survived all attacks upon it and has become more firmly established with

itive charge to the ionosphere. If measurements were made in the storm-free region near the center of the diagram, they would show a descending current of positive charge tending to neutralize the negative charge.

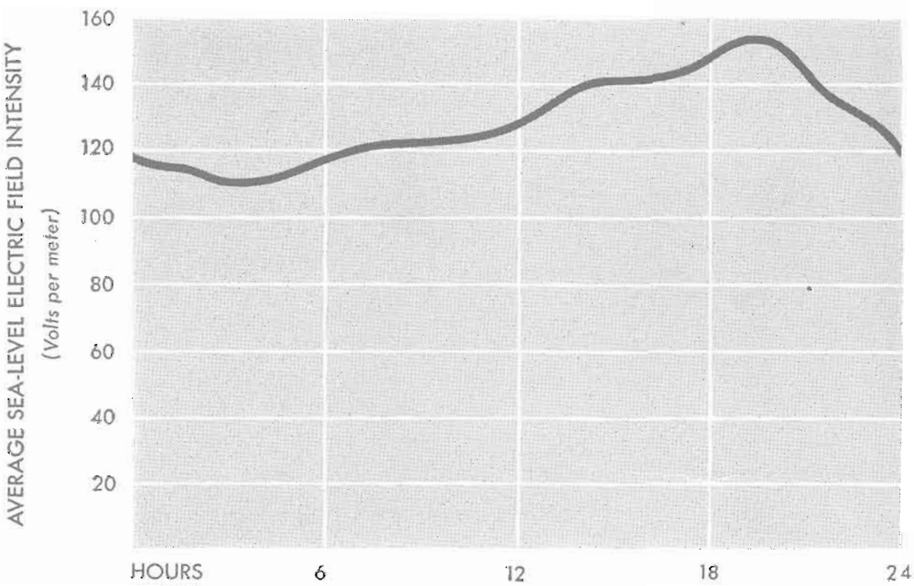
the passage of time. The British meteorologist Sir George Simpson found what he thought was evidence against the theory: in balloon flights he discovered that the air at the base of many ordinary clouds had a positive rather than a negative charge. But it is now believed that these positive charges are negligible compared to the large negative charges in the lower parts of most thunderstorms. Simpson also objected that the conductivity of the upper atmosphere was inadequate to sustain the large positive flow needed to supply the fair-weather currents. The 60,000-foot ascent of the National Geographic Society balloon proved, however, that the conductivity was sufficient at the altitudes it reached.

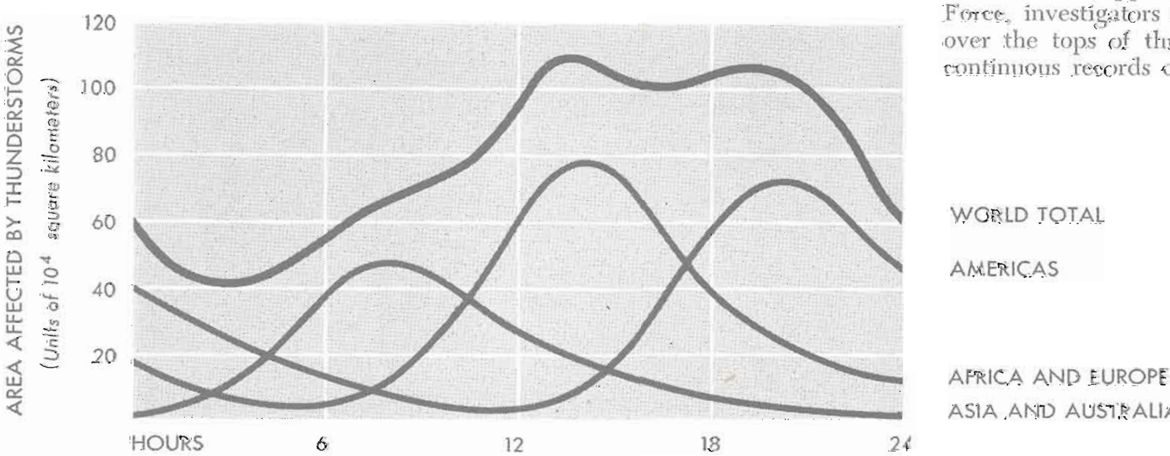
The same flight established that, although the electric field decreases rapidly with height, the ionosphere is still some 400,000 volts positive with respect to the earth! It is this voltage difference that drives positive charge downward through all parts of the atmosphere free from thunderstorms, and which thus tends continuously to neutralize the earth's negative charge. Thunderstorms succeed in driving current in opposition to this high voltage only because they separate charge at so titanic a rate as to create voltage differences of the order of hundreds of millions of volts between their upper and lower charge centers. For this reason it is quite possible for the top of a thundercloud to be at a very large positive voltage above the ionosphere while its base is negative with respect to the earth. The separation of charge is what enables clouds to pump negative charge at a tremendous rate to the earth and thereby replenish its losses.

ONE of the first important tests of the Wilson hypothesis came within a year after he had suggested it. S. J. Mauchly, chief of the terrestrial electricity section of the Carnegie Institution of Washington, analyzed measurements of the electric field intensity that had been made in many parts of the world by the research yacht *Carnegie*. From his analysis he reached the conclusion that the positive voltage of the ionosphere with respect to the earth was at a maximum at a certain time each day: namely 7 p.m. Greenwich Mean Time. This was a curious fact; if Wilson's theory was correct, it should mean that the total thunderstorm activity over the whole earth hit a peak at about that hour each day. The British meteorologist F. J. W. Whipple proceeded to examine world weather records and found that this was indeed the case: as a world average, thunderstorms were most active between 3 and 8 p.m. G. M. T. The explanation has to do with the earth's pattern of land and water distribution. When it is seven in the evening at Greenwich, many noon heat thunderstorms are occurring in the central part of the Western Hemisphere, and it is not long after the afternoon peak of storms in Europe and Africa. All this activity, plus smaller contributions by Asia and Australia, make this one period of the universal day the most stormy on the average over the world. The storms spew out positive charge to the ionosphere and negative charge to the earth at such a rate as to build up the voltage difference to about 15 per cent above the day-long mean.

The crucial question remains: Does the total transfer of negative charge to the earth by thunderstorms balance the leakage of charge from the earth? This question has been difficult to answer. The closest approach was made in 1947 by O. H. Gish and G. R. Wait of the Carnegie Institution. Recognizing the difficulties involved in measuring charge transfer under thunderclouds, they turned to the other poles of Wilson's cells—the top of a thundercloud and the ionosphere. The net current exchange there, they argued, should on the average equal that between the cloud base and the earth. And it should be much easier to measure.

In a B-29 supplied by the U. S. Air Force, investigators made many flights over the tops of thunderstorms. From continuous records of the vertical field





DAILY VARIATION in the intensity of the electric field at sea level is shown in the upper chart. The variation in the number of thunderstorms is given in the bottom chart. The rough agreement between the upper curve and the world total thunderstorm curve indicates that thunderstorms replenish the earth's charge.

LIGHTNING STRIKES from the bottom of a cumulonimbus cloud in this photograph made by Daniel T. O'Connell from the edge of Grand Canyon. Some strokes are photographically reversed by overexposure.

strength and the conductivity, they calculated that the average current was of the order of half an ampere above each active region of a thunderstorm. The total leakage of current from the earth, it will be remembered, is 1,800 amperes. To return that amount of current to the earth there would have to be 3,600 active thunderstorm regions at all times over the whole earth. Gish and Wait have given fairly good reasons for believing that this number of storms is in fact present at all times.

Since the measurements were made at only 40,000 feet, far below the base of the ionosphere, it might be objected that a substantial portion of the ascending positive charge which they measured may not reach the ionosphere to replenish that region's charge. Recently R. E. Holzer of the University of California at Los Angeles and D. S. Saxon of the National Bureau of Standards have examined this question theoretically. On the basis of reasonable assumptions as to the conductivity at great heights, they estimate that 85 per cent of the current measured during a typical flight above a storm does reach the ionosphere and only 15 per cent fountains out and down to the ground. This analysis by Holzer and Saxon considerably strengthens the Gish-Wait experiment.

TO CONFIRM Wilson's thunderstorm hypothesis conclusively the Gish-Wait experiment must be repeated in many parts of the world, and a more thorough count of the world's thunderstorms must be compiled. But it now appears that Wilson's penetrating insight hit upon the correct explanation when he suggested 33 years ago that the earth constantly replenishes its huge charge from thunderstorms, which at any one time cover less than 1 per cent of the earth's surface.