The trilateration data allow three additional linearly independent components (eigenvectors) of the slip to be resolved. Excluding the remaining singular values and their associated eigenvectors from the inverse operator tends to suppress short-wavelength variations in the slip and results in estimated models that are presumed to be smoothed versions of the true slip distribution [R. L. Parker, *Annu. Rev. Earth Planet. Sci.* **5**, 35 (1977)].
23. The 6° difference in orientation between the Pacific–North American relative velocity vector and the strike of the San Andreas fault in central California requires some shortening orthogonal to the strike of the fault {J. B. Minster and T. M. Jordan, in *Tectonics and Sedimentation Along the California Margin*, J. K. Crouch and S. B. Bachman, Eds. [*Soc. Econ. Paleontol. Mineral. Spec. Publ.* **38**, 1 (1984)]}.
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27. For this calculation, we use the natural or minimum-length inverse (*15, 16*). In practice, the natural inverse places nearly all the slip at shallow (2 to 4 km) depth, where the resolution of the network is greatest. Although this calculation is clearly artificial and at variance with the seismic evidence for rupture to depths of at least 10 km, this model does provide a reasonable lower bound on the seismic moment.
28. K. Shimazaki and T. Nakata, *Geophys. Res. Lett.* **7**, 279 (1980).
29. A lower bound of 14 km on the transition depth is reasonable because the occurrence of aftershocks to 14 km demonstrates postseismic and, possibly, coseismic slip to this depth. We do not consider transition depths greater than 22 km here because the best-fitting deep-slip rates for these models exceed the long-term slip rate of 33 mm year^{-1}. Time-dependent response to the 1857 earthquake might have caused the deep-slip rate during the 25-year measurement period to lag the long-term rate. We consider it unlikely that the deep-slip rate during this period exceeded the long-term rate, although this possibility is not inconsistent with the data.
30. The inverse that minimizes the squared difference between the estimated and prior models

$$\sum_{i=1}^{M} (s_i - s_i^{\mathrm{prior}})^2$$

where s^{prior} is the prior model, can be calculated from the natural inverse (*15, 16*) after a change of variables (*31*).
31. C. L. Lawson and R. S. Hanson, *Solving Least Squares Problems* (Prentice-Hall, Englewood Cliffs, NJ, 1974).
32. The ambiguity in rigid body motions involved in calculating station velocities from relative length changes [W. H. Prescott, *J. Geophys. Res.* **86**, 6067 (1981)] were removed by finding the rigid body translation and rotation that minimized the discrepancy with the predicted velocity field.
33. We thank W. Ellsworth, J. Langbein, M. Matthews, W. Menke, D. Oppenheimer, W. Prescott, J. Savage, R. Simpson, and W. Thatcher for advice and thoughtful reviews of the manuscript.

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Abnormal Polarity of Thunderclouds Grown from Negatively Charged Air

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Experiments were carried out in New Mexico to determine whether the electrification processes that lead to the formation of lightning in clouds are influenced by the polarity of the charges in the air from which the clouds grow. The normal, positive space charge in the sub-cloud air was reversed by negative charge released from an electrified wire, suspended across a 2-kilometer-wide canyon. On more than four occasions when the clouds over the wire grew and became electrified, they were of abnormal polarity with dominant positive charges instead of the usual negative charges in the lower part of the cloud. The formation of these abnormally electrified clouds suggests both that the electrification process in thunderclouds can be initiated and that its polarity may be determined by the small charges that are present in the atmosphere.

ALMOST AS SIGNIFICANT AS BENJAmin Franklin's demonstration that lightning is a form of electricity is his observation "that the clouds of a thunder-gust are most commonly in a negative state of electricity, but sometimes in a positive state" (*1*, p. 42). Electrical measurements that have since been made all over the world confirm his finding and show that in nearly all thunderstorms there is a dominant negative charge in the lower part of the cloud. Measurements from airplanes (*2*) and balloons (*3*) show that there is usually also a dominant positive charge in the upper part of these clouds.

This strong bias of polarity has important consequences. The upper, positive part of the dipole attracts negative charge from the upper atmosphere to the top of the cloud by conduction. The lower, negative part of the dipole exports negative charge to the earth by lightning and by point discharge. As a result of these processes, the approximately 1000 thunderstorms that are continuously in progress over the earth bring about 1 kA of negative charge from the atmosphere to the earth. This current, as Wilson (*4*) perceived, is responsible for continuously maintaining a negative charge of about 0.5×10^6 C on the earth and an equal positive charge in the atmosphere.

Modern observations also confirm Franklin's finding that clouds are "sometimes in a positive state." During the usual thunderstorm, negative (downwardly directed, fine weather) electric fields beneath a cloud occur briefly, just after cloud-to-ground lightning (*5*), during gushes of heavy rain, and in the dying stage of the storm (*6*). Occasionally, storms occur that are electrically different from the usual ones. Gunn (*7*) reported several storms that produced sustained electric fields at the ground comparable in intensity to ordinary storms, but these fields were in the downwardly directed, fine weather direction with dominant positive charge aloft. This observation shows that the thunderstorm charge distribution can occasionally be the opposite of that usually encountered. Imyanitov *et al.* (*8*) have reported that the upper parts of some storm clouds have negative instead of positive charge. Data obtained from lightning-detecting networks by Orville *et al.* (*9*) and Rust *et al.* (*10*) provide evidence for the existence of storms that are abnormal in that most of the cloud-to-ground discharges bring down positive instead of negative charge (*9, 10*).

A requirement of any theory of electrification is to explain why, with few exceptions, the electrical dipole in the cloud develops with positive charge uppermost and negative charge below. The various thunderstorm electrification mechanisms proposed can be divided into two classes, depending on the explanations for this charge distribution.

According to the first class, which is based on the so-called "induction," "influence," or "feedback" theories of thunderstorm electrification, the polarity of the dipole is determined by the polarity of weak space charges or electric fields that may be present in the atmosphere during the development of the cumulus cloud before it becomes a thunderstorm. It is possible that a cumulus cloud behaves as a high-voltage influence machine, such as the Kelvin water dropper (*11*) and similar devices developed later (*12*). If a cumulus cloud becomes electrified by a similar mechanism, the polarity of the thunderstorm will be determined by the polarity of the weak charges that are carried up into the

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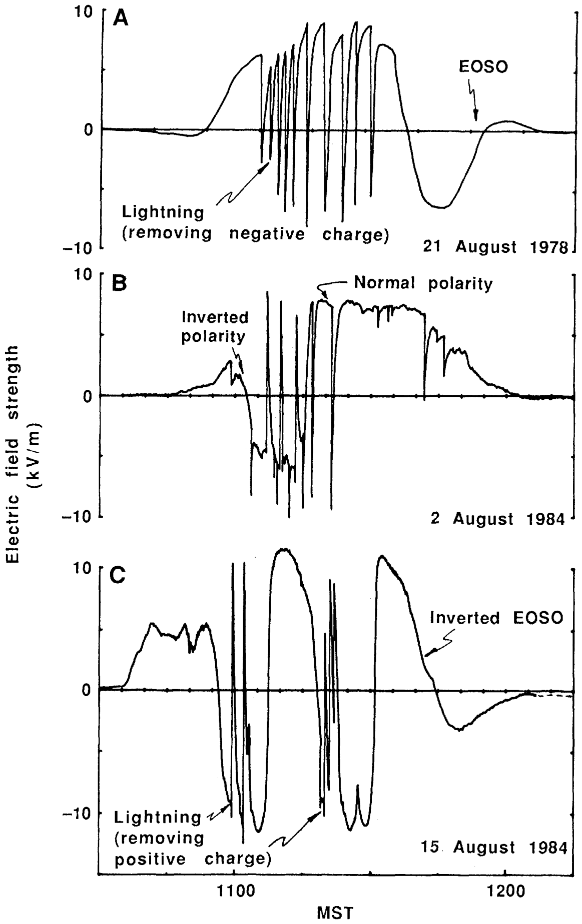

Fig. 1. Comparison of electric field records under a storm of normal polarity and under the abnormal ones observed during the experiments. (A) Normal polarity thunderstorm. [The time axis for (A) is not at the same MST as for (B) and (C), but the axes time ticks are all at 5-minute intervals.] (B) Inverted polarity thunderstorm. Record on 2 August 1984, showing electric fields of anomalous polarity produced by first of two thunderclouds. (C) Inverted polarity thunderstorms. Record on 15 August 1984, showing electric fields of anomalous polarity produced by two successive thunderclouds.

cloud and that initiate the electrification process during the early stages of the cloud's development. The air from which a cumulus cloud grows almost invariably contains the slight positive space charge present in fine weather. Therefore, if an influence mechanism is active and electrification occurs, positive charge will be in the upper, and negative charge in the lower, part of the cloud. Examples of cloud electrification mechanisms that are initiated by preexisting charges or fields include those based on inductive charge transfer between colliding cloud particles (*13*), on selective ion capture by falling precipitation (*14*), and on the formation of screening layers of charged particles at the cloud surface that are transported by convection to form charged regions (*15*).

According to the second class of mechanisms, the initial space charge and electric fields play no part in the development of electrification. In these mechanisms, the polarity of the charge separation process is determined by other variables, such as the phase, concentration, temperature, size, surface characteristics, or purity of colliding or breaking cloud particles. Mechanisms of this type include those based on breaking drops (*16*), glazing of ice particles (*17*), and ice impaction (*18*).

Both classes of explanations must also account for the exceptions—how it is possible that occasionally a thundercloud has negative instead of positive charge uppermost. With mechanisms of the first class, a thundercloud of inverted polarity could develop if the air it grows from contained negative instead of positive space charge. Though uncommon, this is sometimes the case in dust storms (*19*), over breaking freshwater waves (*20*), over waterfalls (*21*), and in the vicinity of another cloud that has already become electrified (*22*). The polarity of the feedback process may also be determined by other factors such as electric fields of external origin or fields developed from within the cloud by the falling of electrified precipitation.

A cloud of inverted polarity could form with the second class of mechanisms if changes occurred in variables, such as cloud particle population, temperature, or impurity concentrations, that reversed the polarity of the charge acquired by precipitation. Saunders *et al.* discussed such a possibility (*23*).

The predictions of influence mechanisms can be tested by determining whether the incidence of clouds having dipoles of inverted polarity is increased if the air from which they grow is artificially supplied with negative space charge. Negative, or positive, charge in the form of ions can be introduced into the atmosphere by corona discharges from an elevated wire that is maintained at a high d-c potential (*24*). Sufficiently large amounts of negative space charge can be released to reverse the polarity of the space charge and electric field for distances up to several kilometers downwind of the wire (*25*).

To our knowledge, before the work reported here, the most extensive experiment to determine the effects produced on clouds by the release of negative space charge was carried out during 1960 in central Illinois (*26*). During that experiment, when the atmosphere was unstable and fine weather cumuli were forming, observations from an airplane instrumented with electric field and charge-measuring equipment showed that space charge released from the wire and carried up into the clouds caused significant changes in the electrical properties of the clouds. When positive charge was released, the upper part of the cloud became positive, and the lower part became negative. When negative charge was released, the upper part of the cloud became negative and the lower part became positive. Evidently the charge carried into the cloud by updrafts attracted the opposite sign of charge by conduction from the surrounding clear atmosphere. This charge was then carried by downdrafts to form the charge center in the lower part of the cloud. The electric field intensities above the modified clouds were as great as 400 V/m. Though these fields were several times more intense than those produced by unaffected clouds nearby, they were weak compared to those in a thunderstorm.

These Illinois experiments showed that the polarity of electrification of a fine weather cumulus can be determined by the polarity of the space charge in the air from which the cloud forms. Under the wind conditions at the time, however, none of these clouds ever grew and became a thundercloud over the charge source.

Further studies in New Mexico were carried out during the summers of 1984 and 1985 to determine whether the inverted dipole observed when negative charge was being released would persist and intensify if the cloud grew and became a thunderstorm. Langmuir Laboratory in the Magdalena Mountains near Socorro, New Mexico, was chosen as the site for these experiments. The probability that a thundercloud will form in that area is higher than at most other locations. Because the speed of the wind there is often low, clouds sometimes form and develop into a thunderstorm without moving more than a few kilometers. Equally important, electric field records made over the past 20 years show that in the summer when an isolated cloud near the laboratory develops and becomes a thunderstorm, the lower part of the cloud invariably carries a negative charge.

The technique used to release negative charge in New Mexico was similar to the earlier one in Illinois. A 2-km-long wire was suspended on insulators between two mountain peaks. The catenary, approximately 400 m above the canyon floor, released negative ions by corona discharge when it was raised to a high negative potential with a d-c power supply. With the usual winds of a few meters per second, the flux of charge emitted into the atmosphere was of the order of 400 μA when the wire potential was about 120 kV.

Each morning when cumulus clouds began to form under the influence of solar heating, the apparatus was put into operation. Negative charge was released from the wire until the clouds nearby became so strongly electrified they threatened to produce lightning that could damage the power supply.

Measurements made downwind of the wire before a cloud formed showed, as in the Illinois experiments, that beneath the plume of space charge the polarity of the electric field had been reversed and its intensity had increased by tenfold. The area affected by the charge release was small, probably no more than a few square kilometers. As experiments have shown, the charge leaks to ground at a rate determined by the electrical time constant of the ambient atmosphere (*25*). Near Langmuir Laboratory the relaxation time was of the order of 3 minutes, so the charge would leak away if it were not rapidly carried into the cloud where the time constant is much longer.

An array of six field meters extending along the mountain ridge for 2 km was used to measure the electric fields of thunderclouds. Data from this equipment were supplemented by other electrical observations, which included the field changes produced by lightning and measurements made from an instrumented airplane and a free balloon carrying an electric field meter.

On several days during the period of the 1984 experiment, clouds developed into thunderstorms near or over the source of negative charge. On two of these days (2 and 15 August), the humidity was so high that the base of the cloud forming over the mountain was below the summit, and the upper portions of the electrified catenary were in the clouds. On these days the negative space charge released from the wire reversed the atmospheric electric field over the summit for 40 minutes or more, and then, as the clouds developed above, all of the field meters began to indicate an intensifying positive charge overhead. A few minutes later (on each day), lightning discharges to ground occurred near the wire and removed positive charge from the cloud overhead. A second, similar, cloud-to-ground flash occurred about 3 minutes after the first one on each of the 2 days. The electric field records for these two storms are shown in Fig. 1. For comparison, the record for a natural thunderstorm is shown, which, being of normal polarity, had negative charge in the lower part of the cloud and produced several lightning flashes that lowered negative charge to ground.

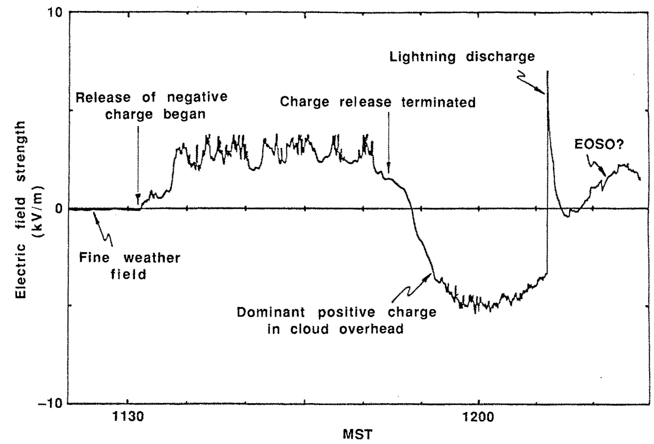

Fig. 2. Record showing electric fields of anomalous polarity produced by a small thundercloud on 24 July 1985. The lightning discharge, which was 2 km to the east of Langmuir Laboratory, removed the positive charge from the cloud.

On 2 August, the anomalous, positive charge in the lower part of the cloud that formed over the site extended over a distance of more than 2 km during a horizontal penetration by the instrumented airplane. The plane started this penetration at 1101 MST and flew from north to south at an altitude of 4700 m. In a continuing penetration through another cloud to the southeast, indications of negative instead of positive charge above the airplane were recorded. At 1110:25 MST, a third lightning discharge to ground again removed positive charge from the lower part of the cloud over the site. This cloud then merged with two larger clouds of normal polarity that had been growing about 2 km away, the one to the southeast and another to the north. The combined system produced three more cloud-to-ground discharges of normal polarity that removed negative charge from the lower regions of the merged clouds before they began to dissipate.

On 15 August, the active cloud overhead subsided after its second anomalous discharge; its electric field thereafter exhibited the first part of the "end-of-storm oscillation" (EOSO) signature in which the charge in the upper part of the thundercloud dominates the surface electric field as the cloud descends and inverted convection occurs (*6*). The remarkable feature on 15 August was that the upper charge during this EOSO was negative instead of the normal positive polarity. Before the end-of-storm sequence was completed, a second cloud turret developed over the east end of the cable, and it too was inverted in polarity, producing three cloud-to-ground discharges that removed positive charge from the cloud's lower regions. The second cloud then subsided and again exhibited an inverted, EOSO, electric field signature.

The instrumented airplane flew through the top of the first turret around 1058 MST at an altitude of 7770 m. The rotation of the electric field vectors as the airplane approached and then penetrated the cloud turret indicated the presence of a dominant negative charge just beneath the plane. (A later analysis of the electric field record during this pass suggests that about 1 C of negative charge was involved.) The electric field intensified abruptly as the aircraft entered the turret and weakened similarly as it departed; this behavior may have been produced by a screening layer of positive charge around the negatively charged cloud top.

The instrumented free balloon (at an altitude of 5500 m) indicated the presence of positive charge between the balloon and the earth. A vertically scanning Doppler radar on the mountain top showed strong downdrafts and precipitation falling from near the cloud top to the cloud base.

One interpretation of these observations is that the upper negative charge came from 2 C or more of negative charge released into the cloud base by the electrified wire during the growth of the cloud. The positive charges in the lower regions of the cloud may have been derived from the positively charged screening layers around the cloud top carried downward by downdrafts and by falling precipitation.

The charge release experiment at Langmuir Laboratory was repeated during the summer of 1985. Though far fewer clouds that were suitable for experimentation formed than in 1984, anomalous distributions of charge were again observed in clouds growing from the region of negatively charged air. Several clouds growing over the negative charge source developed extensive regions containing positive charge in their lower portions. An example is shown in Fig. 2. The measurements reported for 1985 were made with ground-based equipment because the instrumented airplane and balloon systems used in 1984 were not available.

It is conceivable that the abnormal polarity of electrification exhibited by these storms may have been an unusual natural occurrence that was not related to the artificial release of negative space charge during the growing period of the thundercloud. This is unlikely, however. Observations in this region of New Mexico over the past 20 years show that this polarity of electrification very rarely, if ever, occurs naturally in isolated clouds. Of the approximately 1000 thunderstorms whose electric fields have been observed, no isolated cloud above us has exhibited abnormal polarity. That three abnormal storms would have occurred by chance during a 2-week interval seems highly improbable.

The idea that the electrified wire powered by less than 100 W could influence the development of a thundercloud that produces 100 MW may at first strain credulity. However, if the electrification of a thundercloud is brought about by a feedback process similar to that acting in a laboratory influence machine, this growth of charge in the thundercloud can reasonably be expected. In describing his laboratory experiments, Kelvin (*11*, p. 69) wrote, "It is curious, after commencing with no electricity except a feeble charge in one of the jars, only discoverable by a delicate electrometer, to see in the course of a few minutes a somewhat rapid succession of sparks pass in some part of the apparatus . . . ." Just as his apparatus supplied with mechanical energy was capable of multiplying the "feeble charge in the jar" until it produced sparks, so the growing cloud supplied with energy from the atmosphere should be able, by electrostatic induction, to multiply either naturally occurring positive space charge or artificially introduced negative charge until the resultant electric field becomes sufficiently intense to produce lightning. The fine weather electrical process, which may usually initiate thunderstorm electrification, involves a current of only 1 μA and a power of <1 W for each square kilometer.

That the charge released from the wire could have influenced the polarity of the much larger charges forming later in the thundercloud indicates that the electrification process can be of the "feedback" or "influence" kind. It appears that on some occasions enough of the negative charge from the wire is carried up into the cloud to overbalance the other factors that normally determine the electrical polarity of thunderclouds.

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Neuronal Population Coding of Movement Direction

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Although individual neurons in the arm area of the primate motor cortex are only broadly tuned to a particular direction in three-dimensional space, the animal can very precisely control the movement of its arm. The direction of movement was found to be uniquely predicted by the action of a population of motor cortical neurons. When individual cells were represented as vectors that make weighted contributions along the axis of their preferred direction (according to changes in their activity during the movement under consideration) the resulting vector sum of all cell vectors (population vector) was in a direction congruent with the direction of movement. This population vector can be monitored during various tasks, and similar measures in other neuronal populations could be of heuristic value where there is a neural representation of variables with vectorial attributes.

FOR MANY FUNCTIONS CONTROLLED by the brain or variables represented in the brain, the relevant unit is the neuronal population rather than the individual neuron. Elucidating the nature of this representation of information by a neuronal ensemble is a central problem of neuroscience (*1*). We have approached this problem by investigating the brain mechanisms subserving the direction of arm movement in three-dimensional (3-D) space in order to predict directed arm movements from the neural responses of populations of motor cortical neurons.

Rhesus monkeys were trained to reach out and push red buttons that had been lit. A center button was located directly in front of the animal at shoulder level. Eight target buttons were placed at equal distances (12.5 cm) from the center button so that the direction of movements made from the center to targets sampled the 3-D space at approximately equal angular intervals (Fig. 1). In a trial, the center light came on first, and the animal pushed it and held its hand on that button for at least 1 second. Then

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