In 1994, Fishman et al. observed brief (>1 ms) bursts of intense gamma rays, called terrestrial gamma-ray flashes, with the Compton Gamma-Ray Observatory (CGRO) (1). Prior to this observation, intense transient bursts of gamma rays were only known to occur in an astrophysical context. The observed photon energies of more than 1 MeV suggested that the gamma rays were produced by “bremsstrahlung” radiation from high-energy electrons. (Such radiation is emitted when energetic electrons are scattered by nuclei.) The flashes—the most energetic natural photon phenomena on Earth—are caused by upward beams of electrons (“runaways”) that are accelerated by thundercloud fields (2, 3).

On page 1085 of this issue, Smith et al. (4) show, based on data from the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) satellite, that terrestrial gamma-ray flashes are much more common than previously thought and that the photon energies can reach ~20 MeV. The CGRO and RHESSI data may be the first observational evidence of relativistic runaway breakdown, in which seed electrons at relativistic (>1 MeV) energies are accelerated by an electric field, followed by electrical breakdown as a result of their collision with air molecules. Relativistic runaway breakdown can proceed at much lower electric fields than conventional air breakdown (in which ambient thermal electrons must be accelerated to energies sufficient to ionize nitrogen). It may also be an important process in astrophysical plasmas. However, it has never been observed in the laboratory.

Computer models predict (3) that intense, transient electric fields associated with thunderclouds impose a total potential drop between 20- and 80-km altitude of more than 30 MV for large positive cloud-to-ground discharges of over 100 C (see the figure). These fields produce highly nonlinear runaway avalanches, in which accelerated electrons collide with molecules of air to strip even larger numbers of relativistic electrons. This process leads to a rapidly increasing number of relativistic electrons over large regions, with gamma-ray flashes emitted at altitudes of 30 to 70 km. The intense upward-driven relativistic electron beams eventually enter the radiation belts (the near-Earth space populated by energetic particles that are trapped in Earth’s magnetic field). Here, some electrons may become trapped. A fraction of them may then precipitate in regions that are geomagnetically conjugate to intense lightning discharges (for example at the Southern Hemisphere termination of the magnetic field line that originates from a Northern Hemisphere thunderstorm). Here they interact with molecules in the increasingly dense atmosphere to produce optical emissions and x-rays, which are ultimately caused by the release of energy in a lightning discharge in the parent hemisphere.

A total of ~76 terrestrial gamma-ray flashes were observed with the CGRO over the 9-year mission. However, when the instrument was in an optimized energy trigger mode (>100 keV), ~1 event per week was observed. The instrument had a minimum trigger time resolution of 64 μs, thus missing many terrestrial gamma-ray flashes, which have a typical duration of 1 ms (5). Smith et al. show that without this limitation, terrestrial gamma-ray flashes are observed much more often (~15 to 20 per month, even with much smaller (and thus less sensitive) detectors (4). There is clear evidence that terrestrial gamma-ray flashes are associated with lightning (6). For many of the flashes detected by CGRO and RHESSI, radio atmospherics (electromagnetic impulses produced by lightning discharges) were observed at the same time at Palmer Station, Antarctica. These radio atmospherics exhibit the slow tail characteristic of lightning flashes that lead to transient luminous high-altitude phenomena known as sprites (6, 7).

Observations and modeling of sprites (8, 9) confirm the existence of intense, slowly varying electric fields of up to 1 kV/m at altitudes of 30 to 80 km above thunderstorms. When integrated over altitudes of 20 to 80 km, these fields correspond to a total transient potential drop of more than 30 MV (see the figure). Such intense electric fields can produce runaway electron beams via avalanche acceleration (10–13), leading to the emission of bremsstrahlung gamma-ray flashes of an intensity consistent with the CGRO observations (3). However, models of this phenomenon depend strongly on the initial conditions (3, 14, 15), because the runaway process is highly nonlinear and the lightning electric fields vary widely.

How terrestrial gamma-ray flashes form. (Left) The electric field before (black line) and after (red line) a positive lightning discharge that removes 100 C from the top of the cloud (at an altitude of 10 km). After the discharge, the relativistic runaway threshold field (green line) is exceeded above 40 km. Solid and dashed lines are downward and upward fields, respectively. (Right) Schematic of the relativistic electron avalanche and production of gamma rays after the lightning discharge. The scale roughly corresponds to the vertical scale on the left.

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rays at altitudes of 30 to 70 km (3). For electrons >500 keV, the loss of energy due to scattering is insignificant above 70 km because of the low density of air at these altitudes. Therefore, most of these particles must escape upward along Earth’s magnetic field lines into the radiation belts, constituting an injected beam with a total fluence of up to 10³ to 10⁴ electrons/cm² (3, 17).

For cloud-to-ground discharges, the estimated transverse scale of the beam is about 10 to 20 km, whereas for horizontal intracloud discharges, the scale may be as large as ~100 km (3, 12). Direct satellite detection of such beams during injection is thus improbable: To observe the event, the satellite would have to be at just the right location during the ~1 ms of beam duration. However, some of the injected electrons are predicted to form (17) eastward-drifting “curtains” extending over ~70° in longitude within a few minutes of injection. Such spreading would substantially enhance the likelihood of in situ detection, especially shortly after injection, before the electrons drift around the planet and are precipitated into the atmosphere near the South Atlantic, where the Earth’s magnetic field exhibits a minimum.

The satellite observations of hundreds of terrestrial gamma-ray flashes reported by Smith et al. (4) provide an excellent data set on these high-energy phenomena. Coupled with observations of sprites and elves and more comprehensive data on lightning occurrence, the data may allow us to quantitatively understand the mechanisms of runaway acceleration.

References

ARCHAEOLOGY

Patterns of Cultural Primacy
Richard A. Diehl

For more than 100 years, archaeologists have debated the impact of long-distance trade and exchange on the emergence of civilization. Nowhere has this issue been more sharply contested than in ancient Mesoamerica, especially with regard to the Olmecs during the Early Formative Period (1500 to 900 B.C.E.) at San Lorenzo in southern Mexico’s Veracruz state.

San Lorenzo, the largest center in Mesoamerica from the Early Formative Period, covered 700 hectares and was home to several thousand residents. Some archaeologists have argued that San Lorenzo had a defining impact on societies in the neighboring Chiapas, Guerrero, and Oaxaca states and in central Mexico (1–3); others contend that each region witnessed the contemporaneous growth of complex societies that interacted with each other and with the Olmecs as equals (4, 5). The terms “mother culture” and “sister cultures” are often applied to the extreme positions of the debate (6, 7).

On page 1068 of this issue, Blomster et al. (8) provide powerful support for the mother culture school. They demonstrate that some of the Olmec-style pottery found throughout Mesoamerica was manufactured at San Lorenzo and traded over distances of hundreds of kilometers. San Lorenzo thus dominated in the commercial relationships and attendant spread of Olmec iconography and belief systems.

San Lorenzo has been at the center of the Olmec mother culture debate since radiocarbon dates placed it centuries earlier (9) than had been postulated by some archaeologists on the basis of the sophistication of its stone sculptures, especially its famous colossal heads (10). Recent investigations show that in the Early Formative Period, San Lorenzo covered about 700 hectares, many times the area of any contemporary cities in Mesoamerica (11). Its known features include exquisitely carved colossal heads, thrones, and other two- and three-dimensional depictions of rulers, mythical and living animals, and deities (see the figure). The plateau it occupied overlooked the junction of several rivers, thus controlling transportation through-out the entire Coatzacoalcos river basin. Raised causeways led from the rivers across annually flooded ground to the plateau. Terraces holding commoner residences lined the ridge sides; the 100-hectare summit was reserved for elite housing, public architecture, and displays that included sets of stone sculptures.

San Lorenzo’s merchants imported jadeite, basalt, obsidian, Pacific coast shells, magnetite and other iron ores, and probably also more perishable materials.

The three major archaeological projects at San Lorenzo since 1946 (12) have revealed new and at times startling information and have resolved many questions. But each has also left numerous questions unresolved or subject to dispute while raising many new ones. Perhaps the most pervasive is the mother culture–sister cultures dispute. Did San Lorenzo’s leaders maintain contacts with rulers in distant communities? If so, why? And what goods and other things did they seek?

Perhaps the most important question concerns the wide dispersal of Olmec iconic symbols and the belief systems they represent. The symbols are displayed on large stone sculptures, small portable greenstone objects, and pottery. Did all these symbols originate at San Lorenzo, or did societies in Chiapas, Oaxaca, Guerrero, and central Mexico contribute to the pool of what has been mistakenly attributed to the San Lorenzo style? Stone sculpture is rare outside Olman (the Olmec heartland), whereas pottery with Olmec-style iconography occurs frequently, and hence the debate has focused on the latter. One school holds that such vessels were exports from San Lorenzo; others argue that the different centers shared basic ideas but manufactured their