Reports

Television Image of a Large Upward Electrical Discharge Above a Thunderstorm System

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An image of an unusual luminous electrical discharge over a thunderstorm 250 kilometers from the observing site has been obtained with a low-light-level television camera. The discharge began at the cloud tops at 14 kilometers and extended into the clear air 20 kilometers higher. The image, which had a duration of less than 30 milliseconds, resembled two jets or fountains and was probably caused by two localized electric charge concentrations at the cloud tops. Large upward discharges may create a hazard for aircraft and rocket launches and, by penetrating into the ionosphere, may initiate whistler waves and other effects on a magnetospheric scale. Such upward electrical discharges may account for unexplained photometric observations of distant lightning events that showed a low rise rate of the luminous pulse and no electromagnetic sferic pulse of the type that accompanies cloud-to-earth lightning strokes. An unusually high rate of such photometric events was recorded during the night of 22 to 23 September 1989 during a storm associated with hurricane Hugo.

Reports of visually observed lightning discharges from thunderstorm tops into the clear air above have occasionally appeared in the scientific literature since the last century (*1*). Such observations are relatively rare, as the observer must view the storm center from a distant point through clear atmosphere, and the phenomenon may be infrequent. Airline pilots have a unique chance to observe upward flashes, and reports of their visual observations have recently been published (*2*). These events are of interest because they may represent a direct coupling between lightning storms and the ionosphere and magnetosphere and may produce whistler waves and other disturbances. They may also present a type of hazard for aircraft and for space vehicles during the launch phase. We describe here a TV image of a large upward flash and discuss briefly the physics of upward discharges. We also show how the event may help us to understand fast luminous transients from distant lightning storms, some of which were related to hurricane Hugo.

Since 1985, we have made observations of the sky at the zenith on clear dark nights, using three wide-angle telescopic photometers that have recorded many subvisual-level fast transient luminous pulses. The program, known as SKYFLASH (*3*), uses an observing site about 60 km northeast of the Minneapolis–St. Paul metropolitan area at 45°N, 93°W. Most events have been identified as Rayleigh-scattered lightning flashes from storm centers as distant as 1000 km, which usually showed a polarization plane normal to the direction of the storm and were accompanied by a sferic, that is, a burst of electromagnetic radiation emitted by the lightning stroke that produced the luminous flash (the SKYFLASH sferic detector consisted of a large loop antenna and a very high-gain, 300- to 15,000-Hz wideband amplifier recording on one channel of the SKYFLASH oscillograph). An example of a sferic is shown in Fig. 3B.

During the night of 5 to 6 July 1989, we were testing a low-light-level TV camera intended for a sounding rocket flight (*4*) by observing stars and a distant lightning storm. At 2214:22 CST (0414:22 6 July UT), while directing the camera to the northern horizon, we recorded a twin flash originating in distant cloud tops and discharging into the stratosphere. The unprocessed screen image of the video monitor is reproduced in Fig. 1. The flash lasted for two 1/60-s TV fields, with the greatest intensity occurring in the first field. This flash duration must be characteristic of the source, as the persistence time of the image in the intensified charge injection device (ICID) camera was less than one field. The flash was associated with a very active storm center located [by lightning tracking networks (*5*)] on the northwestern side of Lake Superior, about 250 km north of the observation site. The flash image is repeated in Fig. 2B, which is in horizontal alignment with Fig. 2A; we obtained this image by panning the TV camera toward the west, where a dip in the nearby tree line (50 m from the camera) gave a better view of the horizon. Figure 2A reveals the cloud tops and, close to the horizon, the cloud-to-ground lightning activity of the distant storm. The heights of thunderstorm tops were estimated from meteorological soundings from International Falls and St. Cloud, Minnesota, at 0000 and 1200 UT on 6 July to have been about 14 km (*6*). The vertical angular size of the flash, about 5°, was determined by comparison with the constellation Cassiopeia, also recorded by the TV camera (Fig. 2D).

The exact cloud structure in which the upward flash originated is not resolved, but the clarity of the air above the distant cloud tops was shown by stars faintly visible on the TV near the horizon. This clarity is shown in the star-trail photo in Fig. 2C, the first of a series of routine 35-mm patrol camera photos (15-min exposures) of the northern sky, beginning about 15 min after the flash of Fig. 1. The relative angular size of the TV and camera images can be directly compared, as Cassiopeia also appears in the camera photo (upper right; note also Polaris

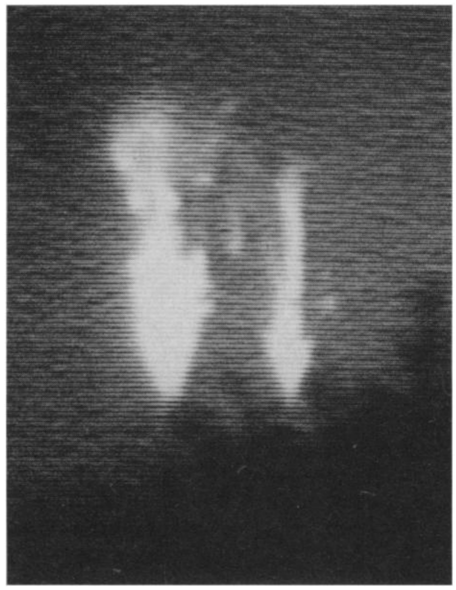

Fig. 1. Low-light-level TV image of the upward electrical discharge. This unprocessed rendition consists of two superposed 1/60-s TV fields (one frame). The objects in the foreground are trees and shrubs about 50 m distant, which are silhouetted against faint sky luminosity as a result of airglow and lights of distant towns. Note the twin fountain-like structure of the discharge and the bright points both in and around the central images. The lack of fine detail in the image may be inherent in the source or may be produced by the long path through the atmosphere at a low zenith angle but was not caused by "blooming" in the TV camera.

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at the top center). In Fig. 2C the distant storm appears as a low-lying cloud bank across the horizon with an angular height consistent with the 14 km derived from soundings. Clear star trails can be seen just above. The region of the sky in which the upward flash was recorded is located just to the right of the bottom center. The flash must therefore have discharged into the clear-air region of the stratosphere (the higher luminosity in the lower center portion of Fig. 2C is due to air glow and the lights of distant towns).

Neither the patrol camera nor the TV camera recorded any other upward flashes during the remainder of the night, although frequent cloud-to-ground flashes were recorded and were faintly visible to the dark-adapted eye viewing the north. We have rejected various possibilities for producing a spurious event, such as searchlights, head lamps, and even fireflies, because of the shape and fast timing of the event and because there were no high-tension transmission lines or TV or radio towers in the line of sight that might have produced electric arcs.

Although at the moment of the upward flash event the SKYFLASH fast oscillograph recorder was temporarily down for reloading, a chart recording was obtained from telescope 1 by light Rayleigh-scattered downward from the zenith. The upward flash pulse was 50 to 100 times as intense as flashes from cloud-to-ground strokes in the same storm diffused by clouds (Fig. 2A) and also registered on the same chart recorder by Rayleigh scattering. Because of the absence of a fast oscillograph record, no coincident sferic data were obtained.

If the flash of Fig. 1 was located near the storm center at a distance of 250 km, its vertical extent was about 20 km and thus much greater than that of cloud-to-ground lightning strokes. The flash was separated into two fountain-like jets as imaged by the TV, but the two structures were simultaneous in time within the 17-ms time resolution of the TV sweep. The separation of the two jets was estimated at 4 km or more, depending on assumptions about the distance and aspect angle. There are a number of distinct bright points of light in the image, and, when the two 1/60-s TV fields containing the image were viewed separately on playback, these persisted into the second field, although the background image had faded. No dendritic (that is, forked) individual lightning streaks appear in the image, and it clearly does not resemble the usual cloud-to-ground or cloud-to-cloud lightning strokes. The somewhat diffuse character of the image was not caused by "blooming" in the TV camera, as its circuits were not overloaded. It is probably due to distortion in the long horizontal view path through the atmosphere at low elevation angle.

Cloud-to-stratosphere discharges are, observationally at least, rare. Wilson made an early visual observation (*7*, pp. 315–316) described as "diffuse, fan-shaped flashes of greenish color extending up into the clear sky" from a thundercloud below the horizon. Similar observations were reported in 1926 by Boys (*8*) and in 1937 by Malan (*9*). Other observations are summarized in (*10*). Vaughan and Vonnegut (*2*) have recently collected 15 reports of visual sightings of cloud-to-clear-air lightning flashes by airline pilots. With a few exceptions, the discharges were described as lightning strokes that went straight up from the cloud tops of large storm systems, which had in many cases reached heights estimated to be near 20 km. As in the case reported here, observations were of a distant storm center in clear air at night. Some observations were made over the north central United States, and sometimes repeated events over many minutes were noted.

The above references seem to be describing a variety of discharge types ranging from small cloud-to-air lightning strokes to long-lasting (seconds) glow regions a few kilometers in extent at thundercloud tops. The flash we have observed is not well described by any of these visual accounts.

Cloud-to-stratosphere discharges, like all lightning, result from high electric fields arising from large local accumulations of charge. In the dipole model of thunderstorm electrification (*11*), positive charge accumulates at the cloud tops and mostly negative charge at the bottoms. This dipole moment may be dissipated by discharges inside the cloud, or alternatively the negative charge may be neutralized by cloud-to-ground discharges. In this case a net positive charge remains on the cloud system, which may be dissipated slowly by conduction between the earth and the ionosphere (*11*). An upward discharge of the type we and others have observed, however, implies that a vigorous cloud electrification process [as discussed in (*12*), for example] coupled with cloud-to-ground strokes must bring the cloud tops to the breakdown electric field strength before the positive charge can be dissipated by other means. In the storm of 5 to 6 July, there was a high level of cloud-to-ground activity, so that one of the necessary conditions for a positive charge buildup was met. However, neither the TV camera nor the lightning location networks (*5*) detected a cloud-to-ground event simultaneous with the upward flash.

In 1925, Wilson (*13*) discussed the physics of electric discharges above thunderstorms. He pointed out that, because of the

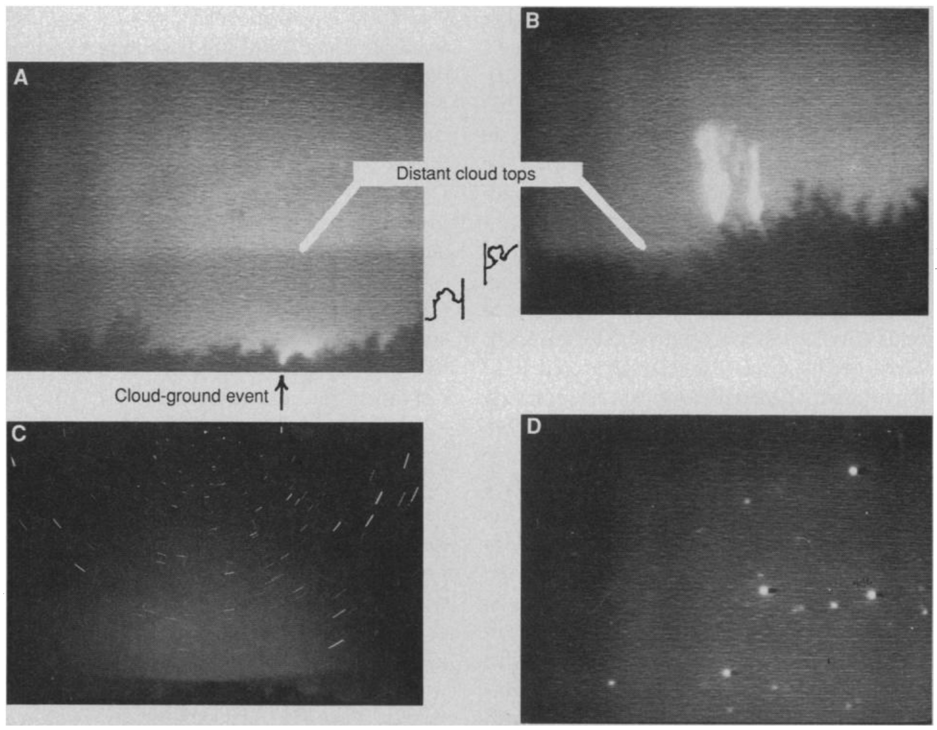

Fig. 2. Night sky features relevant to the flash. (**A**) TV image of storm cloud tops and cloud-to-ground lightning 250 km distant. (**B**) TV flash image with cloud tops horizontally aligned with (A). (**C**) A 15-min star-trail film camera time exposure of the northern sky taken 15 min after the flash recorded in (B). Note the distant storm cloud tops just level with the trees at the center. (**D**) TV image of the constellation Cassiopeia for angular size comparison. The separation of the two near-vertical aligned stars is 6°.

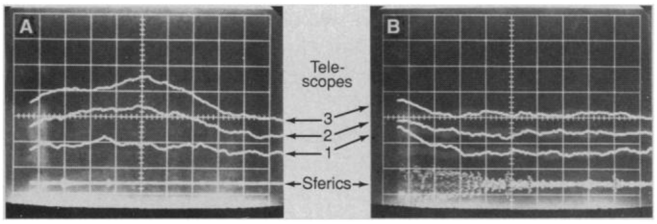

Fig. 3. High-speed oscillograph recordings (duration, 20 ms) by the SKYFLASH telescopes from distant lightning. (**A**) Long event attributed herein to a cloud-to-stratosphere discharge recorded at 0017 CST (0617 UT) on 8 August 1989. Note the 10-ms rise time and the lack of a major coincident sferic (the small blips on the sferics channel are random noise or small uncorrelated sferics). (**B**) A small but typical fast pulse with sferic from a cloud-to-ground stroke recorded at 0038 CST (0638 UT) also on 8 August 1989, 21 min after the pulse in (A). Both events may be from the same storm system. The base levels of the three channels, defined by the noisy traces after the end of the pulse in Fig. 3B, for example, have been offset to avoid overlap. The amplitude differences in the three channels are produced by the analyzing polaroids from the Rayleigh-scattered light signal.

rapid density decrease with altitude and the corresponding increase in the electron mean free path, collisional ionization by "runaway" accelerated electrons may take place in the electric fields expected above typical thunderstorm electric dipoles. In Wilson's model these electrons would be accelerated downward starting at heights up to 60 km and eventually discharge the cloud tops. Despite charge-screening effects, convective surges above the stratiform anvils of large thunderclouds might penetrate the screening layer and carry charge above it to provide intensified local fields sufficient to initiate the Wilson mechanism or a more local process (*12*). The observed flash seems to fit such a physical situation remarkably well. The two discharges originated in small regions, as if from two centers of charge concentration, and then spread moderately while extending a large distance vertically. There exists no theoretical discussion of the factors that determine the vertical extent of the luminosity, but the discharge may be connected to much greater heights by transient electric fields or currents flowing without luminosity.

We postulate that such upward flashes may account for previously unexplained transient flashes recorded by SKYFLASH. Most events, from Rayleigh-scattered light from distant cloud-to-ground lightning strokes (*3*), showed millisecond duration, strong polarization differences in the three channels, and a strong sferic. The example shown in the high-speed oscillograph recording in Fig. 3B is a small event with an amplitude only slightly greater than the noise level where the oscillograph trigger was set, but it may well represent the brightest return stroke of a complex distant lightning flash. Experience with large events from nearby storms supports this conclusion.

There remained, however, a low occurrence rate of events of the type shown in Fig. 3A. Their long rise time (10 ms), long duration (17 ms), and the absence of sferics distinguished them from the majority of lightning flashes. The normal rate for these long events was at most about one per night, and frequently none was seen on a given night (*3*). But on the evening of 22 to 23 September 1989, five or six long events with no coincident sferics were recorded. Furthermore, on this occasion only long events appeared similar to the type in Fig. 3A, but no fast events with sferics of the type in Fig. 3B. It cannot be a coincidence that on the night of 22 to 23 September the eastern coast of the United States was struck by hurricane Hugo. According to published weather maps, a vast area of thunderstorm activity, which extended inland for several hundred miles, was present in a region from Virginia to Florida. The center of this area was 1600 km from our observing site, beyond our usual lightning flash range, and no other appreciable thunderstorm activity was present over the United States. Skies were clear at our observing site. On two later nights (25 to 26 September and 2 to 3 October 1989), thunderstorm activity was low or nonexistent over the United States and no flashes of any kind were recorded.

These observations suggest that our long pulses were generated by lightning storms, and in particular by storms that were effective in propagating light flashes over great distances. Because sferics in the 10-kHz band recorded during SKYFLASH propagate great distances in the earth-ionosphere wave-guide mode with low attenuation and because such sferics did not accompany our long pulses, their absence must also be a property of the storm source for these particular flashes. The slow rise and long profile of these flashes also indicate a different kind of lightning discharge than the 1-ms flashes with sferics that we have frequently observed (Fig. 3B), attributable to cloud-to-ground strokes. We hypothesize that our long events were generated by cloud-to-stratosphere discharges. The 30-ms duration derived from the TV image lies in the correct range. Cloud-to-stratosphere discharges, because of their height and freedom from absorption by the storm cloud system, must be much more effective light sources than cloud-to-ground strokes, as shown by our direct measurement. The downward-directed atmospheric density gradient aids the propagation by being in the correct sense to bend light around the curve of the earth (note, for example, the well-known refraction of the sun when setting). The absence of a ground return and a slow electric current rise rate (as suggested by our long events) may make cloud-to-stratosphere discharges feeble emitters of sferics, although there is at this time no direct evidence on this point. All the evidence indicates that both long events and upward discharges are a characteristic of very large storms, of which hurricane Hugo was certainly an example.

The powerful electromagnetic pulse of lightning strokes has long been identified as the source of whistlers—low-frequency electromagnetic waves guided in plasma ducts along the earth's magnetic field between conjugate regions of the two hemispheres (*14*). Although 10-kHz band sferics propagate worldwide in a ducted mode in the earth-ionospheric wave guide (*15*), it has been difficult to understand how such waves can penetrate the ionosphere and enter the magnetospheric cavity. Hoffman (*16*) proposed a current jet mechanism for the generation of "long train" whistlers. The runaway electron mechanism of Wilson (*13*) and other related discharge processes were invoked to accelerate electrons upward, which then coupled energy into the sferic electromagnetic field, thus producing or maintaining the ensuing whistler in the magnetosphere. Hoffman's figure 1 suggests that a thunderstorm discharge may couple energy directly into the magnetosphere and in many ways was prophetic of our flash image (Fig. 1). But his assumption that electrons are accelerated upward does not agree with current ideas about the charge polarities in thunderclouds.

Nevertheless, the possibility of some kind of a direct process has gained support from recent rocket observations of intense transient electric fields in the ionosphere coincident with lightning strokes in a storm under the rocket flight path (*17*). Also, a direct lightning discharge–ionosphere coupling has been proposed to explain the prompt absorption of very low frequency transmitter signals after a lightning stroke ["Trimpi" events (*18*)]. The cloud-to-stratosphere flash of the type reported here would seem to be the luminous manifestation of a type of discharge that might be effective in coupling thunderstorm energy directly into the magnetosphere.

REFERENCES AND NOTES

1. H. Toynbee and T. Mackenzie, *Nature* **33**, 245 (1886); J. D. Everett and W. H. Everett, *ibid.* **68**, 599 (1903).
2. O. H. Vaughan, Jr., and B. Vonnegut, *J. Geophys. Res.* **94**, 13179 (1989).
3. R. J. Nemzek and J. R. Winckler, *Geophys. Res. Lett.* **16**, 1015 (1989).
4. The TV camera, scheduled for flight on the SCEX (Several Coordinated Experiments) sounding rocket experiment, was an ITT model 4562 ICID with a sensitivity of 10E-5 lux and was capable of recording 6.5-magnitude stars in normal real-time operation.
5. R. E. Orville (National Lightning Detection Network), personal communication; W. Lyons (R-Scan), personal communication.
6. C. B. Moore and D. Raymond, personal communication.
7. C. T. R. Wilson, *Proc. R. Soc. London* **236**, 297 (1956).
8. C. V. Boys, *Nature* **118**, 749 (1926).
9. D. J. Malan, *C. R. Acad. Sci.* **205**, 812 (1937).
10. B. Vonnegut, O. H. Vaughan, Jr., M. Brook, *Bull. Am. Meteorol. Soc.* **70**, 1263 (1989).
11. M. A. Uman, *The Lightning Discharge* (Academic Press, San Diego, CA, 1987).
12. B. Vonnegut, C. B. Moore, R. P. Espinola, H. H. Blau, Jr., *J. Atmos. Sci.* **23**, 764 (1966).
13. C. T. R. Wilson, *Proc. R. Soc. London* **37**, 32D (1925).
14. R. A. Helliwell and M. G. Morgan, *Proc. IRE* **47**, 200 (1959).
15. R. A. Helliwell, *Whistlers and Related Ionospheric Phenomena* (Stanford Univ. Press, Stanford, CA, 1965).
16. W. C. Hoffman, *J. Geophys. Res.* **65**, 2047 (1960).
17. M. C. Kelly *et al.*, *ibid.* **90**, 9815 (1985); R. H. Holzworth *et al.*, *ibid.*, p. 9824.
18. U. S. Inan *et al.*, *ibid.* **93**, 11455 (1988).
19. We thank the many colleagues who have provided reference material and relevant data, including C. B. Moore, M. Brook, W. C. Armstrong, R. E. Orville, W. Lyons, and D. Raymond. We also thank P. J. Kellogg, principal investigator of the SCEX rocket experiment, for the chance to test the TV camera. SCEX is supported by National Aeronautics and Space Administration grant NSG 5373 at the University of Minnesota. The Winckler program at Minnesota in Space Plasma Physics is supported by NASA grant NSG 5088.

17 January 1990; accepted 19 April 1990

Seawater Strontium Isotopic Variations from 2.5 Million Years Ago to the Present

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Measurements of marine carbonate samples indicate that during the past 2.5 million years the $^{87}Sr/^{86}Sr$ ratio of seawater has increased by 14×10^{-5}. The high average rate of increase of $^{87}Sr/^{86}Sr$ indicates that continental weathering rates were exceptionally high. Nonuniformity in the rate of increase suggests that weathering rates fluctuated by as much as ±30 percent of present-day values. Some of the observed shifts in weathering rates are contemporaneous with climatic changes inferred from records of oxygen isotopes and carbonate preservation in deep sea sediments.

THE $^{87}Sr/^{86}Sr$ RATIO OF DISSOLVED oceanic Sr changes slowly on geologic time scales in response to changes in the relative rates of weathering of continental surface and ocean floor rocks. This dependence on weathering rates makes the $^{87}Sr/^{86}Sr$ ratio of ancient seawater a monitor of paleoclimate because weathering is both a function of climate and, as a remover of atmospheric carbon dioxide, a major long-term feedback mechanism in the climate system. We have determined the $^{87}Sr/^{86}Sr$ ratio of oceanic dissolved Sr for the past 2.5 million years from measurements on calcium carbonate sediment obtained primarily from DSDP Site 590 (*1*). This period is one in which changes in the seawater Sr isotope ratio can be compared with other proxy records of paleoclimate and paleoceanography, and thereby a more complete reconstruction of Plio-Pleistocene conditions can be obtained.

Site 590 was drilled in 1300 m of water on Lord Howe Rise in the Tasman Sea (31°S). Use of hydraulic piston-coring methods minimized disturbance of the core (*1*). The recovered sediment is pelagic carbonate ooze; it provides a nearly continuous record of carbonate deposition since 15 million years ago (Ma) and contains well-preserved calcareous microfossil assemblages and little terrigenous material (*1*). Core 590B was sampled at approximately 3-m intervals to a depth of 30 m; this interval corresponds to about 2×10^5 years. We also measured three deeper samples, which extend the record back to 3.6 Ma, as well as several samples from cores 590 and 590A. We assigned ages to the samples on the basis of paleomagnetic reversal stratigraphy (*2*) and their positions within calcareous nannofossil biozones (*3*), using the time scale of Berggren *et al.* (*4*). In addition, two samples from equatorial Pacific piston core V28-238 (*5*) and two from Hawaiian coral terraces (*6*) were measured. Samples of 15 to 100 mg were dissolved (*7*) and analyzed for $^{87}Sr/^{86}Sr$ ratios and concentrations of K, Rb, and Sr (*8*).

The total variation in the $^{87}Sr/^{86}Sr$ ratio of the oceans is less than 2×10^{-4} between 2.5 and 0 Ma (*9*). In order to study the fine structure of this change, standard measurement errors of less than ±0.00001 are needed. To achieve this we used an automated data collection procedure during mass spectrometer runs that minimizes intermeasurement drift, a more intense Sr^+ ion beam to improve counting statistics (*10*), and an appropriate thermal ionization mass dis-

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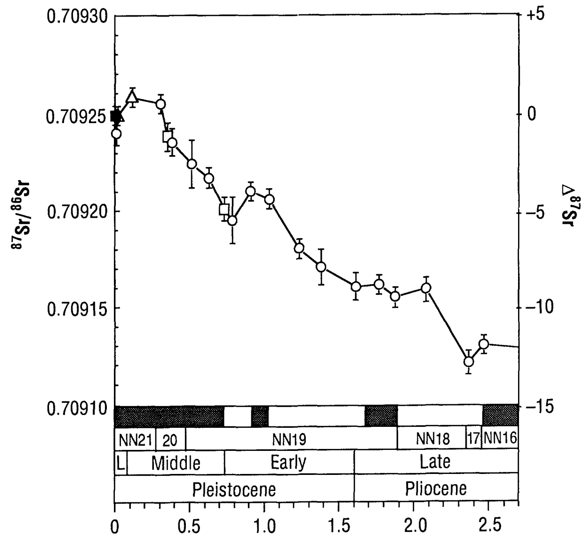

Fig. 1. Measured $^{87}Sr/^{86}Sr$ ratio against age for bulk carbonate ooze from DSDP Site 590 (open circles). Samples were assigned ages based on their positions within calcareous nannofossil stratigraphy (*3*) (lower scale, center) and based on paleomagnetic stratigraphy (*2*) (lower scale, top). The open squares are from core V28-238; the open triangles are from Hawaiian coral terraces. The modern value (solid square) is that for EN-1, the U.S. Geological Survey *Tridacna* Sr isotope standard (0.709249 ± 5); $\Delta^{87}Sr$ is the difference between the measured $^{87}Sr/^{86}Sr$ value and the value for EN-1, multiplied by 10^5. The error limits are ± 2 SEM (Table 1).