SPRITES, ELVES, AND GLOW DISCHARGE TUBES

The venerable field of gaseous electronics inspired the prediction of a lightning-like phenomenon of spectacular extent, shape, and color.

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In the 1920s, the Scottish physicist C. T. R. Wilson predicted the existence of brief flashes of light high above large thunderstorms.[1] Almost 70 years later, Bernard Vonnegut of SUNY Albany realized that evidence for Wilson's then-unconfirmed predictions might appear in video imagery of Earth's upper atmosphere recorded by space shuttle astronauts. He encouraged NASA's William Boeck and Otha Vaughan to look for evidence. Their search was successful. At the 1990 Fall Meeting of the American Geophysical Union, Boeck and Vaughan presented evidence of upper-atmosphere flashes. Evidence also came from the University of Minnesota's John Winckler and his colleagues, who had serendipitously observed a flash in moonless nighttime skies over Minnesota in 1989.

These early findings inspired two independent field programs to target the new phenomenon. In the summer of 1993, Walter Lyons of Mission Research Corp set up detectors on Yucca Ridge in the foothills of the Rocky Mountains.[2] That same summer, Davis Sentman of the University of Alaska Fairbanks (UAF) sought to record the flashes from an aircraft flying over the Great Plains.[3] Within a day of each other, the two research teams had documented what turned out to be a common phenomenon in the mesosphere. In doing so, they initiated not only a new kind of continental-scale field experiment but also—and more important—a new interdisciplinary area of research.[4]

Sentman and Lyons found two broad classes of flash: sprites (named by Sentman) and elves (named by Lyons). The meteorological context of sprites and elves is illustrated in figure 1. These short-lived luminous shapes, now recognized as electrical discharge phenomena, are associated with large thunderstorms called mesoscale convective systems. Often covering entire states in the Great Plains of the US in summertime, these migratory storms frequently contain regions of active convection among regions of weaker stratiform convection. Ground flashes with negative polarity predominate in the active convection regions, whereas less frequent but more energetic flashes with positive polarity predominate in the stratiform regions. The great majority of sprites and elves are initiated by ground flashes of positive polarity.

The ringlike elve in figure 1 (not "elf": the acronym stands for "emissions of light and very low frequency perturbations from electromagnetically pulsed sources") is centered on the vertical channel to ground, whereas the sprite lies on top of horizontally extensive so-called spider lightning in the lower portion of the stratiform cloud. The sprite's horizontal extent is a manifestation of the large pancake-shaped reservoirs of electric charge that feed the positive ground flashes. Such lightning flashes are not generally found in ordinary isolated thunderclouds.

The surging interest in sprites and elves has spurred observation campaigns worldwide. Beyond the extensive findings over North America, sprites have now been documented over South America, Australia, Japan, and Europe. Estimates put the worldwide rate of sprite occurrence at several per minute. As the gallery on pages **XX–XX** demonstrates, sprite researchers have caught numerous events on video that show a remarkable range of shape and form. The first images with conventional video cameras revealed shapes and structures so novel and unexpected that the interpretation of sprites as a basic discharge process was questioned. However, as sprites came into sharper focus with faster, crisper recording methods, what once seemed like diffuse blobs of luminosity became vast collections of luminous channels with lightning-like branching.

A diversity of sprites

The most elemental, and likely smallest, sprites are single vertical columns named C sprites. Large collections of C sprites, whose downward-branching tendrils are known as jellyfish, resemble Fourth of July fireworks. A subset of the sprites with tendrils—often the largest and most energetic—also exhibit upward branching toward the ionosphere, and are named carrots. Very large sprites with diffuse tops and lower tendrils extending down to altitudes of 30–40 km have been dubbed angels and A-bombs. With maximum vertical extents exceeding 60 km, these giant sprites extend vertically three times farther than the largest thunderstorms.

The luminous structures described here occur in most cases more than five storm heights above ground. If these structures are electrical discharges caused by lightning, why do they occur so far away from that lightning? Wilson's theory provided the basic answer, which drew on his earlier electrostatic analysis of lightning. He also benefited from the expertise in gaseous electronics that J. J. Thomson had built at Cambridge University's Cavendish Laboratory. Research at the Cavendish had established the role of free electrons and their mean free path in the dielectric breakdown of gases. This finding led to the prediction that dielectric strength is proportional to gas density.

Wilson proposed that a positive cloud-to-ground flash of the sort depicted near the bottom of figure 1 could be envisioned as a sudden deposition of negative charge into

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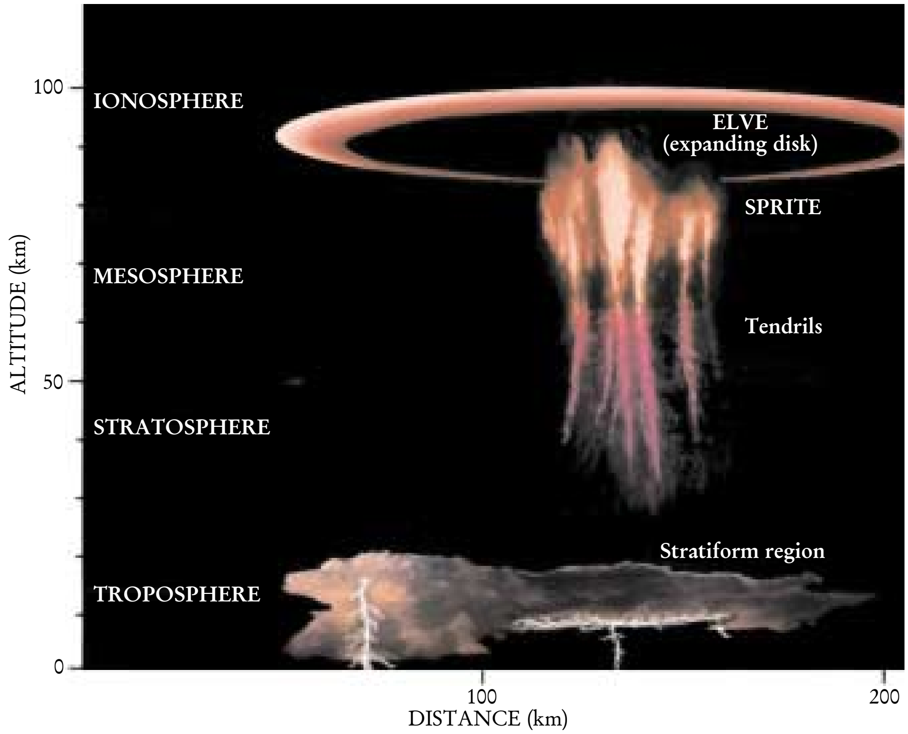


FIGURE 1. SPRITES AND ELVES are triggered by the positive cloud-to-ground lightning flashes that occur in the stratiform regions of mesoscale convective systems. (Adapted from W. A. Lyons, R. A. Armstrong, E. A. Bering III, E. R. Williams, *EOS*, volume 81, page 373, 2000.)

the lower part of the cloud with a corresponding positive image charge appearing an equal distance beneath Earth's surface. Lightning's rearrangement of charge can therefore be represented as a vertical dipole with a charge moment equal to the product of the charge transferred and its height z above ground. The field of a vertical dipole declines like $1/z^3$, but the dielectric strength follows the density of air, which declines exponentially with altitude. These circumstances create an altitude range—well removed from the storm top—where the imposed electric field exceeds the dielectric strength and initiates a lightning-like discharge.

Wilson's predictions for high-altitude breakdown were published in 1925. That same year, Edward Appleton, a student of both Thomson and Wilson at the Cavendish, discovered that the ionosphere reflects electromagnetic radiation, a phenomenon that slightly modifies Wilson's predictions near that region. The main effect of the conductive ionosphere is the prevention of luminous breakdown, and therefore sprites, at altitudes greater than about 90 km. Recent observations by a UAF team confirm this physical picture.

Schumann resonances

In 1994, during storms over the Great Plains, Lyons and Dennis Boccippio of NASA's Marshall Space Flight Center compared video observations of sprites in Colorado with electromagnetic observations from MIT's field station in Rhode Island. The two researchers discovered that the same giant positive ground flashes that cause sprites also excite Schumann resonances—electromagnetic waves in the natural Earth–ionosphere waveguide. This discovery provided an additional experimental means to test Wilson's predictions. Schumann resonances, being global, extend farther than does the vertical charge moment of the lightning, whose electrostatic manifestation is confined to distances from the storm much less than the height of the ionosphere.

Measurements of Schumann resonances and other extremely low-frequency (ELF) radiation from mesoscale convective systems have confirmed that, for large positive ground flashes, the changes in charge moment often exceed 1000 coulomb kilometers. As figure 2 illustrates, such charge moments are sufficient to cause conventional dielectric breakdown at the altitudes at which sprites are observed. For comparison, the charge moments of lightning in ordinary thunderstorms, which Wilson first measured in the early 1900s, are no more than about 100 C km. Such charge moments are too small to initiate dielectric breakdown at sprite altitudes.

ELF measurements also indicate that C sprites are caused by small charge moments, whereas the large angel or A-bomb sprites are associated with the largest charge moments and, presumably, with the greatest charge transfers in any terrestrial lightning flash. Also revealed by the ELF measurements is the presence within the body of sprites of kiloampere electric currents. These currents are consistent with the consequences of dielectric breakdown in air and qualitatively resemble lightning discharge lower in the atmosphere.

Elves are shaped quite differently from sprites and were first identified in 1990 as brief brightenings of the airglow layer in space shuttle imagery. These distant edge-on observations, however, did not reveal the donut shapes characteristic of elves. The vertical return-stroke channel of lightning gives rise to an electric field that exhibits a null directly over the channel and a maximum field that is azimuthally symmetric about the channel axis and shaped like a donut.[5] Improved observations of elves with Stanford University's Fly's Eye instrument demonstrated the speed-of-light time delay between the lightning return stroke and the rapid radial expansion of the elve. Predicted by theory,[6,7] this result clinched the fundamental role of the radiation field from lightning in elve initiation.

Wilson did not anticipate elves, but their location—high above the parent lightning channel—has an explanation similar to that for sprites. The radiation field declines less rapidly with altitude (like $1/z$) than the density of air, guaranteeing that the breakdown threshold is exceeded as long as the lightning peak current is sufficiently large. Observations by several groups have shown that elves generally require large peak currents of 70 kA or greater.

The physical mechanisms outlined here for sprite and elve initiation are both independent of the polarity of the lightning source. Nevertheless, sprites and elves are produced disproportionately by ground flashes of positive polarity. Only two sprites have ever been clearly associat-

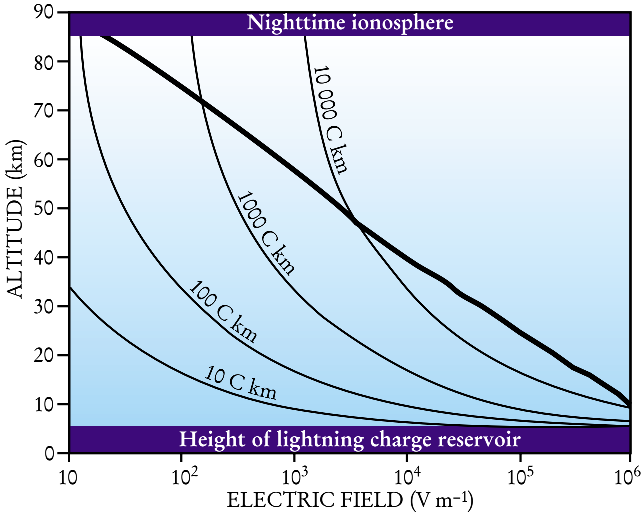


FIGURE 2. PHYSICAL CONDITIONS between conductive Earth and conductive ionosphere necessary for dielectric breakdown and the initiation of sprites, as predicted by C. T. R. Wilson. The bold curve represents the density-dependent dielectric strength of air, while the curved lines represent the electric field strength imposed by lightning for various values of lightning charge moment.

ed with ground flashes of negative polarity, whereas the number of sprites verifiably produced by positive lightning runs to thousands. Although the characteristics of positive lightning (total charge transfer, charge moment, peak current) are indeed different from those of negative lightning, the differences are far too small to account for the pronounced asymmetry.

Like botanical trees, lightning and sprites are both double-ended structures that extend bidirectionally, with one positive end and one negative end. The positive end of the sprite (and intracloud lightning) develops first, to be followed (sometimes) by negative extension. A marked distinction between lightning and sprites is that lightning often initiates in the strongest field and extends into weaker fields, whereas sprites initiate in the very weak field above the thunderstorm and then extend (downward) into the stronger field.

The C sprites shown on pages **XX–XX** are straight vertically-oriented columns, 10 km long and 200 m wide. Together, they form the trunk of the mature sprite. This portion of the tree differs from the more tortuous and more randomly oriented trunk of typical lightning flashes. The origin of this difference probably lies in the conditions that give rise to the two phenomena. In lightning, positive and negative electric charge is separated within the cloud on time scales of minutes. As a result, the electric field reaches the breakdown threshold gradually. In sprites, the electric field is impulsively imposed aloft by lightning below on a submillisecond time scale, causing the breakdown threshold to be suddenly and greatly exceeded. In laboratory discharge experiments, this condition is often referred to as overvolting, and produces discharge paths that are straighter than usual. In conditions of extreme overvolting, a more uniform mode of breakdown is observed in the laboratory, and this may explain the halo, a variant of the typical sprite recently identified by UAF's Gene Wescott and Chris Barrington-Leigh.

The lifetimes of lightning and sprites are mainly determined by the speed at which a virgin channel extends. In the lower atmosphere, virgin lightning channels extend 10 km in 100 ms and propagate at a typical speed of 100 km s^{-1}, whereas sprites extend 30 km vertically and propagate at nearly one-tenth the speed of light in 1 ms. The short duration is undoubtedly why sprites eluded definitive detection until the past decade. Sprites can last longer (tens to hundreds of milliseconds), but at greatly reduced brightness. This persistence has been attributed to the currents from positive ground flashes that maintain an electric field in the sprite region.

The extraordinarily rapid initial growth of sprites is not well understood. Propagation speeds for lightning streamers in thunderclouds are generally explained by the mean drift speeds of electrons driven by electric fields. The electron drift speeds are larger in air of lower density, but, as mentioned previously, the electric fields are also smaller in sprites than in lightning. Overvolting in sprites may boost the speeds, but whether this explanation is adequate remains unclear. Alternatively, an electron runaway process might be responsible. Conventional dielectric breakdown involves particles whose energies are just sufficient to ionize atoms and molecules. By contrast, runaway electron breakdown, an idea that can be traced—again—to Wilson,[8] results in x rays and gamma rays that can enhance propagation speed by photoionization ahead of the breakdown channels. Recent observations have revealed the presence of x rays and gamma rays in the vicinity of cloud-to-ground lightning flashes, but definitive evidence for a runaway mechanism is scant.

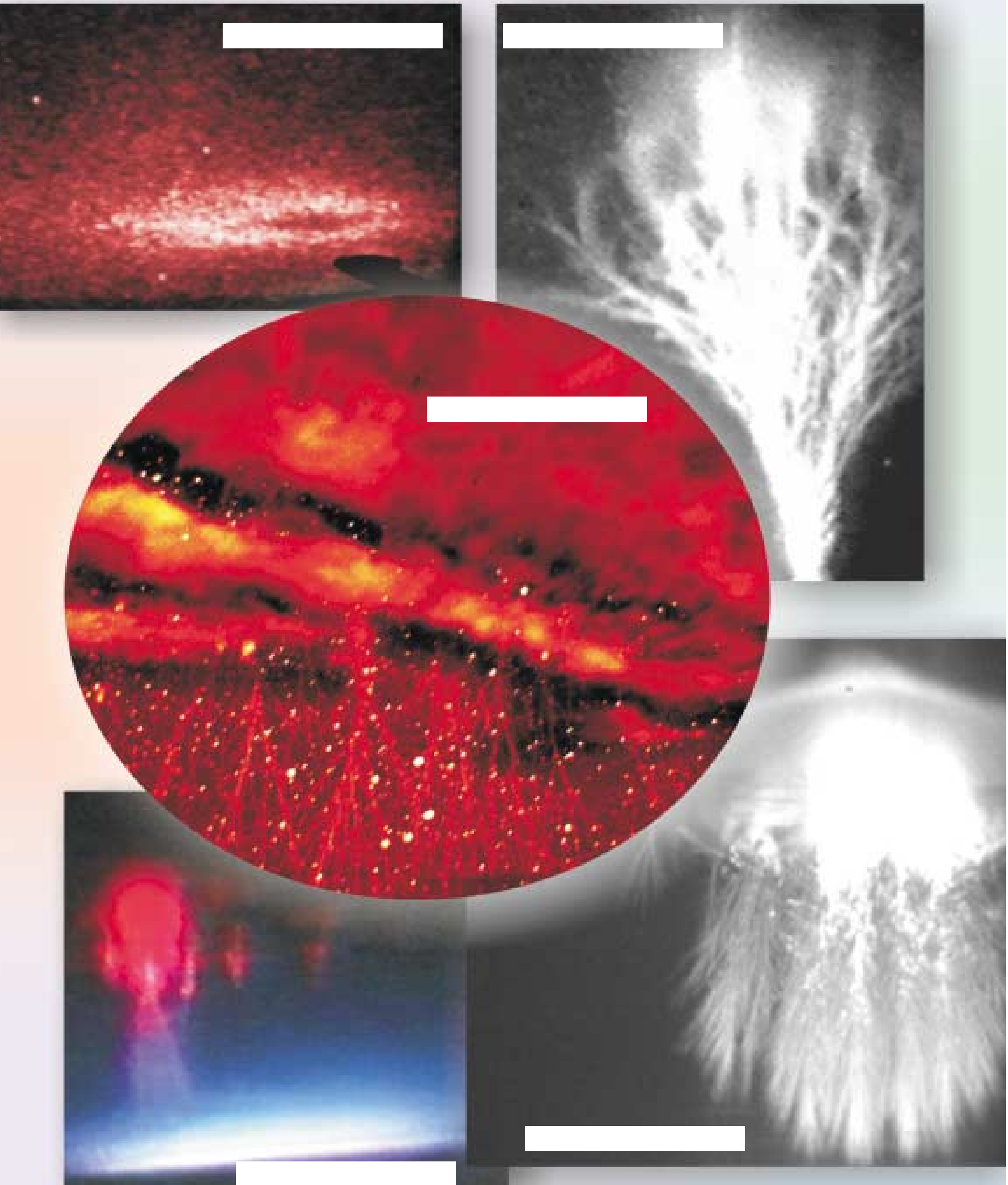
Most observations of lightning charge moments indicate that a runaway process is not necessary to initiate sprites: Conventional dielectric breakdown is adequate. However, a runaway process might explain sprites' polarity asymmetry, as electrons can accelerate upward into air of lower density more readily than downward. Observational and theoretical work is under way to identify the physical conditions for which the electron runaway process should prevail.[4,7]

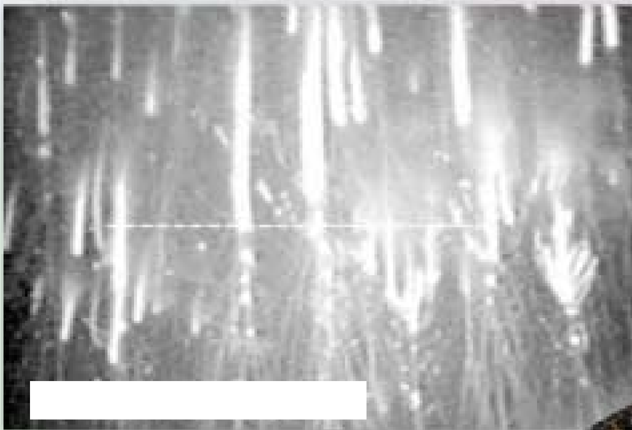
Sprite color

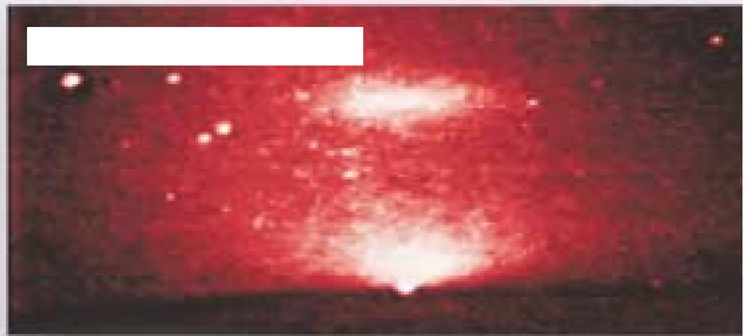
The color of sprites was first identified by a UAF team in 1994. As shown in figure 3, red emission is prevalent in the upper body of the sprite and blue emission in the lower tendrils. The Fairbanks researchers quickly followed their discovery with time-integrated spectral measurements of sprites. Steve Mende and his colleagues from Lockheed Martin Corp's Palo Alto research lab made similar measurements. The two groups' results are mutually consistent, but puzzling.

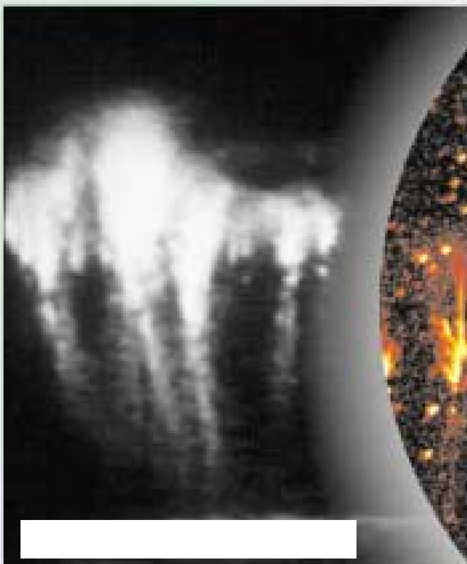
Dielectric breakdown, in which ionization plays a key role, lies at the heart of all luminous phenomena in the atmosphere. Lightning, flames, the auroras, and meteor trails all show abundant evidence of ionization. Sprites, however, stand apart. Their observed spectra lack strong ionization signatures. Indeed, it is now well established that the origin of red sprite light lies in neutral nitrogen molecules excited by colliding free electrons, a process known as nitrogen first positive emission.[9]

The interpretation of this red emission can be traced to investigations, more than a century ago, of the electrically excited glow discharge tube.[10] Figure 3 shows a DC excitation of an air-filled cathode tube at a temperature,









pressure, and polarity that roughly match conditions in sprites. A long uniform region of red emission can be seen near the anode end of the tube. First positive emission got its name from the elongated uniform column in the positive (anode) end of the tube (the designation "first" refers to the ordering of spectral features by wavelength). As is the case with field observations of sprites, no spectral evidence for ionization is found in this region of the tube.

The blue light near the opposite electrode (the cathode) is nitrogen first negative emission, and is caused by the impact of electrons on N_2^+ ions. This emission was first identified in sprites by Russ Armstrong of Mission Research, Matt Heavner of Los Alamos National Laboratory (LANL), and their colleagues. The emission originates in tendrils near the lower end of sprites excited by positive ground flashes and during the initial stages of sprite formation,[11] but is usually not detected from the sprite body in temporally integrated spectra.

The foundation for understanding sprite plasma was laid down by Irving Langmuir in the same decade as Wilson's sprite predictions and Appleton's work on the ionosphere. Langmuir, as director of research at General Electric Co, was deeply concerned with electrical luminescence and, at a very practical level, with lighting. He was fascinated by the positive (anode) column of the glow discharge tube and developed novel experimental methods for measuring free electron concentrations and energies within discharge tubes. Langmuir's most fundamental and far-reaching contribution to plasma physics—the electron plasma frequency—developed from his focus on the uniform plasma of the positive column.[12]

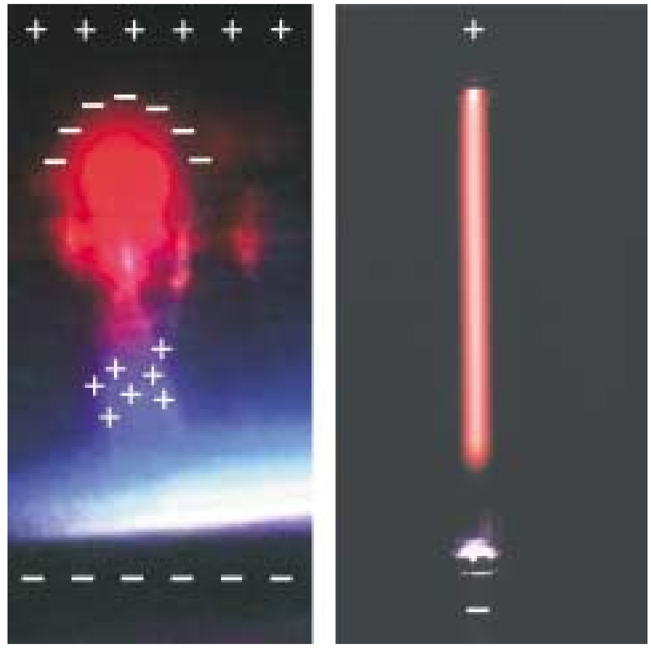


FIGURE 3. SPRITE LIGHT in the atmosphere (**left**) and in a laboratory glow discharge tube (**right**). In both cases, the light near the positive (anode) end is red and arises from the collisional excitation of neutral nitrogen molecules by free electrons. Also in both cases, the light near the negative (cathode) end is blue and arises from the collisional excitation of N_2^+ ions by free electrons.

Plasma frequency

The plasma frequency represents a simple harmonic motion of the free electrons in an electrically neutral plasma with respect to the less mobile positive ion population. The larger the free electron density, the stronger the electrostatic restoring force in this oscillatory motion and the higher the plasma frequency f_p, which is given by

$$f_p^2 = n_e e^2 / m_e \varepsilon_0,$$

where n_e is the electron density; e, the electronic charge; m_e, the electronic mass; and ε_0, the permittivity of free space.

This formula first appeared in a 1906 paper by Lord Rayleigh that concerned a simple pumpkin model for the atom. In the context of ionized gases, f_p marks a fundamental boundary between conductor and dielectric behavior in the interaction of electromagnetic waves with plasmas. When the frequency of the incident wave is large compared with the plasma frequency, the electrons' inertia retards their response and the underdense plasma behaves as a dielectric. As a result, the plasma is mostly transparent to the radiation. When the incident wave frequency is less than f_p, the electrons readily respond so as to exclude the incident field, resulting in reflection of wave energy from the overdense plasma.

These simple predictions are modified in the presence of electron–neutral collisions, but the range of applicability of the equation—from ionospheric sounders to the reflection of light from metals—is remarkable. Metals, in which n_e is about 10^{22} cm^{-3}, are good reflectors at all electromagnetic frequencies up to the optical range, but become translucent in the ultraviolet region. By contrast, the lower atmosphere is transparent and the D region of the ionosphere, where n_e is about 100 cm^{-3}, forms a conductive waveguide only in the ELF and very-low-frequency (VLF) ranges (3–25 kHz). The reflecting waveguide effect in the Schumann resonance frequency range (3–40 Hz) is vital for the global detection and analysis of sprite-producing lightning from a single measurement station.[13]

Lightning, the auroras, glow discharges, and sprites are all luminous plasmas characterized by intermediate concentrations of free electrons. With an electron density of 10^{18} cm^{-3} in the hottest channels (30 000 K), lightning has been shown to backscatter microwaves as a conductor at wavelengths as short as a few centimeters.[14] The auroras, with a luminosity comparable to the brightest sprites, provide strong radar backscatter in the megahertz region and are still detectable by radar in the UHF region (400 MHz). This behavior is consistent with electron densities in the range of 10^5–10^7 cm^{-3}.

Roland Tsunoda and colleagues at SRI International have reported evidence for underdense reflections from sprites at 24 MHz. Robert Roussel-Dupre and Elizabeth Blanc of LANL have interpreted radar backscatter at 2 MHz as an overdense response from sprites. Those observations place the electron density of sprites in the range of 10^4 to 10^5 cm^{-3}, somewhat more dilute than the aurora borealis but of the same order as the electron concentration in the daytime E region of the ionosphere. Observations of backscatter from sprites[15] at VLF (25 kHz) yield consistent estimates of electron density. However, theoretical models by Stanford University's Victor Pasko that treat the lightning-like streamer development of sprites[16] show local electron densities as large as 10^7 cm^{-3}.

The presence of free electrons in sprites in such dilute concentration—some 13 orders of magnitude less than that in lightning channels!—helps resolve the spectroscopic puzzle about the apparent absence of ionization in both the air-filled glow discharge tube and in the body of sprites. An electron density of 10^5 cm^{-3} at an altitude of 70 km corresponds to fewer than one free electron for every 10 billion neutral nitrogen molecules. (The molecular population in an ordinary lightning channel is completely ionized.) Plasma neutrality requires that the free electrons be balanced by positive ions. An upper bound on the N_2^+ concentration in sprites is therefore 10^5 cm^{-3}. On the assumption that the intensities of the spectroscopic signatures are proportional to the numbers of emitting species, one can expect the red emission associated with electron collisions with neutral N_2 to dominate strongly over blue emission associated with electron collisions with the ionized species N_2^+. These considerations indicate that, although sprite plasma is so weakly ionized that it escapes spectroscopic detection, it can still strongly interact with electromagnetic radiation of sufficiently low frequency.

Sprites and elves are a grand natural manifestation of ideas and laboratory experiments conceived many decades ago by Rayleigh, Thomson, Wilson, and Langmuir—all of whom won Nobel prizes—and by a host of 19th century glow discharge tube spectroscopists.[10] Today, active research in this new field is aimed at investigating the possible generation of thunder by sprites, exploring the role of high-altitude ionization in modifying the Earth–ionosphere waveguide, modeling the nonlinear evolution of lightning-like plasma channels in sprites, and understanding the impact of these high-altitude discharges on the chemistry of the mesosphere.

For climate chemistry in particular, the behavior of the totality of sprites and elves could prove as interesting and important as the understanding of individual events. Current research on climate change emphasizes, among other things, extreme weather events and their volatility in response to temperature change. Sprites and elves certainly qualify as inherently extreme events. They are likely to be the focus of research for years to come.

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