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MÉCANISMES PHYSIQUES DU NUAGE D'ORAGE ET DE L'ÉCLAIR
THE PHYSICS OF THUNDERCLOUD AND LIGHTNING DISCHARGE

Lightning effects at high altitudes: sprites, elves, and terrestrial gamma ray flashes

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Note presented by Guy Laval.

DOSSIER

Abstract A fascinating set of newly discovered complex phenomena indicate that thunderstorms and lightning discharges are strongly coupled to the overlying upper atmospheric regions. Lightning discharges at cloud altitudes ($<$20 km) affect altitudes $>$40 km either via the release of intense electromagnetic pulses (EMPs) and/or the production of intense quasi-static electric (QE) fields. The intense transient QE fields of up to $\sim$1 kV $\cdot$ m^{-1}, which for positive CG discharges is directed downwards, can avalanche accelerate upward-driven runaway MeV electron beams, producing brief ($\sim$1 ms) flashes of gamma radiation. A spectacular manifestation of these intense fields is the so-called 'Sprites', large luminous discharges in the altitude range of $\sim$40 km to 90 km, which are produced by the heating of ambient electrons for a few to tens of milliseconds following intense lightning flashes. The so-called 'Elves' are optical flashes which last much shorter ($<$1 ms) than sprites, and are typically limited to 80–95 km altitudes with much larger (up to 600 km) lateral extent, being produced by the heating, ionization, and optical emissions due to the EMPs radiated by both positive and negative lightning discharges. ***To cite this article: U.S. Inan, C. R. Physique 3 (2002) 1411–1421.***

Phénomènes de haute altitude associés aux éclairs : sprites, elves et émissions gamma terrestres

Résumé Un ensemble fascinant de phénomènes complexes étudiés lors de la dernière décennie indique que les orages troposphériques et les éclairs associés sont fortement couplés aux régions atmosphériques supérieures. Les éclairs formés à l'intérieur du nuage (à moins de 20 km d'altitude) ont des effets à plus de 40 km d'altitude via l'émission d'impulsions électromagnétiques intenses (EMP) et/ou la production de champs quasi-statiques (QE) élevés. Ces champs QE, dont l'amplitude atteint 1 kV/m, dirigés vers le bas pour des éclairs nuage-sol positifs, peuvent créer des avalanches d'électrons « runaway », d'énergie de l'ordre du MeV, accélérés vers la haute atmosphère, produisant des bouffées d'émission gamma de courte durée (environ 1 ms). Une manifestation spectaculaire de ces champs intenses est le phénomène de « Sprite », grande décharge lumineuse se développant entre 40 et 90 km, initiée par le chauffage d'électrons libres pendant quelques millisecondes suite à un éclair intense. Les phénomènes lumineux appelés « Elves », de durée beaucoup plus brève que les sprites ($<$1 ms), sont localisés entre 80 et 95 km d'altitude avec une extension latérale beaucoup plus grande (jusqu'à 600 km). Ils sont produits par les effets

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d'échauffement, d'ionisation et d'émission optique associés aux impulsions EMP rayonnés par les éclairs des deux polarités. ***Pour citer cet article : U.S. Inan, C. R. Physique 3 (2002) 1411–1421.***

1. Introduction

Although C.T.R. Wilson predicted nearly eighty years ago [1] that electrical breakdown would occur at high altitudes above active thunderstorms, the first documented visible evidence for such high altitude discharges did not appear in the scientific literature until 1989 [2], leading to the introduction [3] of the term 'sprites'. Wilson's remarkable observation, i.e., "while the electric force due to the thundercloud falls off rapidly with height, the electric force required to cause sparking (which for a given composition of the air is proportional to its density) falls off still more rapidly. Thus, if the electric moment of a cloud is not too small, there will be a height above which the electric force due to the cloud exceeds the sparking limit", laid the foundations of the modern theories of high altitude optical emissions.

Although various undocumented reports of exotic upward lightning and high-altitude discharges and eyewitness accounts (by aircraft pilots and others) did exist [4] over the years, it was the serendipitous first video observation [2] that led to a flurry of activity (both observational and theoretical) in the 1990s that has allowed the classification of the types of phenomena and the identification of the underlying physical mechanisms.

2. Sprites

Many of the initial observations of sprites were conducted in the Midwestern United States, where especially large thunderstorm centers (known as mesoscale convective complexes) become active in the afternoons in regions of Oklahoma and southern Kansas, and move north-eastward, remaining active for

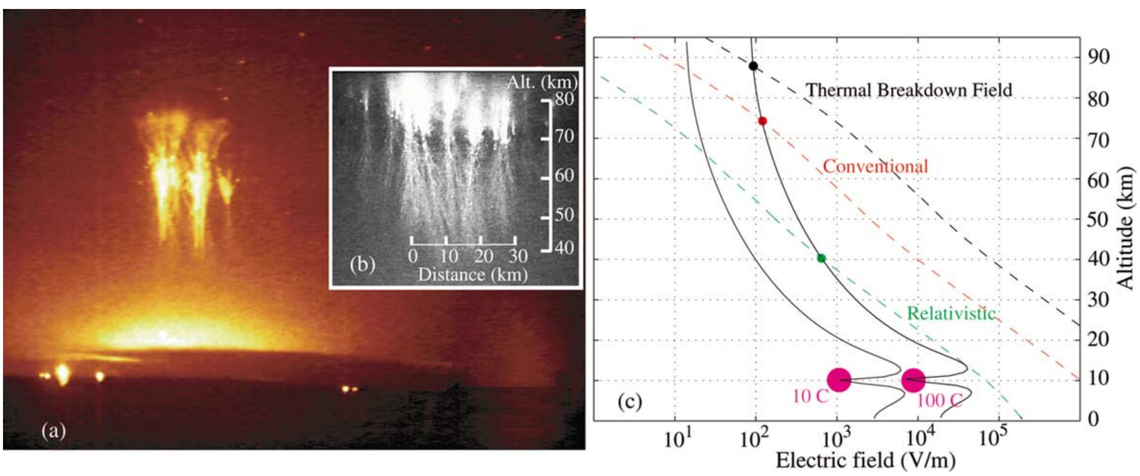

Figure 1. (a) Image of a sprite recorded by an amplified CCD camera during summer 1996 from a field site near Fort Colllins, Colorado, looking towards the east (Courtesy of Lockheed-Martin Palo Alto Research and Development Division). (b) Image of a sprite recorded by the University of Alaska from Jelm, Wyoming, on 24 July 1996 at 04:09:19 UT. The altitude range was determined via triangulation and by the knowledge of the location of the causative lightning discharge. (c) The comparison of the altitude variation of the electrostatic field of 10 C and 100 C charges located at 10 km with that of the different breakdown threshold fields for air.

many hours often until well after midnight. A prime location for observation of the high altitude optical emissions produced by such complexes is the relatively high grounds of north-eastern Colorado, where the summer skies are often clear at night and wherefrom one could view the vast eastern planes towards Kansas, being able to view the thunderclouds themselves, as well as the regions below and above them.

Two examples of sprites are shown in Fig. 1. The larger false-color image shows the view from Colorado towards the eastern planes, with city lights on the ground, the thunderclouds and the bright, scattered-light glow of the causative lightning flashes within them. While no optical emissions are observed immediately above the clouds, spectacular glows exhibiting carrot-like structure are observed at higher altitudes. Such emissions may typically last for 10 to 100 ms thus manifesting themselves in one or several video frames ($\sim$33 ms length). Although the image shown was acquired using an image-intensified CCD video camera, sprites can sometimes be bright enough to be visible in normal (non-intensified) video recordings. The highly transient occurrence of sprites usually requires frame-by-frame viewing. After many summer campaigns during the 1990s, several observers have been able to see sprites with naked-eye, in rare cases involving particularly intense sprites driven by particularly intense thunderstorm activity. Fig. 1(b) quantifies the altitude range of lateral extent of sprites, showing the typical altitude of brightest features being near $\sim$70 km, the diffuse regions lying above this altitude and the tendrils and streamer-like features below it. The lateral extent of individual sprites is highly variable, but can extend to $\sim$30 km as in the case shown. Fig. 1(c) illustrates the physical basis of Wilson's original thinking [1], showing that the

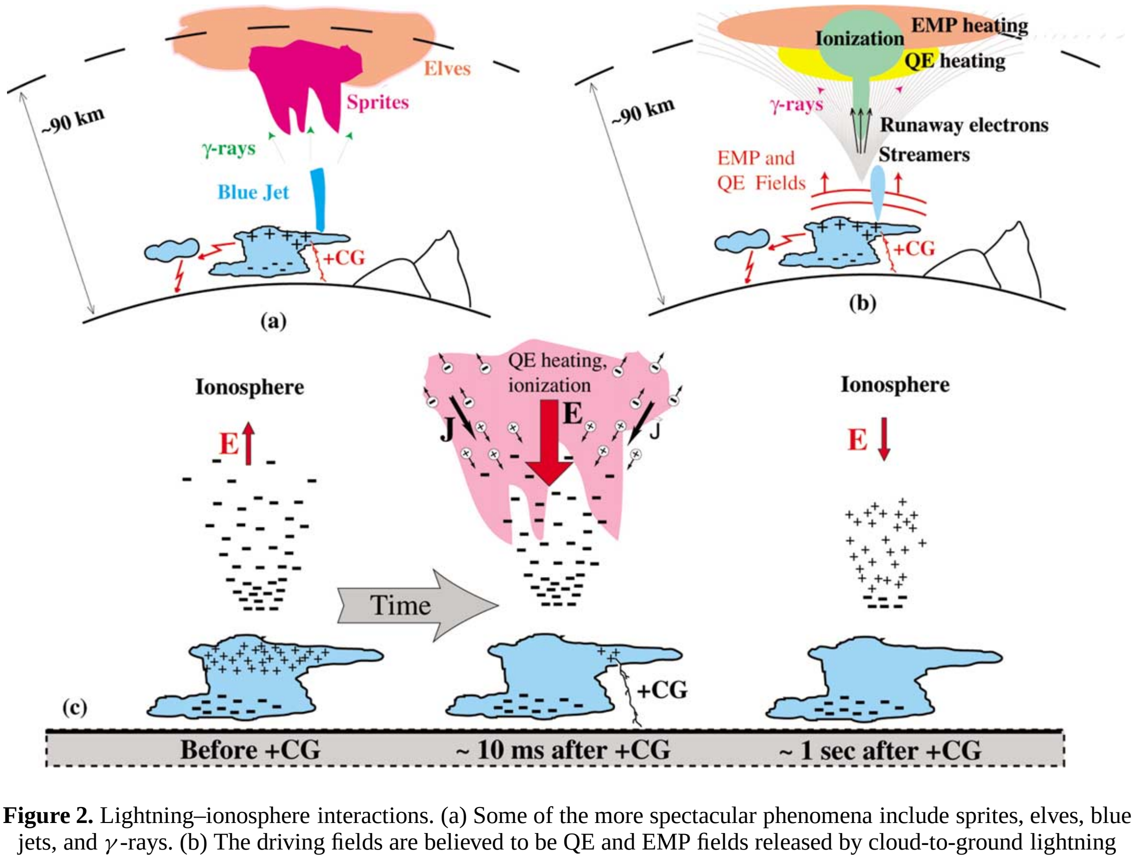

Figure 2. Lightning–ionosphere interactions. (a) Some of the more spectacular phenomena include sprites, elves, blue jets, and γ-rays. (b) The driving fields are believed to be QE and EMP fields released by cloud-to-ground lightning discharges leading to production of streamers, heating and ionization, as well as upward driven relativistic electron beams, producing γ-rays via bremsstrahlung. (c) The temporal sequence of events leading to a sprite. Adapted from [5].

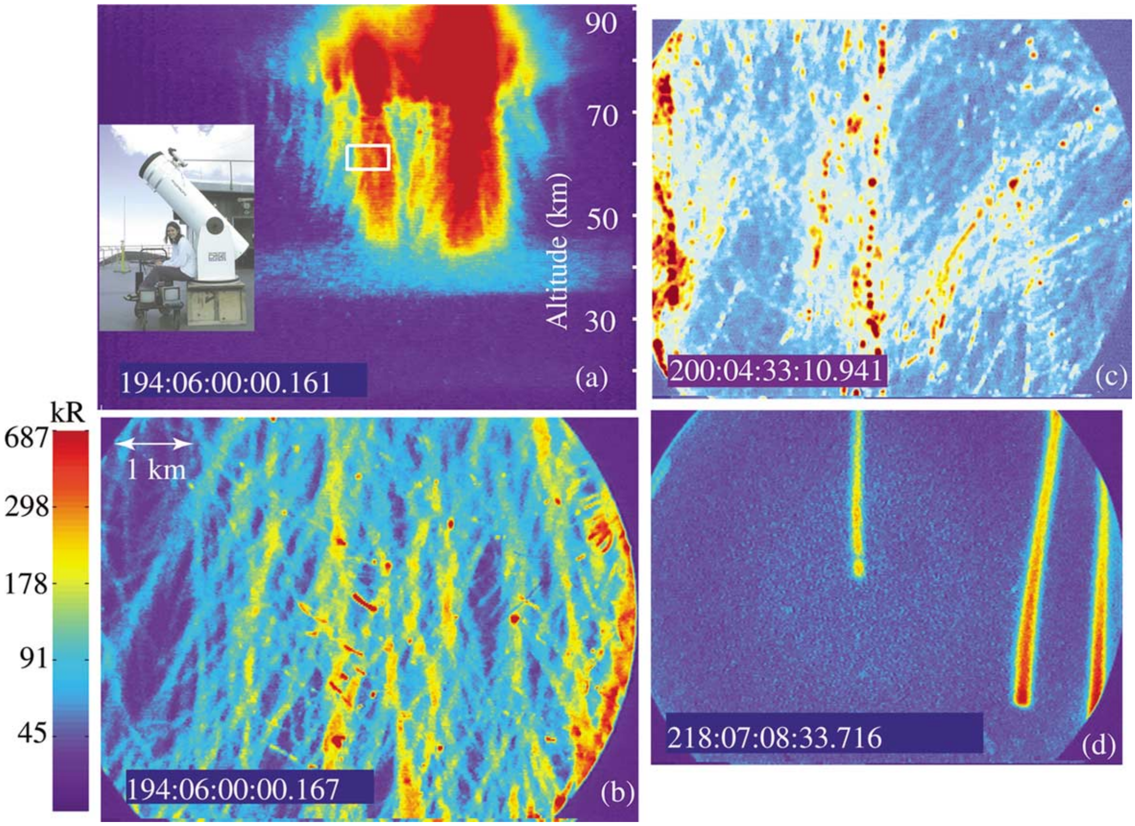

Figure 3. Telescopic imaging of Sprites. (a) The 16-inch wide Dobsonian telescope was used together with a wide-field-of-view camera mounted on its top. The wide field of view image shows a large apparently amorphous sprite in the shape of an "angel" observed on July 13, 1998. The field-of-view of the telescope is indicated as a white rectangle in the middle. (b) The telescopic field of view shows hundreds of streamers. (c) Another telescopic image showing multiple beads and differently oriented streamers with lateral sizes ranging from $\sim$10 m to a few hundred meters. (d) Isolated columns of with $\sim$200 m with apparently no structure across the column. Adapted from [6].

breakdown electric field(s) for air falls of exponentially with altitude in proportion with density of air, while the Coulomb field of newly introduced (or equivalently just removed) thundercloud charge falls of cube of distance, so that this quasi-electrostatic field can exceed the breakdown field(s) at high altitudes. The three different breakdown fields correspond to different thresholds encountered as electrons are accelerated in air, also shown below in Fig. 7(d).

Sprites are merely the most commonly known of the various types of phenomena that were newly discovered during the 1990s, some of which are depicted in cartoon form in Fig. 2(a). The primary underlying mechanisms associated with the different phenomena are summarized in Fig. 2(b), and involve quasi-electrostatic (QE) fields, electromagnetic impulses (EMP) as the basic drivers, which cause heating of ambient electrons, ionization, and upward acceleration of relativistic runaway electrons. Of these, sprites produced primarily by the heating of the ambient electrons, 'elves' produced by the heating of the same by EMP fields, and the γ-rays produced by relativistic electron beams are discussed herein.

A qualitative description of the primary mechanism of sprites [5] is given in Fig. 2(c). As the thundercloud charge separation slowly builds up before a lightning discharge, the overlying high-altitude regions are shielded from the electrostatic fields of thundercloud charges by space charge induced in the conducting atmosphere at lower altitudes. This shielding is a simple consequence of the finite vertical conductivity gradient of the upper atmosphere. When one of the thundercloud charges is quickly removed by a lightning discharge, the remaining charges of opposite charge sign in and above the thundercloud produce a large QE field that appears at all altitudes above the thundercloud, enduring for a time equal to approximately the local relaxation time at each altitude. For positive cloud-to-ground lightning discharges which involve the removal to the ground of positive charge, this large (up several hundreds of volts per meter) field can be thought of as being produced by an equivalent negative charge 'suddenly' introduced at the altitude of the removed charge, thus leading to a downward directed QE field as depicted in Fig. 2(c).

The mechanism described in Fig. 2(c) illustrates the establishment and maintenance of a transient QE field, which in turn leads to electrical breakdown at high altitudes as expected on the basis of Fig. 1(c). The heating of the ambient electrons by the intense QE field causes sufficient numbers of electrons to acquire enough energy so that their impact on Nitrogen molecules excites optical emissions in the first positive band. It is for this reason that sprites are primarily 'red' in color, although the lowest altitude tips of their tendrils can often be blue. The physical nature of the electrical breakdown in sprites is illustrated in Fig. 3, showing telescopic images [6]. While telescopic imaging of a transient and elusive phenomena such as sprites may seem to be fundamentally difficult, one particular feature of the phenomenology of sprites made such observations possible. It was evident based on initial observations that when sprites do occur at some point above a thunderstorm center, they typically continue to occur at nearly the same location for many tens of minutes, until the active thunderstorm centers move or dissipate. This feature allowed the pointing of the telescope upon the observation of the initial few sprites, thus enabling effective capture of the following sprites within the field of view of the telescope. The telescopic views reveal a fascinating degree of fine structure [6], indicating that sprites consist of multiply oriented streamers (Fig. 3(b)), beaded structures (Fig. 3(c)), and isolated columns (Fig. 3(d)). Detailed analysis of telescopic images and their temporal development of streamer structures (aided by associated photometric observations and simultaneous detection of radio signatures of causative lightning flashes) indicate that both positive and negative streamers are present at different altitudes.

The apparent presence of streamer discharges within the body of sprites in turn indicates the presence of ionization columns and intense electrical currents. That such currents do indeed exist was further revealed by direct observations of intense ELF radiation by sprites [7], as illustrated in Fig. 4.

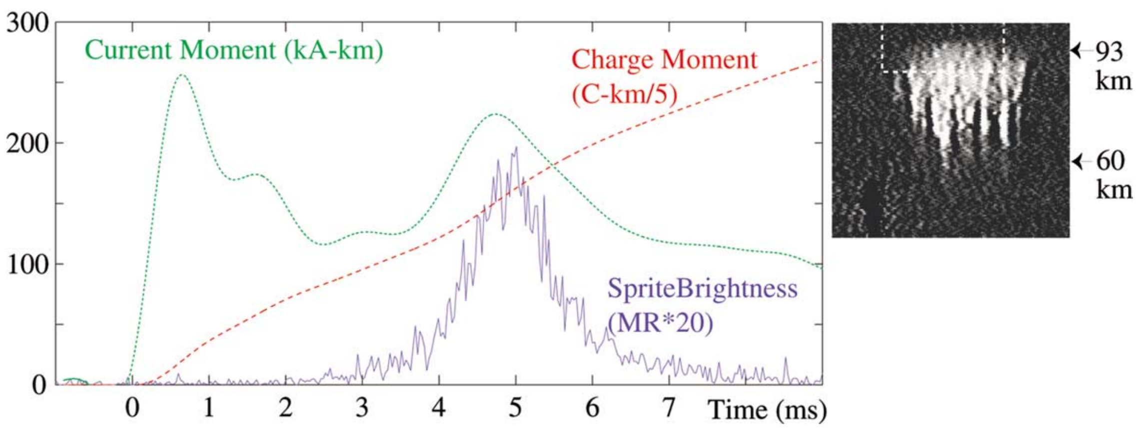

Figure 4. ELF radiation from sprites. The current moment shown in green color was calculated from the ELF waveform observed at the Yucca Ridge field station near Fort Collins, Colorado, ∼670 km away from the location of the causative lightning discharge [8]. The charge moment shown in red color is the cumulative total charge removed, calculated in the manner described in [7].

3. Elves

The high altitude optical emissions known as 'elves' are fundamentally different from sprites, both in terms of their appearance and underlying physical mechanism. The first unambiguous observation of what is now known as 'elves' was reported by [9], describing this phenomenon as 'airglow brightening' and suggesting the mechanism of [10] as the physical explanation. The mechanism put forth in [10] involved heating of the ambient electrons in the ∼80 to 90 km altitude range by the intense EMP radiated by lightning discharges. An important feature of these EMP-driven emissions was their much shorter duration (typically only a few milliseconds) which rendered their observation particularly difficult using video equipment having typical frame durations of ∼33 milliseconds. The first definitive observation of elves was realized using photometers specifically aimed at altitudes above that of sprites [11]. A definitive test of the EMP mechanism as the cause of elves was realized [12] using a specially designed instrument, called the Fly's Eye, shown in the upper right corner of Fig. 5 and consisting of multiple photometers allowing high-time

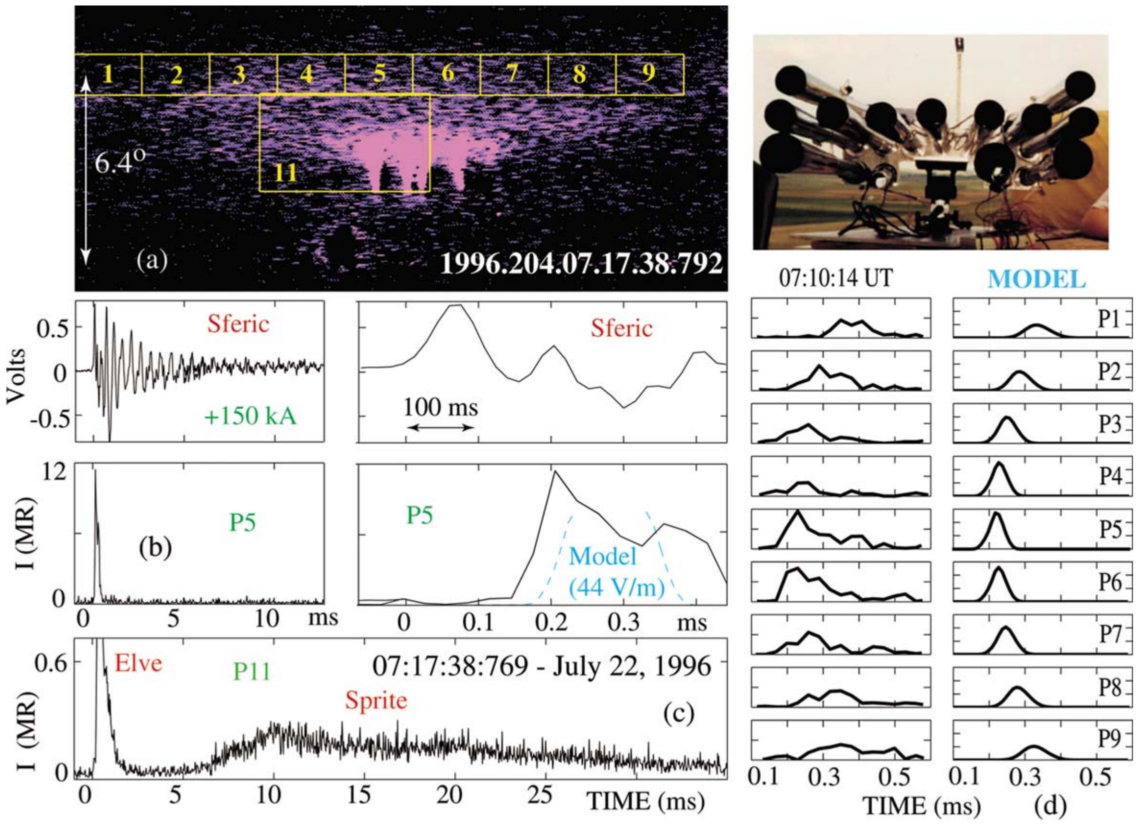

Figure 5. Photometric observations of elves taken from [10]. (a) False color video image of a sprite (bright purple in the center) and a rare image of an 'elve' (seen as a faint purple glow). Also shown are the different portions of the sky viewed by the various photometers of the Fly's Eye instrument (shown on top right). (b) Top two panels show the waveform of a causative radio atmospheric (simultaneously recorded with the photometric data) shown at two different time resolutions. The bottom panels show the associated optical emission intensity observed in pixel P5. Shown in blue is a model prediction of the timing of the appearance of the optical emission in P5. (c) A longer time record of the optical intensity observed in pixel P11 shows the initial intense but brief appearance of the elve emission, followed by the less intense but longer lasting sprite emission. (d) Comparison of the timing of the optical emission in pixels P1 through P9 shows the predicted rapid lateral expansion of the optical emission, with the emission in pixel P5 arriving earliest, confirming that elves are produced by the electromagnetic impulse (EMP).

resolution (tens of microseconds) recording of optical emissions at different adjacent points in the sky. This instrument allowed the documentation of the predicted rapid lateral expansion of the high altitude optical emissions, which is the precise signifying feature of heating of ambient electrons by lightning EMP fields [12]. Elves were thus shown to be unambiguously produced by EMP fields consisting of essentially structure-free (diffuse) optical emissions having a disk-like shape, lying in a narrow altitude range typically above those of sprites, and having a lateral extent of as much as ∼600 km, much larger than that of sprites.

Although several disk-like objects observed in video were originally thought to be elves, the phenomenology of these diffuse flashes that appear atop sprites were shown [13] to be fundamentally different, in that they are produced largely by the QE fields rather than lightning EMP. These types of emissions, referred to as sprite-halos, appear to be the initial manifestations of sprites, before streamer production and columnar emissions begin to form. Modeled and diffuse optical flashes are illustrated in Fig. 6, showing sprite-halos and elves produced by two different lightning flashes having the same peak currents (150 kA) but different durations (and thus charge removal). The causative flash involving fast discharge currents generates primarily an intense EMP and an elve, while that involving relatively slower currents produces intense QE fields and leads to a sprite-halo.

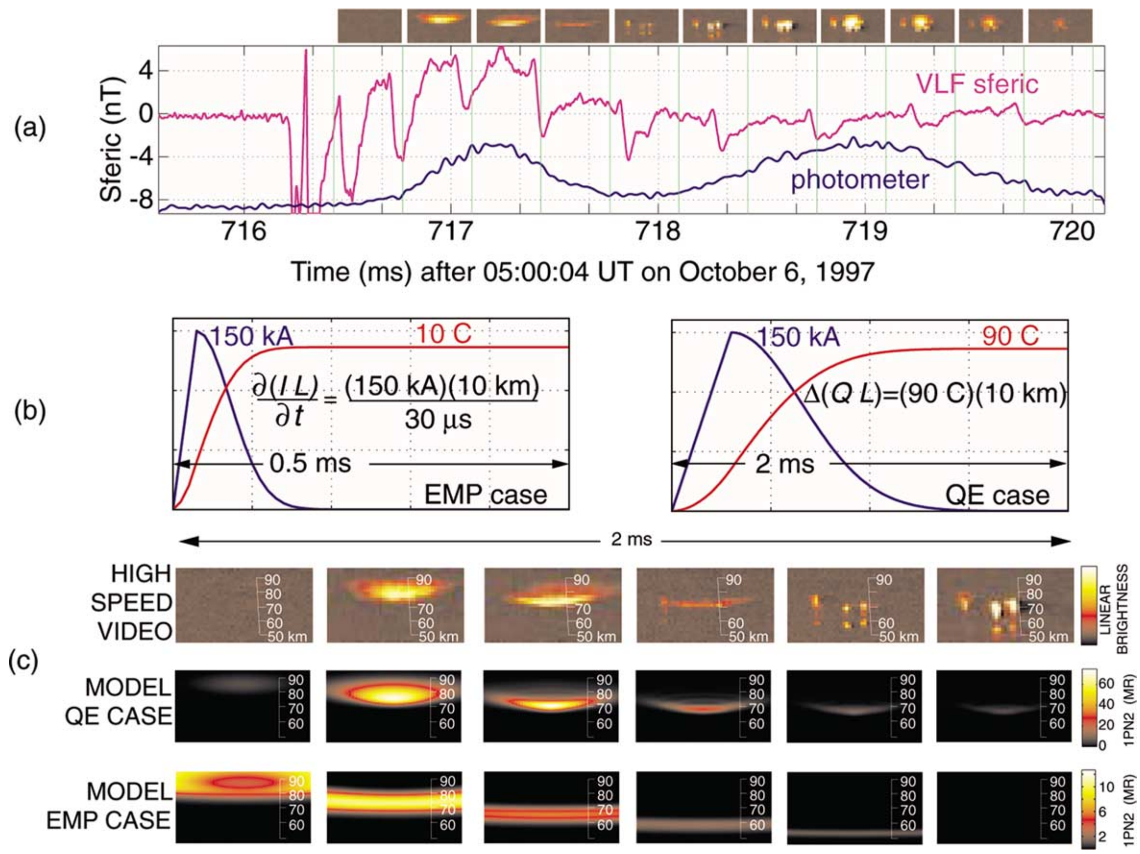

Figure 6. Modeled and observed diffuse flashes. (a) A time-resolved sprite halo, with VLF radio atmospheric and photometer data [13]; (b) theoretical lightning currents used as input to the model; and (c) comparison of observations (false color) and the modeled QE and EMP cases, which emissions in the first positive band of molecular Nitrogen. Figure taken from [13].

4. Terrestrial gamma-ray flashes and runaway electrons

One of the surprising discoveries of the Compton Gamma-Ray Observatory (CGRO) was the detection of γ-rays clearly emanating from planet Earth [14], which were shown to be loosely concentrated in regions of thunderstorm activity and at least in one case [15] associated with an intense lightning discharge exhibiting characteristics similar to those of sprite-producing discharges. With the γ-ray photon energies of the observed flashes extending above 1 MeV, bremsstrahlung radiation from $>$1 MeV electrons was identified as the only viable source, remarkably consistent with early predictions [1] of runaway electrons accelerated at high altitudes by thundercloud fields. Detailed quantitative modeling [16, and references therein] has shown that intense QE fields which exist immediately after large positive lightning discharges can drive avalanche acceleration of MeV electrons above thunderstorms, leading to the production of intense runaway electron beams and γ-rays, as depicted in Fig. 7. The seed for the runaway electron beam are relativistic electrons that are produced by Cosmic ray showers. Since the dynamic friction for such high energy electrons in air is substantially lower (Fig. 7(d)) than that for electrons with $<$100 keV energy, they are efficiently accelerated upward by the intense downward pointing transient QE field, producing avalanche ionization as they collide with molecules of air (Fig. 7(a)).

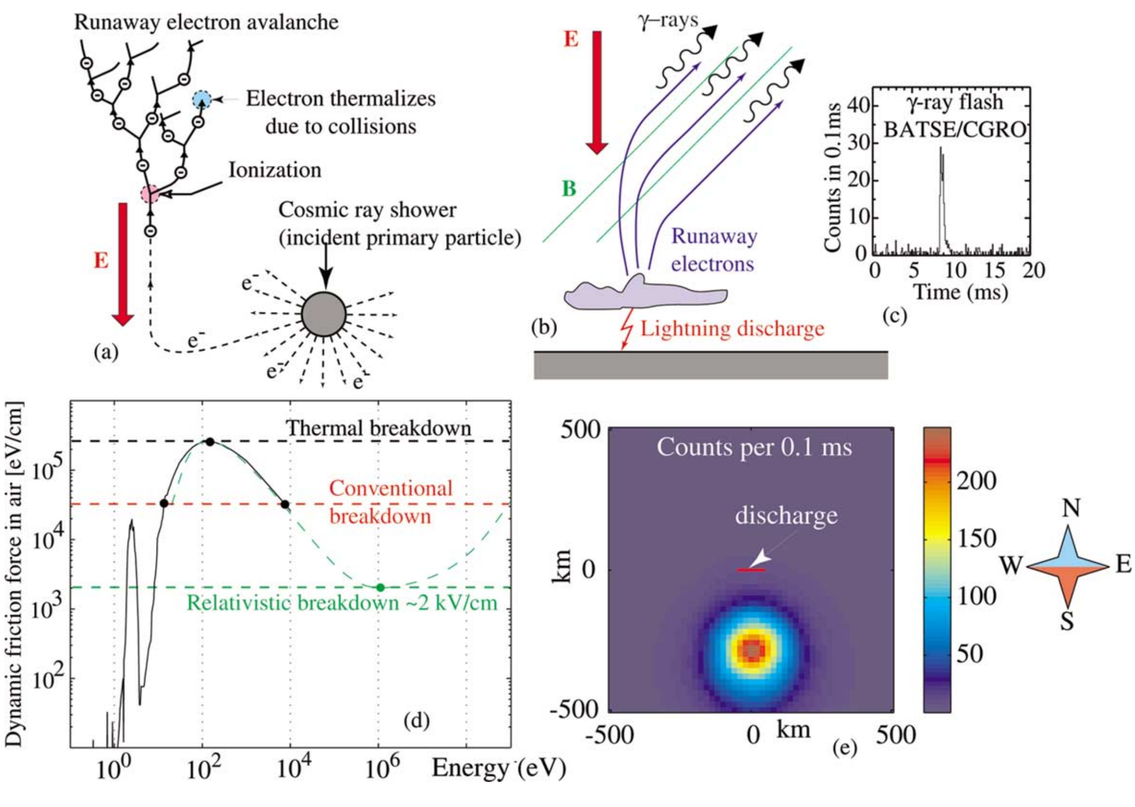

Figure 7. γ-rays and runaway frequency electrons. (a) Description of the runaway electron acceleration process. (b) At low altitudes, where collision rate is higher than the gyro-frequency, the runaway electrons move along the electric field direction, while at higher altitudes they move along the magnetic field. (c) An example of a terrestrial γ-ray flash observed with the BATSE instrument on the CGRO [14]. (d) Dynamic friction force for electrons in air as a function of electron energy, illustrating the relativistic breakdown region for energies $>$ 100 keV, which requires a substantially lower driving electric field as compared to conventional and thermal breakdowns. (e) Model calculation of the γ-ray beam the at the CGRO altitude (500 km) with the calculated photon counts as would be observed by BATSE.

Once it reaches to altitudes above the collision-dominated atmosphere, the avalanching runaway electron beam follows the Earth's magnetic field lines (Fig. 7(b)) and is by now very intense, leading to the production of γ-ray radiation at $\sim$65 to 70 km altitude [16]. The dynamics of the development of the runaway electron beam limits the duration of the γ-ray flash to be typically of order one or two milliseconds, consistent with CGRO observations (Fig. 7(c)). Once it reaches these altitudes, the upward moving runaway electron beam, consisting of 1 to 10 MeV electrons, is now incident on a thin target (i.e., an upper atmosphere which is increasingly more tenuous with altitude) and the beam simply escapes away from the planet along the magnetic field lines. If the magnetosphere were devoid of any plasma, the beam would simply travel along the field line and would precipitate in the geomagnetically conjugate hemisphere. However, since this medium is populated by a thermal plasma with typical particle densities substantially larger than that of the relativistic electron beam, the energetic electrons in the beam interact with the cold plasma via plasma waves, resulting in the scattering of the beam electrons in both energy and pitch angle. As a result of this scattering, a substantial portion of the electrons remain trapped in the mirror geometry of the Earth's magnetic field, forming curtains of trapped electrons (Fig. 8(b)). This process, which is

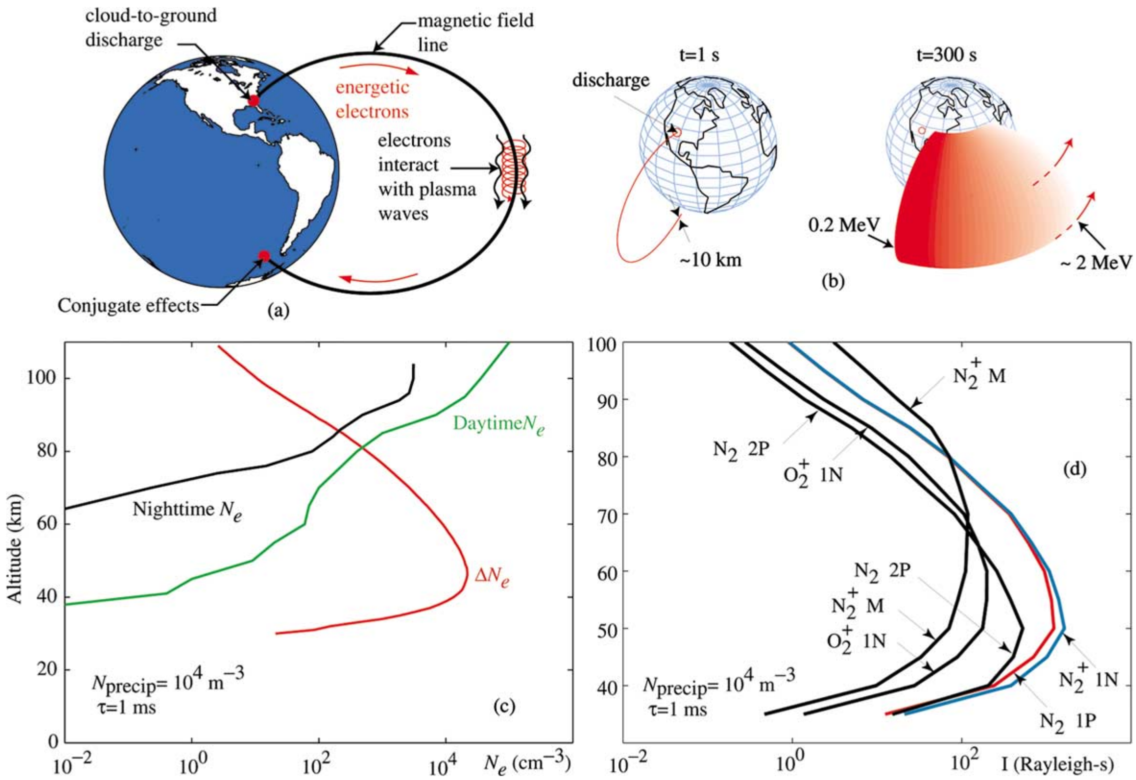

Figure 8. Geomagnetically conjugate effects. (a) Relativistic electron beam escapes upward and travels along the magnetic field lines where it can be scattered in pitch angle and energy due to interactions with plasma waves, with a portion of the particle population precipitating in the conjugate hemisphere. (b) Those particles which are scattered to higher pitch angles are trapped in the Earth's magnetic field, and start drifting eastward, forming trapped electron curtains as the faster electrons move ahead of the slower ones [17]. (c) Altitude profile of secondary ionization produced in the conjugate hemisphere by the precipitating component of the energetic electron beam. The typical daytime and nighttime electron density profiles are shown for comparison. (d) Altitude profile of different types of optical emissions produced in the conjugate hemisphere by the precipitating electron beam. The primary emissions are the first positive (red) band of molecular Nitrogen and the first negative (blue) band of N_2^+, causing the optical emission to be primarily purple in color.

theoretically predicted [16,17] as a direct consequence of the same process that leads to the production of terrestrial γ-ray flashes, is yet to be confirmed by observation. Direct detection (for example on a spacecraft) of such transient electron beams would be unlikely, but the curtains, which may persist for many minutes or hours may be detectable.

Another interesting consequence of the same process, illustrated in Figs. 8(c) and 8(d), is the resultant effects produced in the conjugate hemisphere by the fraction of the energetic electrons that precipitate there. Detailed calculations [18] indicate that bremsstrahlung radiation by the precipitating electrons (which now impinge on a thick target) would lead to production of γ-rays at least as intense as those produced in the parent hemisphere, and that the optical emissions produced would be detectable. Fig. 8(d) shows the altitude profile of the different type of optical emissions as calculated by [18]. Due to the short duration of the electron beam, these optical emissions would be similarly brief, $\sim$1 millisecond in duration, and must be detected using high-time resolution photometers. Detection of such optical emissions, in time association with positive cloud-to-ground lightning discharges occurring in the conjugate hemisphere, would constitute evidence for the existence of runaway electron beams, driven upward and away from Earth above active thunderstorm centers.

5. Summary

Sprites, elves, and terrestrial γ-ray flashes constitute a fascinating menagerie of visible or detectable evidence of intense electrodynamic coupling between tropospheric thunderstorms and the overlying upper atmospheric regions, the mesosphere, the lower ionosphere, and the radiation belts. Other evidence (not discussed here) for such coupling of upper atmospheric regions of our planet include the precipitation of energetic radiation belt electrons as a result of cyclotron resonance interactions with whistler waves launched by lightning discharges and the so-called early/fast subionospheric VLF perturbations, which were known [19] before the first documented observations of sprites.

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