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Fine structure of sprites and proposed global observations.

S. B. Mende and H. U. Frey, University of California, Berkeley, Cal 94720.
R. L. Rairden, Lockheed-Martin Research Laboratories, Palo Alto, CA 94304
Han-Tzong Su and R-R Hsu, Physics Department, National Cheng Kung University, Tainan, Taiwan 70101
T. H. Allin, T. Neubert,
Danish Meteorological Institute, 2100 Copenhagen , Denmark
E. A. Gerken, U. S. Inan, STAR Laboratory, Stanford University, Stanford CA. USA.

Abstract.

In order to understand sprite processes we have to explain the phenomena from spatial scales of a few meters to the scale of thunderstorm cells. The intricate small-scale vertical structuring of sprites or the so called beads are particularly difficult to understand. From a two-station triangulation featuring observations from Kitt Peak, Arizona and Socorro, New Mexico it was possible to make high resolution observations of the sprite structure when the sprite events occurred within the field of view of the narrow field imager. In several cases the lower altitude luminous filamentary structures of C sprites consisted of slant directed, nearly vertically aligned columns of intense pinpoint like beads. The distance of the sprites from the observer was measured and the altitude and vertical spacing of the beads were estimated. The distribution of beads showed that the most frequently observed bead spacing is between 0.6 and 1 km. The vertical and horizontal size of the bright luminous beads was about 80 m or less. The bead spacing showed a trend to increase with altitude and the e folding distance or altitude "scale-height" of bead spacing was found to be 20 and in another case 25 km. In order to make systematic observations of the large-scale sprite morphology a satellite based instrument the Imager for Sprites and Upper Atmospheric Lightning (ISUAL) instrument is planned to fly on the Taiwanese satellite, ROCSAT 2. The instrument will consist of an imager and two bore-sighted photometers. The imager will locate the sprites near the earth limb and make global synoptic measurements while the photometers will measure the spectral and temporal properties of sprites and other upper atmospheric luminous phenomena in a number of different wavelength regions uninhibited by atmospheric absorption.

Introduction.

Optical emissions constitute observational evidence of strong electrical coupling between the troposphere (altitude range of 5-15 km) and the mesosphere/lower ionosphere (altitude range 60 to 100 km). Sprites are the brightest and most frequently observed luminous coupling phenomena between troposphere and mesosphere/lower ionosphere.

Sprites were categorized according to their morphological appearance. The most commonly reported sprites are the so called "carrot sprites" which have a strong luminous center regions, tapering towards lower altitudes while showing a diffuse "hair" region above the body. Near the bottom, the carrots are often accompanied by thin hairline discharges or tendrils. Wescott et al., [1998] observed sprites consisting of thin relatively uniform vertical columns so called columniform or "C" sprites. From limited analysis they concluded that C-sprites follow positive flashes with currents ranging from about 23-100 kA. They measured spectra and they suggest that there are spectral differences between C sprites and other type of sprites. We do not know yet whether the morphological distinctions in the horizontal/vertical structuring have significant relevance to qualitative differences in the underlying electro-dynamic processes. For example it is possible that the tendency to develop full carrot like features with hair and tendrils are the result of strong electric fields and accompanied by substantial discharge while less intense discharges exhibit the features of C sprites. Most sprites are largely elongated in the vertical direction presumably because discharges line up with the predominantly vertical electric field.

Substantial structuring in the horizontal direction was also observed by Sentman et al., [1996] who report occurrences of small, often isolated, patches of bright luminosity that are often distributed throughout the volume or within the immediate vicinity of the sprite at altitudes of 60-80 km. They also reported on observing isolated patches, with scale sizes not exceeding few km, resembling plasma beads and balls and may occur wherever the local breakdown criteria is met within the complex three dimensional structure of nodes and anti-nodes of the radiation field created the underlying lightning stroke. Winckler

[1998] also reported the observation of beads and in their magnified images for example one can discern beads in their Figure 6b. Wescott et al., [1998] also showed example of a few beads in their Figure 5. Very high resolution spatial studies of sprites have been carried out during the Sprite 1998 campaign [Gerken et al., 2000] revealing extensive intricate structural complexity of sprites.

During the 1999 summer campaign simultaneous observations were made with high resolution cameras from Kitt Peak, Arizona and Socorro, New Mexico. The two station observations permitted to obtain triangulated quantitative measurements, which allowed us to examine the properties of the beads in more detail. We were able to measure the sizes and altitude separation of beads occurring underneath “C” sprites.

The detailed morphology of the discharges, their intrinsic structural richness, the conditions which leads to high probability of occurrence and the tendency for sprites to recur in the same region has not been explained. Recent high time resolution investigations have uncovered some of the temporal properties of Sprites and that some ionization does occur in the initial period of sprite formation which subsequently gives way to pure excitation [Armstrong et al., 2000].

Most prior studies used ground or aircraft based observations. The observations were inhibited by the dense lower atmosphere, which produces substantial wavelength selective absorption. For a significant statistical study of the global distribution of the frequency of occurrence brightness time-profile and wavelength content a spacecraft based observing program is needed. The Imaging of Sprites and Upper Atmospheric Lightning (ISUAL) satellite program is designed to fulfill this need.

Description of the observations.

High resolution data were taken at Kitt Peak, with special emphasis to search for luminous clustering or bead production phenomenon. From simultaneous data taken at Socorro, New Mexico, we were able to triangulate sprites and obtain accurate range and altitude information. The instrument used at Kitt Peak was a pair of intensified cameras. One of the cameras, a 300 mm focal length lens intensified CCD camera, had a focal plane consisting of a 25 mm diameter S-20 photo-cathode intensifier tube. This was fiber-optically coupled to an interline transfer CCD. The instrument included a built in video processor, which added annotation on each video frame, encoding time, gain setting and frame integration duration. For sprite viewing the camera was operated at standard video rates (30 frames per second). Another bore sighted camera, had a 50 mm lens and also used a 25 mm S-20 intensifier tube. In this camera a Charge Injection Device (CID) was optically coupled to the intensifier. Data from a time code generator were superimposed on both video signals, which were separately recorded on Hi-8 videocassettes. A team of researchers representing the Lockheed Martin Research Laboratories, the National Chen Kung University of Taiwan, and the Danish Meteorological Institute of Denmark operated the instruments. The University of California, Berkeley provided the most field instruments and coordinated the observations.

The Socorro instruments, a long focal length telescope [Gerken et al., 2000] and the bore sighted wide field (50 mm focal length camera provided by the Lockheed Martin Palo Alto Research Laboratories) were operated by Stanford University.

Several spectacular sprite events were recorded on Aug 8, 1999. Some of these events were analyzed in some detail. Several stars were identified in the wide FOV camera and in the Socorro wide field frame to provide a basis for triangulating the sprite at 220:04:22.3. Another sprite was observed in the Kitt Peak wide field cameras at 220:04:22.4 only 100 msec later which was not inside the telephoto field of view. From the data sets concerning several stars it was possible to construct a generalized expression which associated a value of azimuth and elevation for any pixel coordinate x and y. The tips of three sprite clusters were identified from the similarities of the images from both stations and azimuth and elevation of the tips of the sprites were obtained. These data combined with the station coordinates were used in a triangulation program previously developed for barium ion cloud position determination. The triangulated range (distance) from the Kitt Peak observers were found to be about 680+-10 km for the triangulated tips of the sprites for the sprite occurring an 8/8/1999 day 220 04:22:09 UT.

	lat	lon	range	alt
Kitt Peak	26.38	251.097	680	75.97
Socorro	26.11	251.17	895	76.02

Table 1.Tthe results of the triangulation for Sprite observed at 220-04-22-09

The NLDN data was examined for the 04:09:22 second periods and we found the events which had positive lightning discharges and they were found closely consistent with the triangulated results.

Stars were also identified in the images taken by the 300 mm telephoto and a linearized relationship between azimuth, elevation and pixel x,y space was found in the telephoto view. Greater relative accuracy was obtained by the use of the telephoto lens. Using the range distance obtained from the wide field triangulation (See table 1) the azimuth and elevation of each pixel was determined as single points in space and the true altitude was estimated above the oblate spheroid earth surface. Thus the altitude of each Sprite feature including the altitude of the beads was determined.

Figure 1. Telephoto Sprite image. The various features were labeled as clusters and branches

Figure 1 shows the example of a sprite. The upper portion of the so called C sprites are bright and continuous and they abruptly end at the same lower altitude (74.5 km +- 1.5 km) with the notable exception of the brightest branch of Cluster 2 which appears to come lower. Below that altitude one can see distinct "beads". For the purposes of the analysis presented here we arbitrarily identified 3 clusters and branches within the clusters.

The diameter of the beads is close to instrument resolution, although some of the stars visible on this image (e.g. just above the left branch of Cluster 3) are somewhat sharper than the beads associated with cluster 3. Each CCD pixel in the 300 mm telephoto system was estimated to be 83 meters in diameter at 680 km distance.

The bead spacing distances were sorted into 0.2km bins from 0 to 2.4 km. The distribution is double peaked at spacings of 0.6 and 1 km with 12 events in each spacing range. The apparent minimum at 0.8 km may not be significant. Figure 2 shows the statistical distribution of the altitude differences between consecutive beads from all branches of all sprites in figure.

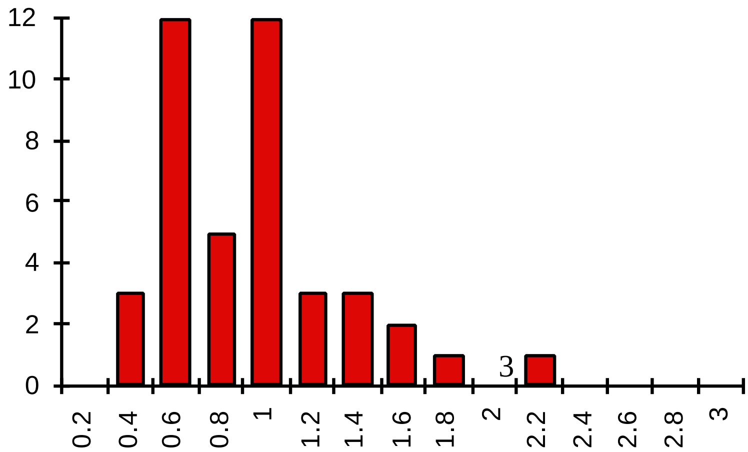

Figure 2. Distribution of the altitude spacing between beads.

It was interesting to investigate whether the bead spacing varies systematically with atmospheric pressure. Figure 3 is a scatter plot of the bead altitude vs. bead spacing for all the beads measured on Figure 2. The symbols represent the branches of the bead in Figure 1. Although the scatter is quite large there is a trend that the bead spacing is increasing with altitudes. This trend is more or less present in each branch and can be seen as an overall trend.

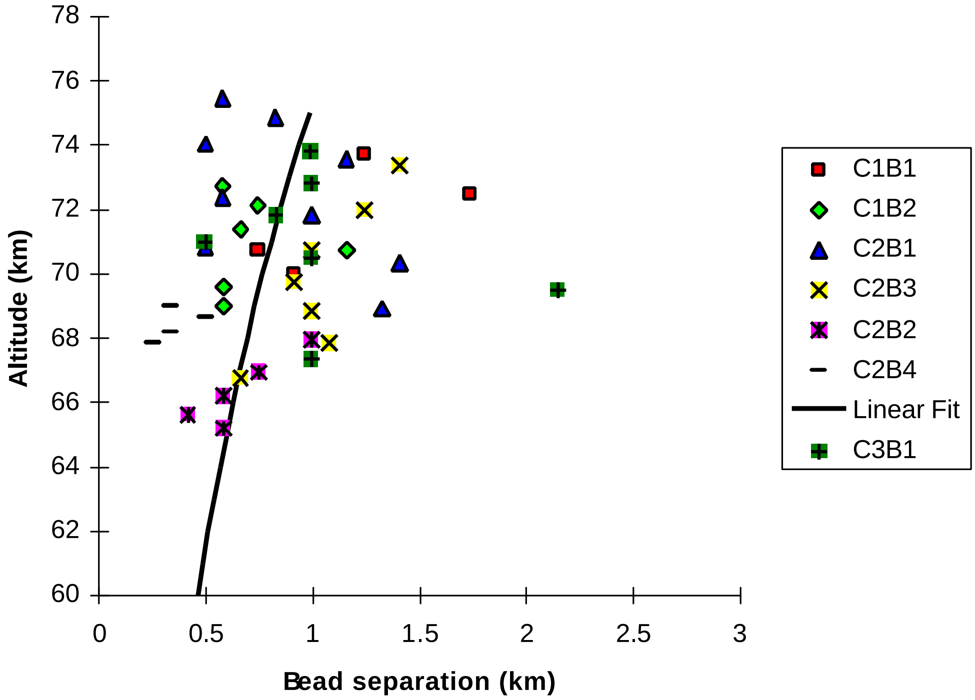

Figure 3. Bead Separation as a function of altitude.

One would expect spacing to increase with pressure/altitude as the mean free path increases. If the bead spacing were proportional to the mean free path then the plot of log of the spacing against altitude should have a slope of 1/H where H is the scale height. The curve representing the regression analysis of the natural logarithm of the bead spacing as a function of altitude is labeled as "Linear fit" on Figure 3. Linear regression analysis showed a value of 20 km for the "bead scale height" for the event at 04:09:22.

A similar sprite exhibiting extensive bead structure was observed at 04:34:27 on the same night. This sprite was also observed both at Kitt Peak and at Socorro. The bead separation "scale height" in this case was found to be 25 km which considering the scatter of the data can be regarded as relatively good agreement with the 20 km obtained from the 04:09:22 event.

Discussion.

High spatial resolution triangulated observation of sprites revealed interesting properties of the beads under c sprites. These beads are spatially well defined and appear to form near vertical strings at the bottom of c sprites below 74 km. The vertical spacing of the beads on average is less than one km. We examined the dependence of the bead spacing with altitude and found that there is a slight variation with altitude and the bead separation tends to increase slowly with altitude. The "scale height" or the logarithmic variation of bead spacing with altitudes, was about 20 km in one case and 25 km in another. The scale height of the atmosphere at sprite altitude is about 6 km. This shows that the bead formation phenomena are not solely dependent on the atmospheric mean free path. The atmospheric scale height is about 6 km at these altitudes. The externally impressed electric field electric field decreases with altitude probably as an Inverse Square or inverse cube law. One would therefore expect a longer "bead scale height" than the atmospheric scale height.

As the precursor lightning discharge occurs in the thundercloud at a large distance below, in the mesosphere the externally superimposed quasi- electrostatic field should not have a fine structure. The fine scale structure exhibited by beads show strong light emission modulations indicating localized fine structure. One approach to explain sprite structure has been associated with the larger scale variations with gravity wave induced changes of the neutrals [Pasko et al., 1997]. However the wavelength of directly observed gravity wave induced variations are multi kilometer in scale. Another possible structural variable is the pre-existent ambient electron density that could exhibit fine structuring because cosmic ray produced contribution to the electron density. Such electron source is indeed a requirement for generating runaway electrons which are needed in the current explanation of seeding thunderstorm associated gamma ray events [Russell-Dupre and Gurevich, 1996,Russell-Dupre et al., 1998]. Structuring of sprites have also been explained as caused by the interference of electric fields produced by the electromagnetic pulse (EMP) of an intricate current system within the cloud during the lightning event [Valdivia et al., 1997, Valdivia et al., 1998.]. However the observed time delay between the precursor lightning, the elv which is caused by EMP and the sprite is inconsistent with such an "instantaneous" production mechanism of sprites.

If we assume that sprites are in a relatively uniform exponential atmosphere and are produced by the superposition of a quasi-static electric field induced by the cloud to ground discharge. The quasi-static electric field (downward directed, negative) is smooth and diminishes with altitude according to some model. The critical field, which is required for either excitation or ionization, falls off exponentially with altitude following the atmospheric density. The quasi-static electric field can reach the magnitude of the critical field since the critical field falls off faster than the electric field since the critical field falls off faster than the electric field. At the lowest altitude where the electric field exceeds the critical excitation field the ambient electrons will excite the air molecules and faint tendril glows could be expected. At the point where the electric field is above the critical value for ionization ions and electrons will be produced. We associate beads and lower boundary of the bright region in the C sprites where the excitation and a bright intensity enhancement will be seen which are associated with the body of the C sprite.

Although it has not been specifically measured it is safe to assume that the bulk of light emission in the beads is the N_2 first positive red emission. The excitation potential of this emission is about 8 – 10 eV [Mende et al, 1995, Hampton et al., 1996]. The most remarkable property of the beads is their relatively short altitude extent and their relatively constant spacing along the vertical direction. The sprite intensity was measured in the wide field of view image by comparison of the sprites to the luminosity of observed stars in the same field of view. It was found that each digitized video unit is equivalent to 2 kR of red light. Some of the Sprite features were found to be over the maximum of 256 units. Thus a representative sprite intensity was >500 kR. The beads are considerably brighter than this and therefore require electron multiplication hence the association of sprites with the region where ionization takes place. We have measured the bead intensity and they range in the 1.5 – 2 MR level. Thus substantial electron multiplication (~40) is required to produce the required intensities. At 80 km the same calculation gives that the needed electron multiplication is 400 and it increases rapidly with decreasing atmospheric density. In summary we expect that substantial electron multiplication and subsequent charge generation and possible space charge separation should take place to provide the observed large intensity variation characteristic of the bead appearance. Regions of positive space charge would push the local excitation/ionization potential above the critical value producing bright beads while regions of negative space charge produce dark regions.

The situation is analogous to a situation where a rigid insulator surrounded by vacuum is bombarded by electrons of energy higher than the secondary emission critical potential. The ionization i.e. secondary electron production would produce a positively charged region with the electrons carrying negative charge to the adjacent regions. This action would result in small regions of positive charge with intense local excitation with adjacent regions having retarding electric field which is slows the electrons below the critical potential. Thus the size of the bright regions would be defined by the mobility of the ions, (which would be zero in the example of a rigid insulator) and the size of the dark regions would be related to the mobility of the electrons. It can be shown that during the sprite' s ionizing phase (few msec) the electrons with a kinetic energy of 10 eV would travel of the order of about 1 km which is consistent with the bead separation distance.

The understanding of the physics of sprite production could be greatly improved if we understood the atmospheric conditions favoring occurrences of sprites and other luminous phenomena. A systematic program to observe the global distribution of sprites would be of great value. To make systematic and global observations of sprites and related phenomena a satellite based instrument the Imager for Sprites and Upper Atmospheric Lightning (ISUAL) instrument is planned to fly on the ROCSAT 2 Taiwanese satellite. A satellite-based instrument will provide global coverage and will allow observations unhindered by atmospheric extinction or cloud problems. The instrument will consist of an imager and two bore-sighted photometers. The imager will image sprites (and other luminous phenomena) near the earth limb spatially separating them from tropospheric lightning. The photometers will measure the spectral and temporal properties of each sprites in a number of different wavelength regions. By correlating the measured global sprite distributions with other atmospheric data we hope to gain insight into the physics of sprite production.

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