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A Hertzsprung-Russel Approach for Taxonomy of Lightning Discharges

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***Abstract*—This paper proposes a new approach for classification of lightning discharges with the purpose of achieving a more holistic understanding of lightning phenomenon. The approach is derived from the famous Hertzsprung-Russell (HR) diagram, which allowed demonstrating dynamic sequences of stellar evolution and predicting existence of nuclear fusion. Arranging lightning discharges in a manner similar to the HR diagram allows revealing correlations between lightning luminosities and discharge current densities or the effective temperatures. Lightning optical signatures are defined by the dominant-wavelength while their variations are determined by the identity of tropospheric gases and density of their excitation. This dominant-wavelength spectral signature of lightning gives an objective measure for the unique characteristics of each discharge and provides a new and elegant research tool. The advantage of plotting different lightning strikes on a single HR-like diagram is the simple display of taxonomic features of known lightning characteristics thus revealing patterns in lightning behavior in a manner not previously recognized.**

Keywords—lightning taxonomy; lightning classification; lightning Hertzsprung-Russell diagram; lightning dominant-wavelength signature; lightning research tool

Foreword

Teachings of the renowned philosopher Henry Bergson set forth views that for a human mind, enduring of time continuously persists by lasting prolongation of the past into the future—a continuum composed of temporal heterogeneity, where multiple conscious states are overlapped into the perceived indivisible whole. This multiplicity is enumerated by the means of externalizing, and even the ordinary color spectrum gives rise to the undeniable existence of a constant difference due to variety of the nuances of color. The habitual way of knowing is an attempt at explaining consistency and meaning by assuming the contingency of order in the multiplicity of differences within the seeming disorder. In Bergson's creative impulse, it is reconciling the relativity and complementarity of the diversity instantiated in the multitude of scientific knowledge and metaphysical thought that is capable of recognizing the absolute totality defined by its coincidence with the emergence of new knowledge.

I. Understanding Lightning

Varying states of air thermodynamics provide a range of conditions and mechanisms of lightning plasma formation and generate plasmas with dissimilar parameters, electron temperatures and concentrations. Thus, pressure has a strong effect on plasma influencing its respective luminosity, energy, and state of its components. Plasma behavior is extraordinarily subtle and complex, and is characterized by the emergence of unexpected behavior via spontaneous formation of interesting spatial features such as striations on a wide range of length scales. Qualitatively different plasma properties can be observed if matter clusters and aerosols are actively present in the discharge system, leading to enhanced ionization due to particles chemical and catalytical activity. These dusty plasmas play a role in thunderstorm genesis influencing cloud microphysics and electrification [Fridman, 2004].

Central to the Earth system's ecology is the idea of an ecosystem being a complex adaptive system exhibiting emergent properties. Termed as lightning ecology, it defines the relationship of bio-system community to manifestations of static and dynamic electricity as one of the greatest forces in the environment [Komarek, 1973]. Causing perturbations to green house gas distributions, lightning imbalances Earth's energy budget contributing to climate forcing and feedback processes [Romps, 2014]. Natural systems are notorious for producing unexpected behaviors; and an authentic unpredictability of lightning always exhibits characteristics that cannot be deduced from the elemental properties of the event alone. Emergence of the higher-level behavior is enabled by interconnectivity and interdependence of elements, groups, classes, and sub-systems and the relationship between these organizations with their surroundings. Complex functioning of these interactive networks is given by a mutated self-organization adapting to the collective behavior of all components involved in response to a change-initiating event.

Profound research has been conducted in the attempt to explain lightning phenomenon. New insights are being continuously obtained through evolving investigations; however, gaps in scientific knowledge continue to persist requiring revisiting organizational structure and tendencies in the approach. This paper proposes a novel strategy to piece together existing information to start building a more holistic and unified understanding of lightning phenomenon.

II. Behavioral Economics of Lightning: Variations in Space, Time, and Energy

Lightning process is variable in its nature presenting with multiscale temporal and geographical distributions and variations in the characteristic quantities of waveform, peak current, polarity, luminous intensity, and temperature. Temporal distribution shows general correlation with the Carnegie Curve; and also it cycles over the diurnal and annual time scales following the peak solar activity. Geographically, the global activity is bound to three regions over the tropical land masses of Africa, South America, and Southeast Asia. Attributed to being a proxy for the intensity of atmospheric convection, observations point toward increased lightning activity with reduced precipitation; thus, moisture, temperature, continentality, and height of thunderstorm cloud base all define rate of lightning formation, activity and intensity [Price, 2008].

The perceived color of light emitted by lightning is defined by the dominant-wavelength emissions as a function of the discharge duration and the branch and channel profile. It is determined by the identity of tropospheric gas mixture, its altitude-dependent density, and the degree of excitation of chemical species involved. Air being a permanent mixture of mainly oxygen and nitrogen contain variable quantities of aqueous vapor and carbon dioxide, which vary perpetually with numerous atmospheric conditions. Emissions of light by the Lewis-Rayleigh afterglow prevalent in diffuse air plasmas give rise to appearance of orange to yellow-green or violet to pink hues as the discharge dissipates. Influenced by surface chemistry, afterglow intensities are maximized at the lowest temperature and pressure at the orange-color wavelengths. As a result, lightning discharges in air present with visually detectable dynamic range of colors and hues varying among white, yellow, purple, violet, blue, cyan, or green, Figure 1. Atmospheric extinction accounted by Rayleigh and aerosol scattering and molecular absorption, variability in water vapors, dust, rain, or hail—all add uncertainty to the influence of the existing variations in air chemistry on the emitted light produced by lightning discharges.

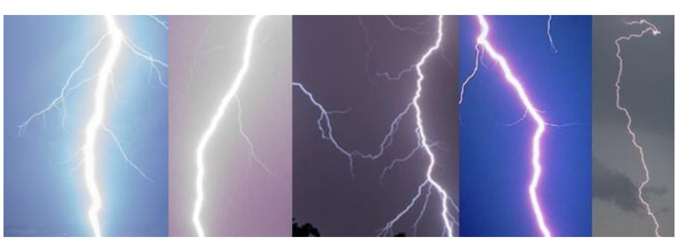

Fig. 1. Colors of Lightning.

Finally, statistical analysis of the maximum brightness across several spectral channels in the UV-IR range showed dominance by the red-wavelength bandwidth, followed by the infrared and the ultraviolet emissions, respectively. While intensity varied within each specified spectral channel, the trends informing of the brightness variability within each individual discharge have not been addressed [Offroy, 2015]. Analysis of the spatial variability in brightness of branched lightning channel suggested the inverse brightness–current relationship, which was coincident with the previous findings referenced in this work [Shimoji, 2017]. The peak optical power emitted by rocket-triggered and natural lightning were proportional to the square of the peak current [Quick, 2014]; while the higher first stroke currents occurred over ocean in contrast to those on land [Nag, 2017].

III. A Hertzsprung-Russel Approach for Taxonomy of Lightning Discharges

Constructed in 1900s, famous Hertzsprung-Russell (HR) diagram portrays stellar classification in terms of logarithmic measure of luminosity against spectral characteristics, or the effective surface temperatures [Tayler, 1994; Eddington, 1926], Figure 2. Analysis of a large number of stellar spectra identified most prominent common elements allowing classification of stars into the spectral types, Figure 3; however, it was realized that with only little difference in the chemical compositions of stars, temperature plays a key role in the appearance of stellar spectra.

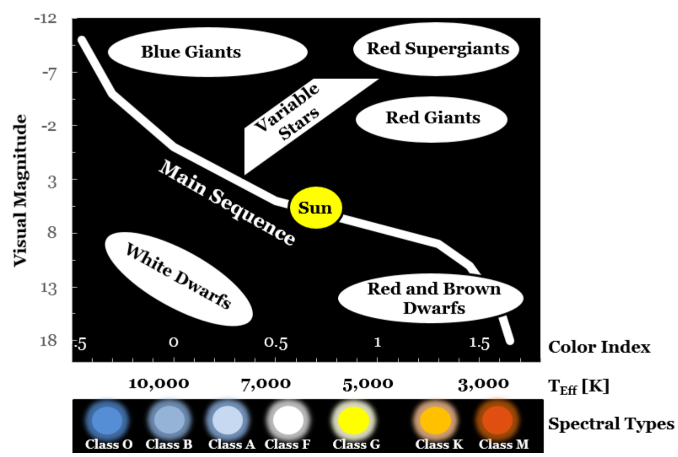

Fig. 2. Hertzsprung-Russel Diagram (The Sun is G2 Class).

Spectral Type	T_{eff}, K	Main Features
O	50 000	Ionized helium and metals, weak hydrogen
B0	25 000	Neutral helium, ionized metals, hydrogen stronger
A0	11 000	Balmer lines of hydrogen dominate, singly ionized metals
F0	7 600	Hydrogen weaker, neutral and singly ionized metals
G0	6 000	Singly ionized calcium most prominent, hydrogen weaker, neutral metals
K0	5 100	Neutral metals, molecular bands appearing
M0	3 600	Titanium oxide dominant, neutral metals
R, N	3 000	CN, CH, neutral metals
S	3 000	Zirconium oxide, neutral metals

Fig. 3. Stellar Spectral Types and Effective Temperatures [Tayler, 1994].

The importance of the diagram was in showing that the stellar distribution in the galaxy was not uniform but contained distinct trends of correlation between luminosity and color.

With three prominent regions—the main sequence, giant and dwarf branches, the diagram informs of the internal structure and stage of the evolutionary cycle of a star based on its position in the diagram. Constructed models of the evolving stellar structures can predict changing luminosity, color, and the future evolutionary stage of a star, as depicted by stellar migration from the main-sequence toward the giant and supergiant branches, eventually collapsing into a dense white dwarf.

Arranging lightning discharges in a manner similar to the HR diagram potentially allows revealing correlations between the lightning plasma luminosities and the discharge channel gradients of the effective temperature. The dominant-wavelength color of the discharge is governed by the electric current density, which defines both luminosity and the color temperature of plasma in accordance with the volt-ampere characteristics of the discharge mode. Differences in the emitted light would be defined by the power density of the discharge and the location of emissions in the gas discharge path. Sharp color and luminosity discontinuities would be expected given by the nature of the phenomenon during transitions from dark to normal glow and to the arc mode currents. Essentially, the proposed lightning HR diagram provides an organizational structure of statistical and geographical distributions and affords an elegant display of the phenomenon evolution patterns in a manner not previously recognized. Differences in the datasets will reflect varying storm dynamics against their electric power and air chemistry. Combining this representation with other known taxonometric characteristics such as flash rate and atmospheric convection parameters, can allow constructing thunderstorm energy balance and model stages of its development. Regionally and globally integrated contents of lightning energies could be finally related to the Earth's budget and solar flux transport; and ultimately, to the framework of the global electric circuit. Resolving discharge signatures in time will allow elucidating correlations between optical emissions and electronic transitions to establish continuity across micro and macro processes in operating plasmas of tropospheric lightning.

IV. Conclusions

Classification based on observations is a fundamental step in science. Importance of establishing an ordered system is in revealing natural and evolutionary relationships among the quantities, from which physics could be inferred. Tremendous progress in lightning research has led to discovery of many physical processes occurring in these discharges; and for small datasets, the cause-effect relations have been established in the framework of atmospheric parameters. However, the planetary-scale behavioral economics of lightning system remains hard to comprehend as the system's complexity escalates to the uncertainty of interpretation. Similar to problems in astrophysics, there is no possibility to obtain in situ measurements of environmental and electrical characteristics in the conceived charged centers of electrified clouds where lightning leaders form. Reproduction of realistic conditions and processes of leader formation with ensuing lightning-like discharge in a laboratory also presents with an arduous task. Then, how could the proposed classification of lightning plasmas advance understanding of the long-standing science question on physics, or the knowledge of the nature, of initiation of lightning discharges?

It was a great human endeavor to construct the stellar Hertzsprung-Russell diagram, which, in essence, provides an observational scatter plot but also depicts an obvious mass-luminosity relationship of the clustered organization. This simple demonstration presented astronomers with the key insights and realization of different phases of the stellar life cycles and led to the idea of the core-envelope structure of stars. Exemplified by another breakthrough of the Mendeleev's periodic table of the element—one of the most important tools in the history of chemistry—his organization allowed deriving relationships between various element properties but also predicting chemical properties and behaviors of undiscovered or newly synthesized elements. Mendeleev was not the first chemist at this attempt, but he recognized the trends to predict the properties of missing elements.

In the science of lightning, while generation of the HR-type arrangement will provide the first indication of existing classifiable features, further cross-fertilization of ideas and convergence of information through multidisciplinary collaborations is indispensible for establishing proper taxonomies of the phenomenon. As the data coverage extends across the full range of wavelengths from radio to gamma-rays, these observable data volumes add up, sorting through which is required for extracting hidden dependences or mutual relations between seemingly unrelated values. Further scientific breakthroughs will become possible with continuous monitoring and generating large datasets to be analyzed by data mining and machine learning techniques to uncover incomprehensible trends, establish taxonomic classifications and realize the physics-based lightning behavior model.

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