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ANALYZING ISUAL SPECTROPHOTOMETER DATA USING A TWO-COLOR DIAGRAM METHOD

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ABSTRACT

Transient luminous events (TLEs; sprites, elves, jets and etc.) are lightning-related optical flashes occurring above thunderstorms. Since the first discovery of sprites in 1989, scientists have learned a great deal about the morphological, spectroscopic and electromagnetic characteristics of TLEs through ground and spacecraft campaigns. However, most of the TLE studies were based on events recorded over US High Plains. To elucidate the possible biasing effects, space-borne observations are needed and have their merits. Imager of sprites and Upper Atmospheric Lightning (ISUAL) on the FORMOSAT-2 satellite is the first instrument to carry out a true global measurement of TLEs from a low- earth orbit. In this short paper, we apply a common astronomical data analysis technique, two-color diagram, on the ISUAL spectrophotometer (SP) data. By choosing appropriated bandpasses and converting the measured flux of TLEs into the unit of magnitude, two-color diagrams of TLEs can be constructed. We demonstrate that two-color diagrams, which were constructed from the narrow- band spectrophotometer data, can be used to classify different types of TLEs and trace their temporal evolution. The amount of reddening due to Earth's atmosphere can also be estimated from two-color diagrams assembled from the broad-band spectrophotometer data.

Key words : two-color diagram — methods: data analysis — techniques: photometric

I. INTRODUCTION

Transient Luminous Events (TLEs) are upward terrestrial discharges occurring occasionally between thunderclouds and the ionosphere. The lifetime of TLEs varies from several to hundred of milliseconds. Due to their faint and fleeting natures, TLEs are hard to be seen by naked eyes but are easy targets for low-light level imaging systems. The first TLEs was a sprite, which was recorded by Franz et al. (1990) on the night of 6 July 1989. As of this writing, several lightning-induced luminous phenomena have been identified, now including sprites, blue jets, elves and gigantic jets (Franz et al., 1990; Wescott et al., 1995; Fukunishi et al., 1996; Su & Hsu et al., 2003). Since the effects of TLEs on the Earth's environment remain to be clarified (Lyons et al., 2000), TLE study is a very active research frontier in the atmospheric science.

ISUAL is the first satellite payload dedicated to global measurements of TLEs and has the potential to deliver crucial data in unraveling these mysterious phenomena (Chern et al., 2003). In this article, we report some initial results from the ISUAL experiment. We adapted a two-color diagram method, which is a common technique in observational astronomy, to analyze the ISUAL spectrophotometer data. Our results demonstrate that two-color diagrams could be employed to identify different types of TLEs, to trace their temporal evolution, and to estimate the reddening effect of Earth's atmosphere on the observed TLEs.

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II. INSTRUMENT AND DATA REDUCTION

ISUAL was activated on 6 June 2004, successfully passed a series of fine-tunings and tests, and began its observation on early July 2004. ISUAL payload consists of an auxiliary electronic unit and three sensor packages, including an intensified CCD imager, a six-channel spectrophotometer (SP), and a red/blue- band array photometer (Chern et al., 2003).

The ISUAL SP contains six photomultiplier tubes and operates at a 10 kHz acquisition rate. Their bandpasses and main features are:

Broad-band SP channels:

- Ch1, 150-280nm: N_2 LBH long wavelength bands, to reveal the UV signature of sprites and jets and is less affected by parent lightning (threshold $\sim$ 8.4 eV)
- Ch4, 623-750nm: N_2 1st positive emission, N_2(1PG), for sprite measurements, (threshold $\sim$ 7.50 eV)
- Ch6, 250-390nm: to detect sprites and much attenuated lightning

Narrow-band SP channels:

- Ch2, 337.0nm: N2 2nd positive band(N2 (2PG)), induced by energetic electrons hence functioning as a particle energy "spectrophotometer" (threshold $\sim$ 11.18 eV)
- Ch3, 391.4nm: N_2^+ 1st negative band (N_2^+(1NG)), energetic electron detector in sprites and aurora (threshold $\sim$ 18.56 eV)
- Ch5, 777.4nm: mainly for OI(1) lightning emission, a lightning detector (threshold $\sim$ 10.8 eV)

Two-color diagram is a common technique in astronomy, which is often used to trace the variation of one or two parameters concurrently. For instance, U-B versus B-V is used to estimate the interstellar reddening and spectral type. Here we use two-color diagrams to classify the types, to trace the temporal evolution, and to estimate atmospheric reddening of the recorded TLEs. Since all six SP channels were well-calibrated in the lab, therefore the readout counts can be readily converted into scientific unit, photon flux or megaRayleigh , at a given high voltage of PMT. The detected flux then can be converted into a "magnitude" under the following definition:

$$m = -2.5 \times \log(F) + C, \quad (1)$$

where m: magnitude, F: photon flux, and C: a constant (zero is chosen here).

Color index CI is defined as the difference of the magnitudes of two bandpasses:

$$\mathrm{CI} = m_1 - m_2, \quad (2)$$

Conventionally, $\lambda_1 < \lambda_2$, therefore, larger CI means redder.

By selecting sensitive color, "color" can be correlated to physical or chemical quantities. Through trial and error, we selected three narrow-bandpasses, Channel 2, 3 and 5 as the bases of two-color diagrams ($m_2 - m_3$ vs. $m_2 - m_5$) to trace the temporal variation and to classify the types of TLEs. We could also construct two-color diagrams using the three broad-bands, Channel 1, 4 and 6 to diagnose the atmospheric absorption.

III. RESULTS AND DISCUSSIONS

(a) TLE Classification

Two typical TLEs — an elves and a sprite, as well as a typical lightning are illustrated in Fig. 1-3. The data points in the interval of -3~-1 ms (minus means before event trigger) are marked as yellow, in -1~+1 ms as red, in +1~+3 ms as green, and in +3~+5 ms as navy blue. Although these events all exhibit brightening at triggering times, they behave very different in the two-color diagram. The tracks of elves and sprites move toward lower-left corner then return to the origin, but the track for lightning remains in a confined region. These results indicate that channel 2 of SP at 337.0 nm is a good tracer of TLEs, since it only registers excess photon flux at the presence of TLEs. The slope and the length of the tracks on two-color diagram can be used to classify the TLE types; elves treks with a steeper slope and longer track than that of the sprites. The slopes of TLEs also reveal the rise time of the TLE emissions. The rise times further reflect the causative mechanisms of these two types of TLEs; elves are the result of the ionosphere heating from electromagnetic pulses (EMPs) emitted by cloud-to-ground discharges, and sprites are optical emissions from de-excitations or re-combinations of nitrogen molecules after they were impacted by energetic electrons accelerating by the residual E-field following cloud-to-ground discharges. The rise time of the sprite emissions would be longer than that of the elves; since sprites are induced by energetic electrons that are naturally more dispersive, therefore have emission rise times that are longer than the elves-causing EMPs.

To extract the physical quantities of the TLEs from the spectrophotometer data quantitatively, fluxes from other non-TLE emission sources have to be subtracted. However, the light reflected from the Earth varies with lunar phase and the amount of clouds. Airglows also contribute substantial photons in some SP channels, especially for the broad-band ones. Therefore, a quantitative subtraction of non-TLE contributions to the spectrophotometer flux currently is not possible, only qualitative descriptions could be attempted for most of the ISUAL TLEs. As we just demonstrated, the channel 2 of SP at 337nm is a very sensitive detector of TLEs. This emission is hard to be observed on the ground due to strong UV absorption of Earth's atmosphere. Thus ISUAL could provide valuable UV information of TLEs. To hunt for unknown types of TLEs, the ISUAL experiment will use SP Channel 2 as the event trigger.

(b) Atmospheric Reddening

To diagnose atmospheric absorption, we select elves with their parent lightning blocked by the solid Earth. For these elves, the distance between FORMOSAT-2 and the TLEs is typically greater than 3000 km and the majority of the photon flux came from the TLEs. In the 30 elves that fit this criterion, we bin the events further by their distances; group 1 and group 2 have a mean distance of 3795 km and 4288 km, respectively.

The three broad-band SP channels, Channel 1,4 and 6, were chosen as the basics to assemble two-color di-

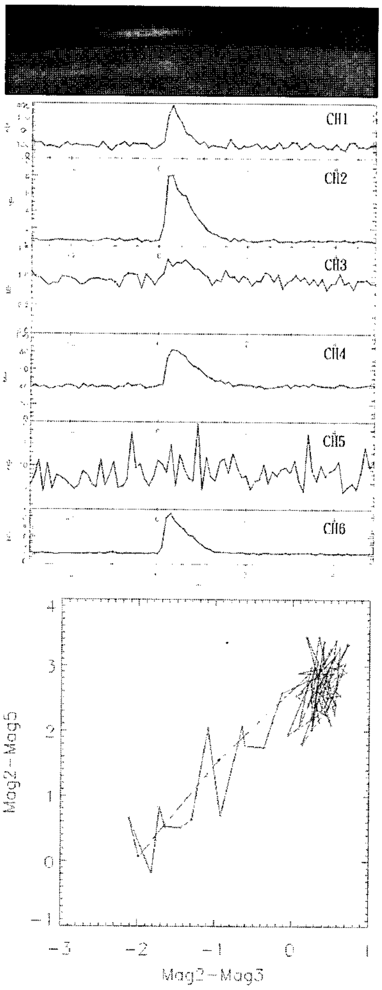

Fig. 1.— An elves on 2004/08/28 14:43:21.722 over the Philippines. The parent lightning was located behind the earth limb, thus the detected flux mainly came from the elves. The evolution track moves toward left lower corner.

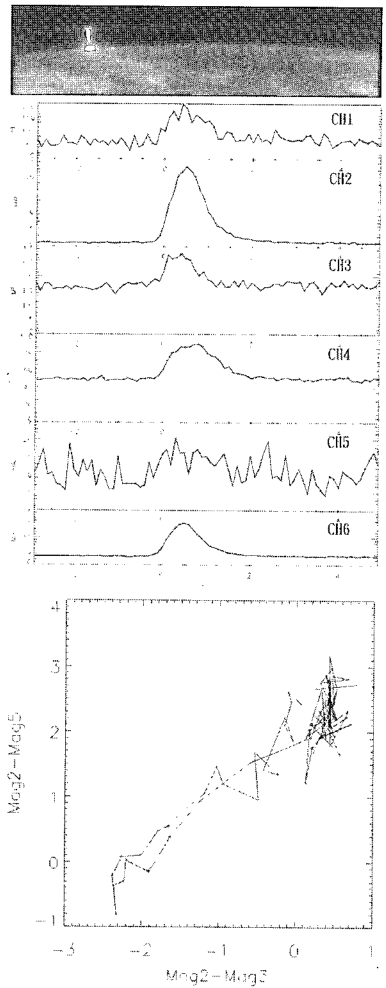

Fig. 2.— A sprite on 2004/07/30 16:28:20.462 over the Philippines. The parent lightning was located at the earth limb and was partially blocked. Thus, most of the detected photon flux was contributed by the sprite. The evolution track moves toward left lower corner with a smaller slope comparing with that of the elves shown in Fig. 1.

agrams. We compute color64 ($m_6 - m_4$) and color16 ($m_1 - m_6$) at the time when elves reached their maximum flux in channel 2, under the assumption that the spectra of all elves are similar. In Fig. 4, group 1 and group 2 congregate in the upper and the lower sections of the color64 vs color16 diagram, but exhibit less dichotomy in X-direction (color64). This indicates that atmospheric absorption of the Channel 1 and 4 bands is more significant than that of the Channel 6, and Channel 1 flux reduction was greater than that of the Channel 4. With 500 km separation between the two groups, the Channel 1 flux shows an 88% reduction with respect to Channel 4 flux by moving from group 1 to group 2.

This result proves that atmospheric absorption is an important flux removing mechanism, and the flux in Channel 1 would be greatly reduced with increasing TLE-spacecraft distance. To properly reduce the ISUAL spectrophotometer data, quantitative correction of atmospheric absorption is an important task, especially for blue and UV bands data.

IV. CONCLUSION AND FUTURE WORKS

A two-color diagram was used to analyze ISUAL TLE spectrophotometer data. We have successfully demonstrated that two-color diagrams can be used to classify TLEs and to estimate the amount of reddening in SP data due to atmospheric absorption. On the two-color diagram, lightning and TLEs follow distinct tracks, with elves possessing a steeper slope than that of the sprites. However, further works are clearly needed before quantitative corrections or extractions can be routinely performed. List of works to be done in the near future are:

1. Create a global distribution map of TLEs: ISUAL has recorded more than six hundreds of TLEs in the first 4 months of operation. These data can

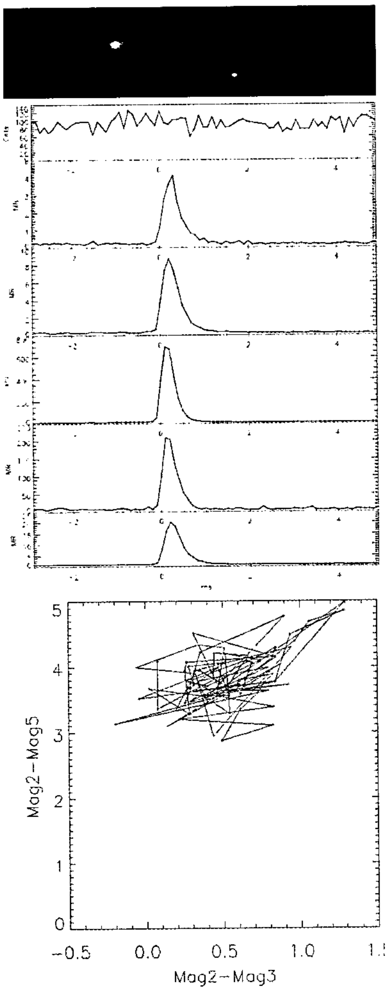

Fig. 3.— A typical lightning event on 2004/10/15 18:07:47.046. Total brightness of this event is similar that in the sprites or elves, but the evolution track on the two-color diagram confines to a very small ambit.

be used to create a preliminary global distribution map of TLEs, and it can be compared with results from other ground observation facilities like VLF and ELF networks.

2. Study two-color diagrams construct from other SP bandpasses: ISUAL SP is able to provide three broad-band and three narrow-band spectral information, concurrently. We hope to explore other possible two-color relations that are close related to physical or chemical parameters.
3. Modeling the track on the two-color diagram: To determine the signatures of TLEs, we'll begin theoretical works to simulate the tracks for different strength of causative electric fields and reddening by the atmosphere in the line of sight.

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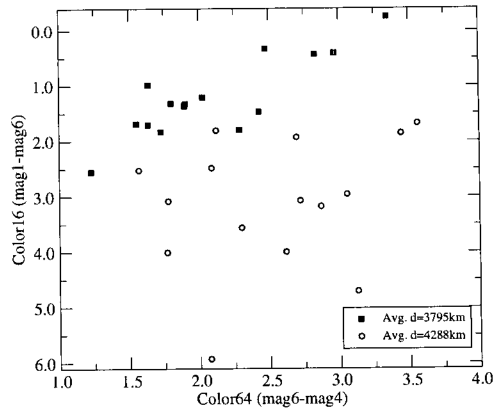

Fig. 4.— Two-color diagram of the 30 selected elves that with no parent lightning in the FOV. Group 1 is elves with an average distance of 3795km and is marked by blue squares. Group 2 is elves with a mean distance of 4288km and are marked by red circles.

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