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A novel technique for remote sensing of thunderstorm electric fields via the Kerr effect and sky polarization

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[1] Quantitative knowledge of the magnitude as well as spatial and temporal structure of quasi-static electric fields above a thunderstorm, both prior to and immediately after a lightning discharge, is crucially important for understanding the electrodynamic effects of tropospheric weather on the upper atmosphere. At present, such electric fields are typically only measurable by balloon- or aircraft-borne electric field meters launched near, above, or into the cloud. We herein propose a new low-cost ground-based spatially- and temporally-resolved technique for measurement of near-thunderstorm electric fields via electrically-induced birefringence (Kerr) effects on natural sky polarization, providing detection in clear air near or above thunderclouds. Such measurements would greatly help understand the effects of lightning and thunderstorms in the upper atmosphere, including sprites, blue jets, and terrestrial gamma-ray flashes. **Citation:** Carlson, B. E., and U. S. Inan (2008), A novel technique for remote sensing of thunderstorm electric fields via the Kerr effect and sky polarization, *Geophys. Res. Lett.*, *35*, L22806, doi:10.1029/2008GL035922.

1. Introduction

[2] Thunderstorm electric fields are of great interest to many areas of geophysics. Lightning initiation [*Solomon et al.*, 2001; *Marshall et al.*, 2005], sprites [*Sentman et al.*, 1995; *Pasko et al.*, 1995], elves [*Fukunishi et al.*, 1996; *Inan et al.*, 1996], blue jets [*Pasko et al.*, 1996], gigantic jets [*Su et al.*, 2003], and terrestrial gamma-ray flashes [*Fishman et al.*, 1994; *Smith et al.*, 2005; *Inan et al.*, 2006] are all directly involved with or are driven by these powerful electric fields. However, at present such fields can only be measured with local methods, either at ground level or by balloon-borne instruments launched near or within the cloud (see review by *MacGorman and Rust* [1998, chapter 7]). Such single-point measurements do not allow accurate estimation of the overall structures inside and outside the cloud. The launch, operation, and recovery of balloon- or aircraft-based experimental apparatus also pose logistical problems, especially in the thunderstorm context. Remote sensing techniques are thus particularly attractive as they may provide spatial resolution without many of the logistical difficulties.

[3] However, remote sensing of such electric fields is difficult with existing technology. One possible method is to observe the Stark effect: excite the target volume with a laser and infer the electric field from the shape of the resulting emission lines. This technique is often used in laboratory plasma physics experiments (see review by *Levinton* [1999]). Lidar-type measurements have also been suggested, as have optical effects such as higher harmonic generation [*Gavrilenko et al.*, 2000]. These methods require suitable emission lines, a controlled artificial source, and a known line of sight to a receiver, a setup for which signal loss and background noise are difficulties that may be insurmountable in thunderstorm conditions.

[4] We herein describe a new method of remote sensing of thunderstorm electric fields by electrically-induced birefringence (Kerr) effects on naturally polarized background skylight. We show that thunderstorm electric fields exert a measurable effect on this background skylight, propose an apparatus to measure the effects, demonstrate that the device can attain the required sensitivity, and discuss the potential advantages and disadvantages of this new scheme.

2. Storm Kerr Effects on Polarized Skylight

[5] The Kerr effect occurs when an electric field distorts the electron structure of a material, resulting in an anisotropic electric susceptibility [see *Hecht and Zajac*, 1997, and references therein]. Incident electromagnetic waves polarized perpendicular and parallel to the applied field encounter different indices of refraction (birefringence) resulting in a phase shift between the perpendicular and parallel polarizations.

[6] In the Kerr effect, the difference in index of refraction for parallel and perpendicular polarizations is given by

$$\Delta n = nKE^2$$

where n is the index of refraction, K is the Kerr constant, and E is the applied electric field. This difference results in a phase shift

$$\phi = \frac{2\pi l}{\lambda_0}\Delta n$$

where l is the path length and λ_0 is the vacuum wavelength. The effect is small in air and is directly proportional to the density, with $K \simeq 2.3 \times 10^{-25}$ m^{2}V^{-2} at sea level [*Weinheimer*, 1985; *Kumada et al.*, 2002].

[7] The action of the Kerr effect is shown schematically in Figure 1: a linearly polarized incident wave travels into an electric field region where it is decomposed into separate perpendicular and parallel polarized components. The Kerr effect Δn results in a phase shift between these two components producing an elliptical polarization as the wave exits the region. This polarization suggests that atmospheric

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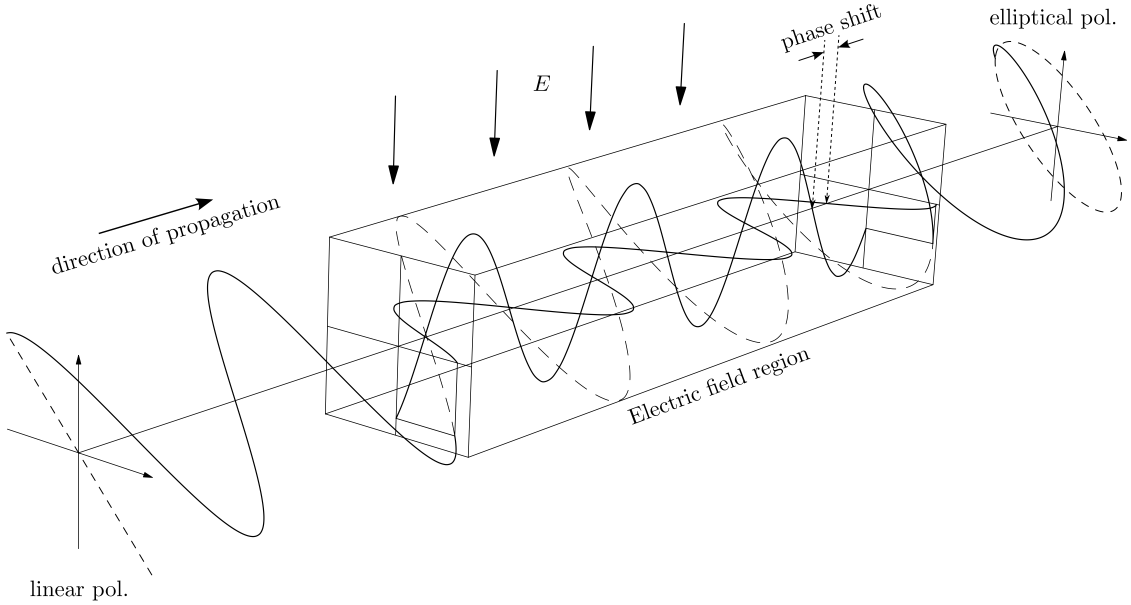

Figure 1. An exaggerated Kerr-type effect: A linearly-polarized incident wave travels into an electric field region. In the electric field region, propagation is treated as independent parallel and perpendicular polarization components, each of which propagates at a different speed due to the Kerr effect. This results in a phase shift between the components, which then sum to give an elliptically-polarized wave as it exits the electric field region.

electric fields may produce an observable effect on polarized light.

[8] The light source for the type of measurement we envision must be stable and of a known polarization state. Scattered sunlight from clear sky meets these requirements. What one sees as blue sky is sunlight undergoing Rayleigh scattering off molecules throughout the atmosphere. Right-angle Rayleigh scattering results in light which is linearly-polarized in the plane perpendicular to the incident light [*Jackson*, 1999]. The clear sky observed in directions ~90° from the sun is therefore observed as linearly polarized. The degree of linear polarization in such directions can approach 100% with 80%–90% being typical for clear sky conditions [*Pust and Shaw*, 2006], though the degree of linear polarization is reduced by multiple scattering and indirect illumination.

[9] Sunlight polarized by scattering at nearly 90° can therefore be perturbed by electric fields near thunderstorms. The signature observed at ground level is an elliptically-polarized component present in light originating from regions of background sky near thunderclouds. A possible geometry for this measurement is shown in Figure 2.

[10] The size of the effect can easily be approximated from the relations given above. For wavelength $\lambda = 500$ nm, we have $\phi_{[\mathrm{rad}]} \simeq 3 \times 10^{-9} l_{[\mathrm{km}]} E^2_{[\mathrm{kV/m}]}\, n/n_0$ where n/n_0 is the atmospheric density relative to sea level, ϕ is measured in radians, l in km, and E in kV/m as indicated. Typical static electric fields within or near a thundercloud have been measured to reach $E \simeq 100$ kV/m [see, e.g., *Coleman et al.*, 2003; *Merceret et al.*, 2008], while modeled quasi-static fields after large lightning discharge reach similar magnitudes [e.g., *Pasko et al.*, 1997]. Such fields have length scale $l \simeq 1$ km, giving a nominal phase shift of $\phi_0 \simeq 3 \times 10^{-5} n/n_0$ (e.g., $\phi \simeq 10^{-5}$ at 10 km altitude). The elliptically polarized component is then joined by skylight from the atmosphere between the region of interest and the observer (e.g., adding an unperturbed component stronger than the perturbed signal by a factor of ~3 for a region of interest at 10 km altitude).

3. Instrument

[11] A possible instrument to measure these effects is shown in Figure 3. Light from the sky is focused by a crude lens or mirror assembly onto a quarter wave plate. The intensities of the polarization components at ±45° to the slow axis of the quarter wave plate are then separated by polarizing filters and measured by a pair of photodiodes. This combination of wave plate, polarizers, and photodiodes measures the intensity of the left- and right-hand circularly polarized (LHCP, RHCP) components of the incident wave. When no electric field exists, the incoming signal contains no elliptical polarization so the LHCP and RHCP components have equal intensities. If an electric field is present, the elliptically-polarized incoming light represents unequal LHCP and RHCP components and thus produces unequal intensities on the photodiodes. The photodiode signals can then be processed electronically to extract the phase shift, which serves as a measure of the electric field strength.

[12] Analysis of the performance of this instrument with Mueller matrices (for example, as discussed by *Hecht and Zajac* [1997]) gives the intensity measured on each photodiode as

$$I_{\pm} = \frac{I_0}{2}\left[1 \pm \frac{I_\mathrm{s}}{I_0}\chi \sin(2\theta)\sin(\phi)\right]$$

where $I_0 = I_\mathrm{s} + I_\mathrm{n}$ is the total intensity, I_s is the “signal” intensity (background sky), I_n is the “noise” intensity (foreground sky), χ is the degree of linear polarization of

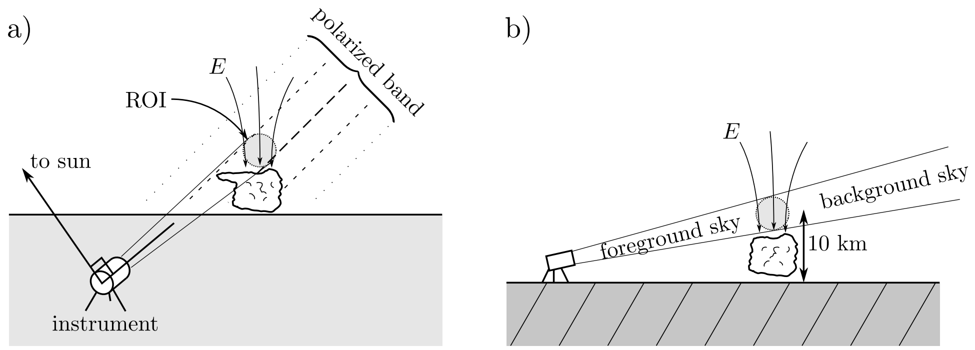

Figure 2. Possible measurement geometry. (a) A region of interest (ROI) above a storm is observed roughly 90° from the sun. Any electric fields in the ROI will cause Kerr-effect perturbations in light from the background sky. (b) Side view. The light from the background sky travels through the ROI at altitude, then is polluted by light scattered from the intervening atmosphere (foreground sky).

the background sky, θ is the angle of the electric field with respect to the dominant sky polarization, ϕ is the Kerr effect phase shift, and the ± distinguishes the photodiodes.

[13] The phase shift due to a 100 kV/m *E*-field acting over 1 km for air at 10 km altitude was given above as $\phi \simeq 1 \times 10^{-5}$. The atmospheric depth of a region of interest at this altitude gives $I_s/I_0 \simeq 1/4$. For typical atmospheric conditions, $\chi \simeq 0.8$. Given a mid-afternoon observation of a thunderstorm as shown in Figure 2, $\theta \simeq 45°$. Substituting these numbers gives

$$I_\pm = \frac{I_0}{2}\left(1 \pm 2 \times 10^{-6}\right)$$

indicating that the changes in I_+ and I_- would be about 1 part in 10^6. Measurement of such small changes in intensity is generally difficult, suggesting a difference measurement scheme where sum and difference intensities can be acquired separately with relative ease.

4. Measurement and Sensitivity

[14] The principles of the Kerr effect method as described above are thus straightforward. The key remaining question is whether the effect is detectable. As discussed above, the intensity changes are of order one part in 10^6. The electric fields that produce these intensity changes can vary on a timescale of milliseconds, so we require that the instrument measure the intensity to better than 1 part in 10^6 with an integration time of 1 millisecond. The sensitivity is mainly determined by fundamental physical limits due to the brightness of the sky and the noise and dynamic range requirements of the measuring device, though other noise sources are possible.

[15] The main physical limitation on intensity measurements is the Poisson statistics (shot noise) of the number of photons arriving at the detector every millisecond. A sensitivity of one part in 10^6 therefore requires $\geq 10^{12}$ photons per millisecond. The brightness of the daytime sky is 2 to 20 $\mathrm{Wm^{-2}sr^{-1}}$, corresponding to 5 to 50 × 10^{15} photons $\mathrm{m^{-2}sr^{-1}ms^{-1}}$. Shot noise limits therefore require a modest geometric factor of 2 $\mathrm{cm^2sr}$. While no fundamental physical limitations prevent the measurement, the collecting area, angular resolution, and focusing optics must be traded off to meet this requirement.

[16] The resulting intensity measurements do not directly give the electric field strength since they also depend on I_s, χ and θ as well. I_s can be inferred from I_0 and the altitude of the region of interest, χ can be measured with crossed linear polarizers, and θ can be inferred from the geometry of the measurement together with models of the electric field structure. The only remaining undetermined parameter is ϕ, the Kerr effect phase shift, which directly gives the value of the effective lE^2. The effective lE^2 is most accurately expressed as an integral of E^2dl over the electric field region, though estimates of the electric field can be attained with model-driven assumptions about l. With a part in a million intensity sensitivity, if $l \sim 1$ km, the electric field can be measured to an accuracy of $\sigma_\mathrm{E} \simeq 100$ kV/m every millisecond, while if $l \sim 10$ km the accuracy becomes $\sigma_\mathrm{E} \simeq 30$ kV/m. If time resolution is traded for greater sensitivity, a timescale of 100 ms instead of 1 ms improves phase sensitivity by an order of magnitude and the electric field resolution by a further factor of ~3 to $\sigma_\mathrm{E} \simeq 10$ kV/m.

[17] The instrument itself should be insensitive to vibration and alignment changes as the intensity measurements are not sensitive to the relative alignment of instrument and sky. Flow birefringence (a Kerr-like alignment effect due to

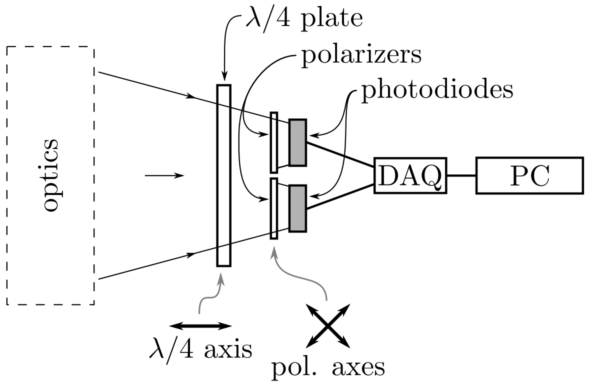

Figure 3. Proposed instrument layout. Light from the sky is collected in a simple optical system, passed through a quarter-wave plate, then through polarizing filters aligned at ±45° to the quarter-wave plate axis. In this configuration the photodiodes act to measure the intensity of the left- and right-hand circularly polarized components.

velocity gradients [see *Boyer et al.*, 1978; *Weinheimer*, 1985]) should not contribute significantly as its effects are limited to a thin boundary layer near the Earth's surface. Electromagnetic and stray light interference due to lightning discharge are also relevant, but can easily be minimized, monitored and compensated for.

[18] Though the intensity measurements and extraction of the electric field strength are nontrivial, the simplicity of the suggested instrument has many advantages. The optics are not required to reach a sharp focus, as accurate imaging is not necessary. Precise angular alignment of the instrument is not required as the intensities are independent of global alignment. The instrument can be built using off-the-shelf optical and electronic hardware and thus can easily be built with multiple sensors arranged in an array to allow for simultaneous monitoring of multiple regions of interest near a cloud, a configuration that would also help constrain the length scale of the electric field. Such viewing would produce a low-resolution high-frame-rate electric field image, which would be extremely useful for analysis of the quasi-static and dynamic electric fields involved in lightning discharge.

5. Discussion

[19] The method described above provides a remote sensing technique for measurement of thunderstorm electric fields. The technique allows for targeting of the region of interest with a single instrument. Crude electric field imaging can be accomplished with an array of instruments targeting nearby regions of interest. Such targeting is a clear advantage over existing techniques involving local electric field measurements by instruments launched above or near the cloud. The proposed device can measure these electric fields with timescales as short as 1 ms, short enough to capture some of the time structure of lightning discharge, with greater *E*-field sensitivity possible over slower timescales.

[20] Additions to the experiment would help connect the technique to conventional results. Measurements in conjunction with VLF radio observations would allow for comparison of Kerr effect electric field signatures to lightning parameters and would help extract less-significant intensity fluctuations by analysis of time coincidence with known electrical activity. Simultaneous capture of video and analysis of meteorological data would further help put the observations in the context of existing results. Joint campaigns with balloon-borne instruments or lightning mapping array observations (e.g., those described by *Coleman et al.* [2003]) would also help understand and calibrate the measurement method.

[21] The main limitation of our method is that it requires a line of sight containing clear background sky both near a thunderstorm and near 90° from the sun. This constraint requires a sufficiently isolated storm, a mobile observatory to position the instrument with the appropriate geometry, and limits the technique to the observation of electric fields outside the thundercloud. The observations are also limited to daytime, which unfortunately precludes joint operations with sprite campaigns and restricts the measurements to daytime electrical conditions.

[22] In spite of these limitations, the Kerr effect measurement method introduced here could provide a wealth of information of direct relevance to sprite, blue jet, and terrestrial gamma-ray flash research. For example, the technique allows direct observation of the temporal and spatial variation of the above-cloud electric field and thus can clearly confirm or refute quasi-electrostatic models for fields proposed to drive sprite production or TGF emission.

[23] The instrument can be constructed with existing off-the-shelf hardware, but requires great attention to detail in order to minimize noise, maximize dynamic range, and combine the optical, physical, meteorological, and electronic aspects. Similar ideas have been proposed in the past, but were substantially more complicated, did not have the benefit of modern electronics, and did not include the possibility of using background sky polarization as a light source [*Weinheimer*, 1985; *Gavrilenko et al.*, 2000].

6. Summary

[24] We herein describe the use of the Kerr effect perturbation of naturally-polarized background skylight to observe electric fields above and around thunderclouds. The technique is limited to daytime lines of sight containing clear sky near thunderstorms, but has many advantages over existing electric field measurement techniques including spatial and temporal resolution. The resulting measurements would shed light on thunderstorm electric fields and especially how those electric fields are involved in sprites, blue jets, and terrestrial gamma-ray flashes. These very active areas of research would greatly benefit from such new information.

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