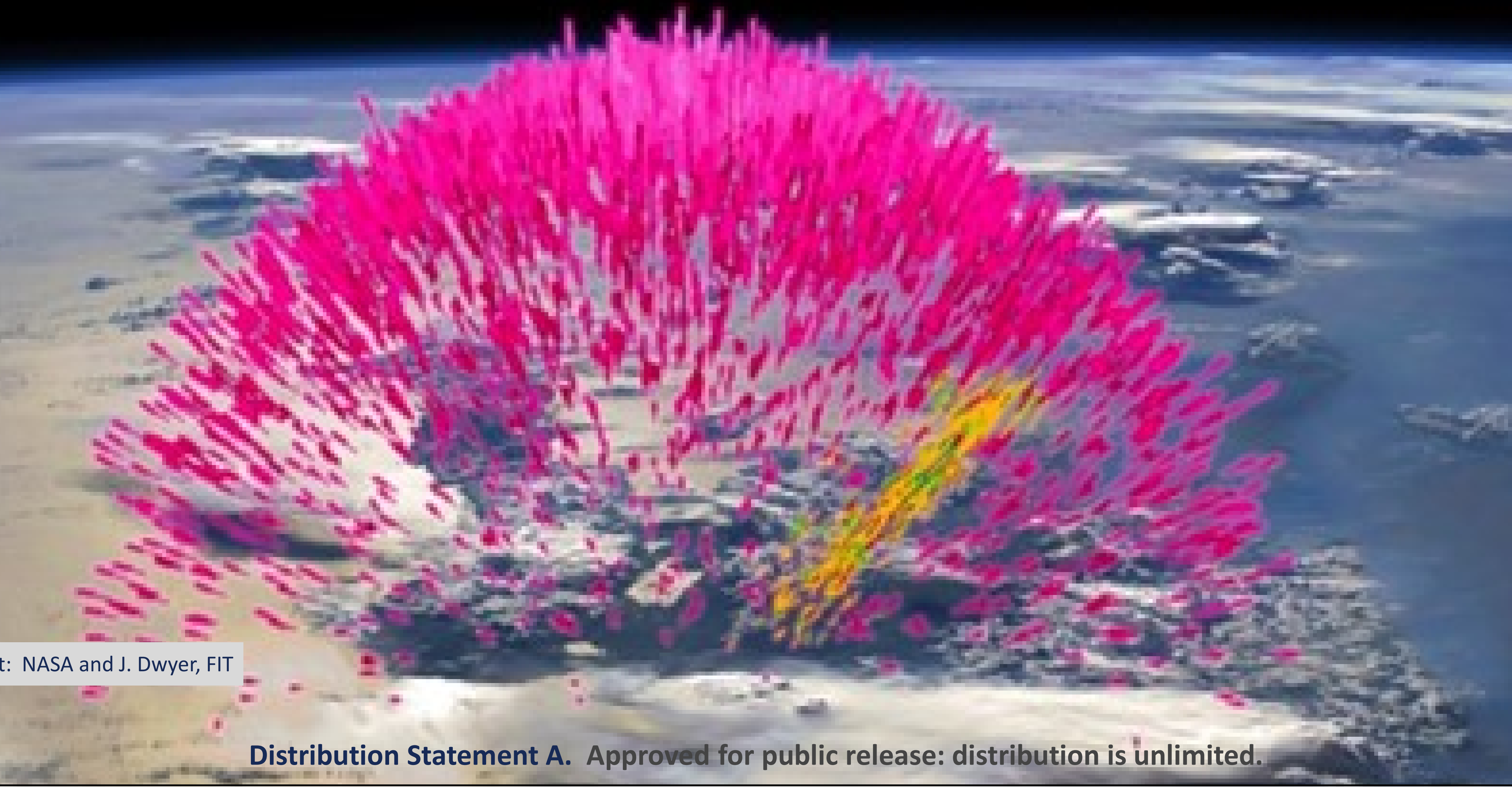
Thunderstorms Bubble and Burst in Gamma Rays

J. Eric Grove, U.S. Naval Research Laboratory



Overview

- Thunderstorm and lightning basics
- Summary of ionizing radiation from thunderstorms
- Underlying physics
- Terrestrial Gamma-ray Flashes observed from space
- New insights from in-situ observations from high-altitude aircraft
  - July 2023 ALOFT campaign

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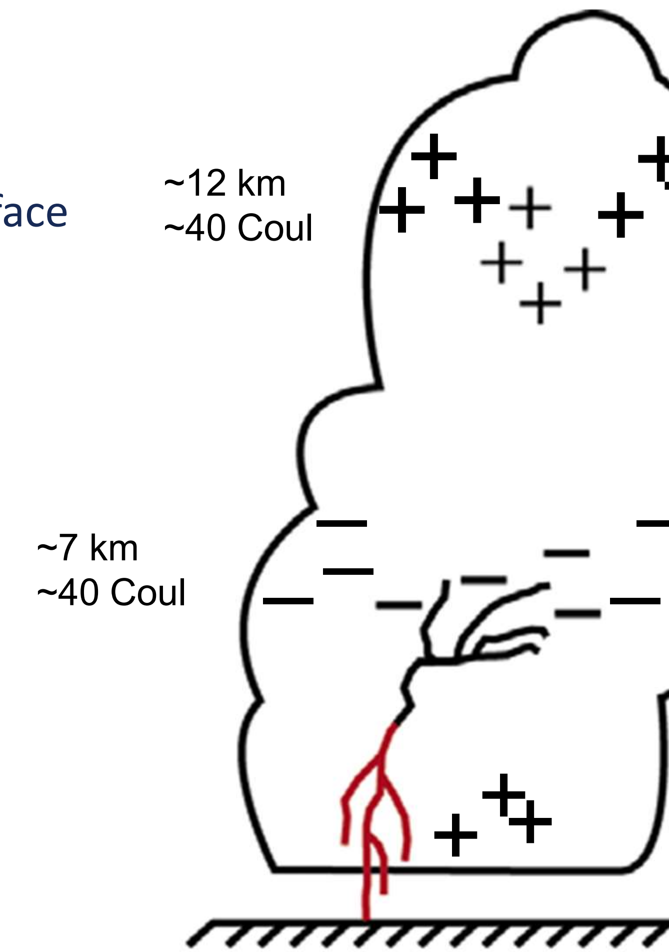
Thunderstorm and lightning basics

nical text: Rakov and Uman, 2003, *Lightning: physics and effects*, Cambridge Univ Press

Typical Florida summer



nderstorms

- Global number ~2000 active at any one time, covering ~10% of Earth surface
- Charge separation
  - Dipole (or tripole, or more) charge distribution
  - Small ice crystals carry positive charge
  - Graupel* carries negative charge
- Electric field ~100 kV/m over km scales, potential up to ~100 MV

* Graupel: Supercooled water drops frozen onto snow/ice crystals

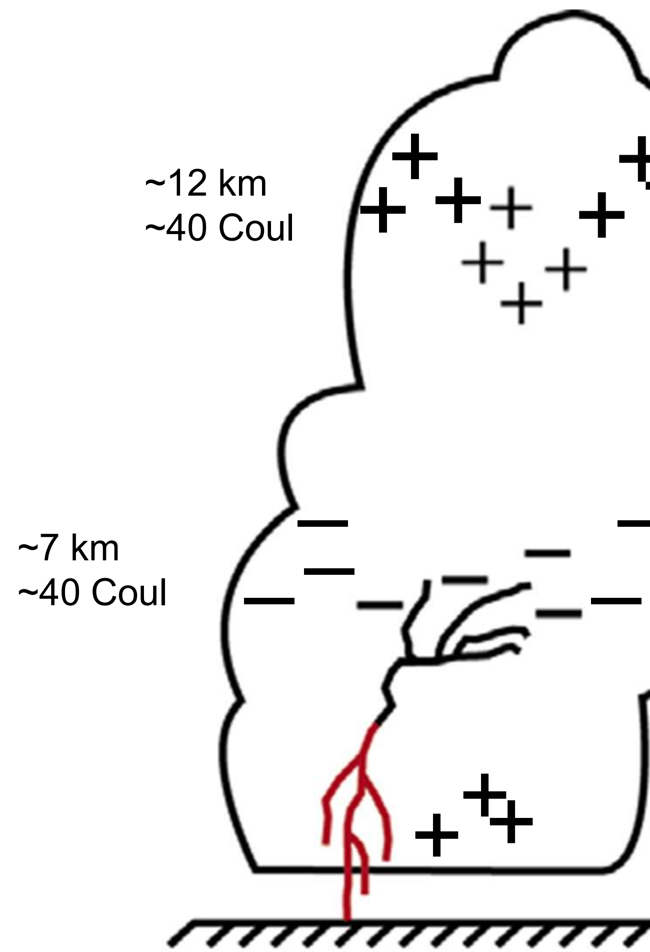
Adapted from Williams et al., 2006, JGR

Thunderstorm and lightning basics

tning

- Global rate ~50 per sec, ~1.5x10^9 per year
- ~1000 discharges per storm
- Cloud-to-ground (CG) discharge ~50-500 MJ in 100+ ms
- CG process
  - Initiation, how??
  - Leader steps toward ground, carrying negative charge
    - Step length ~50 m
    - Step interval ~50 us
  - When leader nears ground, upward positive leaders rise and connect
    - Several strokes
    - Stroke interval ~50 ms
    - Stroke current ~10+ kA

Typical Florida summer

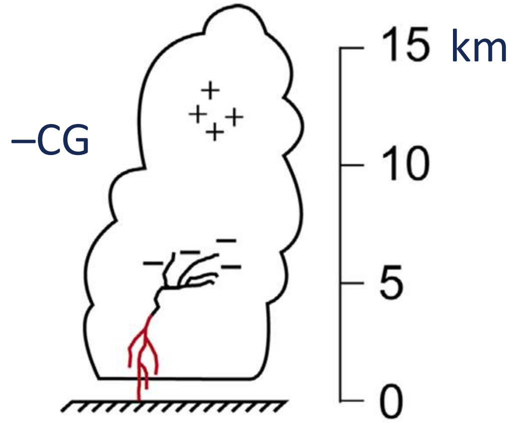


Adapted from Williams et al., 2006, JGR

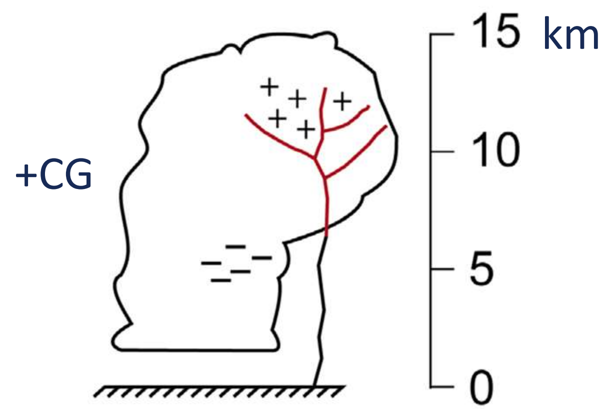
Lightning rogues' gallery

tning is a strong radio emitter, from few Hz to >300 MHz

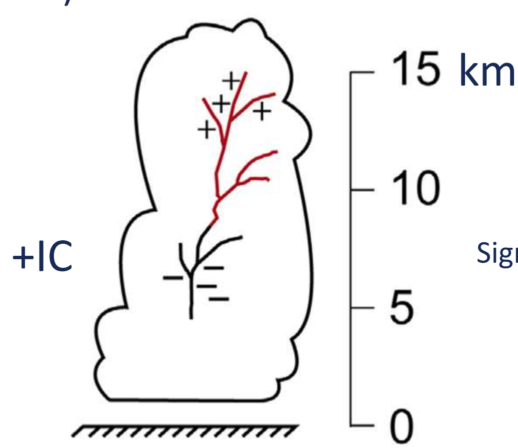
- Negative cloud-to-ground (-CG)
  - Common, ~25% of all lightning
  - "Less strong" radio source



- Positive cloud-to-ground (+CG), from anvil
  - Rare, "bolt from the blue"
  - High voltage, high current: large charge moment, >50 C km
  - Stronger radio source, peaking in VLF (3–30 kHz)



- Positive intra-cloud (+IC), similarly -IC
  - Very common, ~75% of all lightning
  - "Less strong" radio source

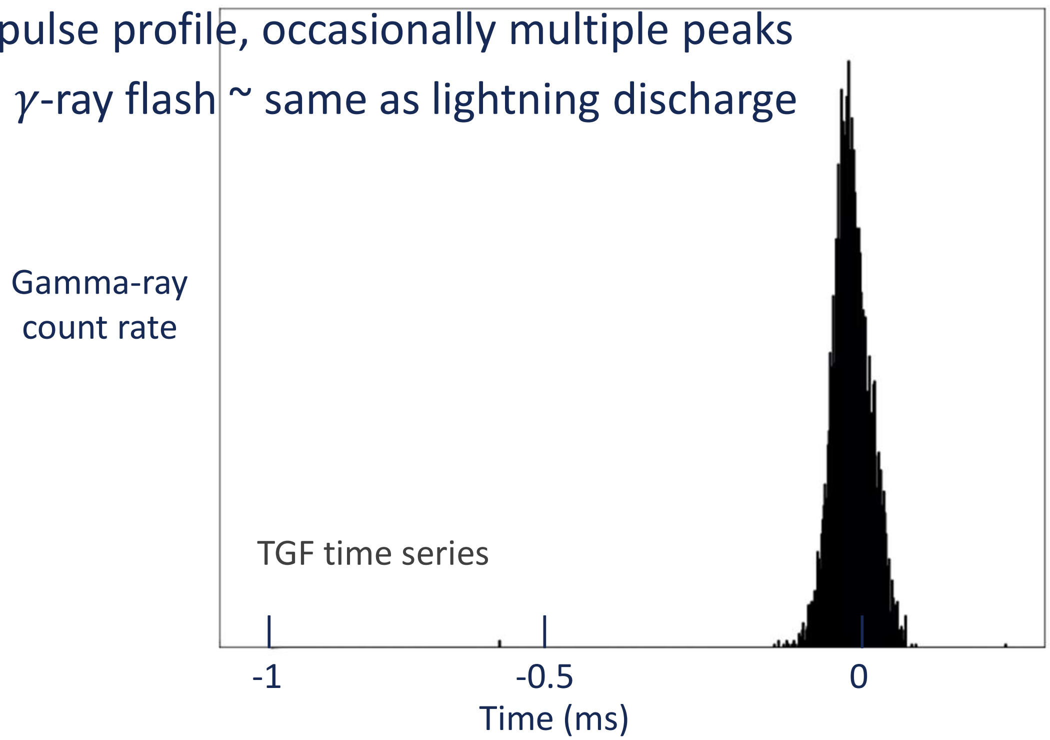


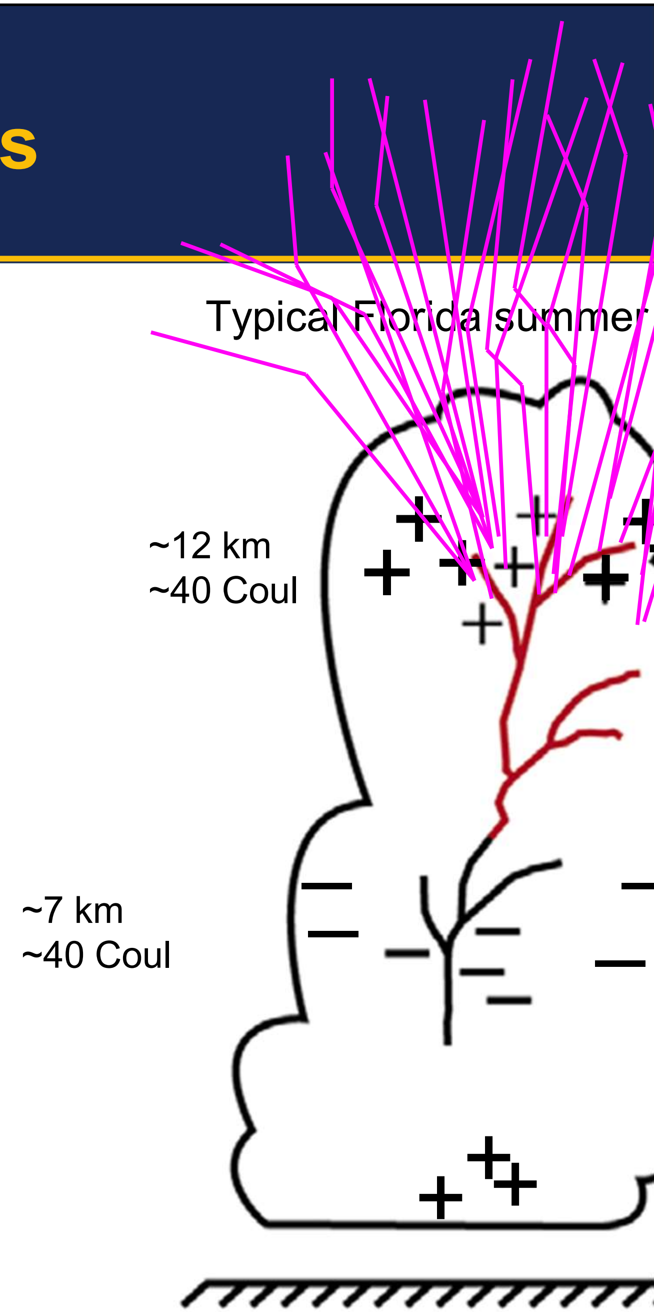
Sign convention: +IC moves negative charge upward

From Williams et al., 2006, JGR

Ionizing radiation from thunderstorms

restrial Gamma-ray Flashes (TGFs)
- Intense sub-ms flashes of MeV γ rays, particles
  - Discovered 1994; key observations 2005, 2010++, 2023
- Mostly upward-going
- Associated with intra-cloud (IC) lightning
- Smooth pulse profile, occasionally multiple peaks
- Power in γ-ray flash ~ same as lightning discharge





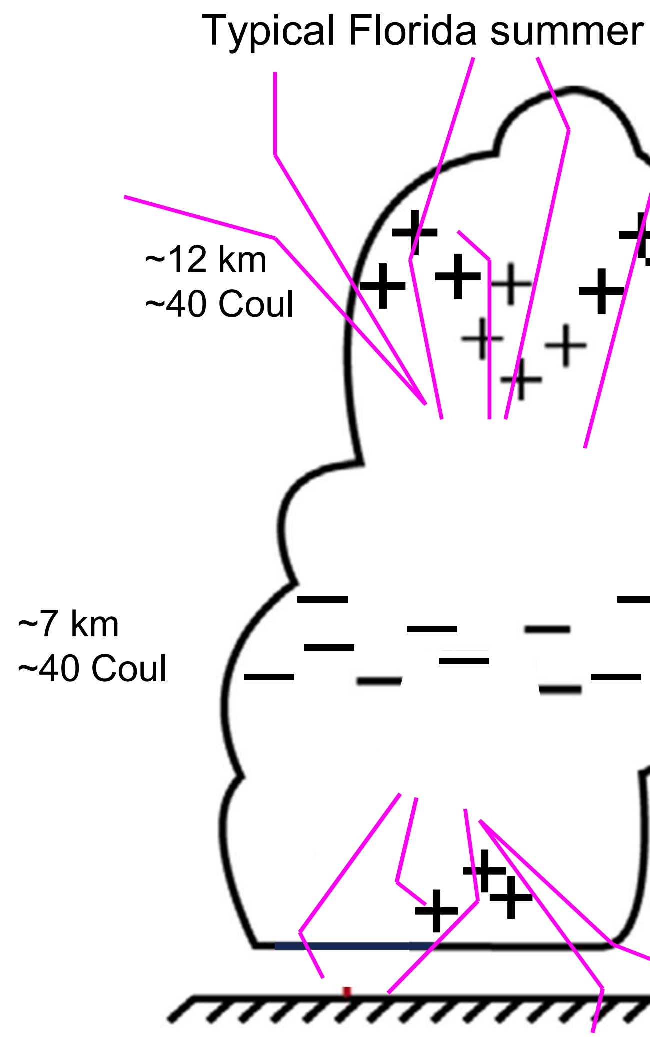
Adapted from Williams et al., 2006, JGR

Ionizing radiation from thunderstorms

mma-ray glows

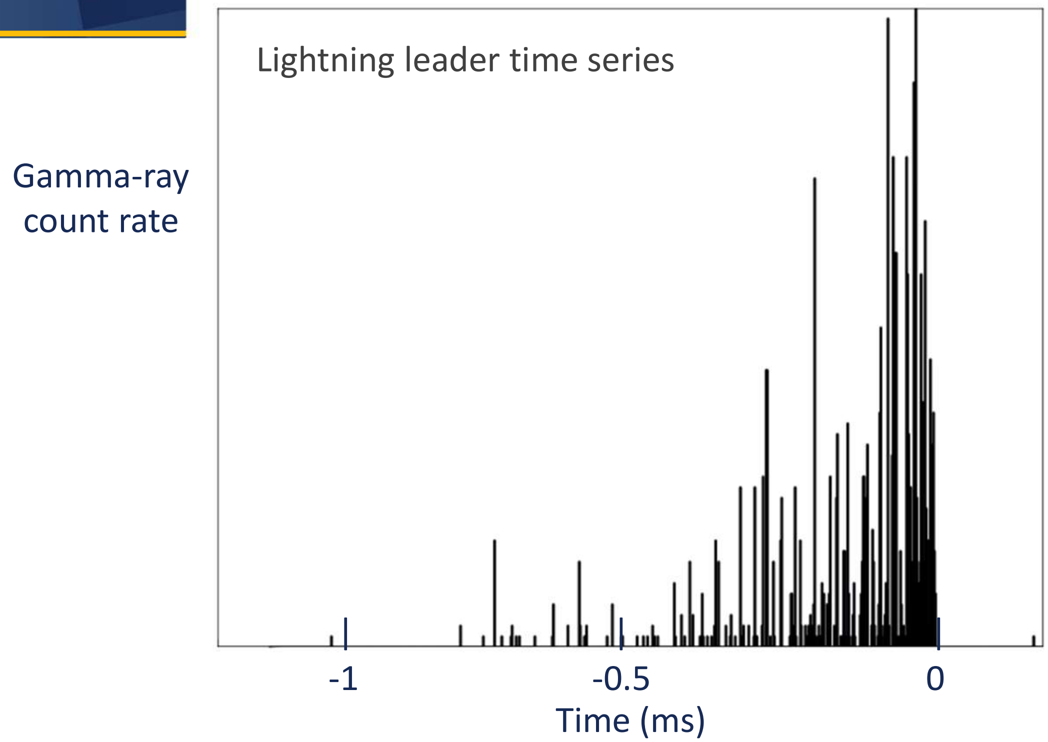
- Modest flux of MeV γ rays
- Discovered 1985; key observations 2010++, 2023

- Quasi-stationary. No, quite variable
- Duration up to tens of seconds. No, much longer; regions glow for hours
- Extending over 10-20 km. No, up to hundreds km; areas up to 10^4 km^2



Adapted from Williams et al., 2006, JGR

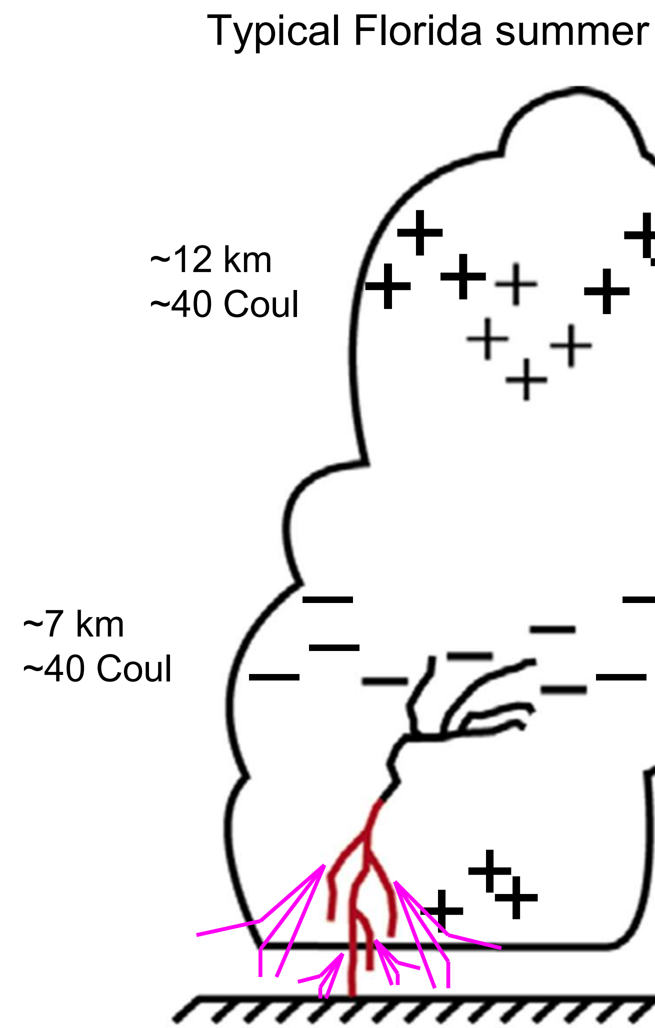
Ionizing radiation from thunderstorms



- Discrete pulses, each corresponding to individual step of lightning leader

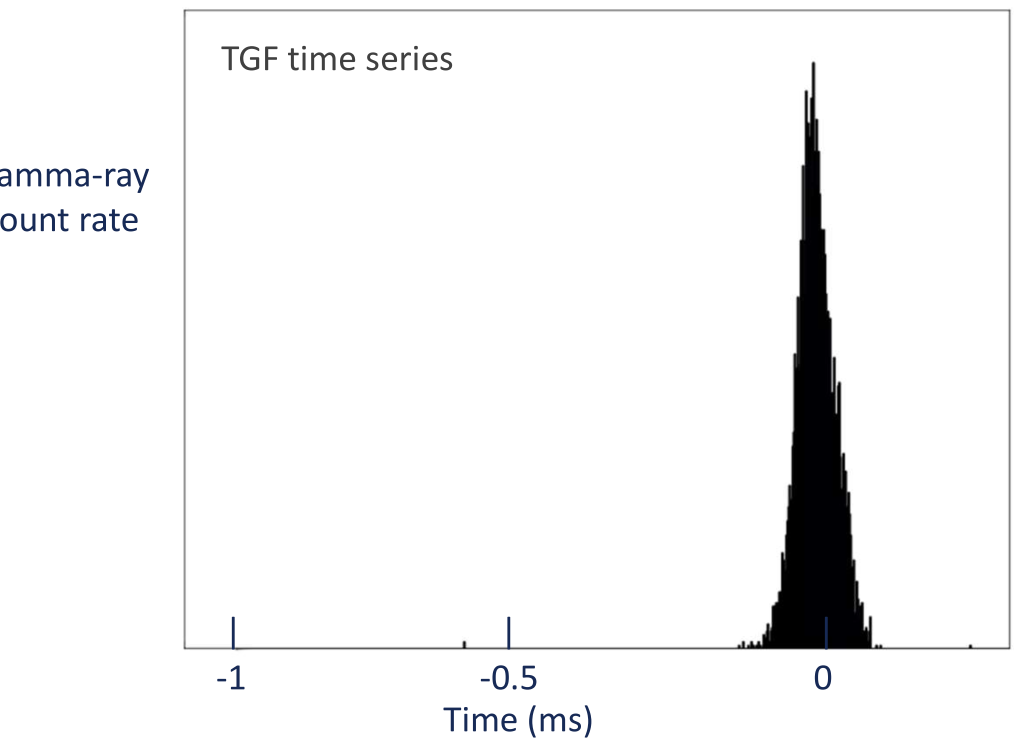
ays / γ rays from lightning leaders

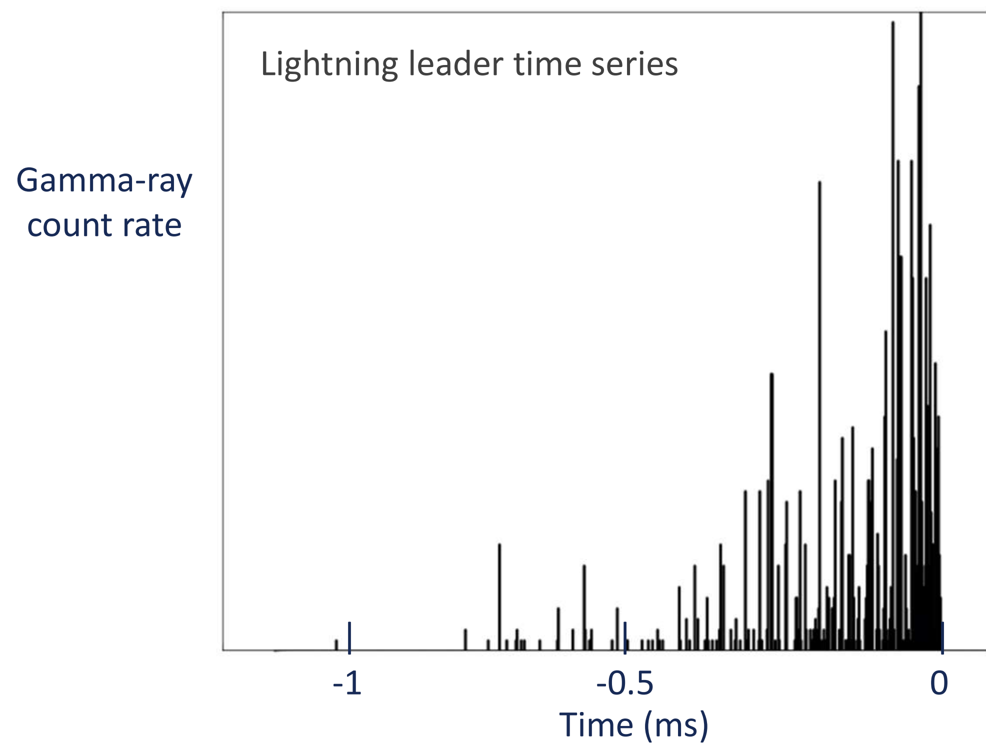
- Series of microsecond flashes of hard X-rays from "stepped leaders" in CG lightning
- Discovered 2001; key observations 2003, 2004++



Adapted from Williams et al., 2006, JGR

Comparing TGFs and lightning leader X-rays



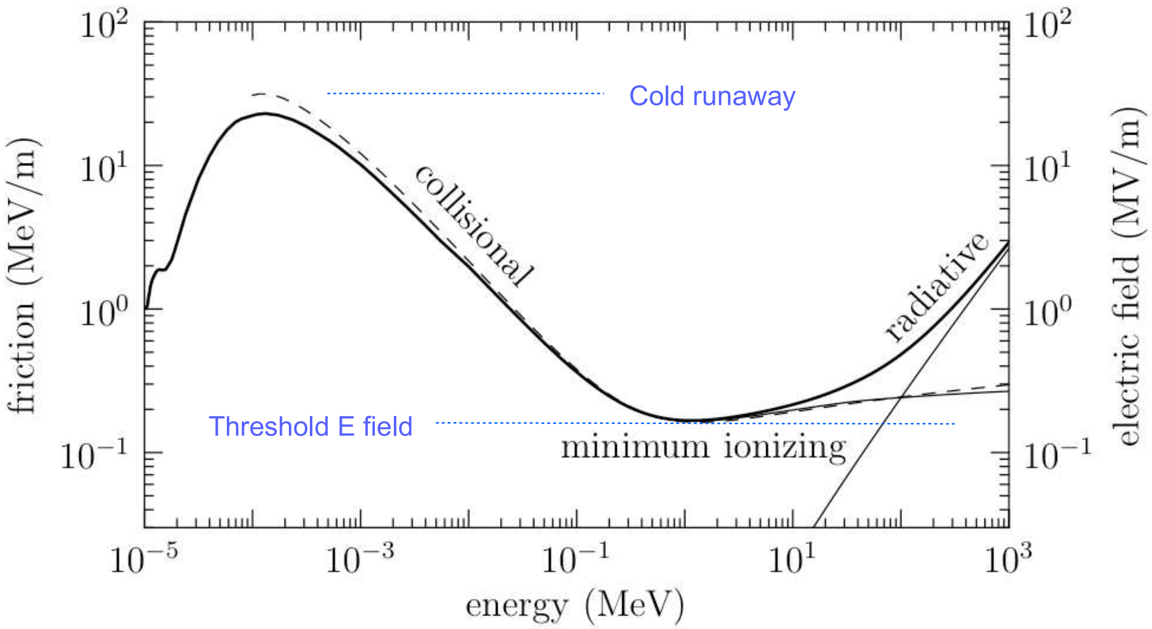


Data from NRL ground-based measu

e series are fundamentally different

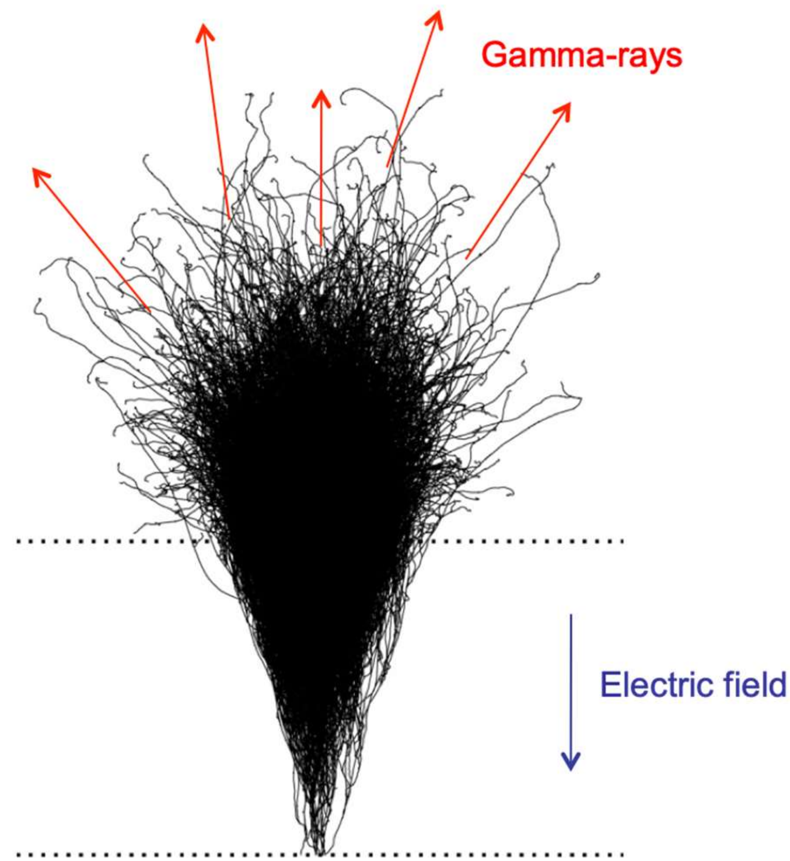
Runaway avalanche basics

rgy loss and gain for electron in air with electric field



ctrons in strong E field in air

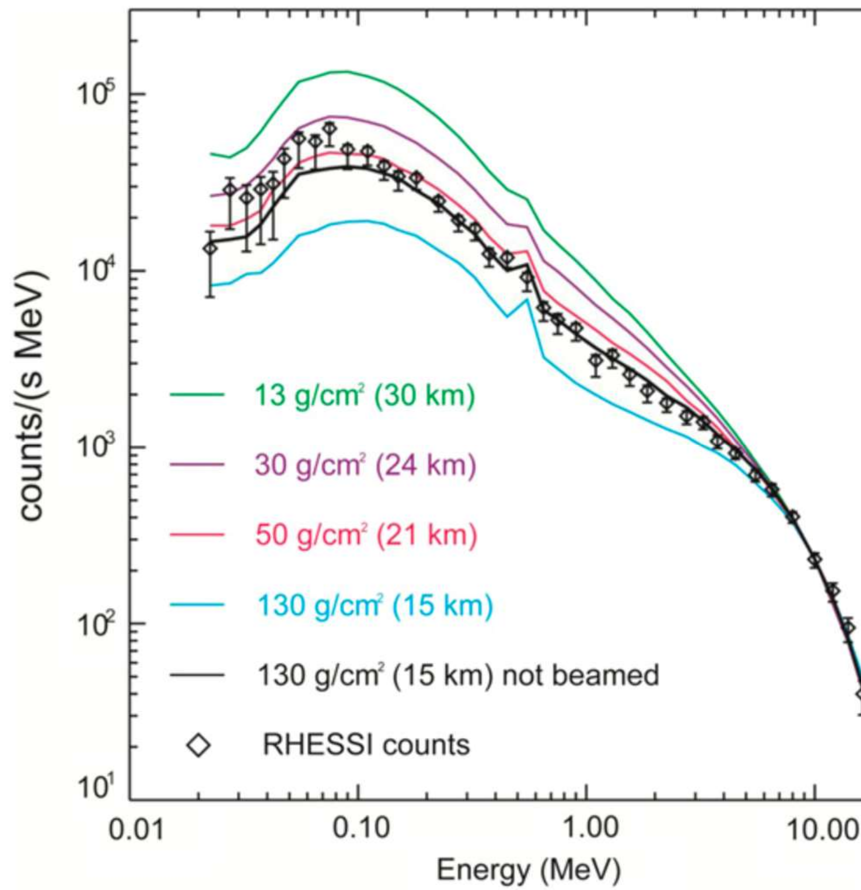
- Accelerate to relativistic energies
- Radiate bremsstrahlung γ-rays
- Create daughter electrons that accelerate, radiate



Adapted from Dwyer et al. 2010, JGR

Gamma-ray spectrum from RREA

- ativistic Runaway Electron Avalanche
  - Bremsstrahlung from relativistic electrons
    - $dN/dE \sim (1/E) \exp(-E/E_c)$
  - Modified by scattering, attenuation in atmosphere



From Dwyer & Smith, 200

Site of runaway avalanche?

Maybe it's both

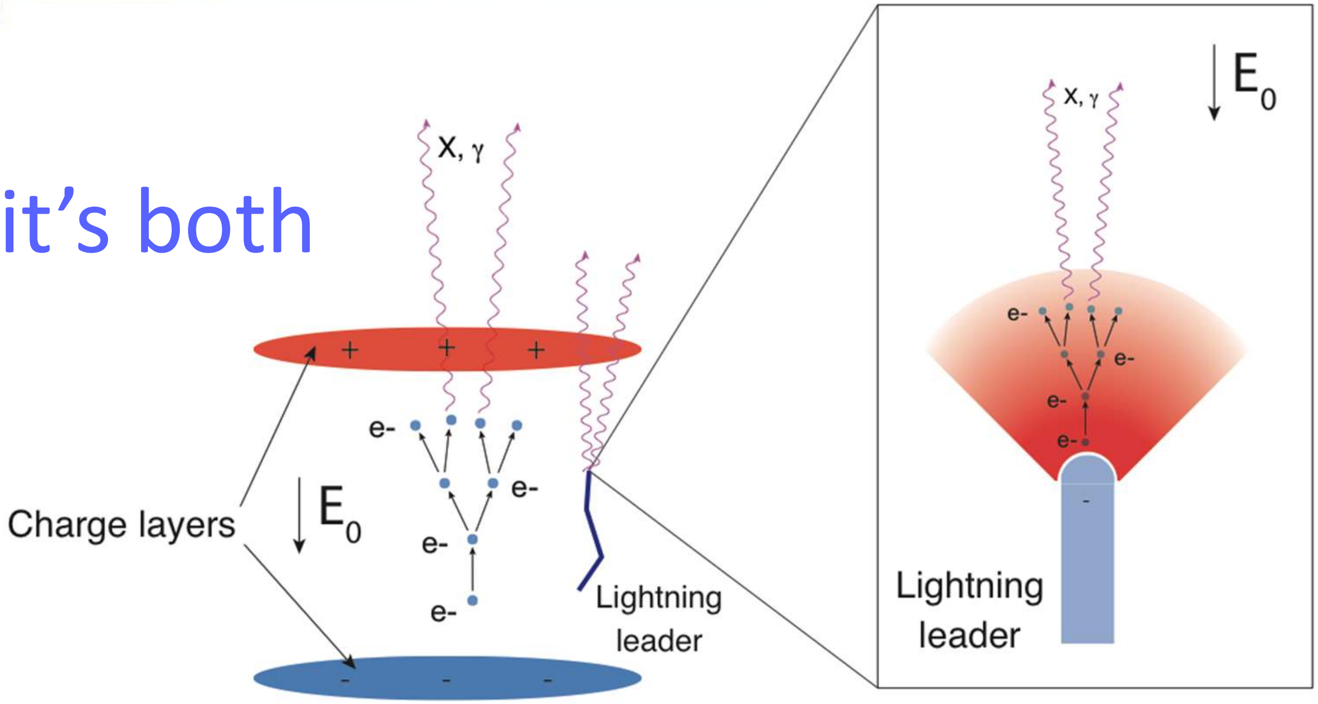


Figure courtesy S. Celestin

ativistic Runaway Electron Avalanche (RREA)
n feedback

- Strong ambient electric field (~300+ kV/m)
- Large scale (~100 m to ~1 km)

RREA: Gurevich et al. 1992
With feedback: Dwyer 2003, 2012

Thermal runaway in lightning leaders / streame

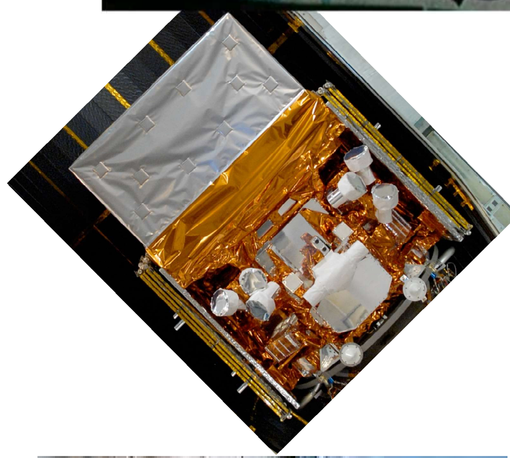
– Very strong local field (>10 MV/m)
– Small scale

Moss et al. 2006; Celestin & Pasko 2011

TGF observation from space

covery by BATSE (1992-2000)

- Compton Gamma Ray Observatory
- 78 TGFs in 9 years



gest data set with Fermi (2008 onward)

- Gamma Burst Monitor ~800 TGFs per year
  - TGFs are short (~0.1 ms); are bright VLF radio sources; are associated with coastal thunderstorms

RHESSI

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t sensitivity with ASIM

- Attached to Internation Space Station
- Cohosted with optical lightning sensors
  - TGFs are associated with lightning leaders and +IC lightning discharges

Photos not to scale!

Correlation of TGFs with thunderstorms

ive TGF regions are active thunderstorm regions

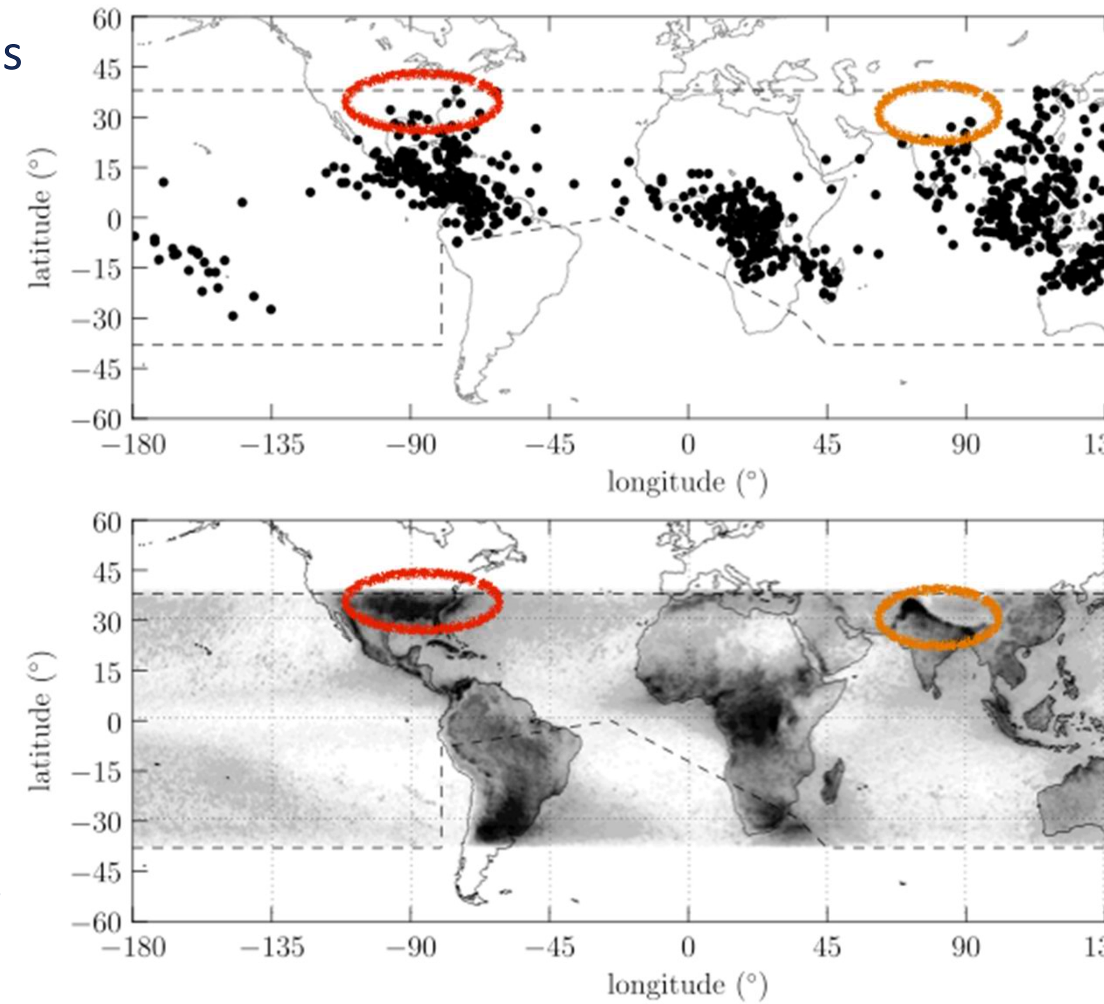
ographic correlation

- Land masses
- Coastal regions

wever, note important differences

- TGF rate is low in North America, Himalayas, mid latitudes
- Slightly low in Central Africa

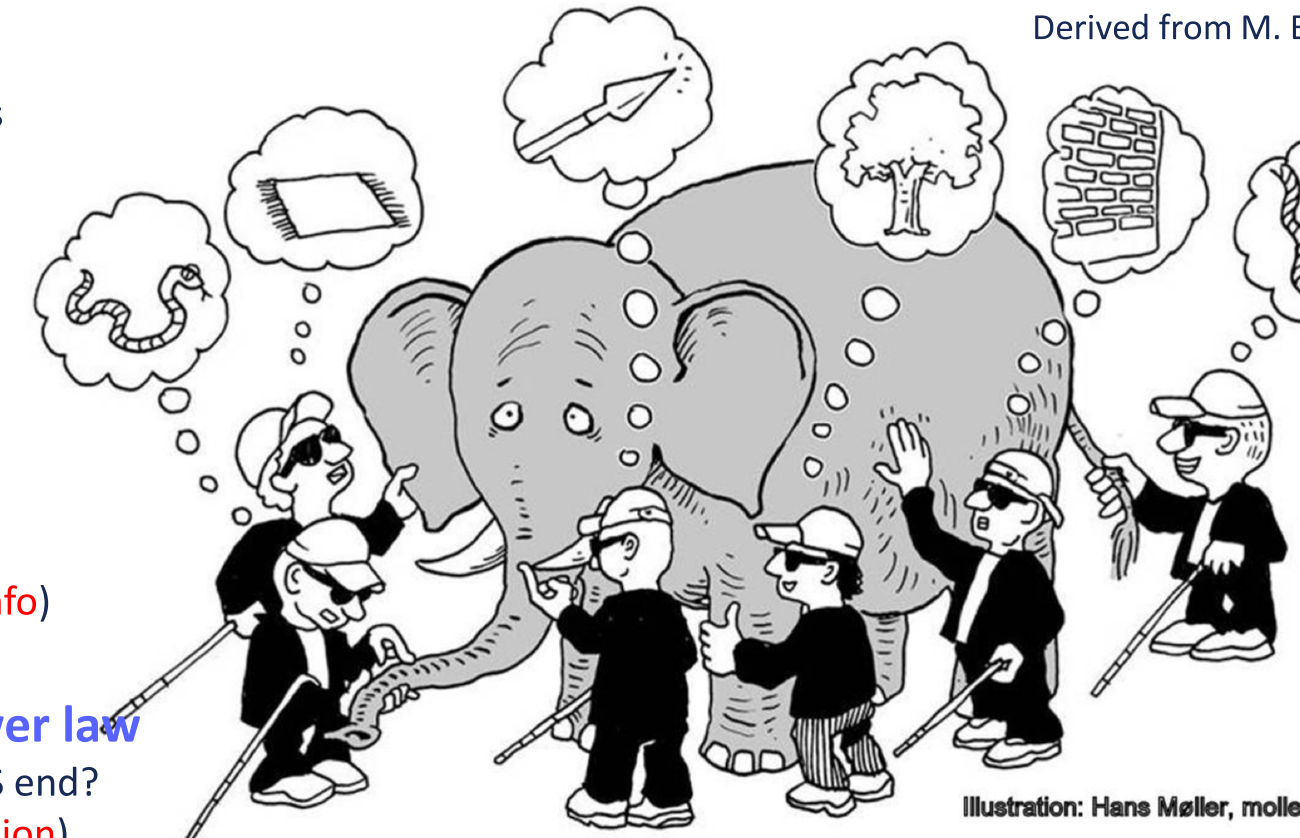
- What is different about those storms?
  - Tropopause is higher in tropics than in temperate zone
  - What else? (Active research area)



Location of TGFs (upper) from RHESSI and lightning (lower) from TRMM-LIS

What do we know about TGFs?

Derived from M. B



1. TGFs are fast
Average duration ~ 0.1 ms
(Direct observation)

2. TGFs are energetic
Average photon energy ~ MeV
(Direct observation)

TGFs are bright
ast 10^{17} relativistic electrons; ~100 kJ
deling of observed fluence – but there is new info)

4. TGF intensity is distributed as power law
But do weak TGFs exist? Where does logN/logS end?
(Direct observation – and there is new information)

5. TGFs are associated with thunderstorms and lightning
Many are related to IC lightning
(Correlation studies; direct observation)

6. TGFs are produced below storm clo
(Direct observation; spectral modeling)

What do we *not* know about TGFs?

ong many, many other things….

v are they produced?
- Are they preferentially produced by a particular thunderstorm / lightning / weather phenomenon?
- What is the relationship between lightning and TGFs? Is +IC leader necessary? Is large-scale field necessary

v often do they occur? Energetics?
- What is the maximum energy per photon? Per TGF?
- Do very weak (low intensity) TGFs occur? (New info: yes they do.)
- What portion of energy budget of thunderstorm is in TGFs?

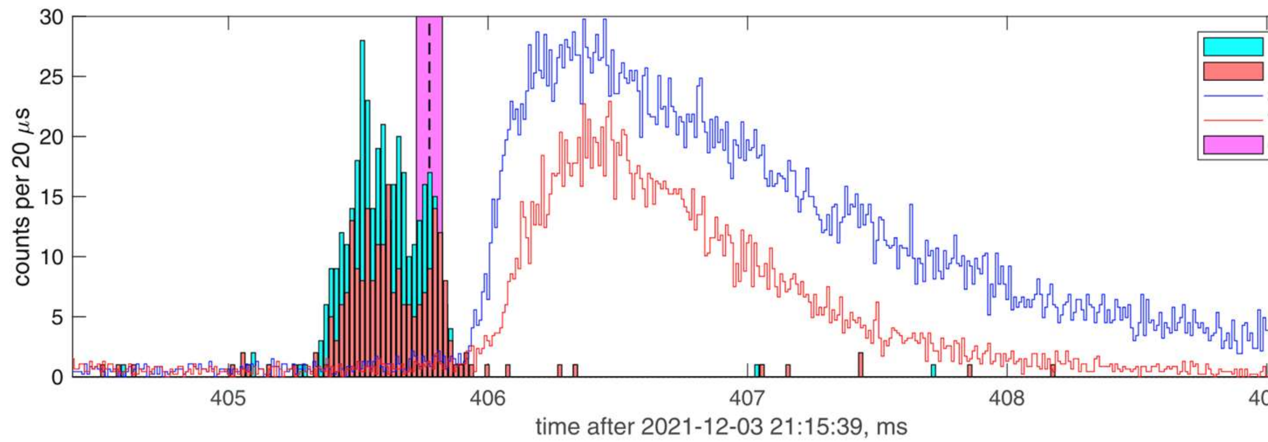
at is the impact of this energy transfer on the dynamics of the atmosphere, on climate?

TGF association with +IC lightning

Fs are associated with early stage of +IC lightning

- Upward-propagating, negatively-charged leader (optical 777 nm and 337 nm)
  - Note that optical emissions are delayed by scattering in thundercloud
- TGF (gamma rays) at onset, or slightly preceding, large current pulse (VLF radio)

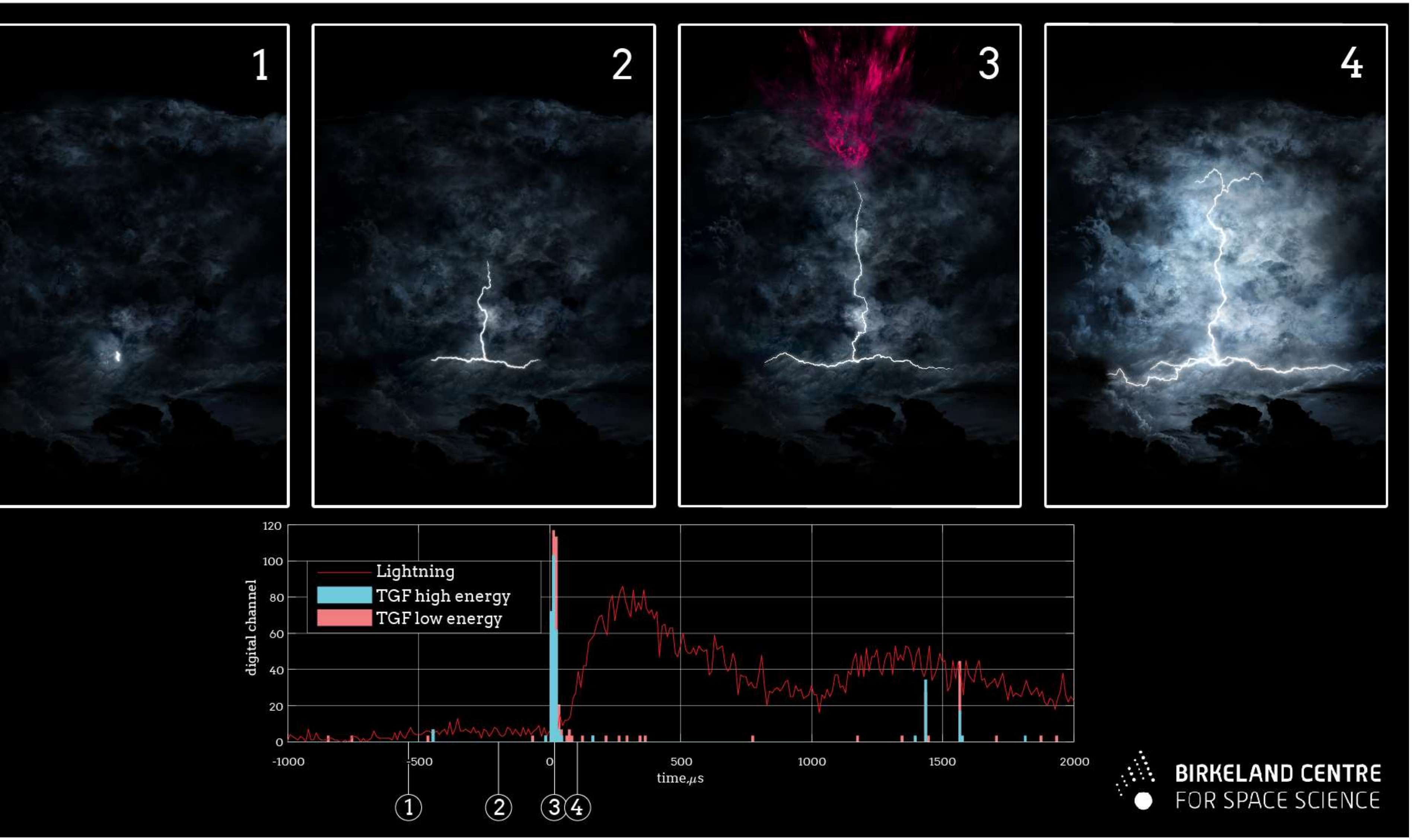
From Mezentsev et al., 2024



Cyan and brown: gamma-ray lightcurves
Blue: 337 nm from N_2(2P), excited by cool electrons of strea
Red: 777 nm from OI, excited by hot plasma of leader chann
Magenta: VLF radio from large current pulse

: cohosted gamma-ray and optical instruments
ASIM

TGF association with +IC lightning



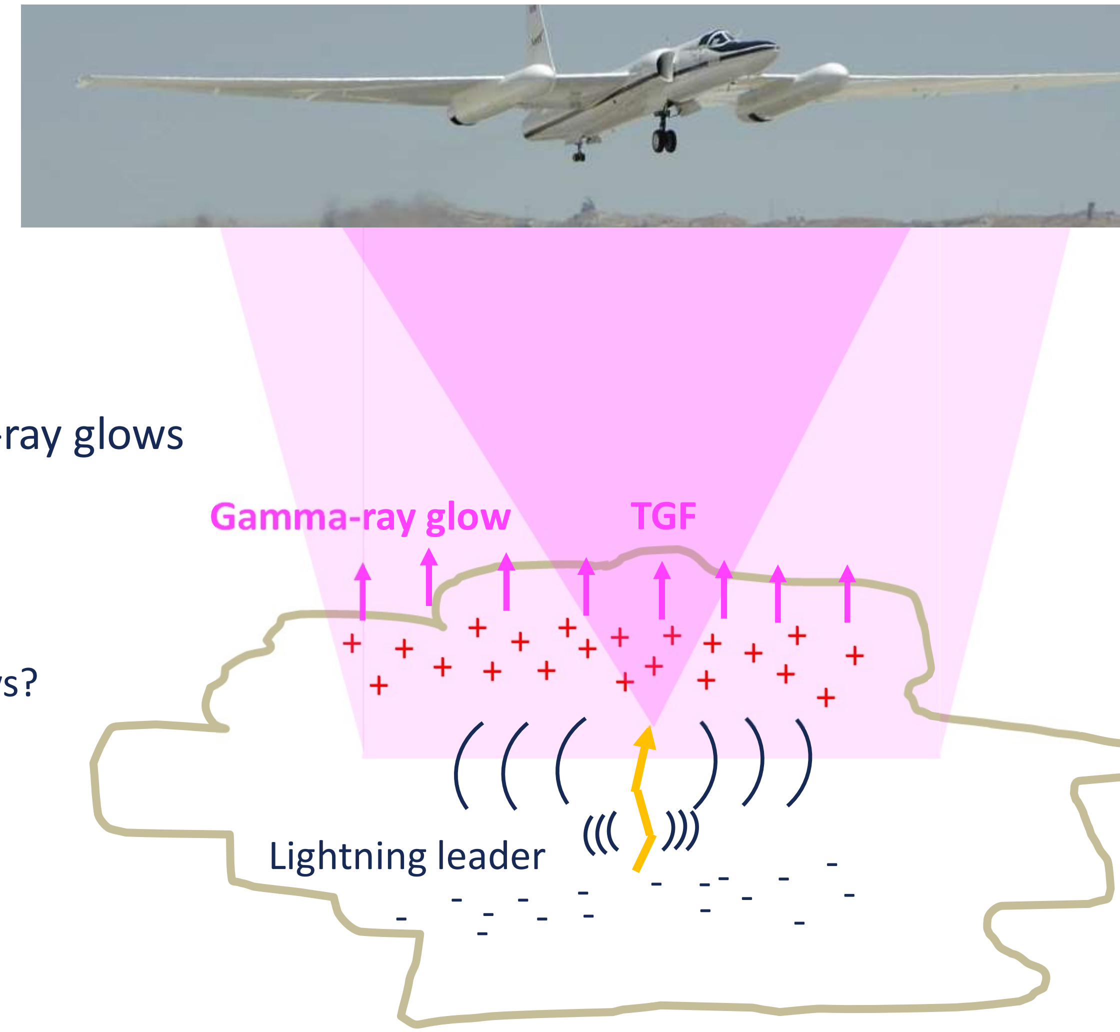
AGU 2019 press

Recent results

OFT campaign

- July 2023 overflights of Caribbean and Florida coastal thunderstorms in NASA's high-altitude ER-2 research aircraft
  - Principal Investigator: Nikolai Østgaard, University of Bergen, Norway
  - Project Scientist: Tim Lang, NASA MSFC
- Full complement of diagnostic instruments
  - Gamma ray spectrometers: University of Bergen; **U.S. Naval Research Laboratory**
  - Optical (337 nm, 777 nm) photometers: NASA MSFC
  - Electric field, field change: UAH, NASA MSF
  - Microwave radiometers
  - Radar
  - Complementary ground-based radio

Key scientific questions

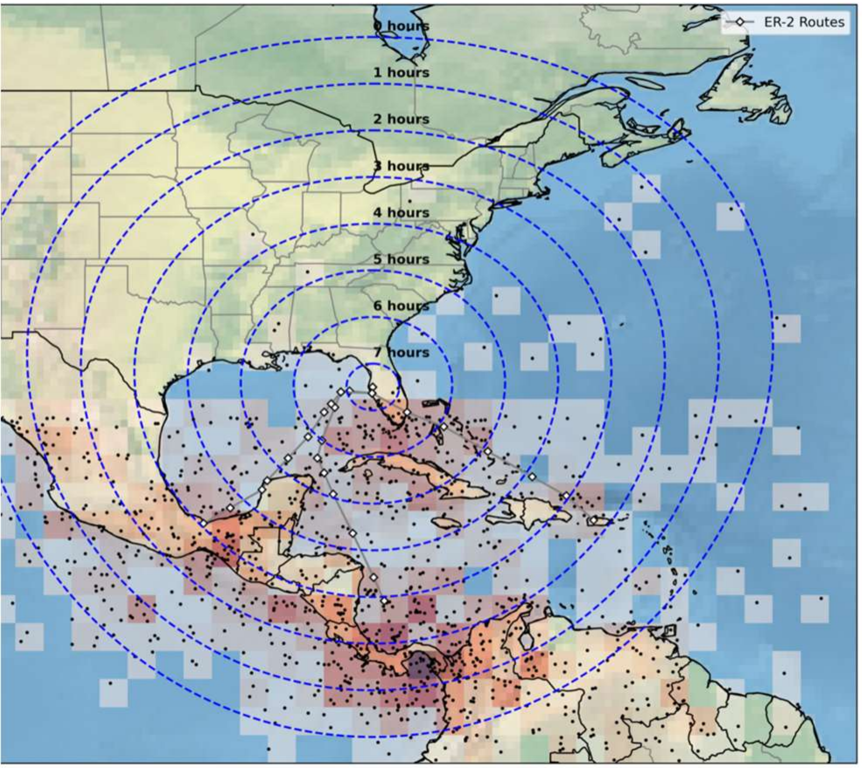


entific targets

- Terrestrial Gamma-ray Flashes (TGFs) and gamma-ray glows
  - How and under what conditions are TGFs produced?
  - Do weak TGFs exist?
  - Is there a connection between TGFs and glows??
  - How extended in space and time are gamma-ray glows?

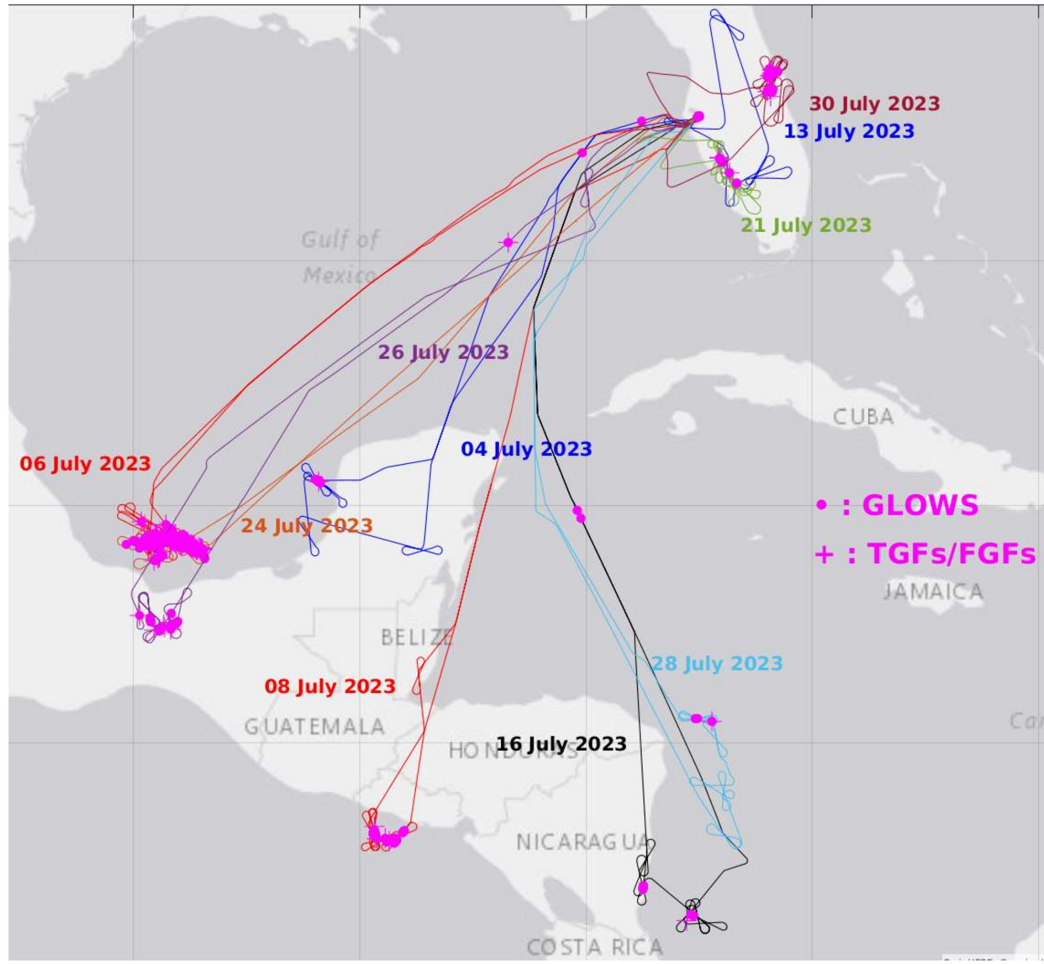
Figures courtesy N. Østgaard

ALOFT campaign summary – July 2023



torical record of TGF detections from space during northern Summer months

Ten ALOFT flights, each with 2-4 hours on target

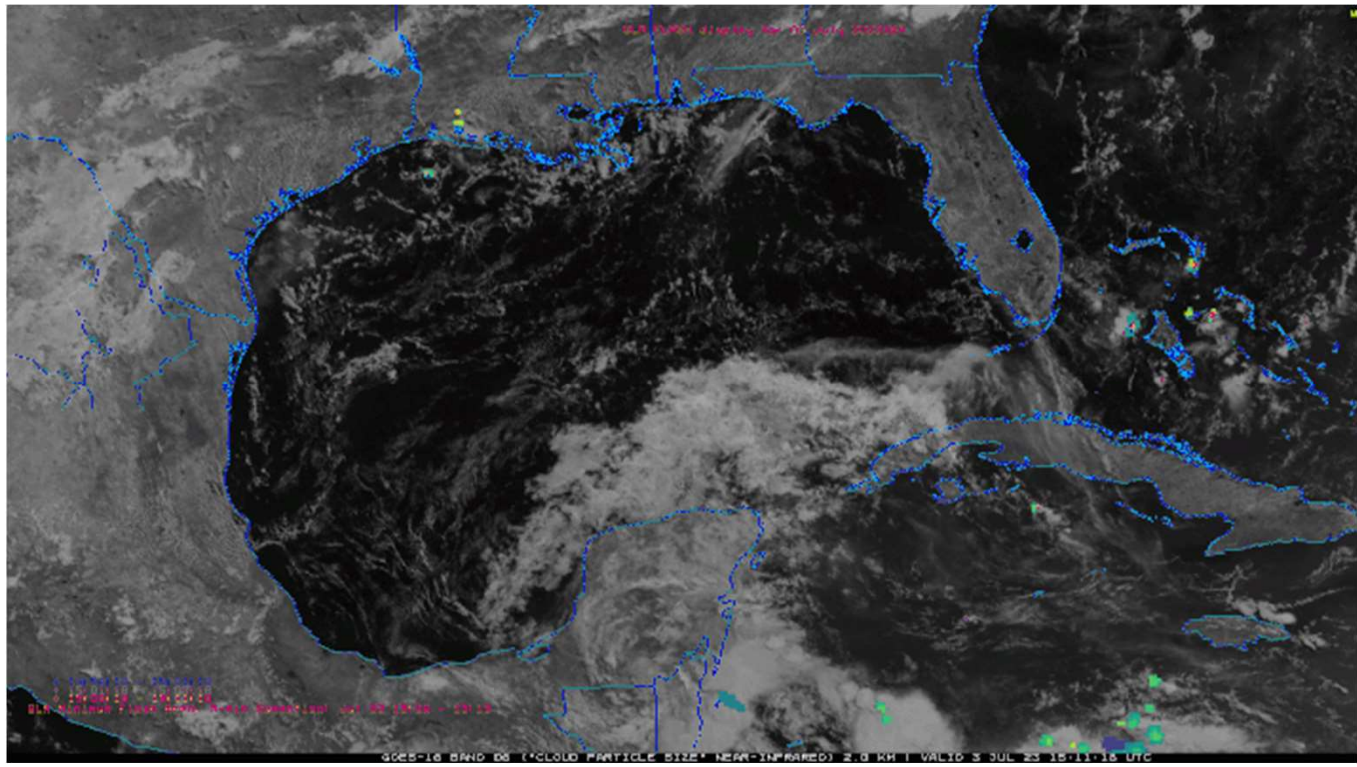


Figures courtesy N. Østgaard

What did we see?

- 0 flights
  - More than 100 TGFs
  - More than 500 glows
  - New phenomena…

4 July



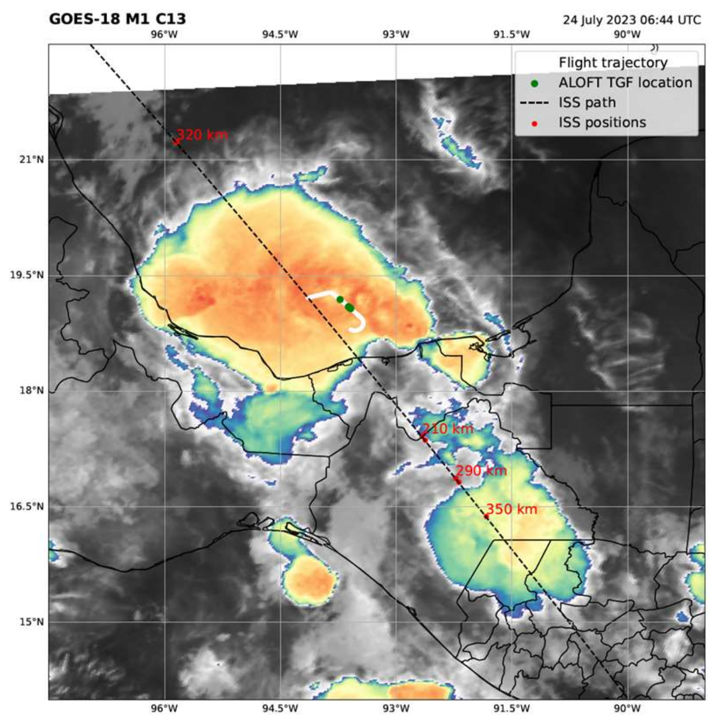
NOAA's GOES Geostationary Lightning Mapper data

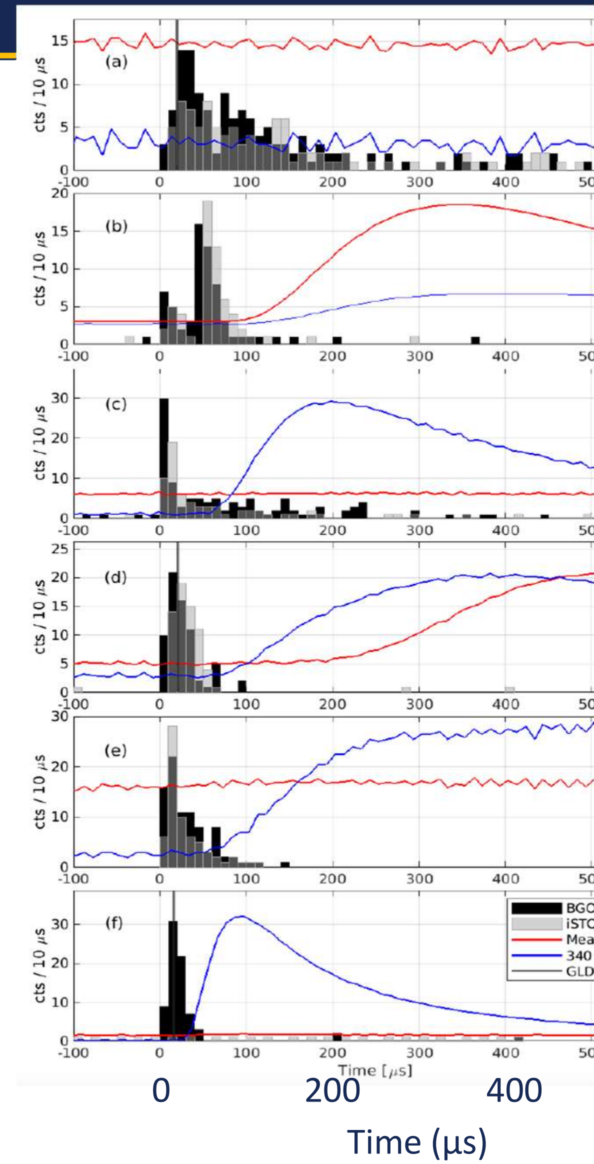
Do weak TGFs exist? Yes, they do.

Bjørg-Engeland et al. 2024

- …erflight of one storm during an ISS-ASIM pass
  - Six TGFs detected by ALOFT on ER-2, while none detected by ASIM
  - Fluence at source 2-5 orders of magnitude lower than space-observed TGFs
  - Of >100 total TGFs in ALOFT campaign, only ~3-5 had intensity that could be seen from space

- **Weak TGFs exist**
- **TGFs are much more common than previously known**





Figures from Bjørg-Engeland et al. 2024, GRL

Glows are long-lasting and variable

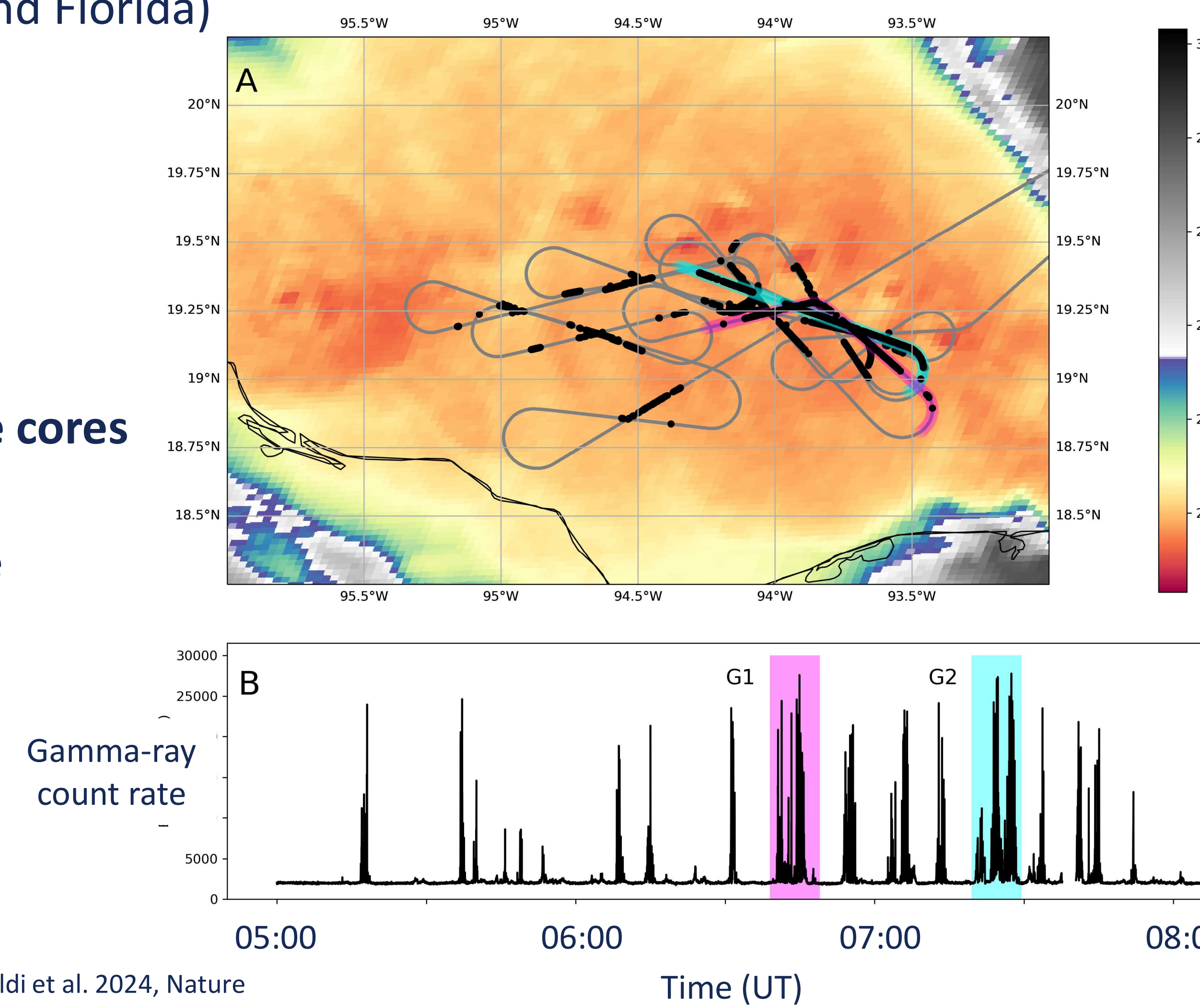
Marisaldi et al. 2024, Nature

- ws are **common** (in coastal Caribbean and Florida)
  - 9 of 10 flights showed similar behavior
- wing **regions are large**
  - ~10,000 km^2
- wing **regions are long-lasting**
  - Up to at least 3 hours (longer?)
- ws are **associated with deep convective cores**
  - From radiometer and radar data
  - Multiple glows, some overlapping, per core

to making these observations:

- Realtime downlink of γ-ray data

Bay of Campeche, Mexico, 24 July 2



From Marisaldi et al. 2024, Nature

Glows are long-lasting and variable

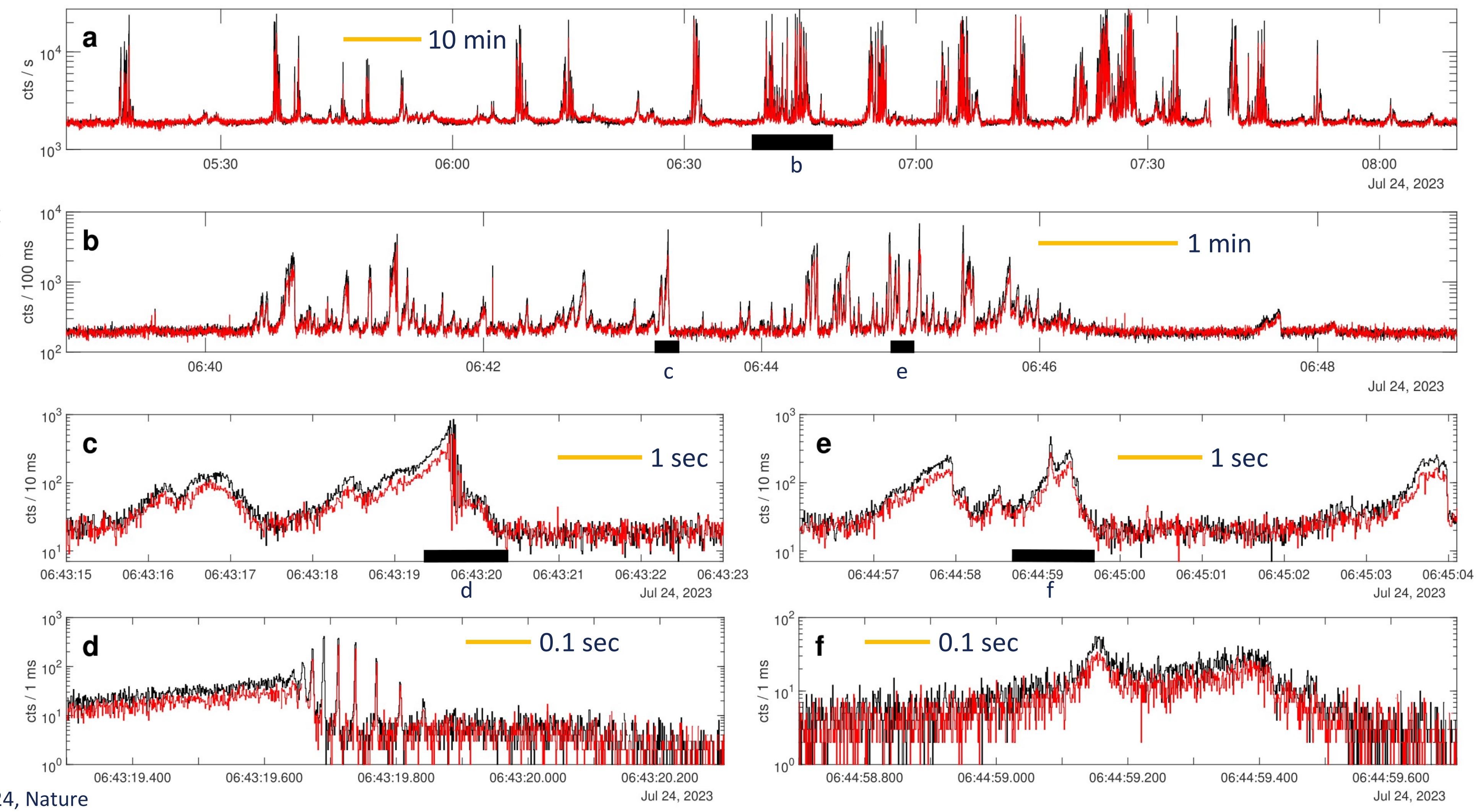
Marisaldi et al. 2024, Natur

Bay of Campeche, Mexico, 24 July 2

y count rate

instrument

instrument



isaldi et al. 2024, Nature

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Glows are long-lasting and variable

Marisaldi et al. 2024, Natur

ws are **bright**

- Up to 12x background (1-sec timescale)
- Peak flux << TGF

ws are **dynamic and variable**

- Strong evidence for intrinsic variability
  - Typical rise times (few sec) << airplane motion
  - Many glows are terminated by lightning discharges
  - Some glows are terminated by TGFs!
  - Some glows fade
- Electric field is strong and variable

w **spectrum**

- Consistent with RREA

Bay of Campeche, Mexico, 24 July 2

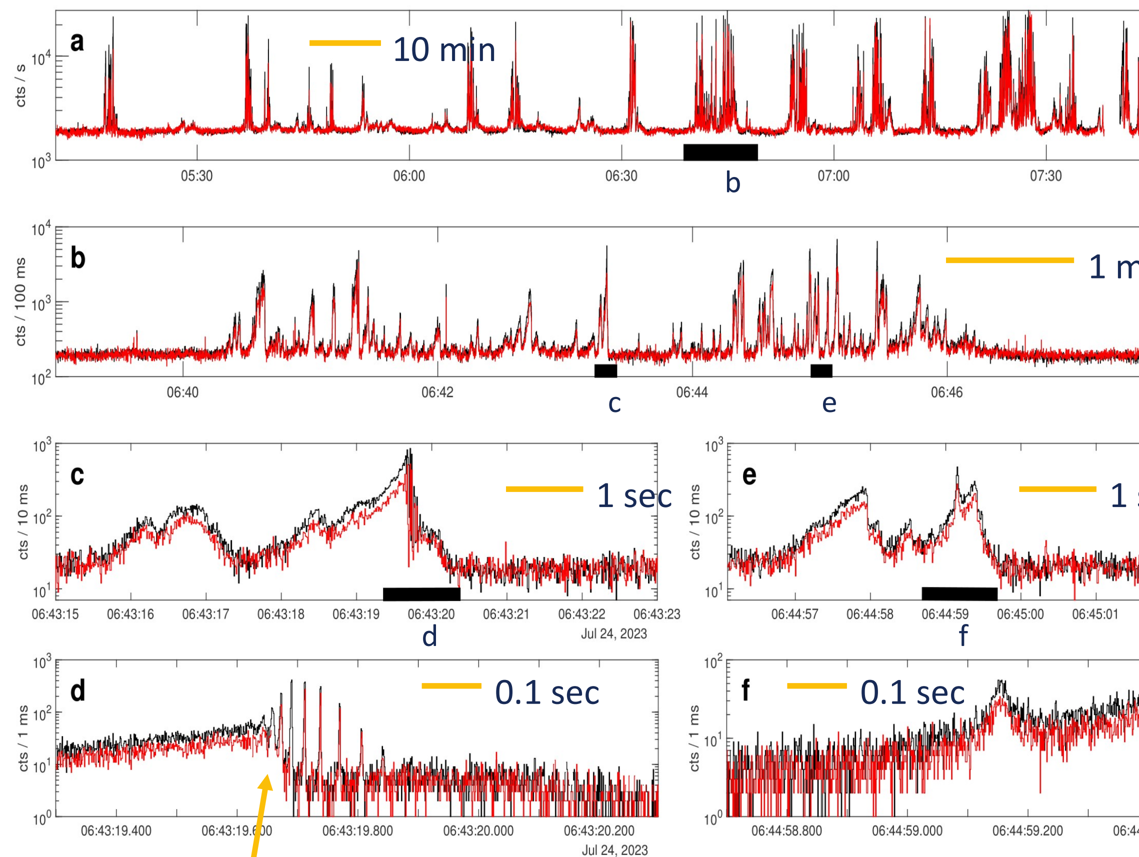


Figure from Marisaldi et al.

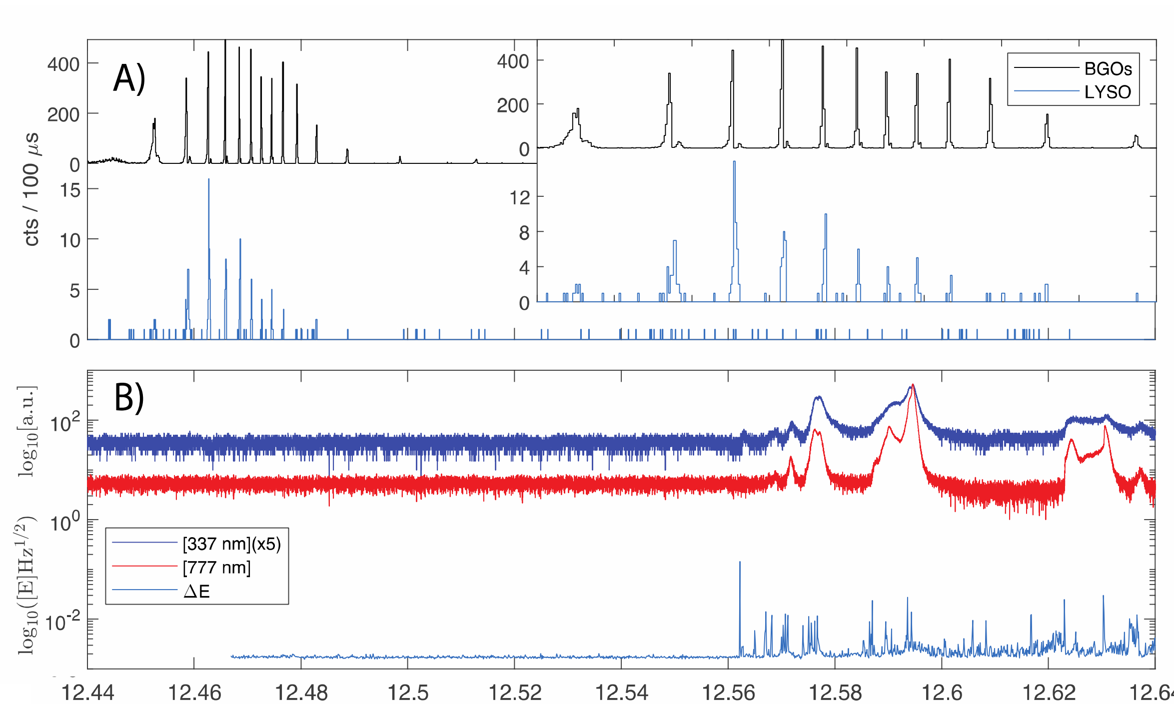
What's this?? Something new…

New! Flickering Gamma-ray Flashes

Østgaard et al. 2024, Nature

ckering Gamma-ray Flashes" (FGFs)

- **Multiple gamma-ray pulses**
  - Pulse width ~ 1 to 3 ms
  - Duration ~ 10 to 300 ms
  - Bright, but peak flux not detectable from space with current instruments
  - Spectrum consistent with RREA
- **No optical signal**
- **No E-field change or radio**
  - But followed by lightning discharge



Gamm

337 n

777 n

E-fielc

Time (sec)

From Østgaard et al. 2024, N

12 gamma-ray pulses

Lightning discharge ~50 ms later

estions

- What is relationship with lightning, with TGFs, with glows?

Flickering Gamma-ray Flashes

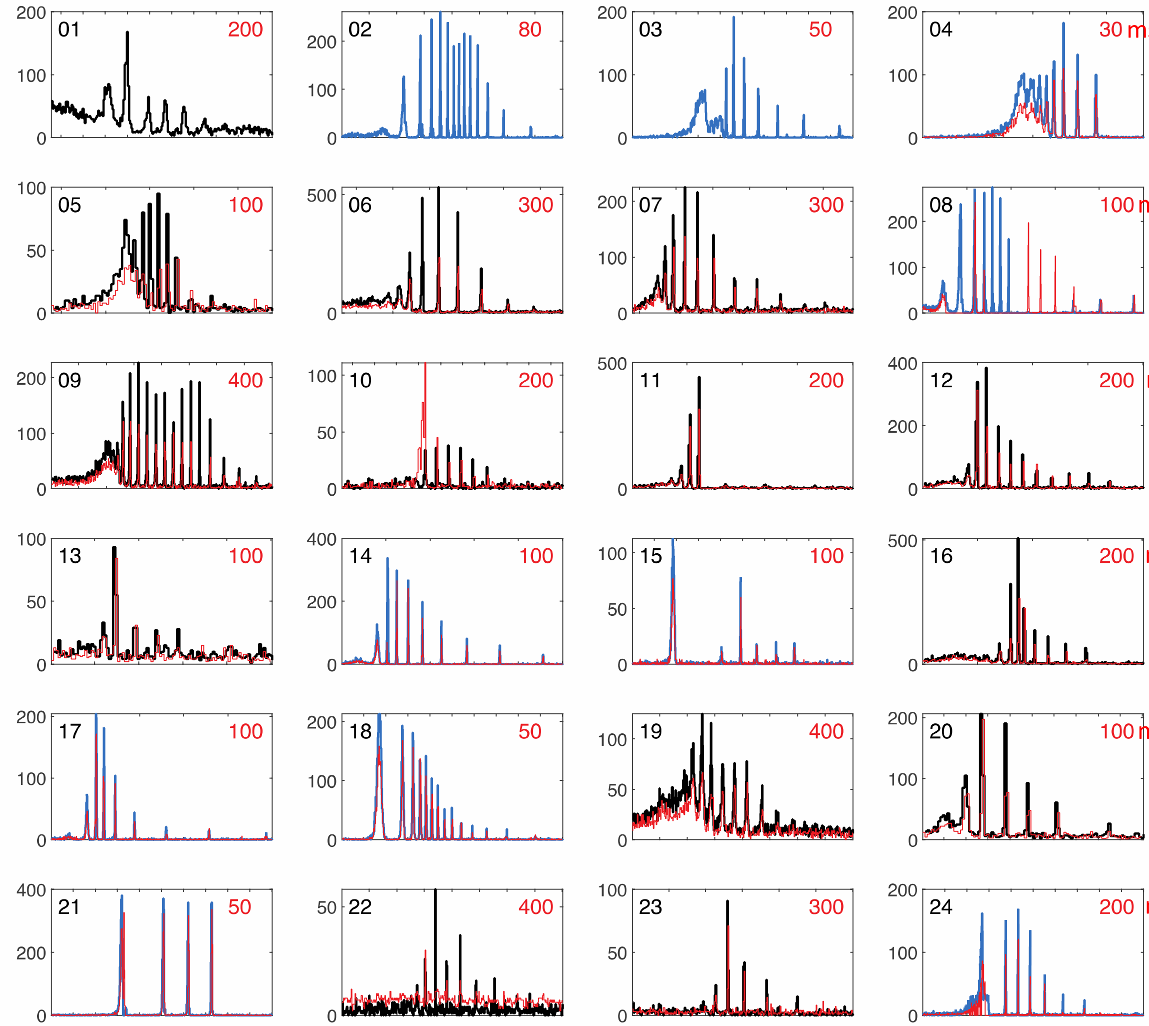
Østgaard et al. 2024, Nature

s are not rare

- At least 24 examples in ALOFT campaign
- Observed on 5 of 10 flights

ltiple pulse structure

- Possibly consistent with Relativistic Feedback Discharge (Dwyer 2012)?
- Low-energy electrons from first pulse discharge the field, terminate the pulse
- Low-energy ions re-establish accelerating field and initiate subsequent pulse



Blue, black: BGO
Red: iSTORM

From Østgaard et al. 2024,

ALOFT summary

ting close makes a difference

- More than **500** glows
- At least **24** Flickering Gamma-ray Flashes
- More than **100** Terrestrial Gamma-ray Flashes

Event type	Duration	Peak flux (relative)	Gamma spectrum	Optical?	Radio?	Related to glows?
Glows	1 – 100 s	1 – 100	RREA	No	No	–
FGFs	10 – 300 ms	100 – 5×10^4	RREA	No	No	Yes
TGFs	10 – 1000 μs	5×10^5 – 1×10^8	RREA	Yes	Yes	Yes

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Conclusions

- nderstorms are most powerful natural terrestrial particle accelerators

- nderstorms glow in gamma rays and create Terrestrial Gamma-ray Flashes
  - Launch MeV γ-rays and charged-particle beams into space
  - Particle accelerator at altitudes accessible by aircraft

- derlying physics some combination of cold runaway and relativistic feedback discharge (maybe)
  - New, different kind of electrical breakdown in thunderstorms
  - May play important role in thunderstorm activity and discharge
  - May play important role in atmospheric chemistry and dynamics, in climate

- h energy atmospheric physics, a new field

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