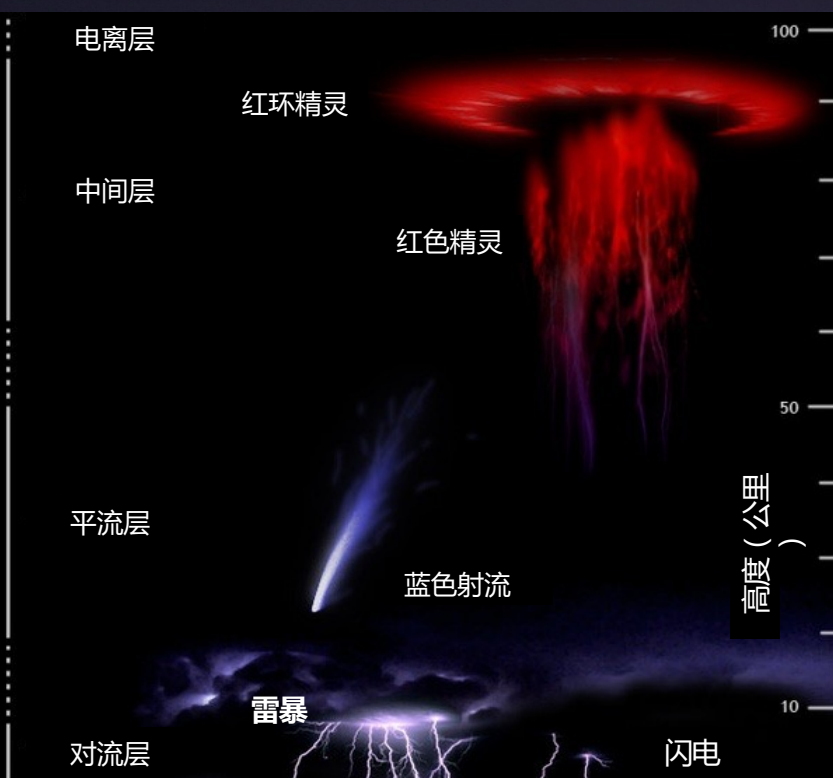


# 对流层雷暴的临近空间电磁效应和高能辐射效应研究



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中国科学技术大学  
地球和空间科学学院

合作者：

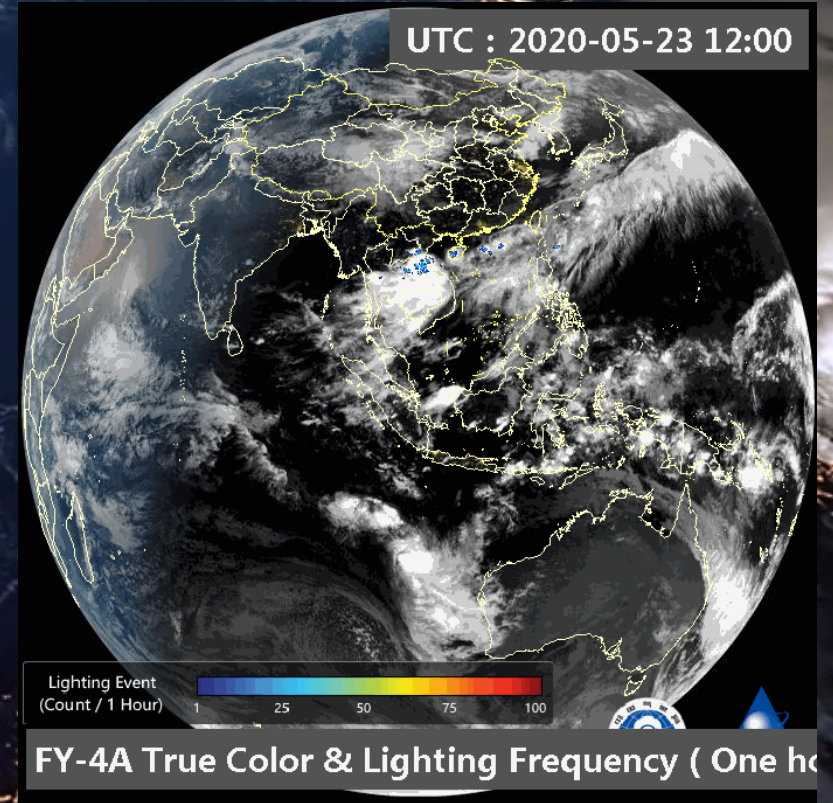
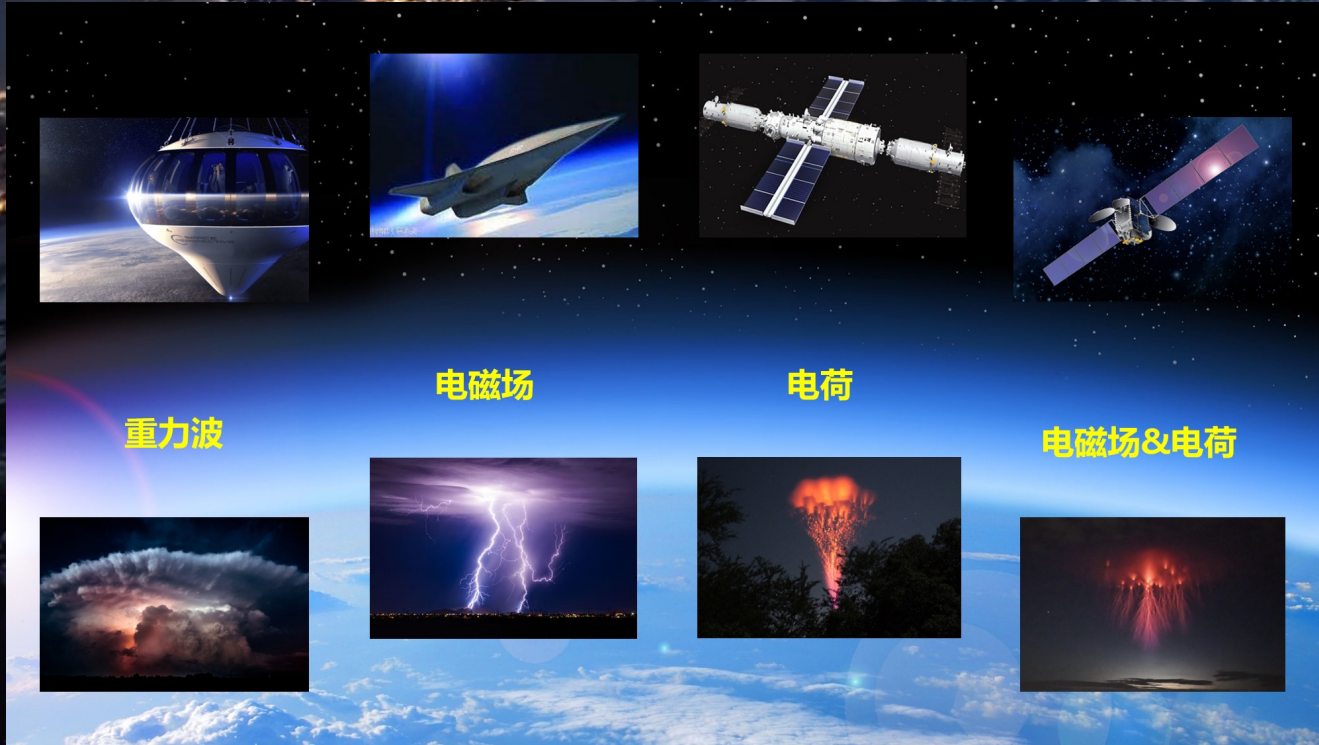
祝宝友、雷久候、薛向辉等（科大）

熊少林（高能所）

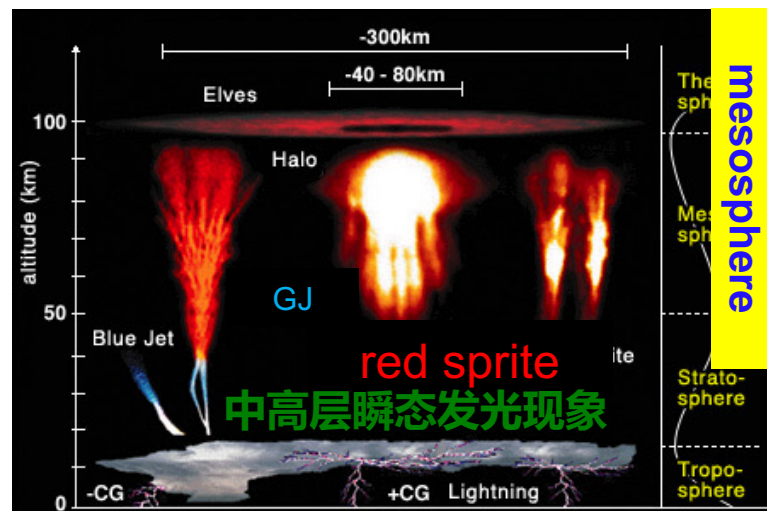
郝秀书、蒋如斌、张鸿波等（大气所）

吕凡超、樊艳峰、张阳、吕伟涛等（气科院）

# 地球各圈层之间的耦合-地球系统科学



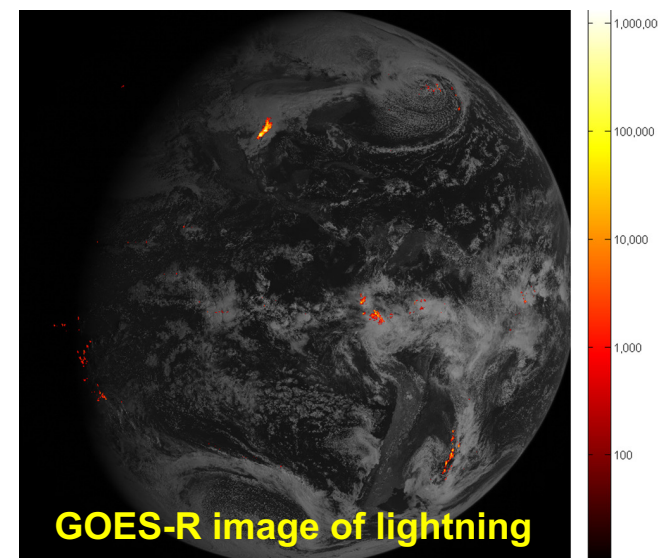
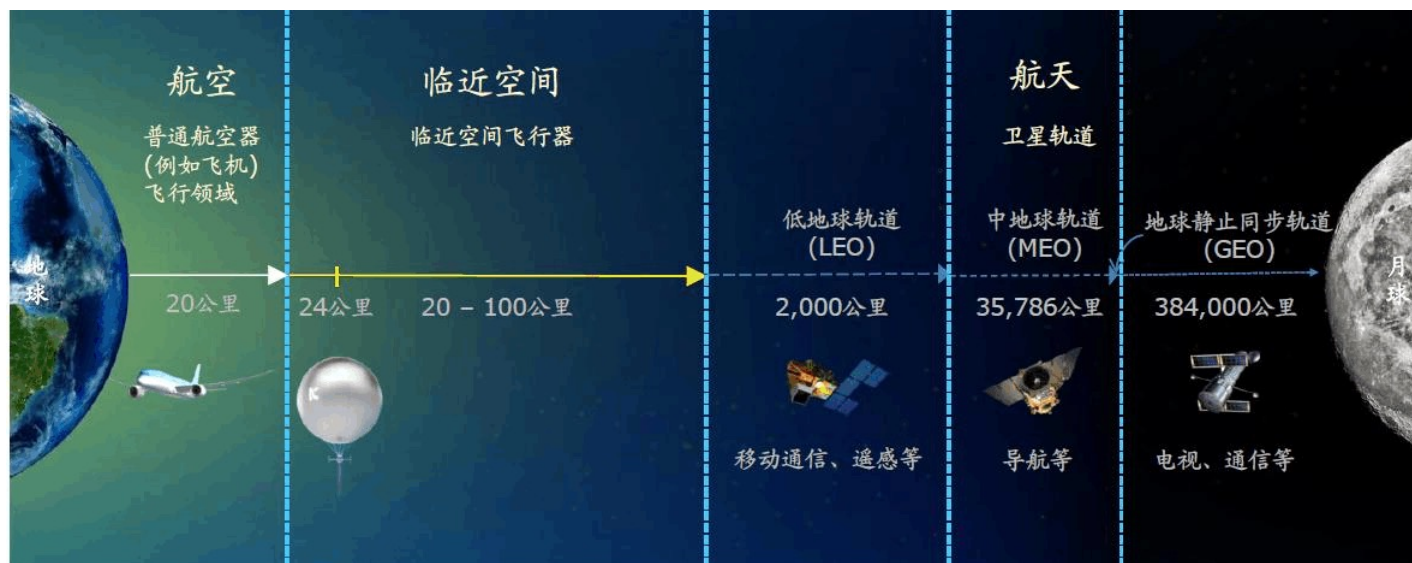
# 闪电及其近地空间电磁效应



Franz et al. (1990)-Science; Pasko et al. (2002)-Nature



Fishman et al. (1994)-Science



# 目录

1

雷电物理及探测技术

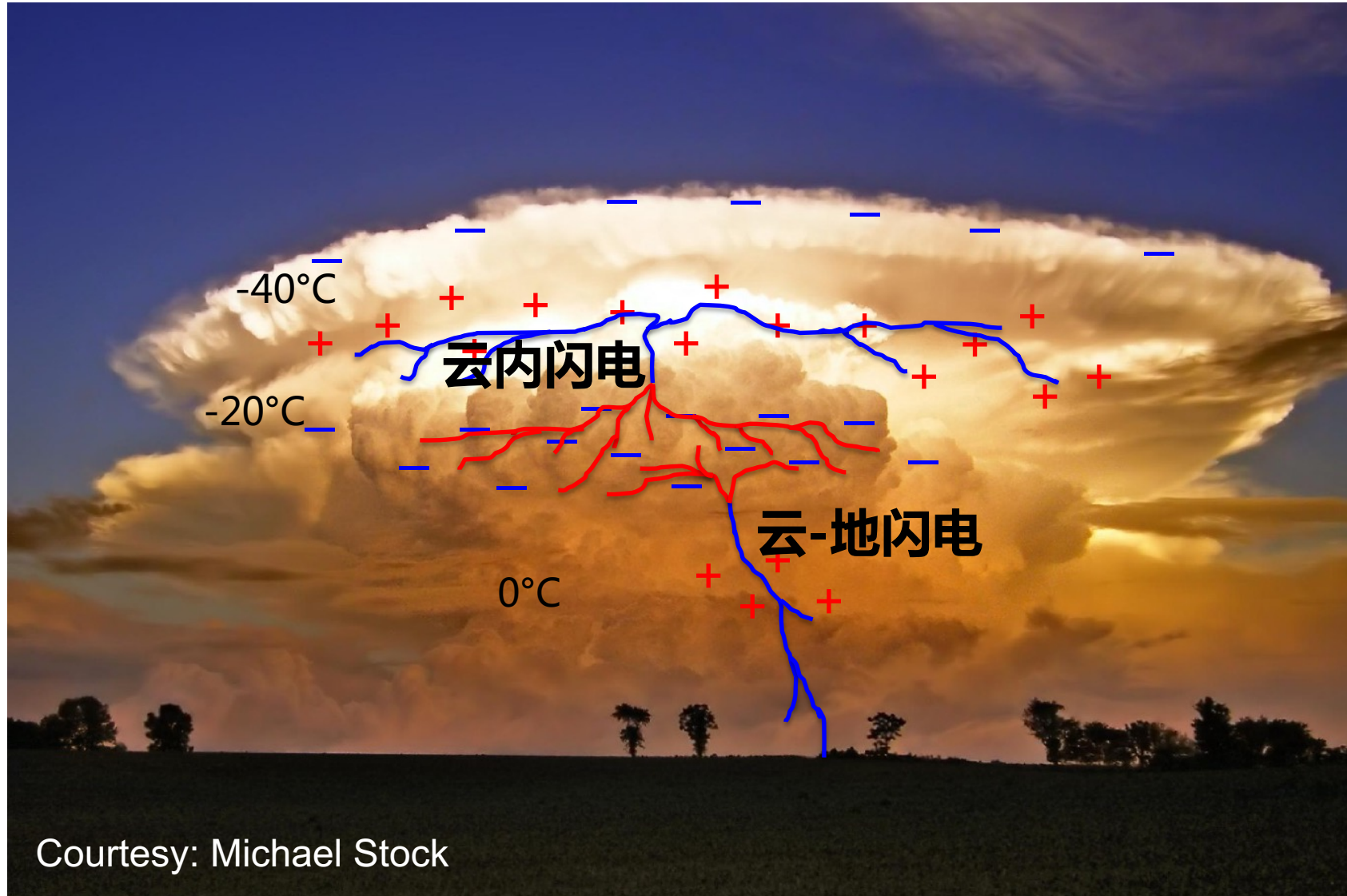
2

中高层放电现象

3

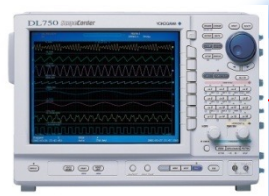
深对流雷暴强云闪过程

# 雷暴和闪电

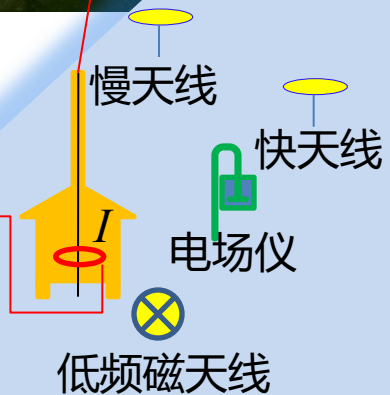


# 低频磁场测量在人工雷电实验中的引用

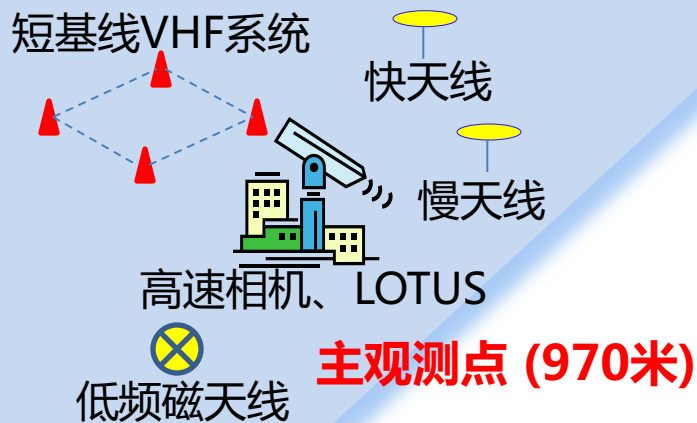
- 通道底部的电流测量
- 不同距离处的电磁场测量
- 高速光学及短基线甚高频系统的闪电观测
- “电-高能-光-磁”综合测量
- 地面多站的闪电成像观测



DL 750



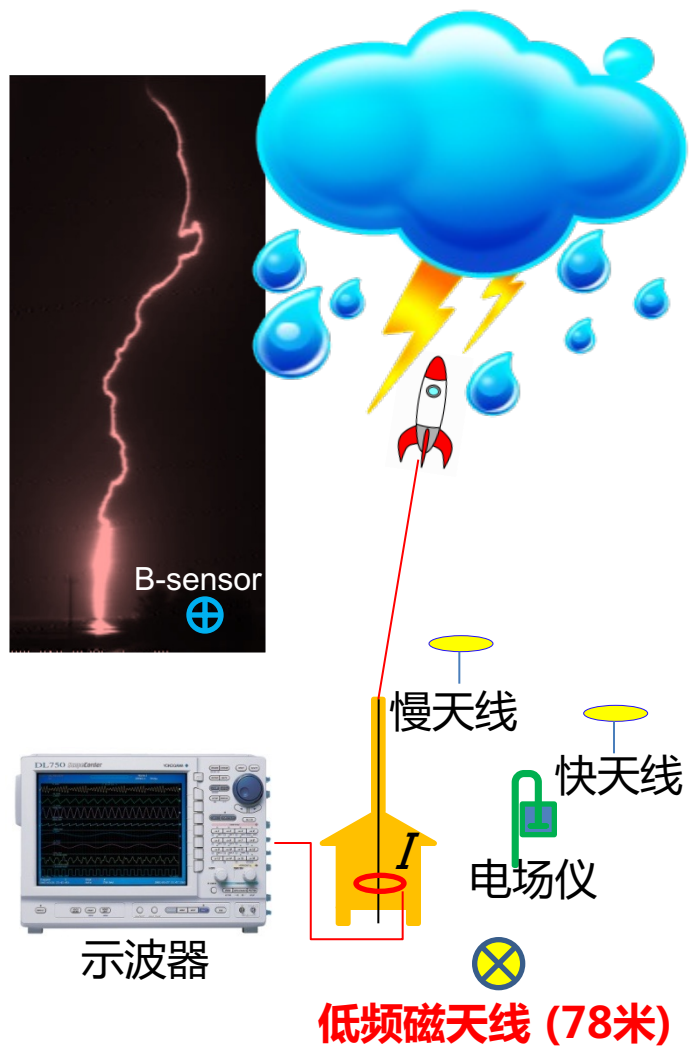
引雷点 (30-78米)



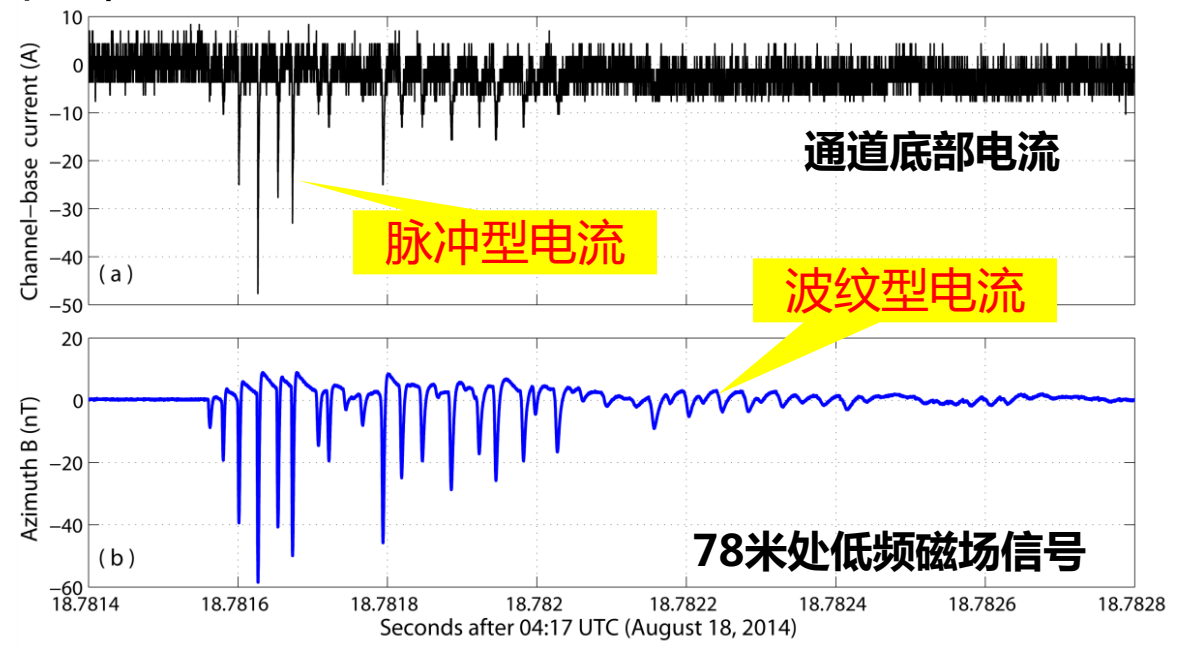
(Courtesy: Dong Zheng)

17:46:08, 7 June 2011

# 人工引雷弱放电过程的磁场测量

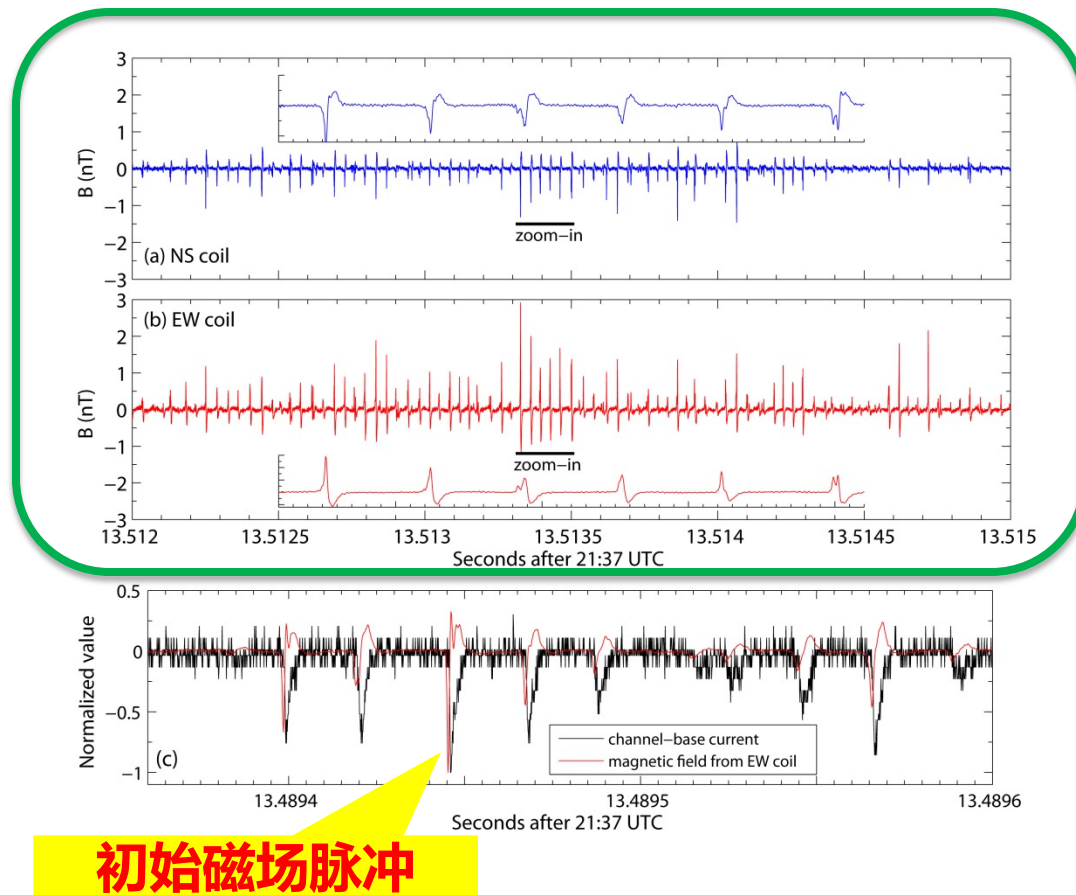
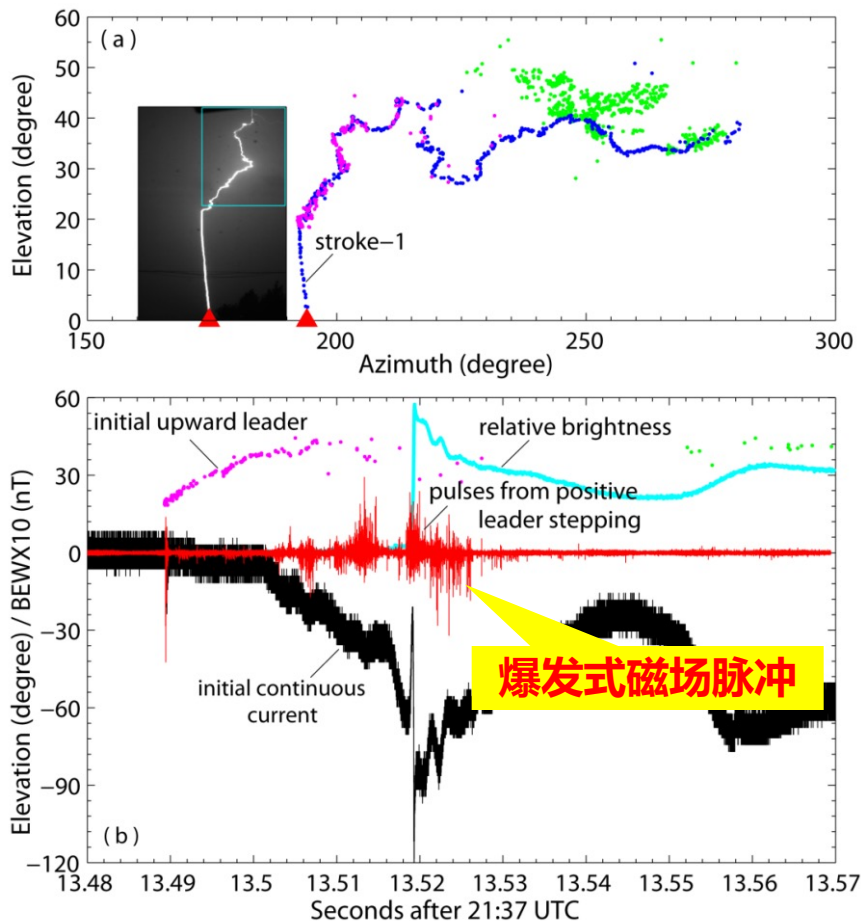


- 闪电通道的延长增加阻抗，导致脉冲型电流产生衰减（“低通”滤波效应）
- 类似的特征在山东和广东的人工引雷试验中均有观测，具有普遍性



樊艳峰 等(2016); Lu et al. (2016); Fan et al. (2018JGR)

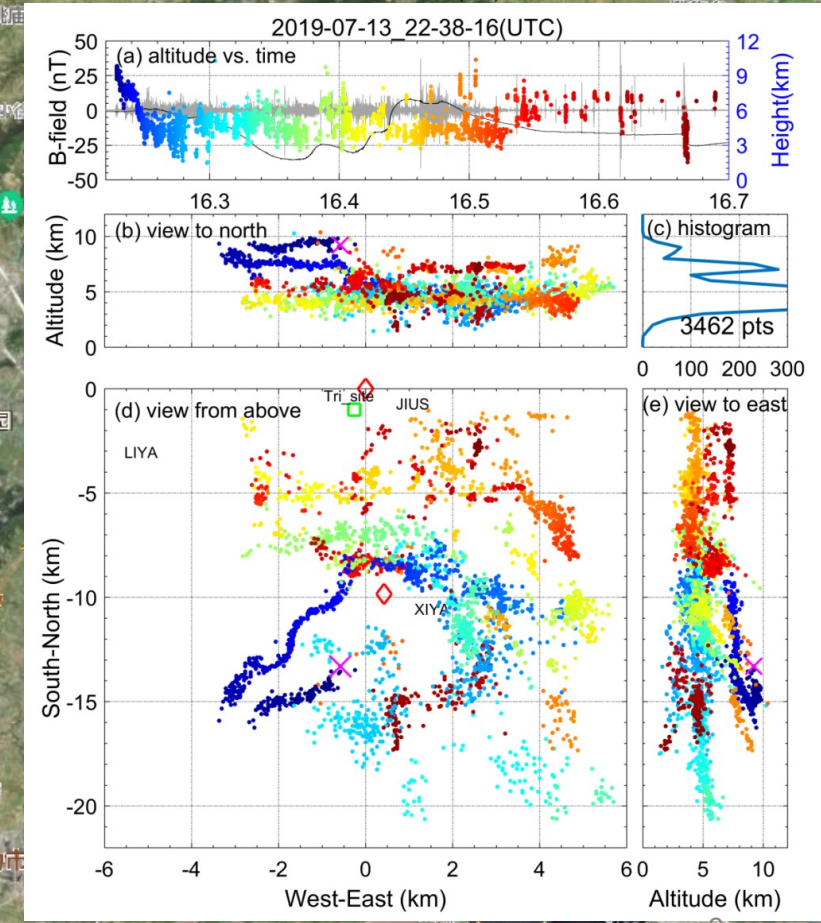
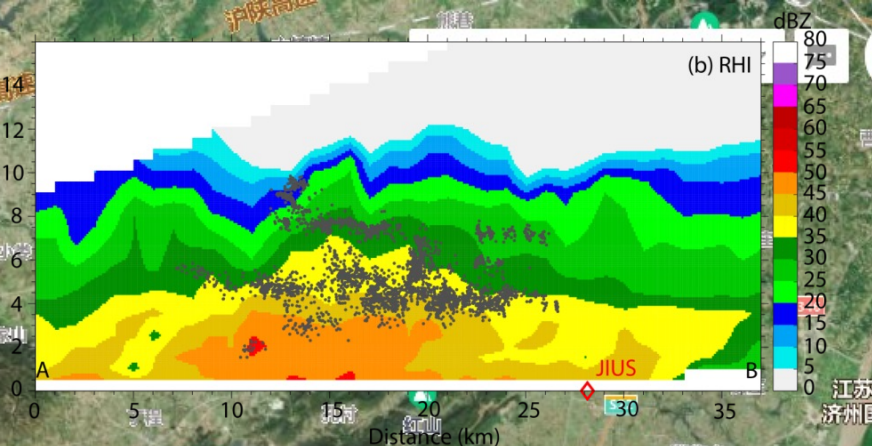
# 初始连续电流阶段的爆发式磁场脉冲



- 人工引雷上行先导发展期间的普遍现象（持续时间：3-12毫秒）
- 脉冲间隔一般大于20微秒

Lu et al. [2014]



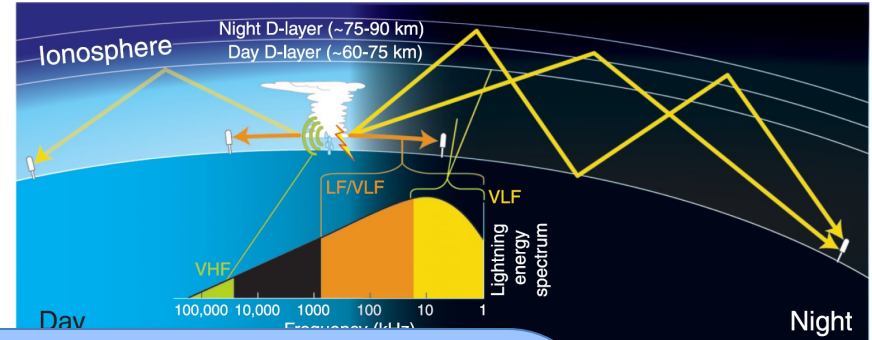
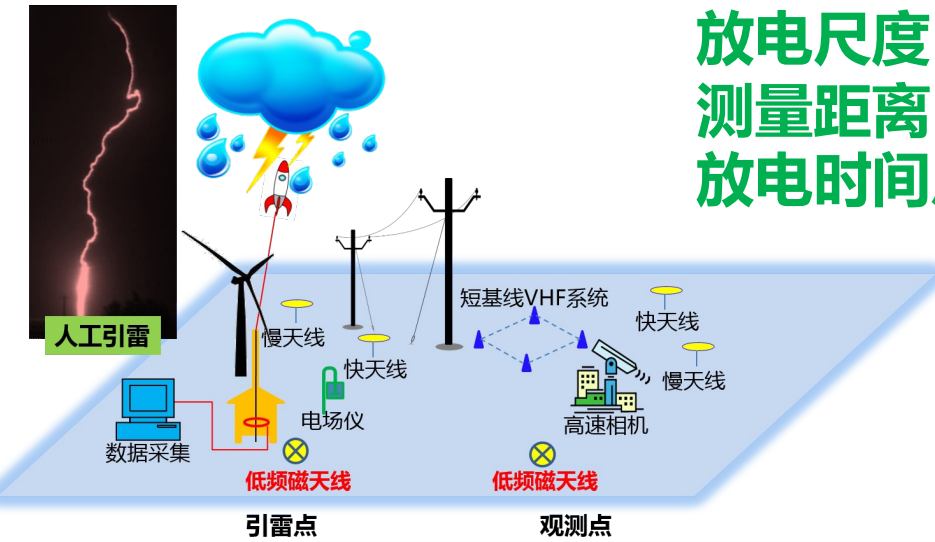


低频磁场信号采集系统

# 合肥地区三维闪电定位网建设

# 在四维空间等比例放大

放电尺度：米量级 → 公里量级  
 测量距离：百米到公里 → 百公里到千公里  
 放电时间尺度：微秒 → 毫秒量级



$$B(t) = \frac{1}{2\pi\epsilon_0 c^2} \int_0^h \left( \underbrace{\frac{\sin \alpha(z')}{R^2(z')} i(z', t - \frac{R(z')}{c})}_{\text{感应场}} + \underbrace{\frac{\sin \alpha(z')}{cR(z')} \frac{\partial i(z', t - R(z')/c)}{\partial t}}_{\text{辐射场}} \right) dz'$$

$$E(t) = \frac{1}{2\pi\epsilon_0} \int_0^h \left( \underbrace{\frac{2-3\sin^2 \alpha}{R^3(z')} \int_{t_b}^t i(z', \tau - R(z')/c) d\tau}_{\text{静电场}} + \underbrace{\frac{2-3\sin^2 \alpha}{cR^2(z')} i(z', t - R(z')/c)}_{\text{感应场}} - \underbrace{\frac{\sin^2 \alpha}{c^2 R(z')} \frac{\partial i(z', t - R(z')/c)}{\partial t}}_{\text{辐射场}} \right) dz'$$

# 闪电电磁场的计算

麦克斯韦方程

$$\begin{cases} \nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{H}}{\partial t} \\ \nabla \times \mathbf{H} = \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \sigma \mathbf{E} + \mathbf{J}_s \end{cases}$$

$$B(t) = \frac{1}{2\pi\varepsilon_0 c^2} \int_0^h \left( \frac{\sin \alpha(z')}{R^2(z')} i(z', t - \frac{R(z')}{c}) + \frac{\sin \alpha(z')}{cR(z')} \frac{\partial i(z', t - R(z')/c)}{\partial t} \right) dz'$$

感应场

辐射场

$$E(t) = \frac{1}{2\pi\varepsilon_0} \int_0^h \left( \frac{2-3\sin^2 \alpha}{R^3(z')} \int_{t_b}^t i(z', \tau - R(z')/c) d\tau + \frac{2-3\sin^2 \alpha}{cR^2(z')} i(z', t - R(z')/c) - \frac{\sin^2 \alpha}{c^2 R(z')} \frac{\partial i(z', t - R(z')/c)}{\partial t} \right) dz'$$

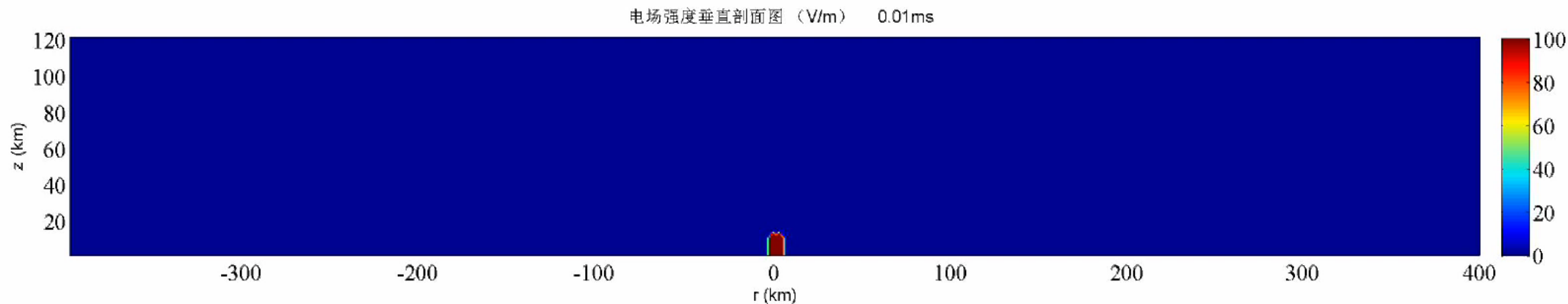
静电场

感应场

辐射场

全波 (full-wave) 模型

传输线 (transmission line) 模型



# 目录

1

雷电物理及探测技术

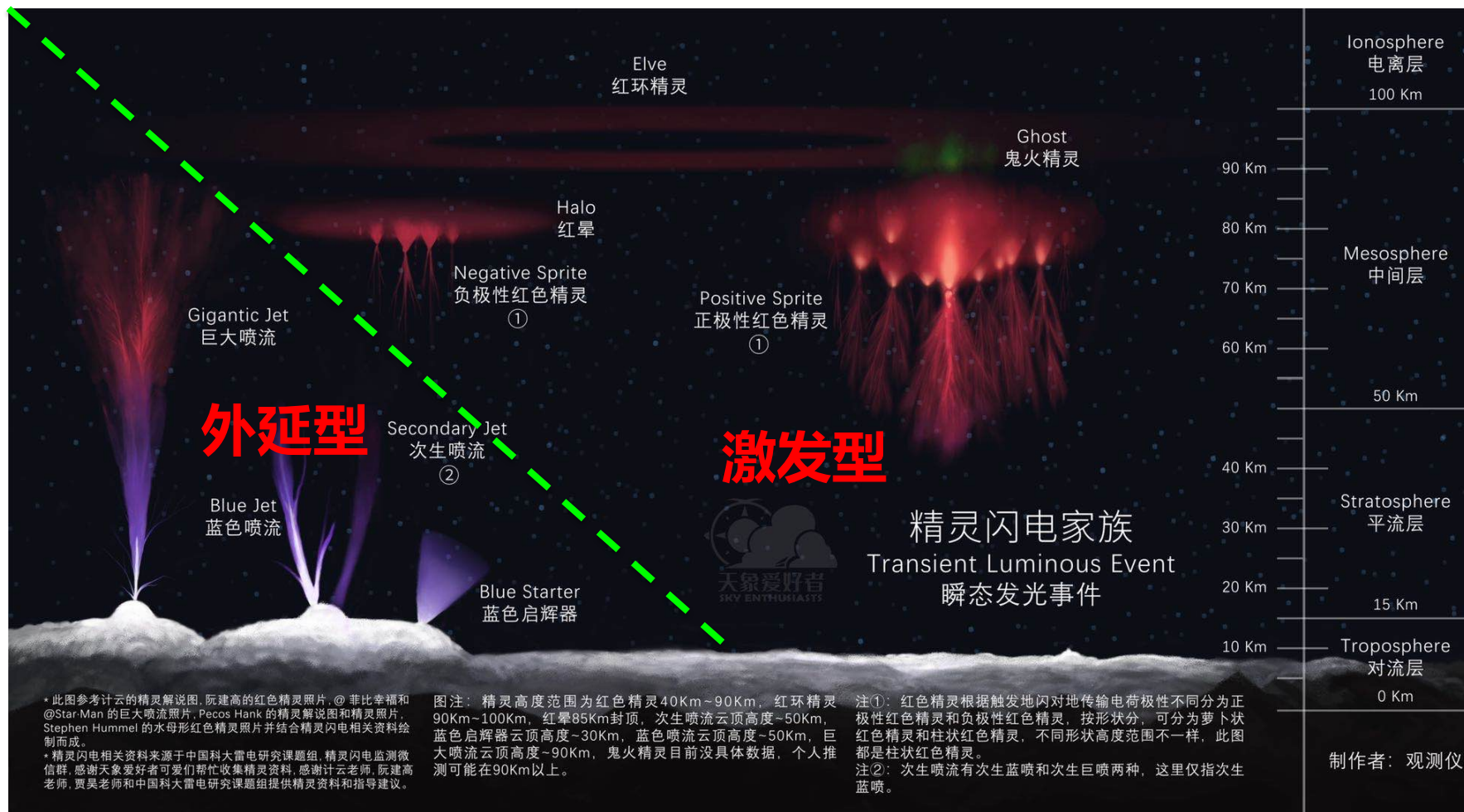
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中高层放电现象

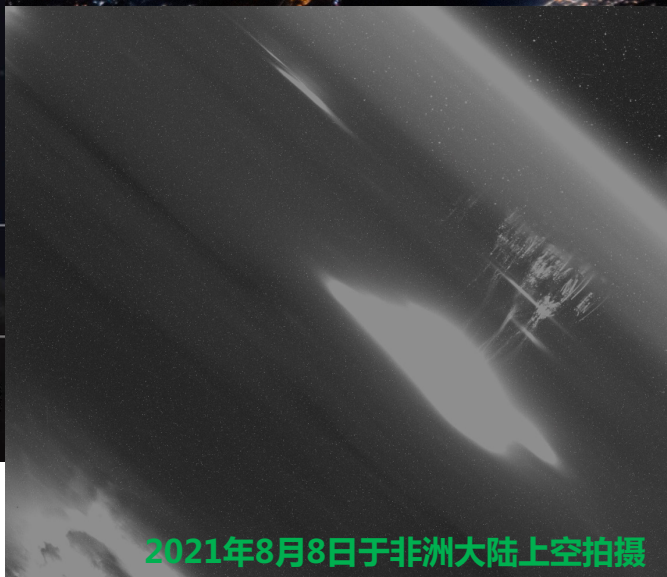
3

深对流雷暴强云闪过程

# 中高层放电现象 (瞬态发光事件)



国际空间站于北京时间2021年9月10日06:42:31在意大利半岛上空观测到的红色精灵



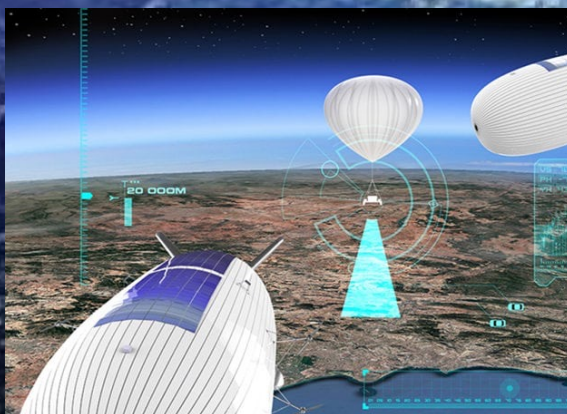
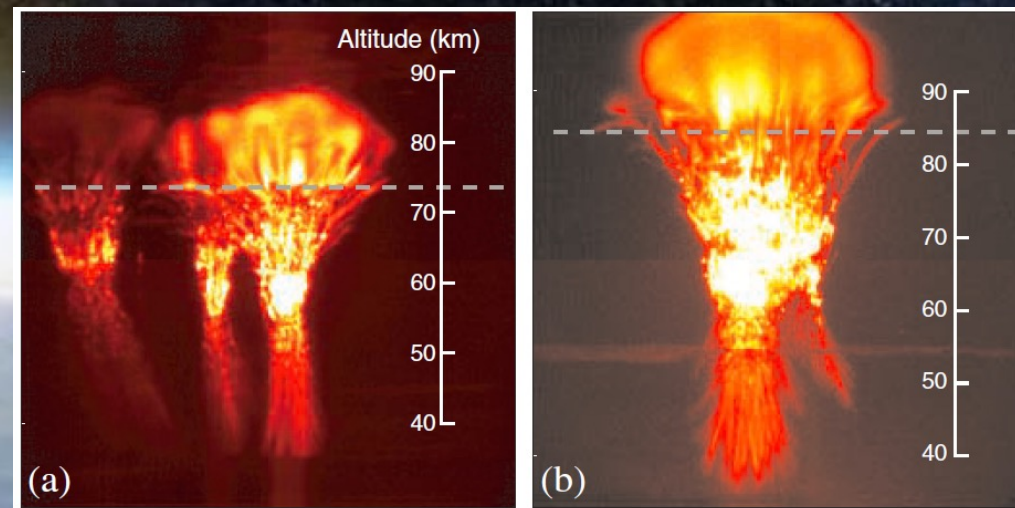
由中国“精灵闪电”爱好者集体制作

“仰望1号”空间天文望远镜看到的红色精灵

# 为什么要研究中高层放电现象？

**临近空间**：高度位于20公里到100公里之间的地球大气层

伴随着新一代航空器、浮空器和亚轨道航天器的发展，临近空间正在成为开展高技术应用和国防安全活动的新领域，运载火箭、人造卫星、载人飞船等航天器以及导弹武器的研究、试验和应用，都需要临近空间气象保障。

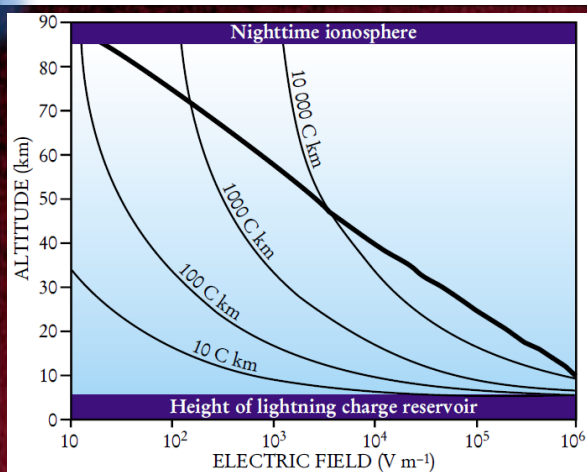
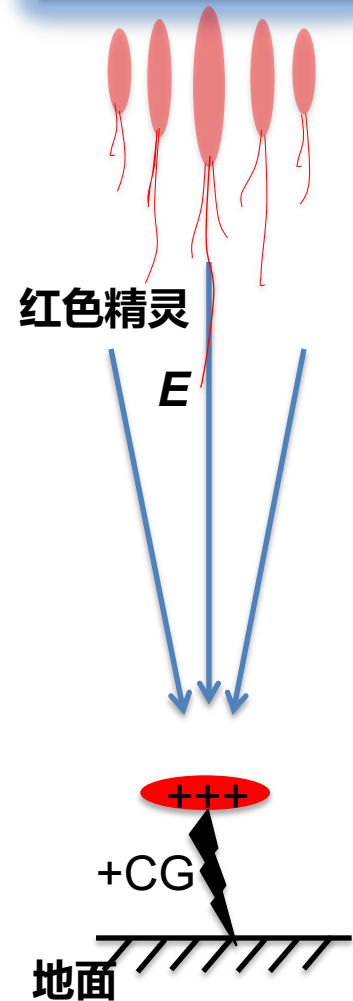


- 5倍以上声速
- 超高速飞行引起空气电离放电，成为电磁信号发射源

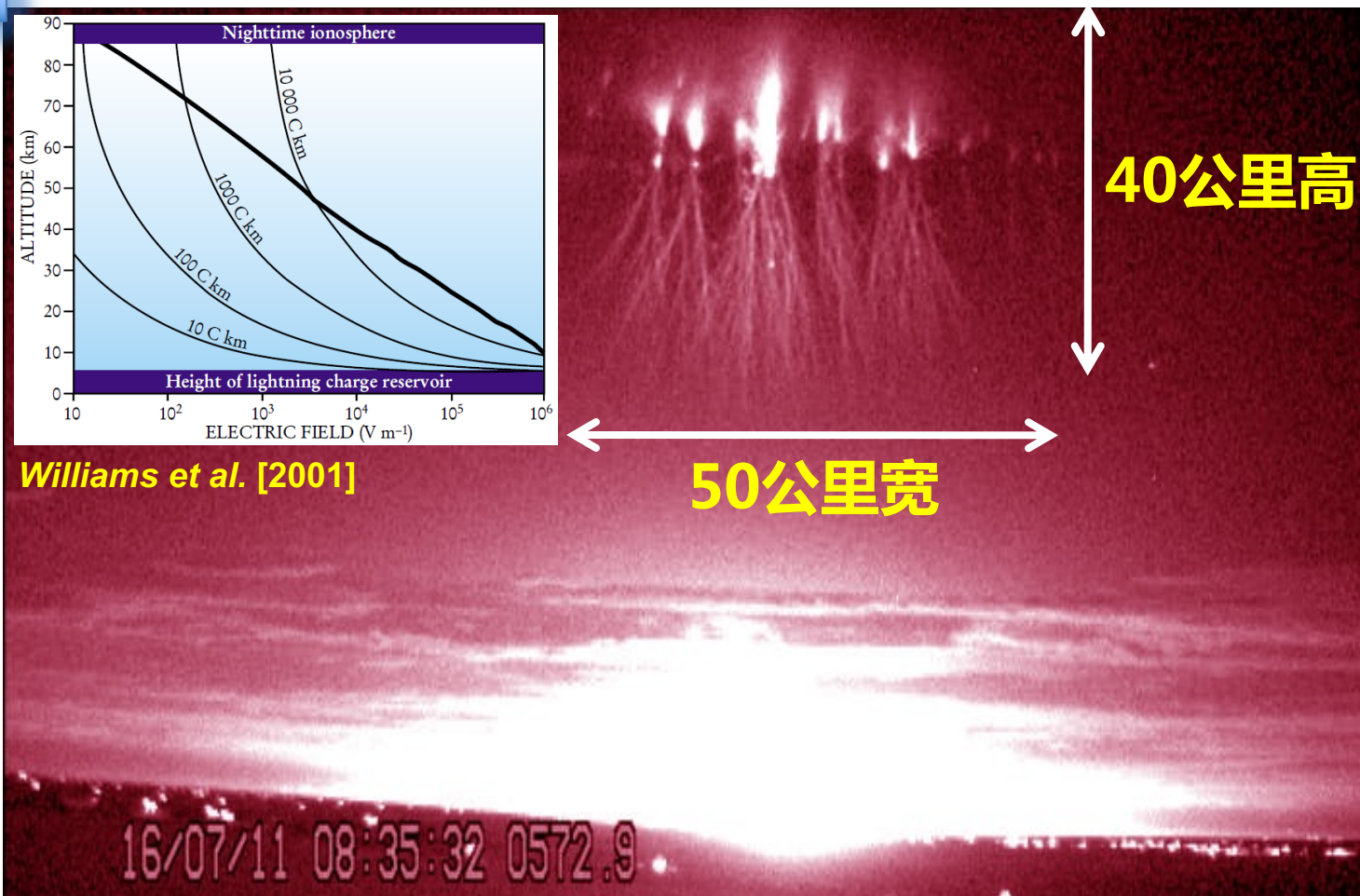
# 红色精灵 (red sprite)-雷暴上空的烟火

闪电对地电荷传输 → 瞬态激发电场 → 中高层大气击穿 → 后继流光发展

电离层

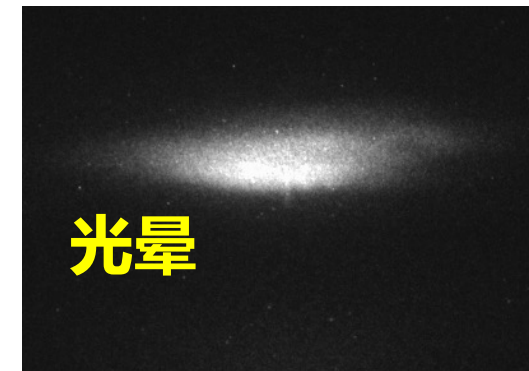


Williams et al. [2001]



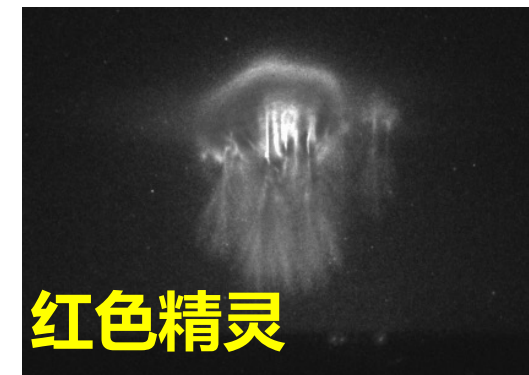
2011 July 16, 08:35:32 UT

Bennett, Colorado



光晕

回击之后1.5毫秒



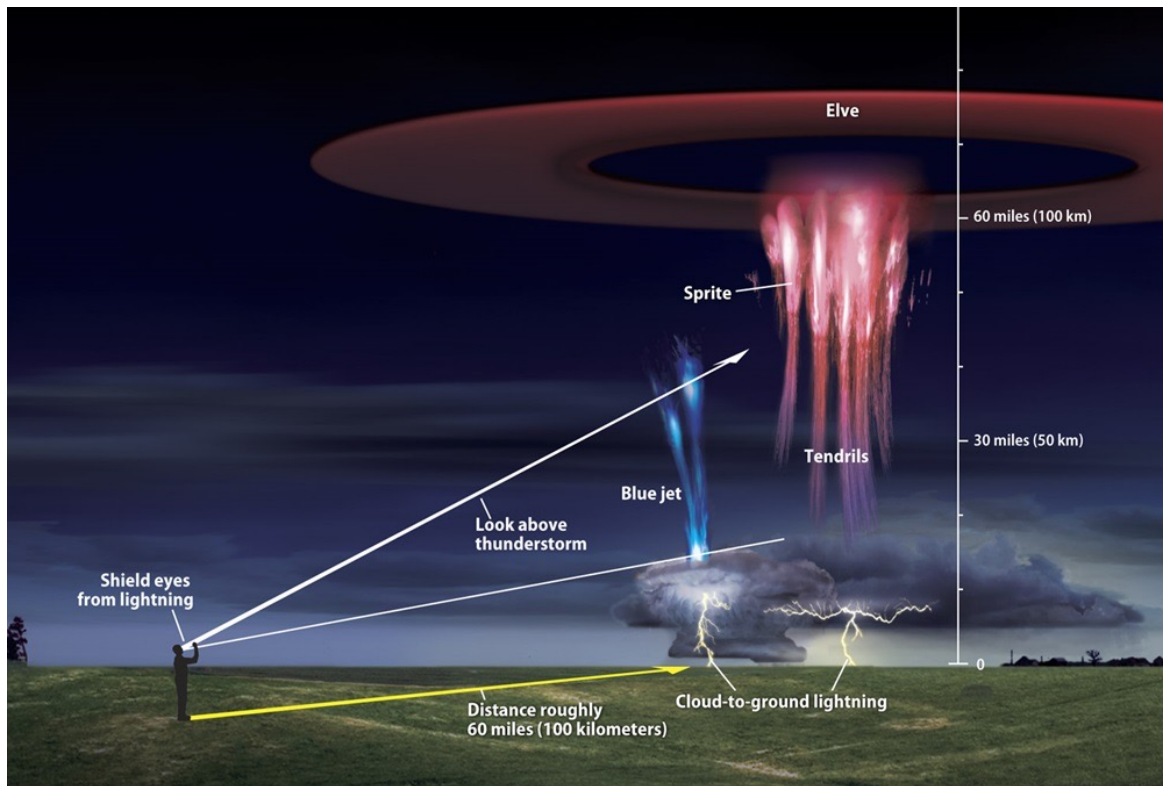
红色精灵

回击之后4毫秒

拍摄距离：237公里

# 中高层放电现象的观测

- 远处有活跃的雷暴 (300-600公里)
- 观测点附近没有遮挡视线的云层，城市光污染较少
- 视线方向上空气比较清新，星空可见



双通道成像系统连接示意图



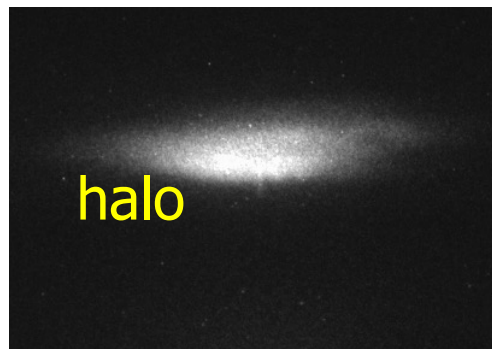


# 夜间的红色精灵观测

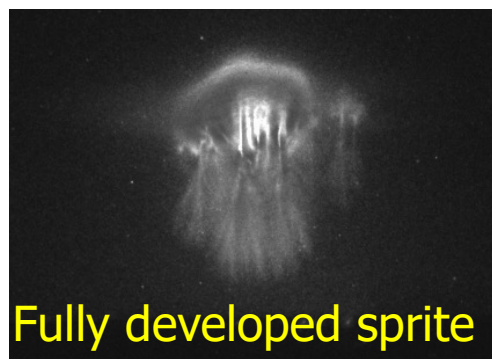


2012年6月16日拍摄于美国堪萨斯州

# 红色精灵的高速光学观测



1.5 ms after stroke

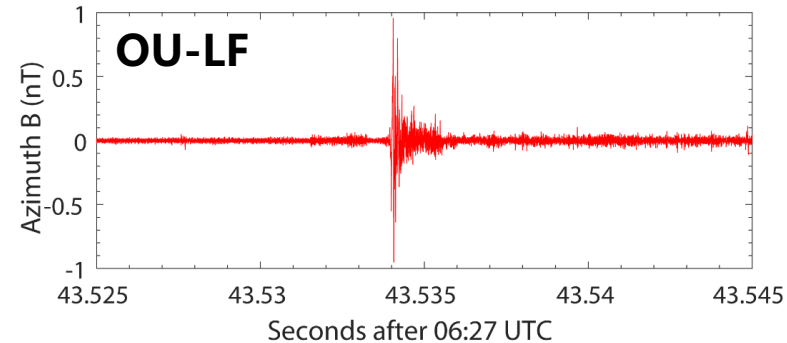
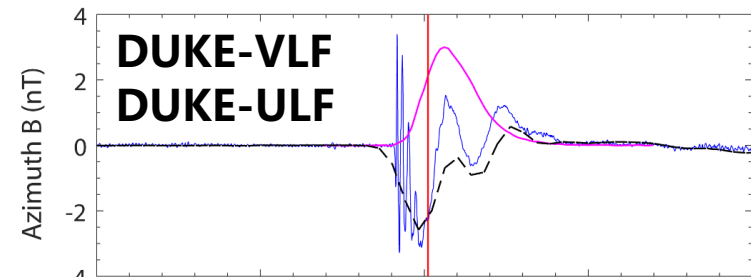
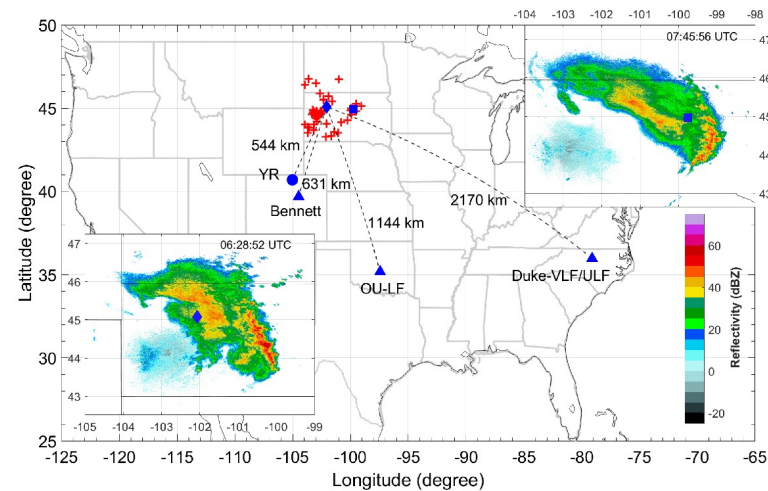


3.7 ms after stroke

Recorded at 8000 fps by Phantom V711

Obtained by Water Lyons with support from DARPA-NIMBUS Program

➤ 多频段磁场用于解析不同时间尺度的放电过程



Ren, Lu et al. (2021GRL)

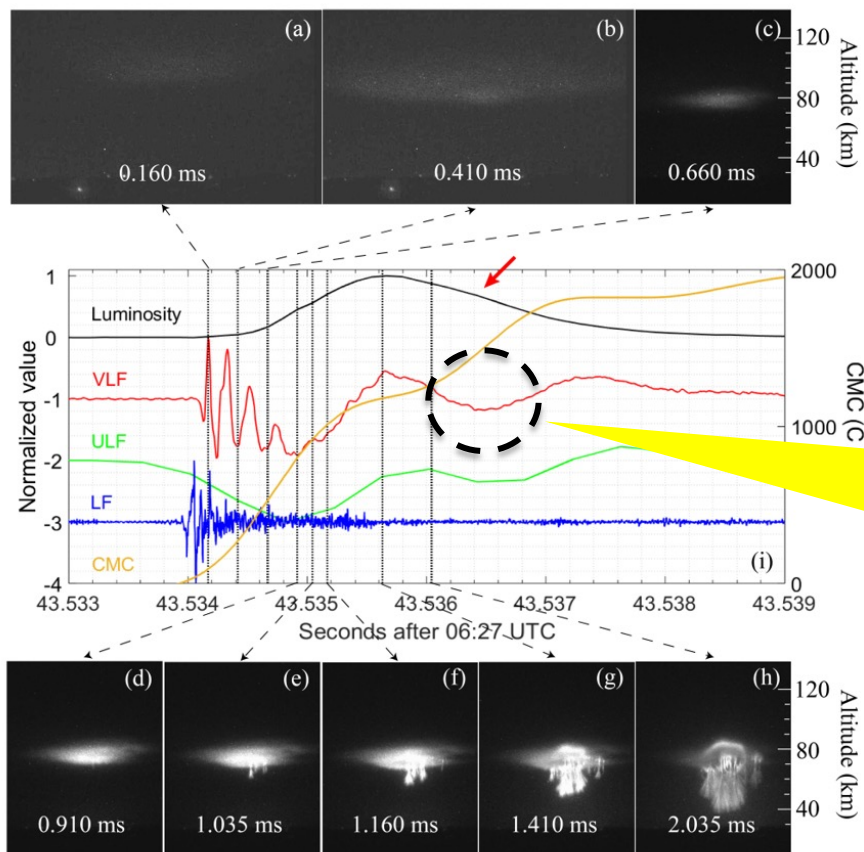
# 亚毫秒级母体闪电-红色精灵关联性分析

$$E(t) = \frac{1}{2\pi\epsilon_0} \int_0^h \left( \underbrace{\frac{2-3\sin^2\alpha}{R^3(z')} \int_{t_b}^t i(z', \tau - R(z')/c) d\tau}_{\text{静电场}} + \underbrace{\frac{2-3\sin^2\alpha}{cR^2(z')} i(z', t - R(z')/c)}_{\text{感应场}} - \underbrace{\frac{\sin^2\alpha}{c^2 R(z')} \frac{\partial i(z', t - R(z')/c)}{\partial t}}_{\text{辐射场}} \right) dz'$$

静电场

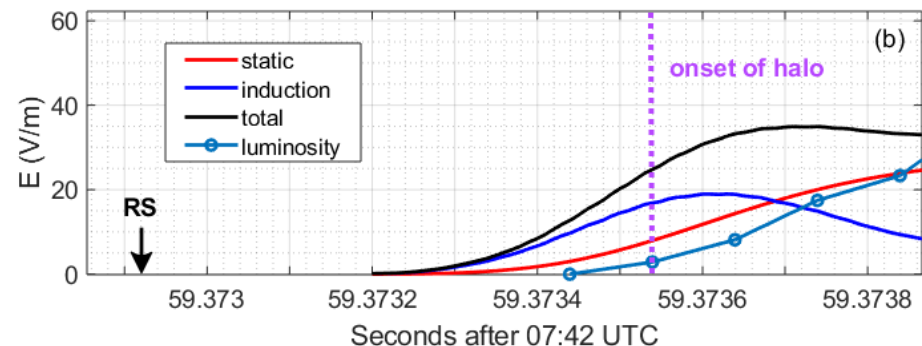
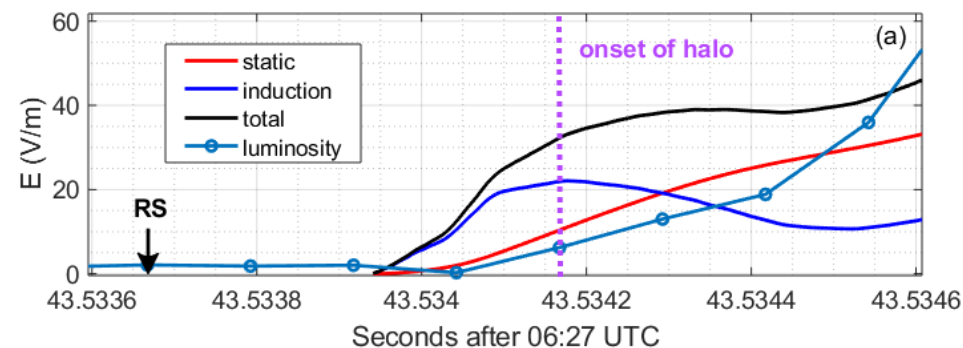
感应场

辐射场



红色精灵自身电流形成的超低频磁场信号

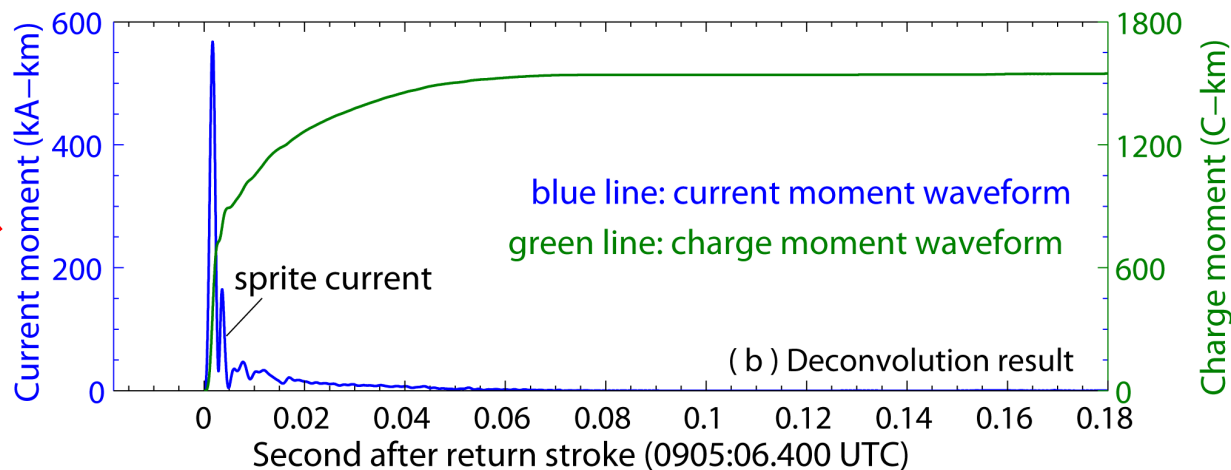
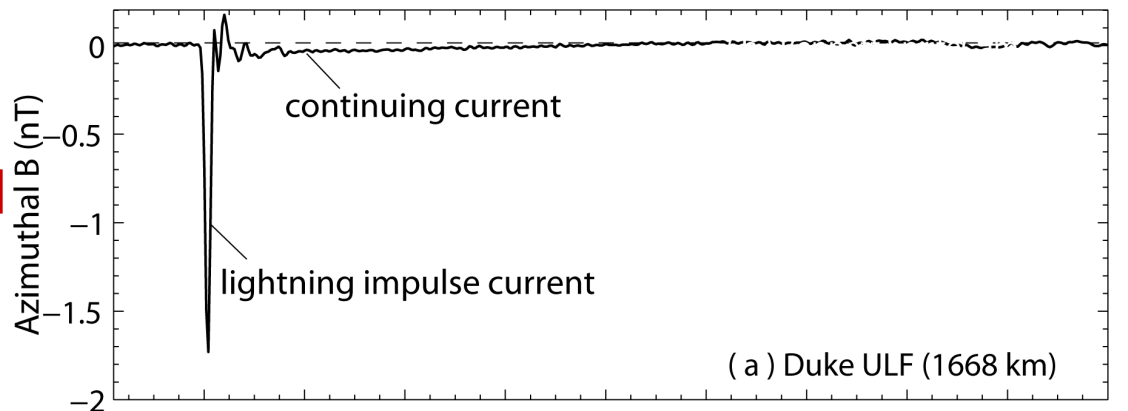
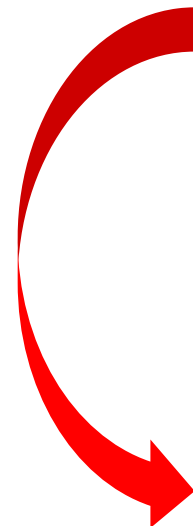
Ren, Lu et al. (2021)



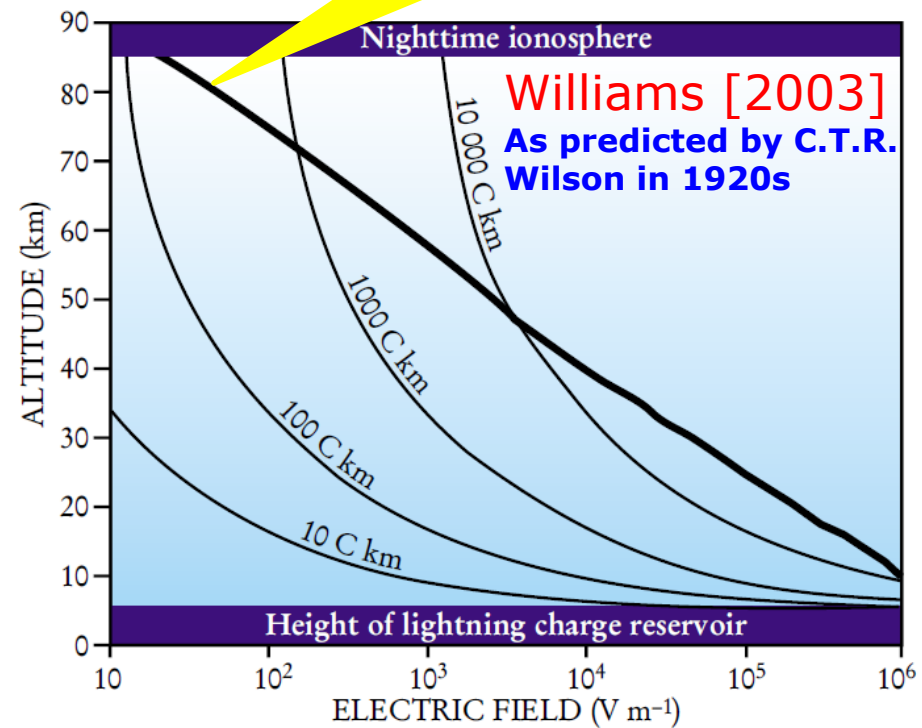
➤ 电流直接相关的感应场分量在光晕的形成中占据主导地位

# 如何估算闪电电荷传输的强度？

De-convolution



空气介质击穿电场阈值随高度指数衰减



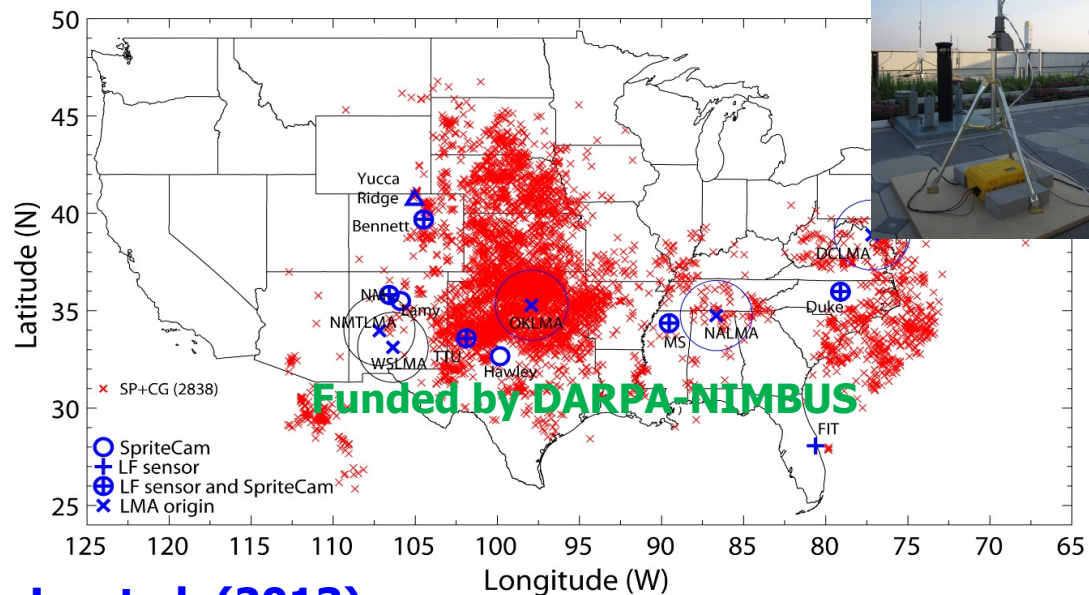
**iCMC**: impulse charge moment change

脉冲电荷距

= Charge transferred within 2 ms after return stroke × Height

# 不断扩展的观测数据集

## ➤ 2009-2013年北美地区地基观测



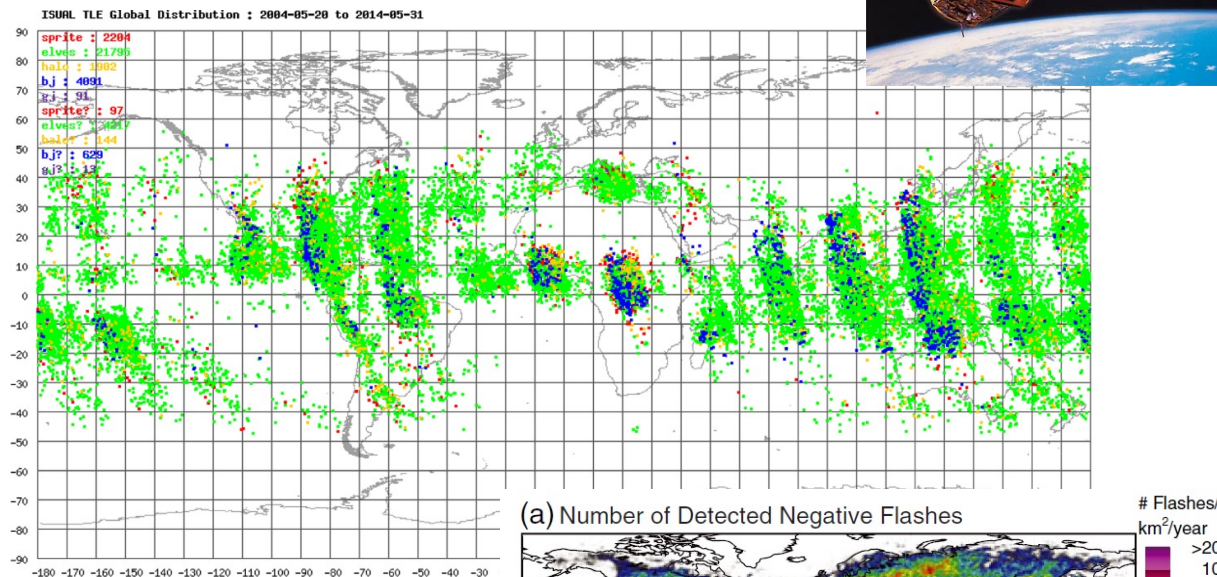
Lu et al. (2013)

- 2800余次中高层放电事件及同步闪电信号
- 负极性红色精灵事件比例大约为0.2%

## ➤ 2016-2022年东亚地区地基观测

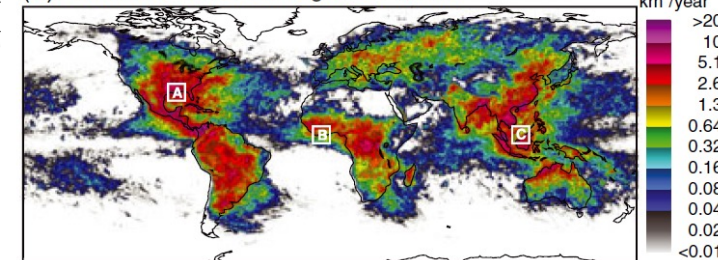
## ➤ 2016-2022年加勒比海地区地基观测

## ➤ 2004-2015年ISUAL空间观测



Chern et al. (2015)

(a) Number of Detected Negative Flashes

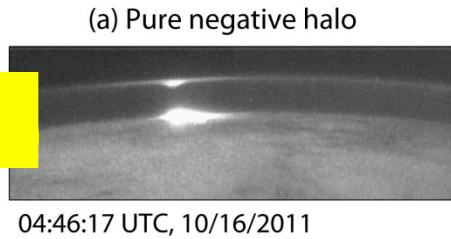


## ➤ 30000余次中高层放电事件观测

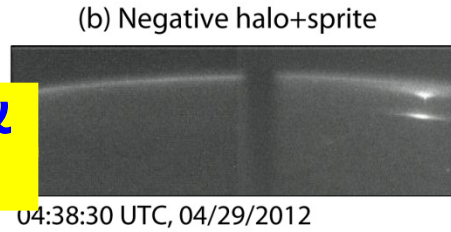
## ➤ 北美地区同步射频闪电信号数据

# ISUAL观测个例

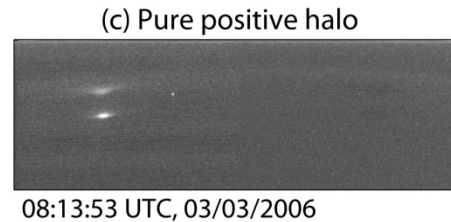
负极性光晕



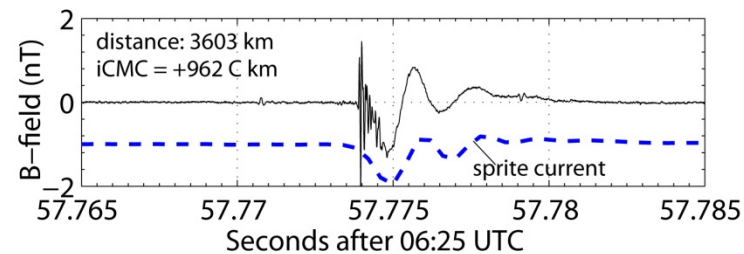
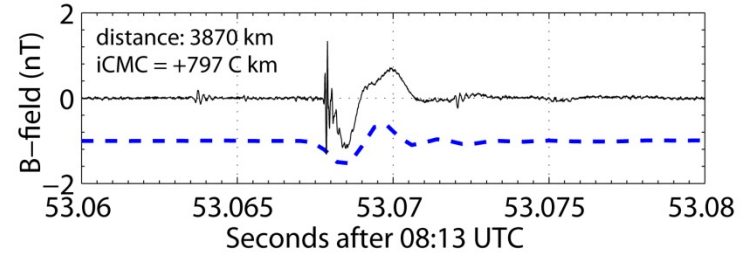
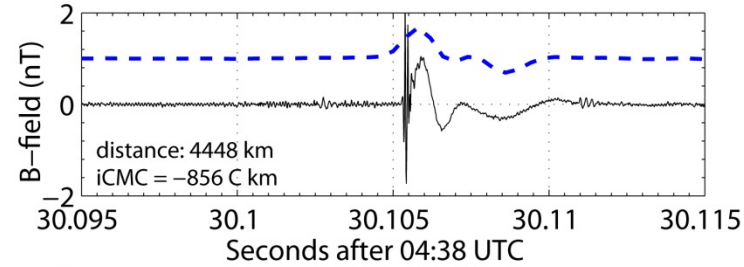
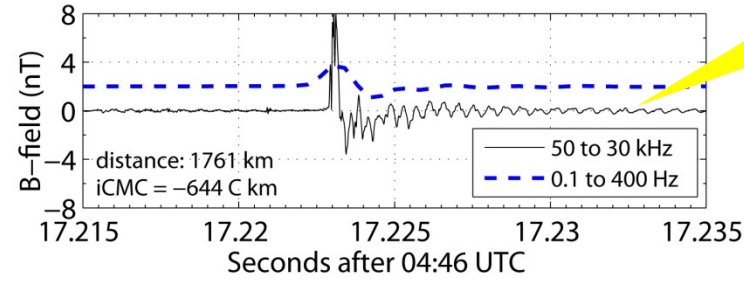
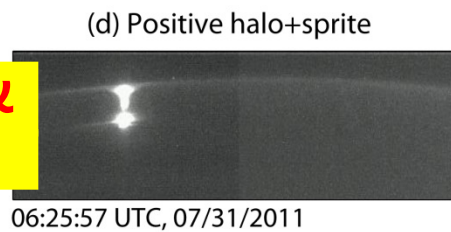
负极性光晕 & 红色精灵



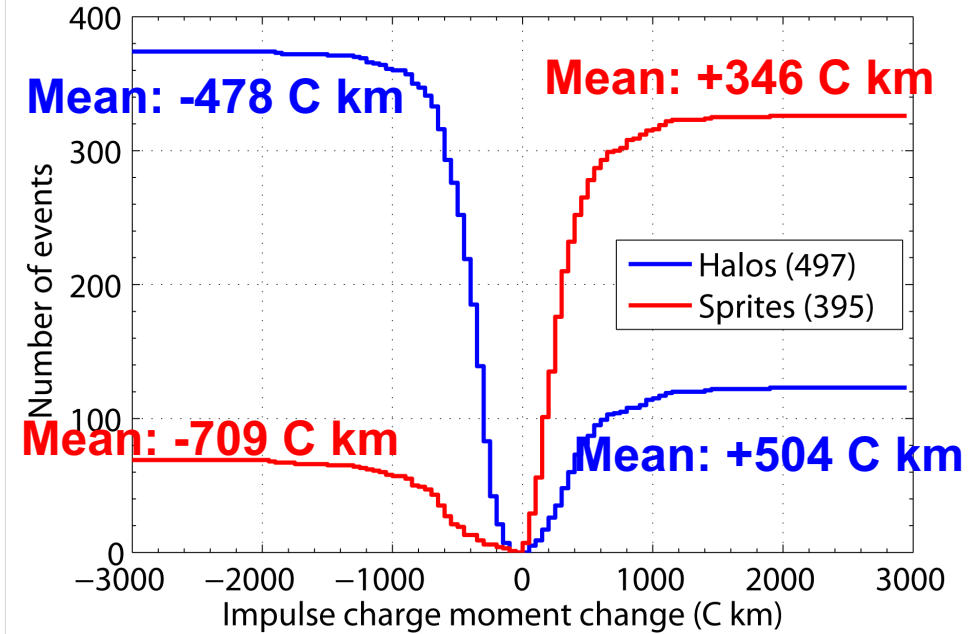
正极性光晕



正极性光晕 & 红色精灵



同步宽频磁场信号 (确定雷电极性与强度)



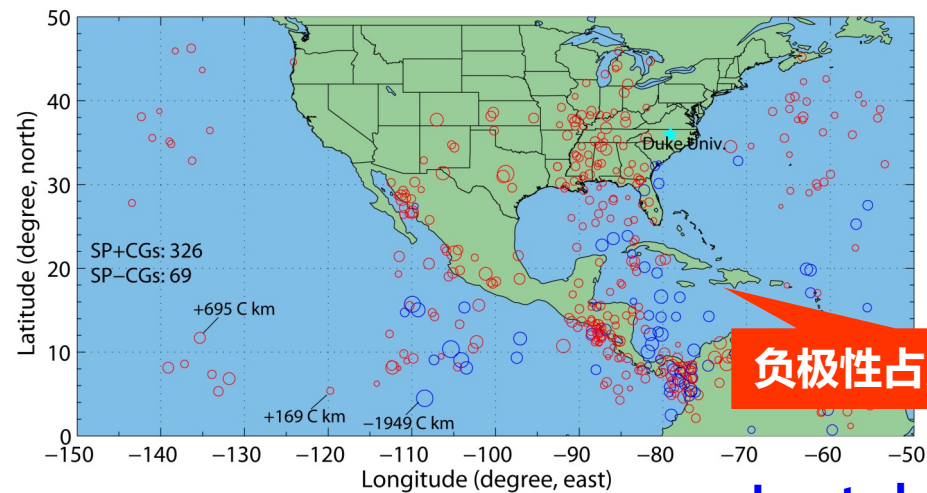
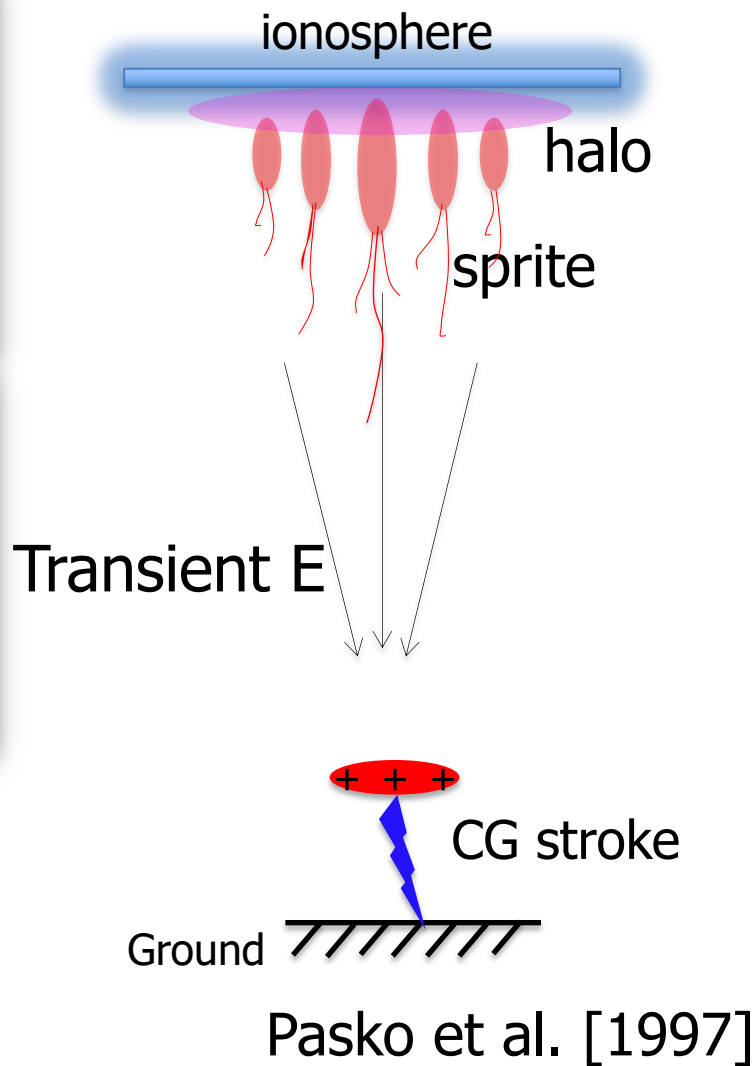
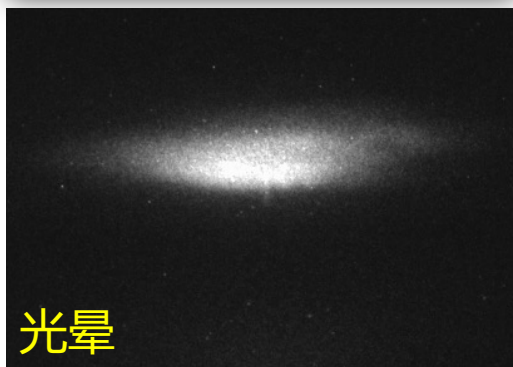
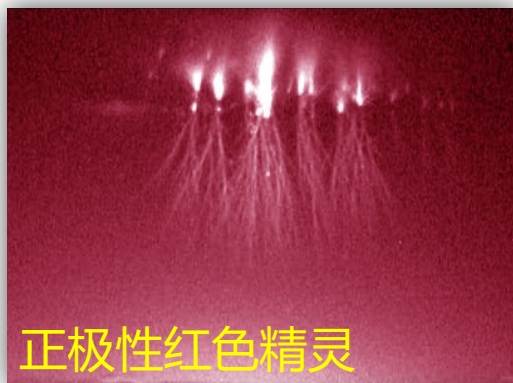
- 光晕的形成没有明显的母体闪电极性依赖性
- 负极性红色精灵的产生需要更大的脉冲电荷矩

Lu et al. (2017)

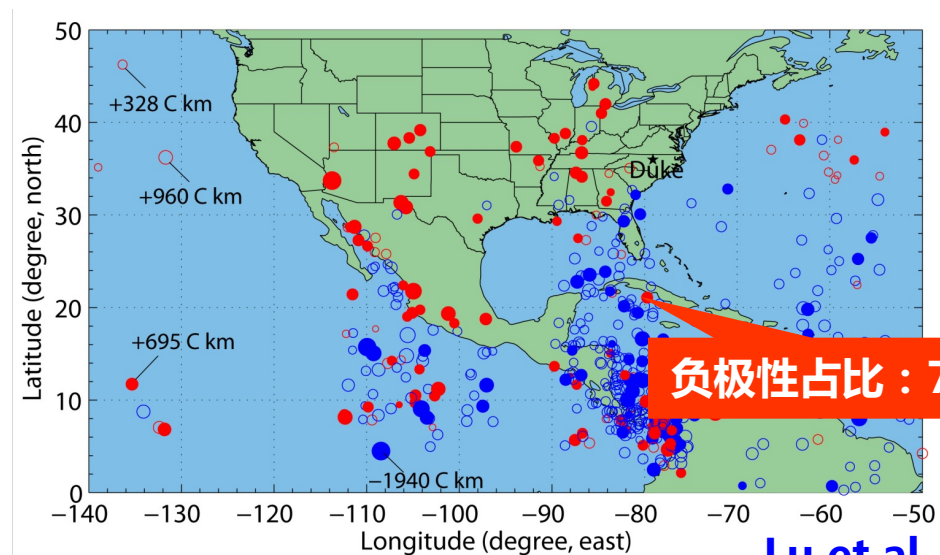
7/22/22

# 红色精灵-光晕在海陆地区的主导极性差异

红色-正极性；蓝色-负极性



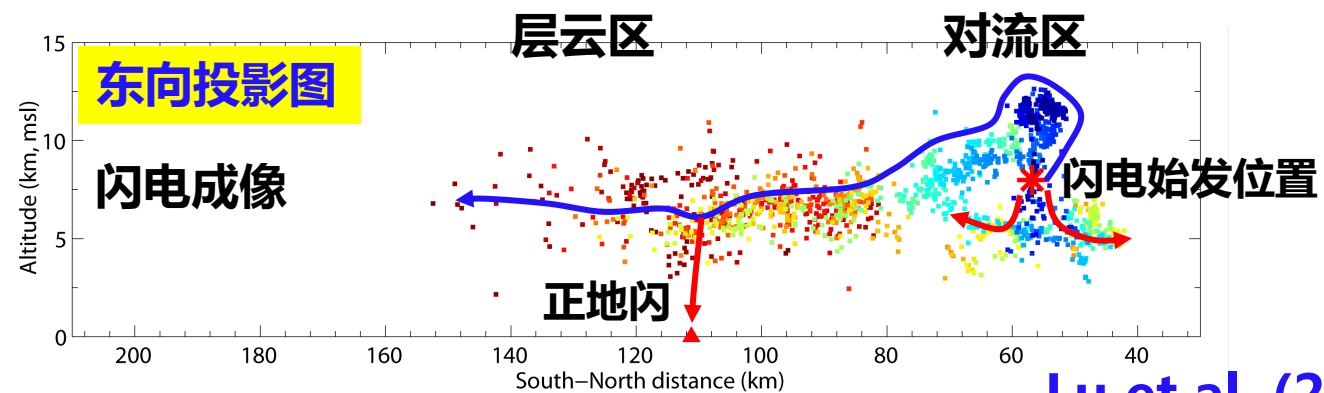
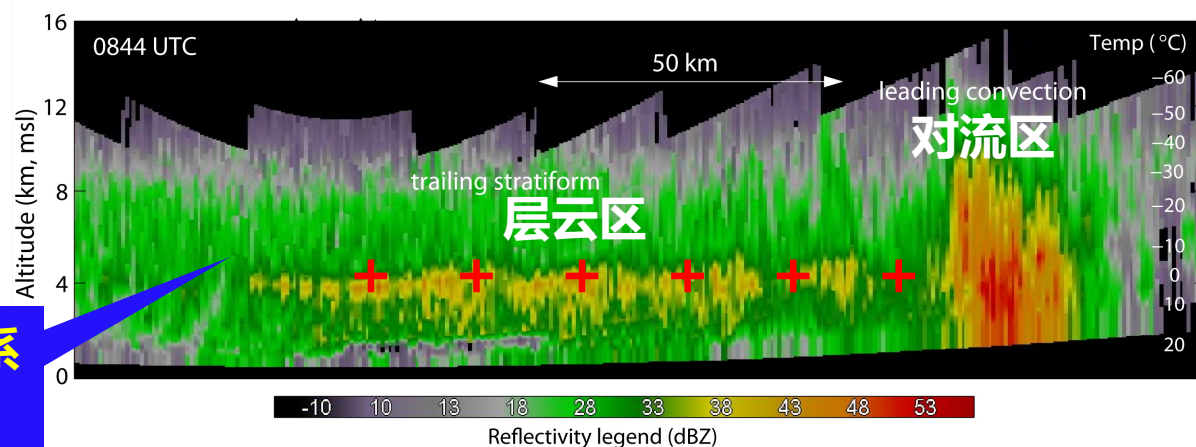
Lu et al. (2017)



Lu et al. (2018)

# 正极性 “红色精灵” 母体闪电的典型形态特征

中尺度对流系统  
雷达剖面



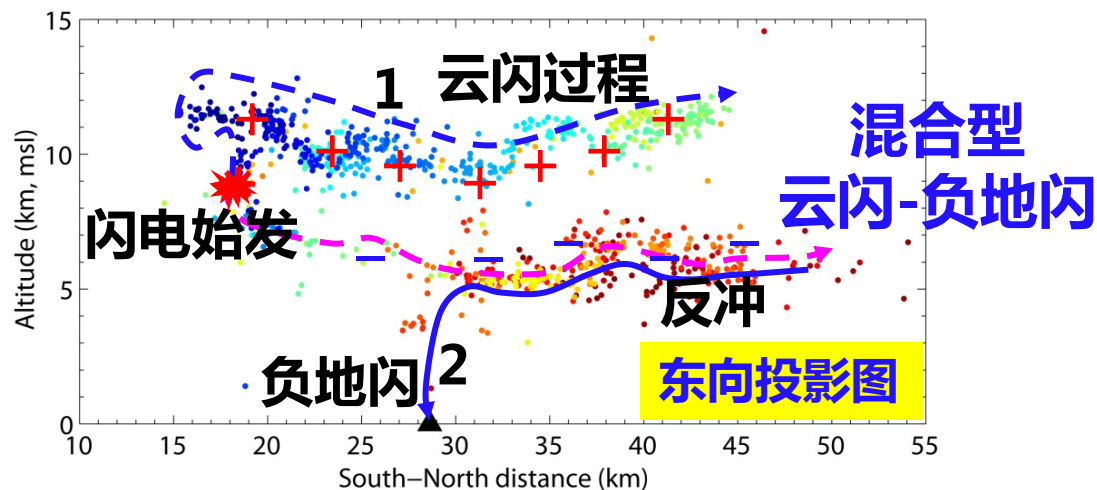
Lu et al. (2013)

- 中尺度对流系统中“红色精灵”母体闪电一般从对流区开始，并发展到层状云区后产生对地电荷释放，产生“红色精灵”



# 负极性“红色精灵”母体闪电的形态特征

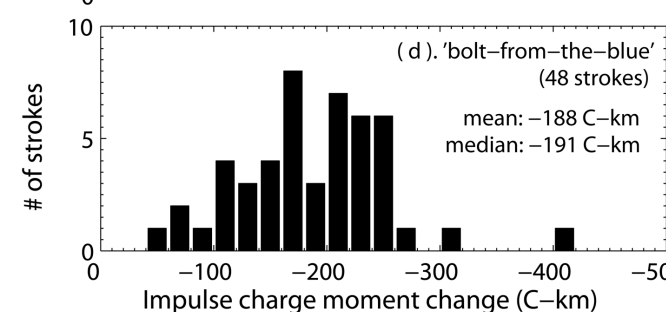
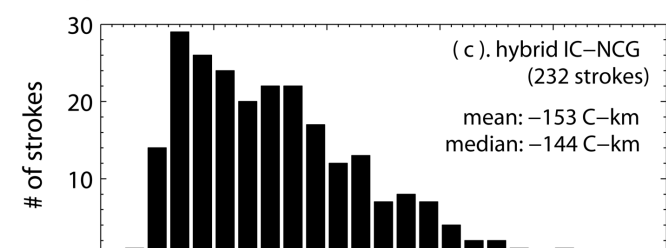
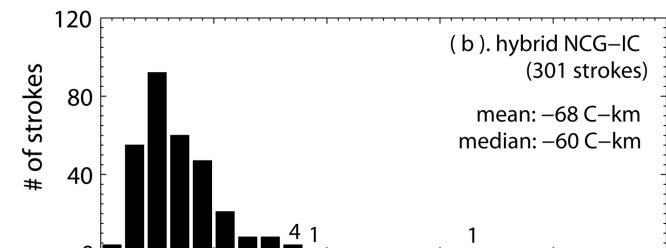
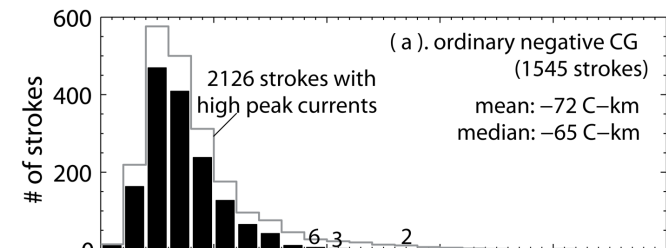
产生“红色精灵”  
的负地闪类型



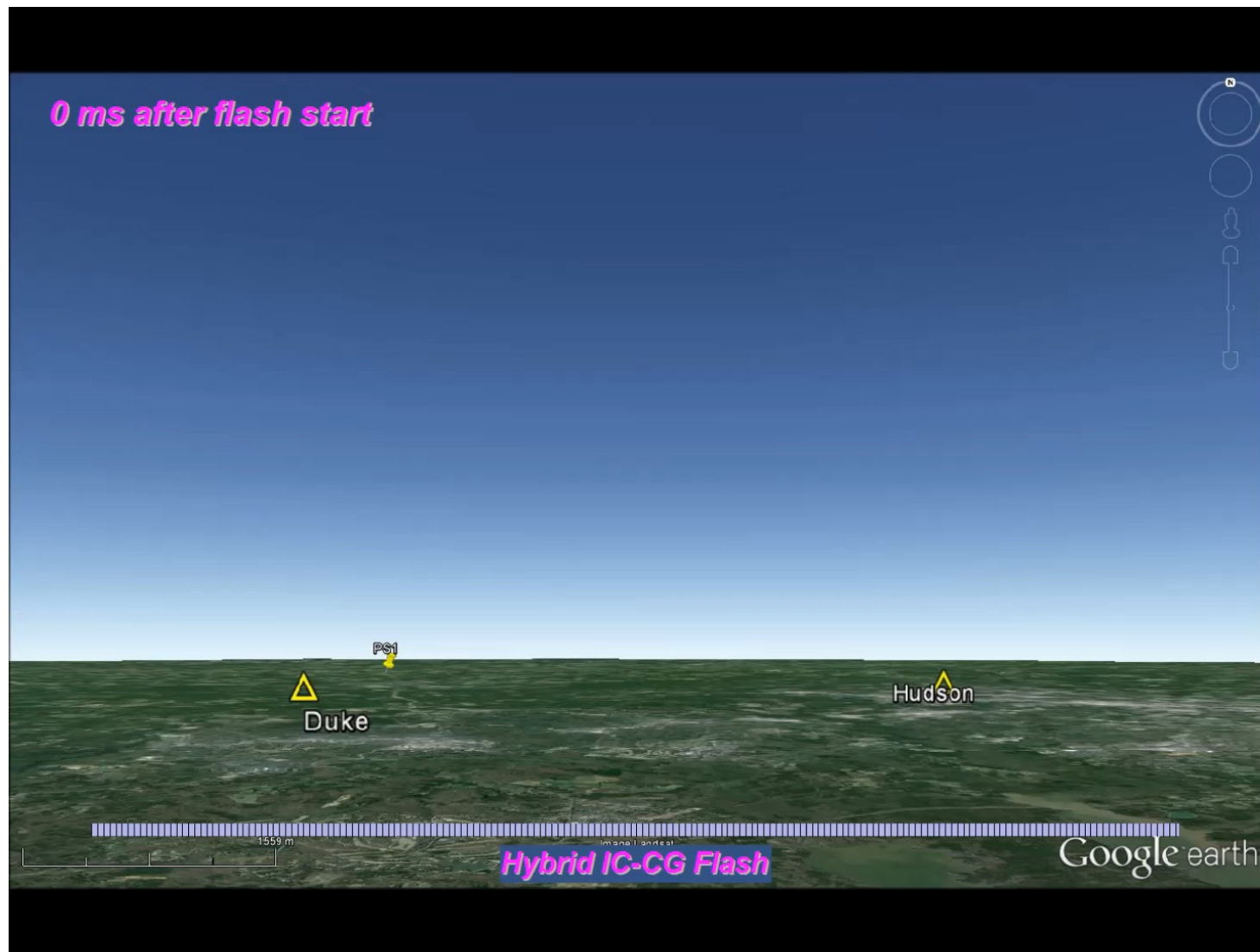
## 其它类型的负地闪



Lu et al. [2012JGR]

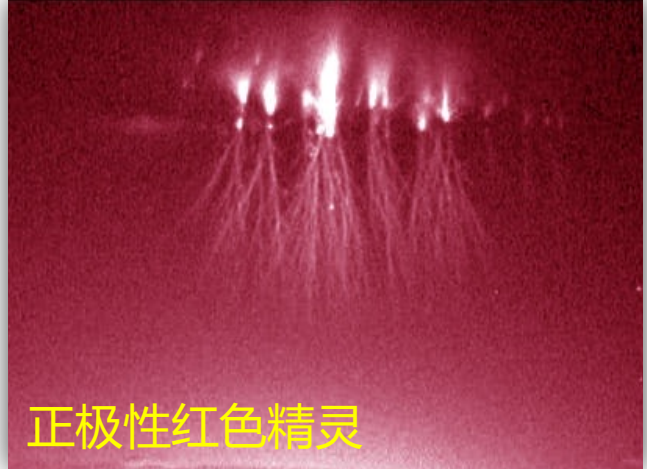
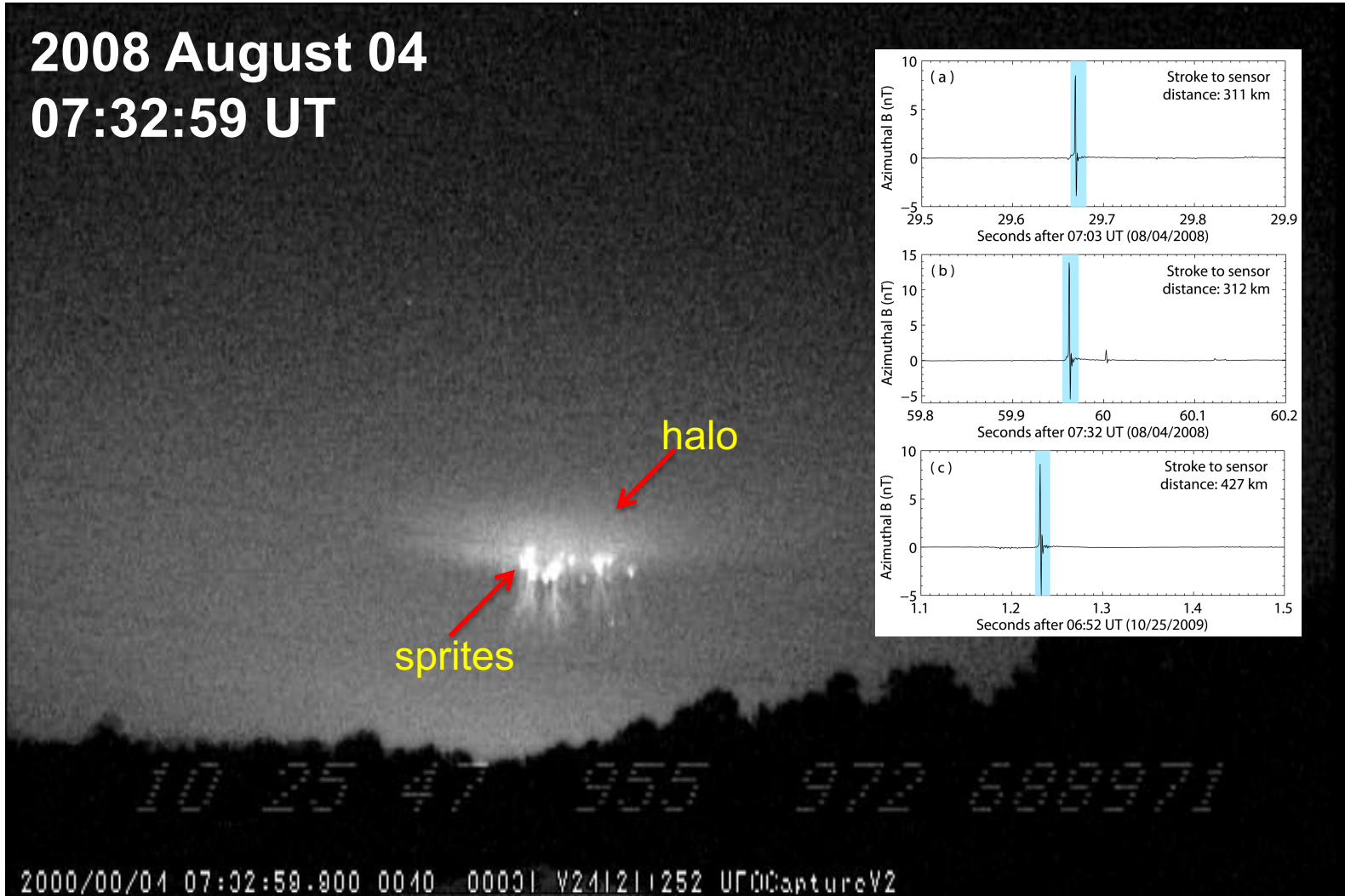


# 一次混合式云闪-负地闪的三维成像



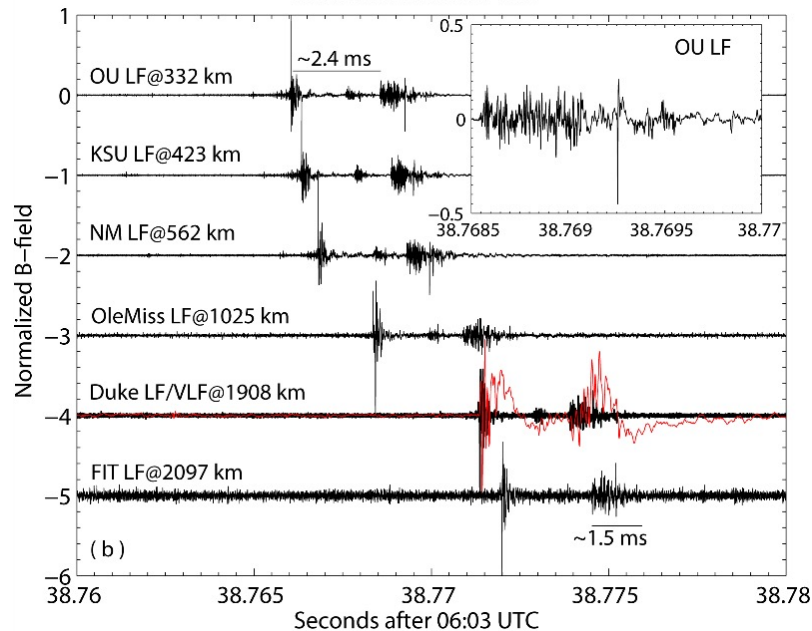
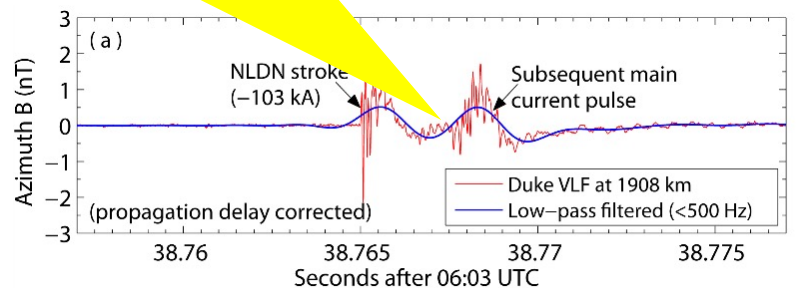
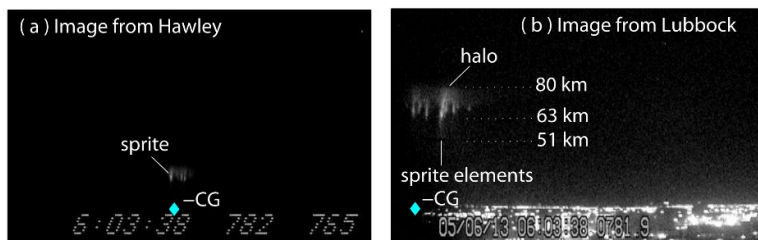
由吕凡超提供

# 目前研究重点-负极性 “红色精灵”

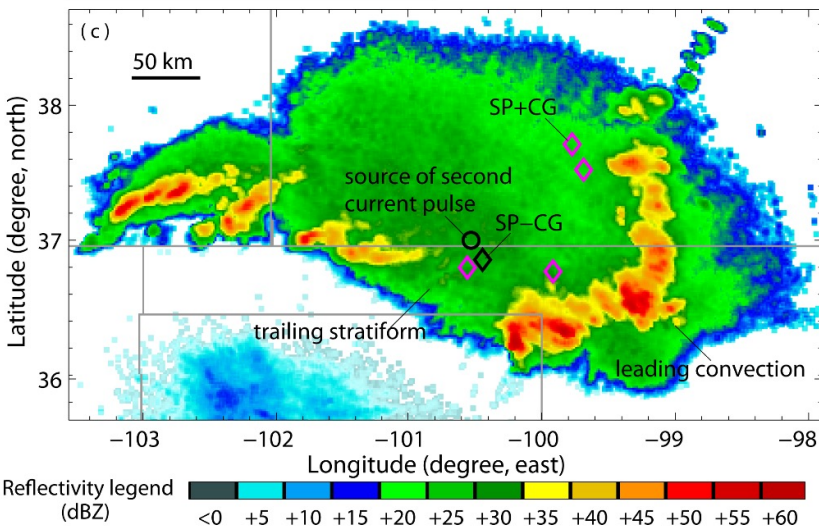
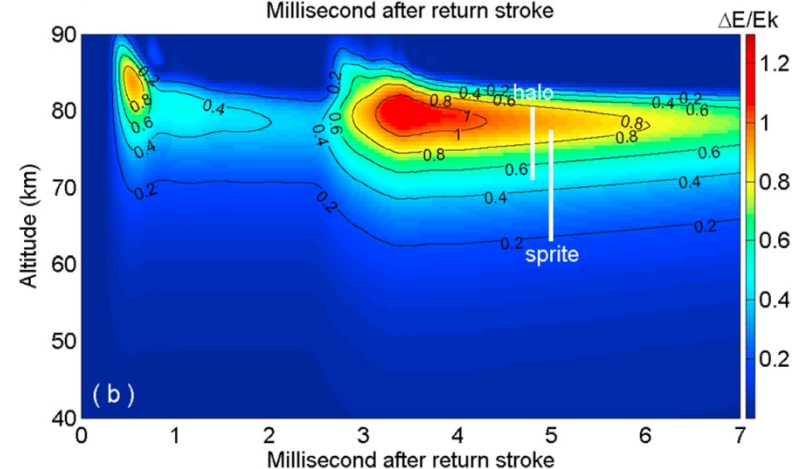
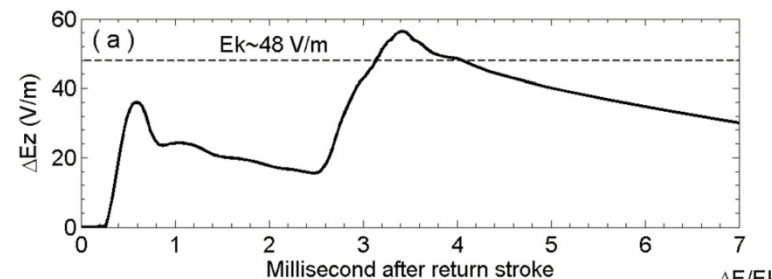
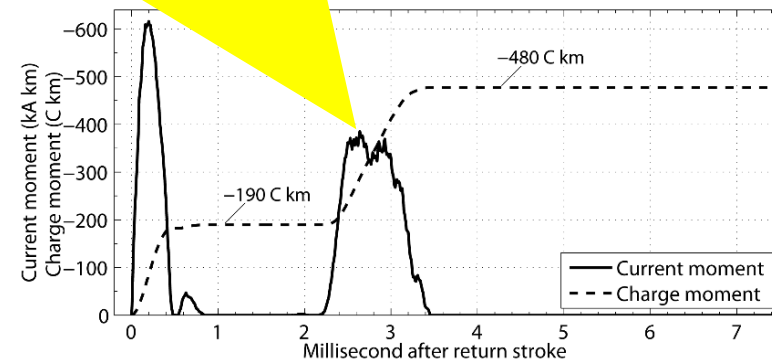


# 反常个例一：一般负地闪产生的红色精灵

## 多站射频磁场数据

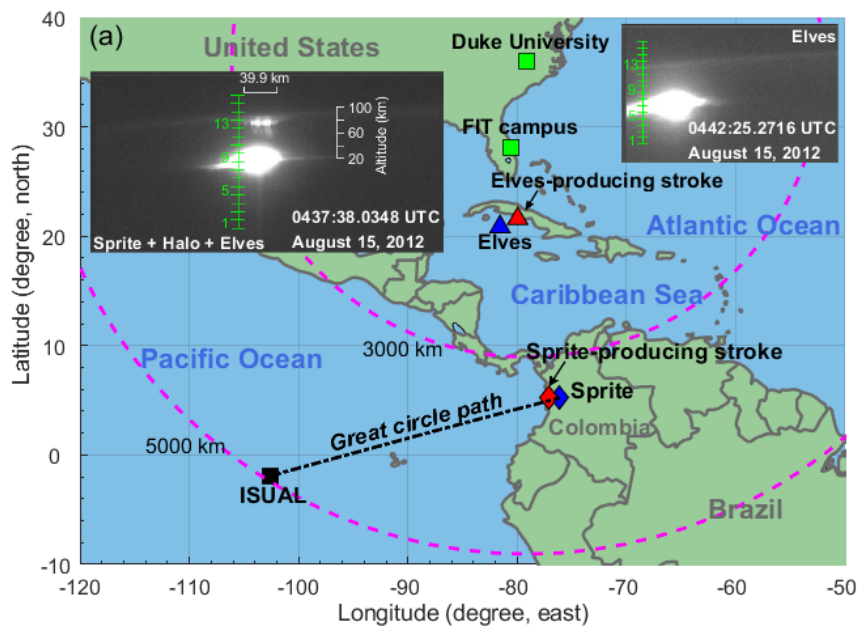


M过程导致的额外电荷传输加强了中高层电场扰动



Lu et al. (2016)

# 反常个例二：负极性“红色精灵”的电流信号

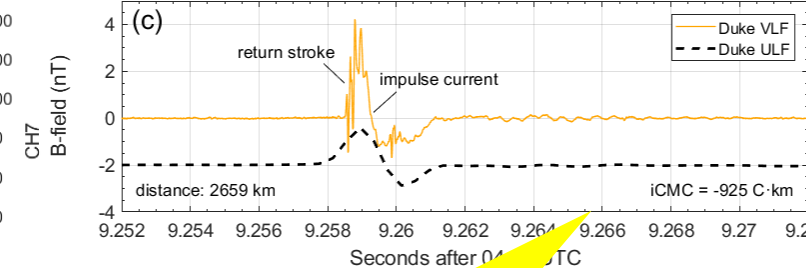
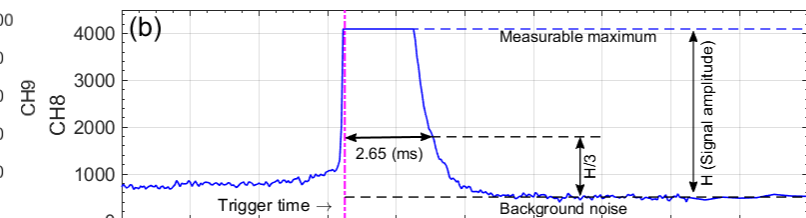
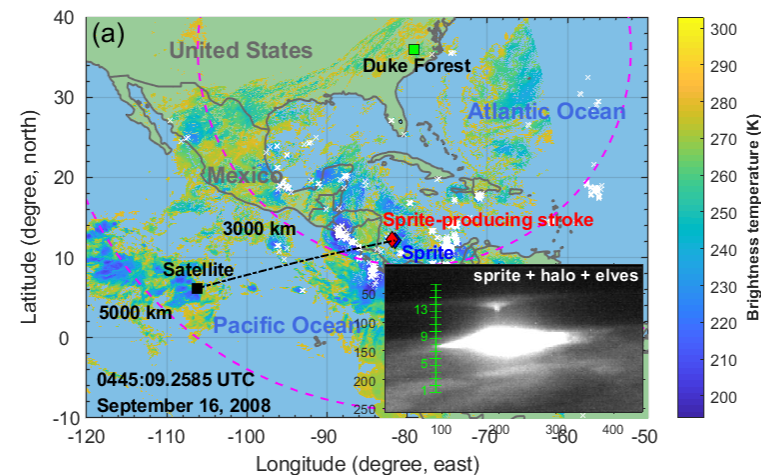
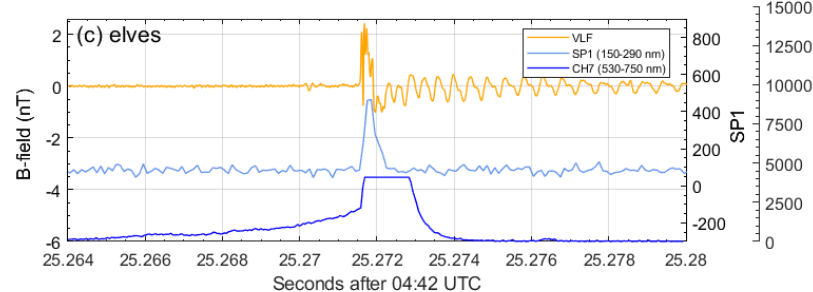
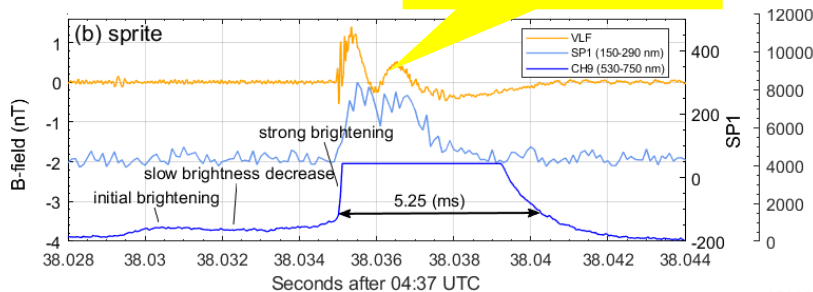


Wang et al. (2021)

- 母体闪电电流持续时间格外的长 (超过4毫秒)
- 电离层底部区域是否存在一些异常状态?

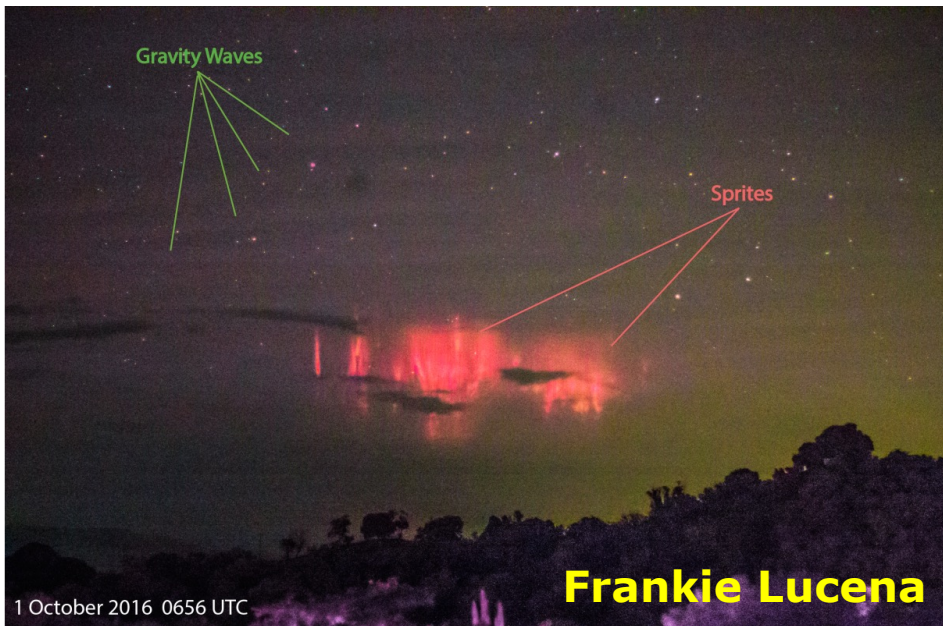
➤ 首次观测到负极性红色精灵的超低频电流信号

为什么?

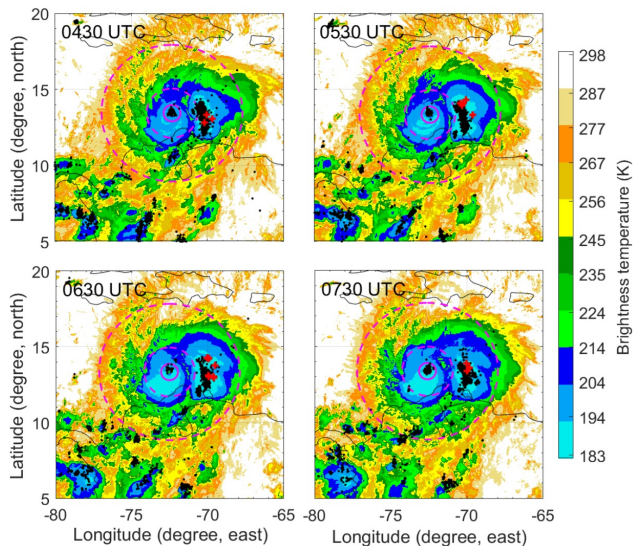
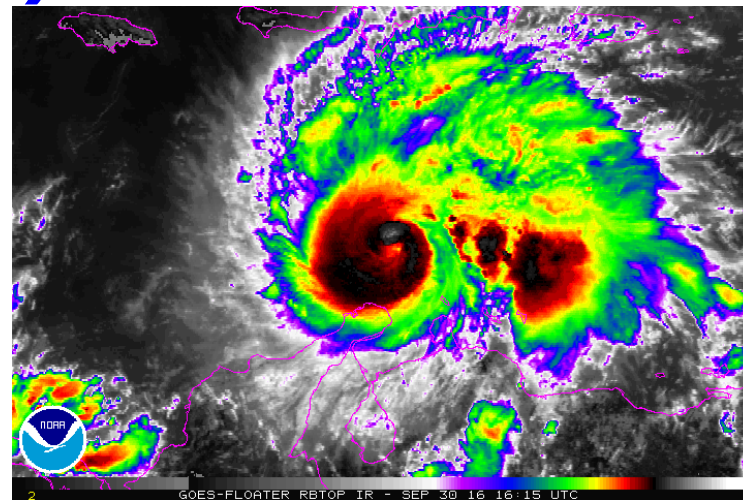


一般个例

# 个例分析：Hurricane Matthew (2016)

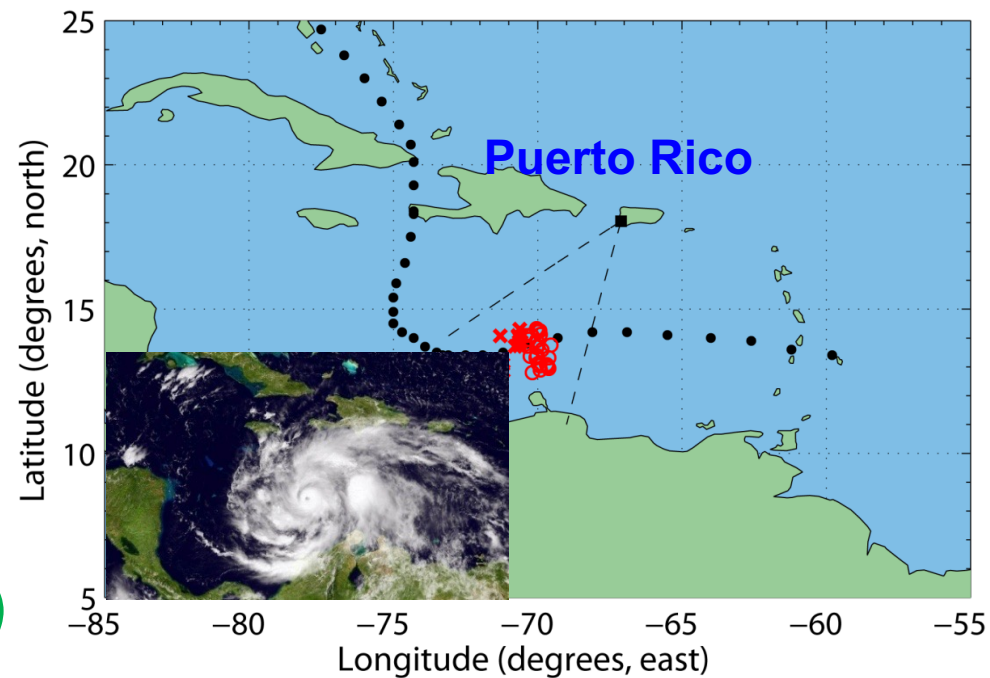


2016年10月1日：  
30 sprites  
2016年10月2日：  
11 sprites



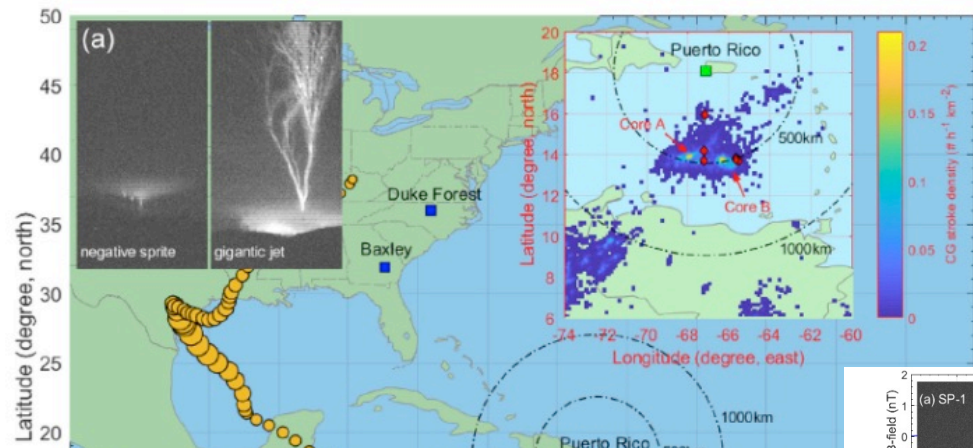
- 全部为正极性红色精灵
- 产生于外雨带云系，类似于陆地中尺度对流系统的层状云区

Huang et al. (2018)



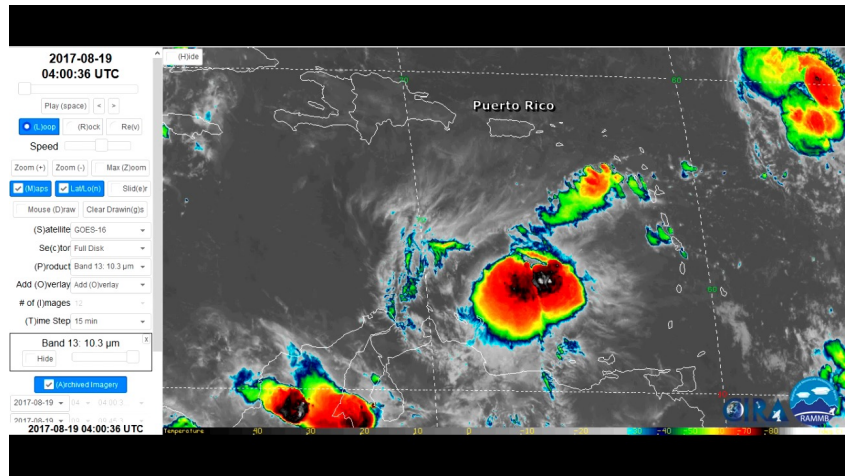
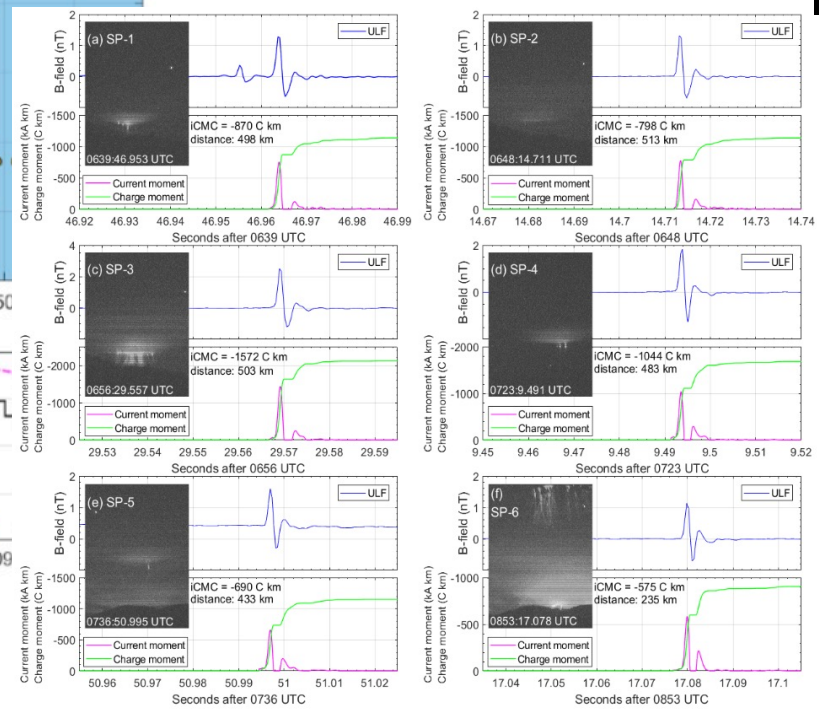
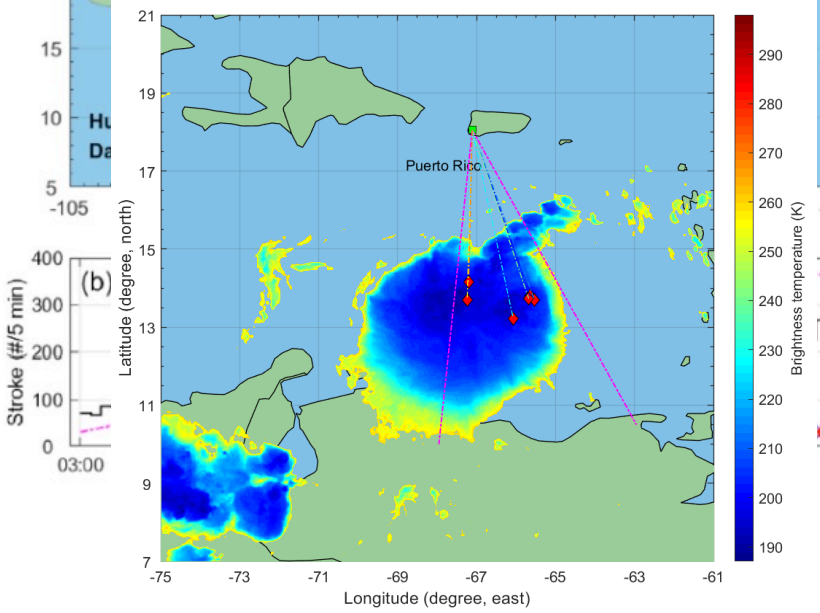
# 个例分析-热带风暴哈维Harvey (2017)

➤ 共产生7次巨型喷流和6次红色精灵（全部为负极性）

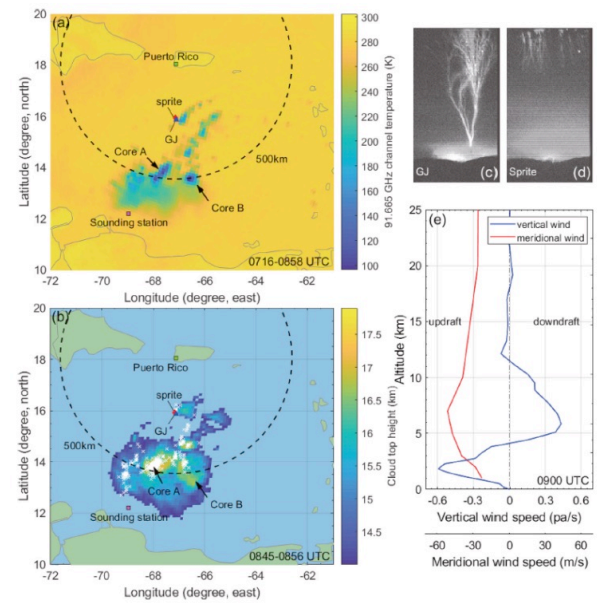


➤ 全部为单回击闪电过程

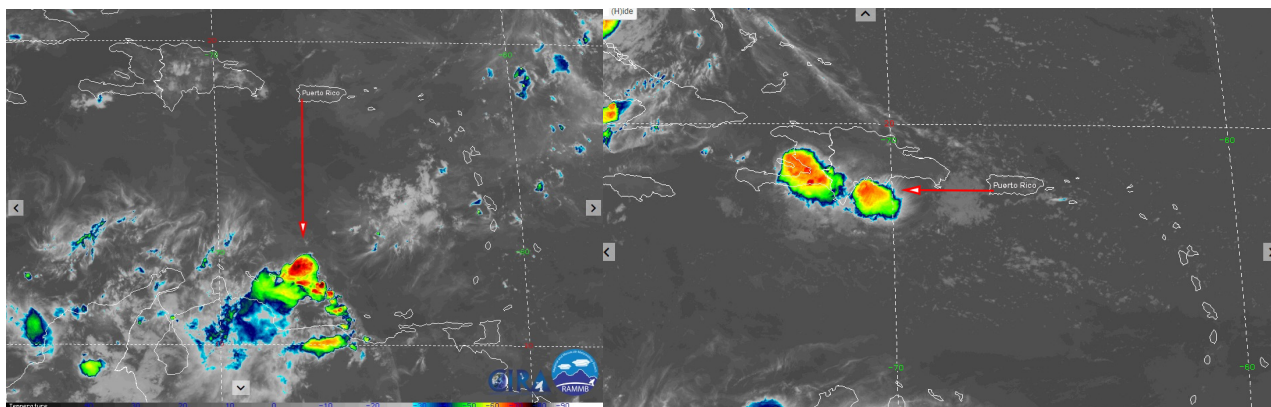
➤ 红色精灵形态特征和母体闪电强度特征均和陆地雷暴个例相似



Wang et al. (2021)

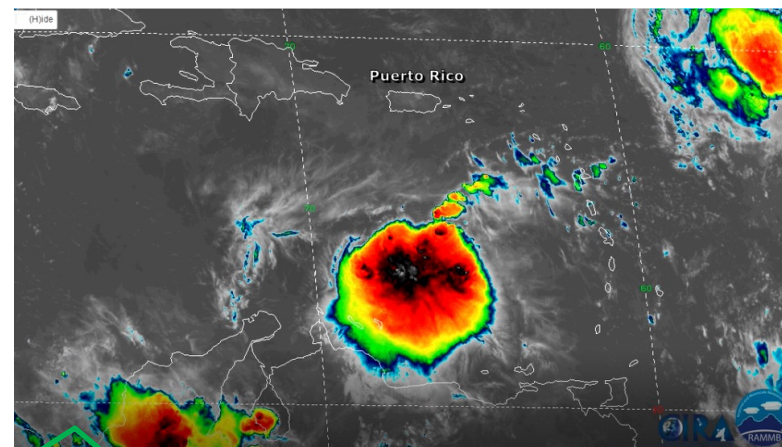


# 不同海洋雷暴类型产生红色精灵差异-初步结果



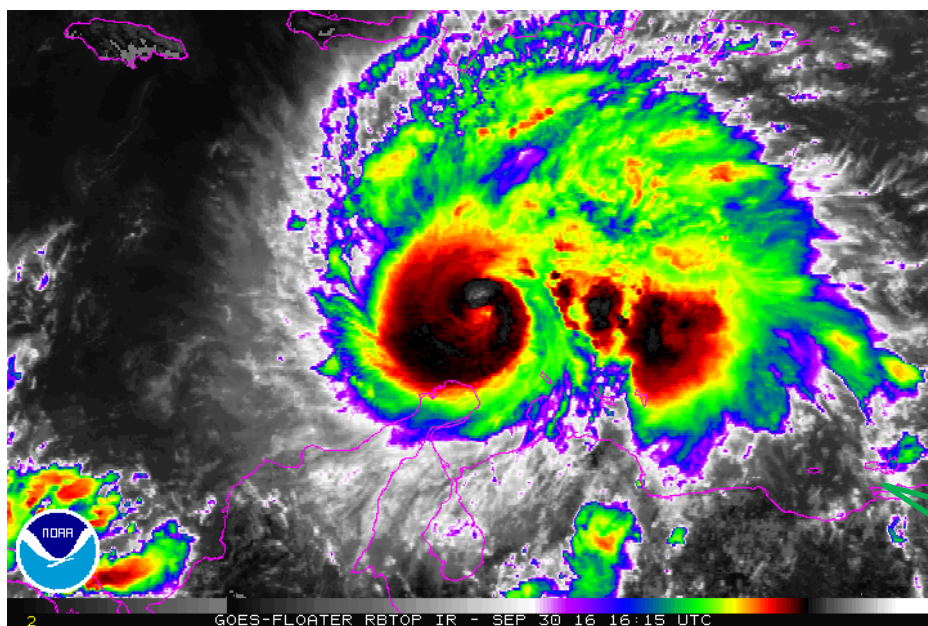
王庸平等 (2021)

海洋小单体雷暴，以产生正极性红色精灵为主（同“两洋一海”赤道地区类似？）



Wang et al. (2021)

热带风暴主要产生负极性红色精灵，体现海洋雷暴同陆地雷暴的差异

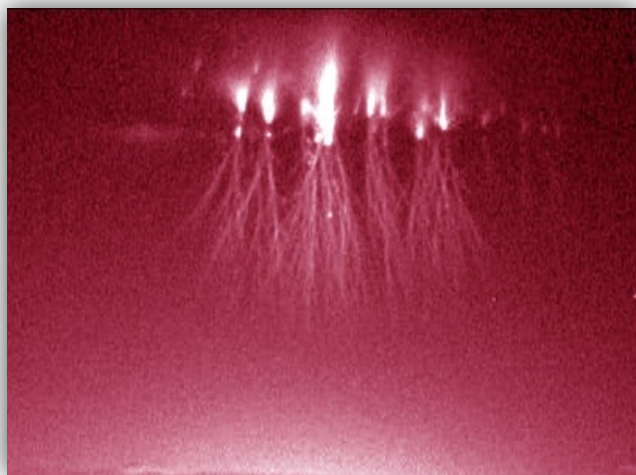


Huang et al. (2018)

飓风产生红色精灵集中在外雨带，并以正极性为主（类似陆地中尺度对流系统）



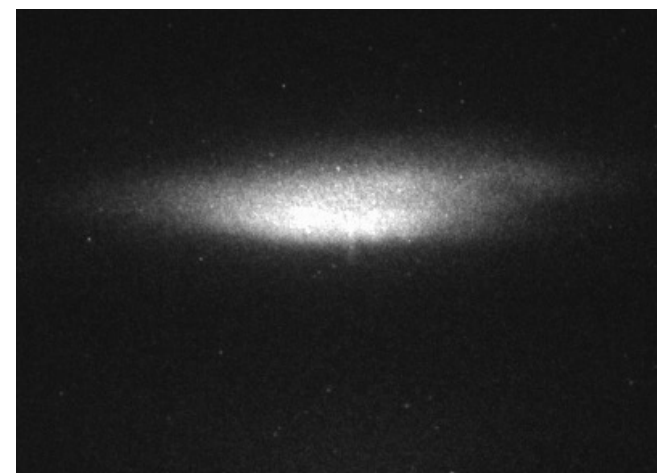
# 报告内容小结 (后面还有20多页)



正极性红色精灵



负极性红色精灵

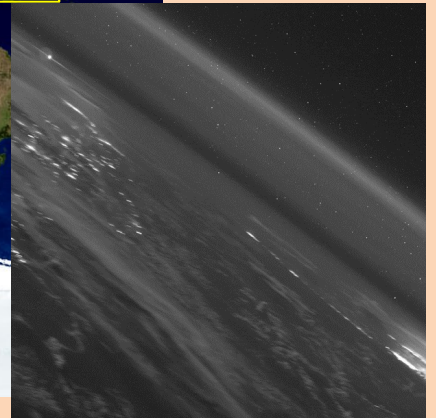
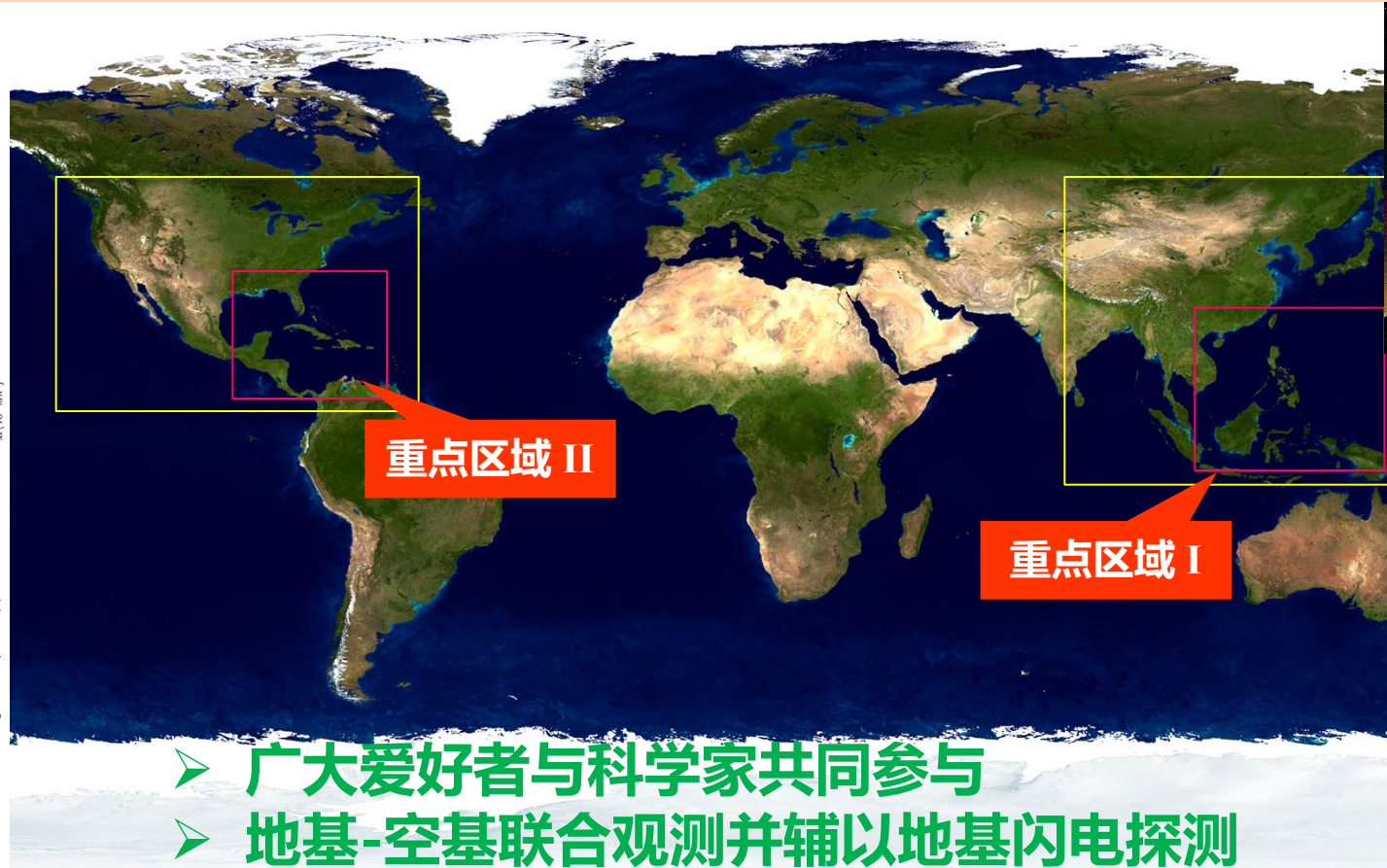
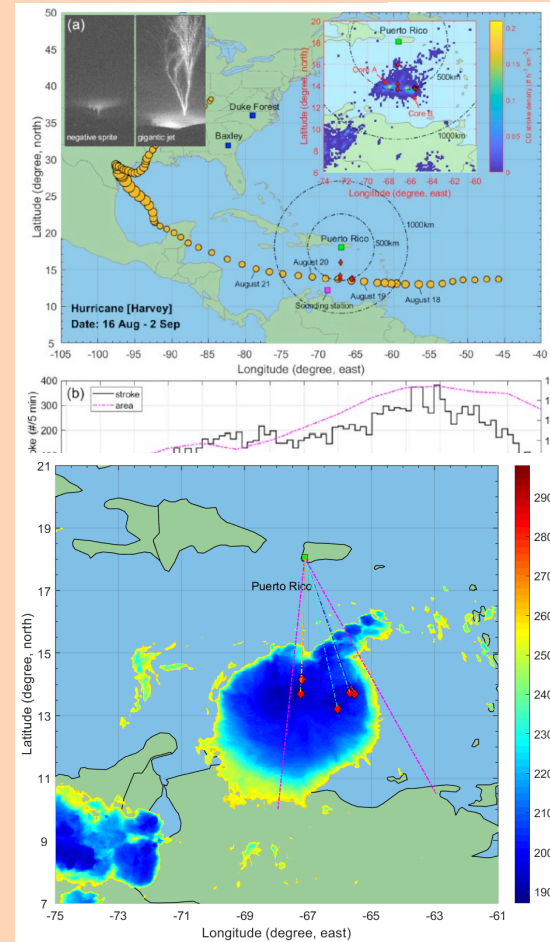


光晕

1. 大陆上的红色精灵绝大多数由正极性地闪产生 ( $>99\%$ )
2. 海洋性雷暴能产生较多的负极性红色精灵 ( $\sim 18\%$ ).
3. 至于光晕, 海洋性雷暴产生的负极性地闪占据了主导地位 ( $\sim 75\%$ ).
4. 正、负地闪的不同放电尺度是红色精灵形态极性差异的主要原因。

**海洋中的负极性地闪 (或雷暴) 为什么如此不同?**

# 海陆地区雷暴中高层放电现象的差异性研究



- 广大爱好者与科学家共同参与
- 地基-空基联合观测并辅以地基闪电探测

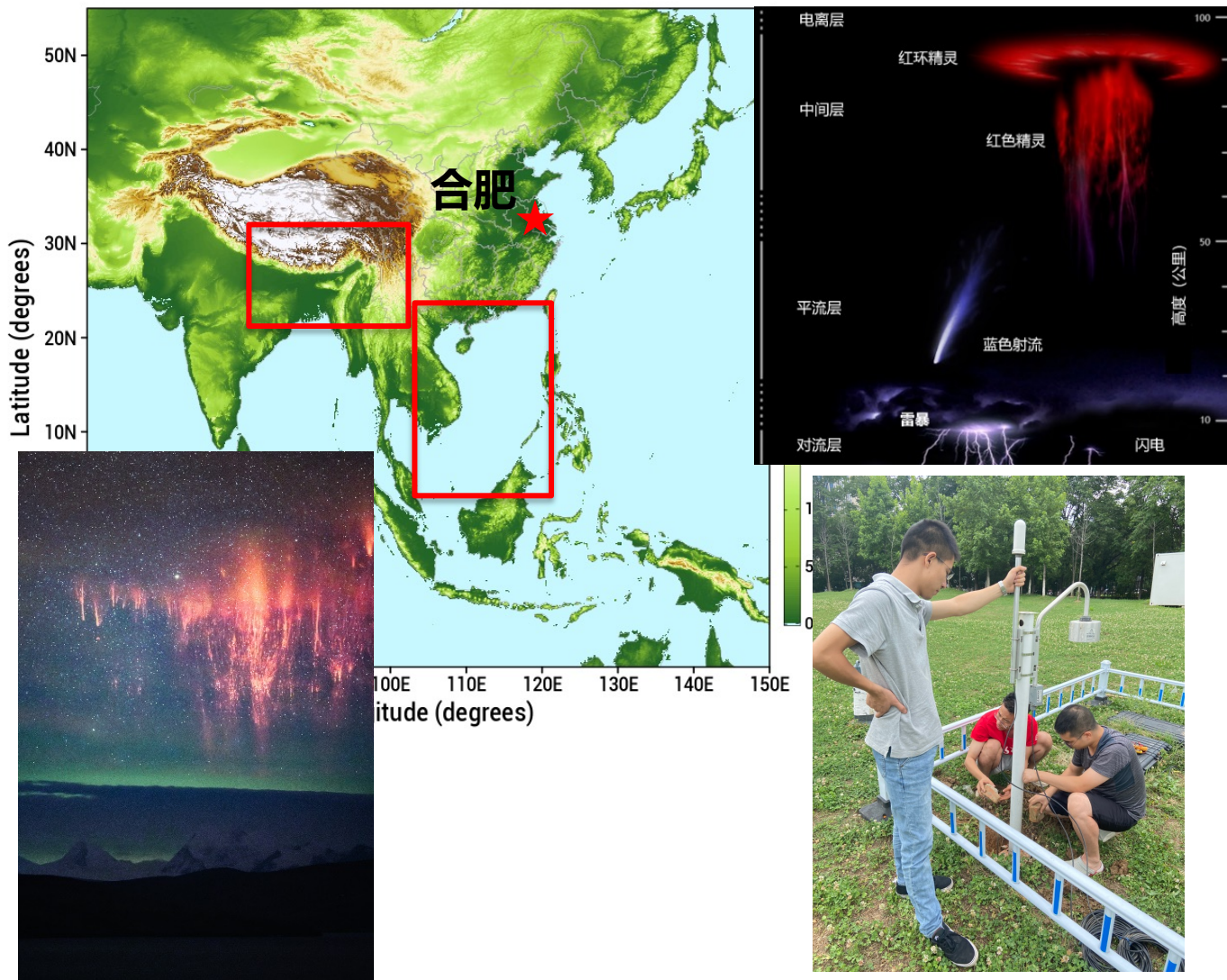
- 对地电荷传输时间尺度影响中高层放电事件形态
- 海陆地区的雷暴电荷结构有何区别？

王庸平等(2021)

Ren, Lu\* et al. (2021@GRL)

Wang, Lu\* et al. (2021@JGR)  
Wang, Lu\* et al. (2021@GRL)

# 亚太地区雷暴临近空间电磁效应研究



➤ 中国大陆三级阶梯地形下的中高层放电现象母体雷暴特征；

➤ 海陆地区中高层放电现象母体雷暴特征的比较研究；

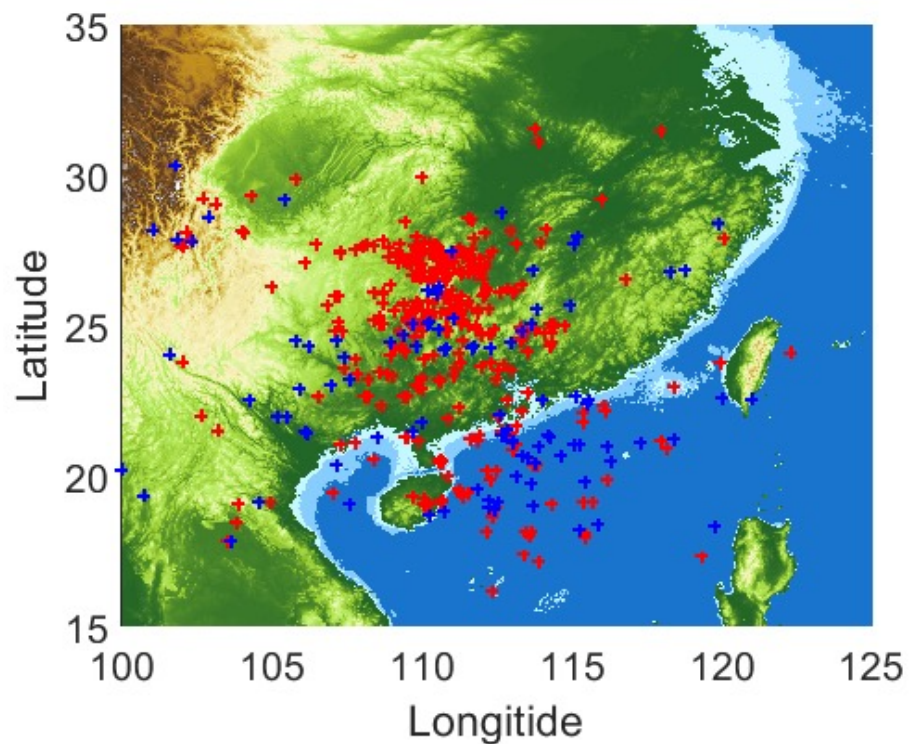
➤ 混合下垫面情形下的地球-电离层波导天电信号传播特征；

➤ 不同类型中高层放电现象对低电离层区域的影响研究；

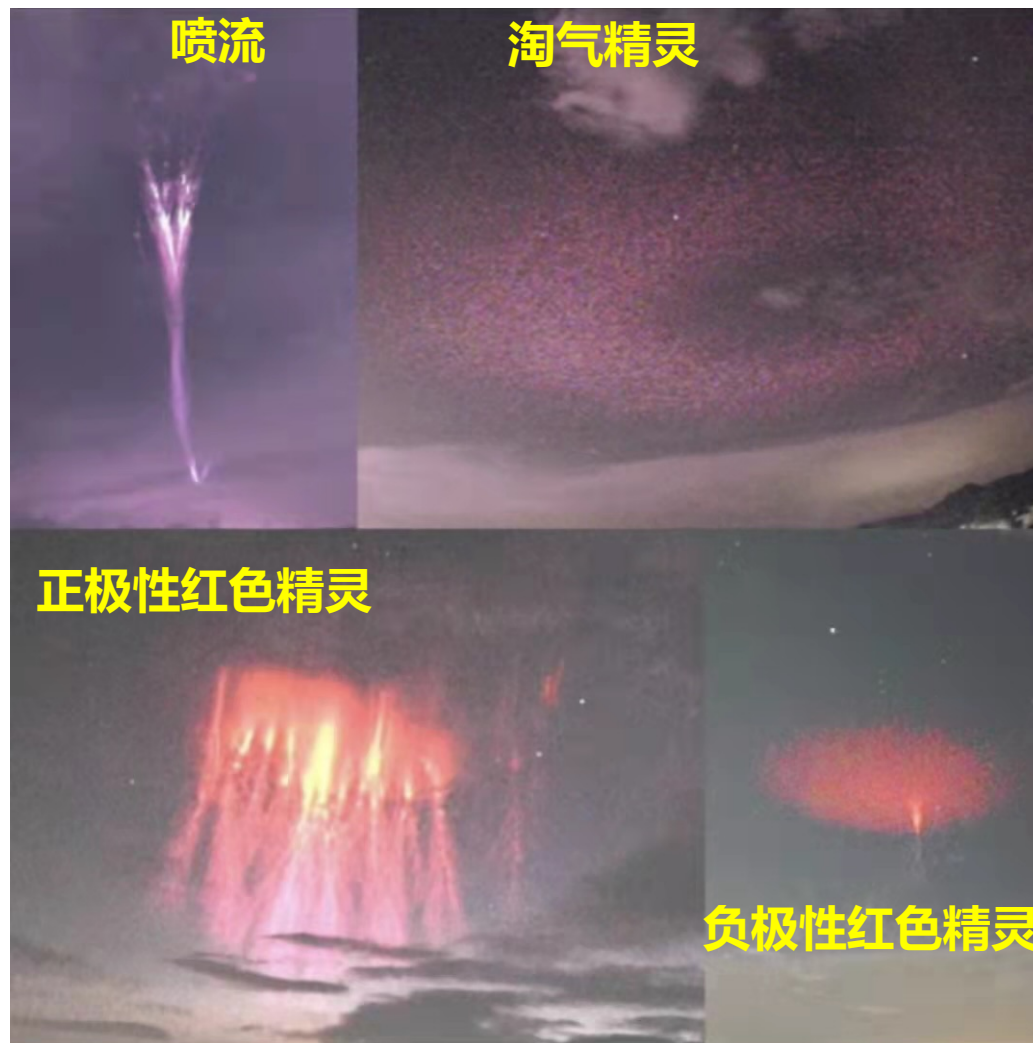
➤ 人工智能方法在对流层雷暴-中高层大气电磁耦合研究中的应用。

2022年5月20日青藏高原南麓精灵群事件

# 2021年中高层放电现象爱好者地基观测结果

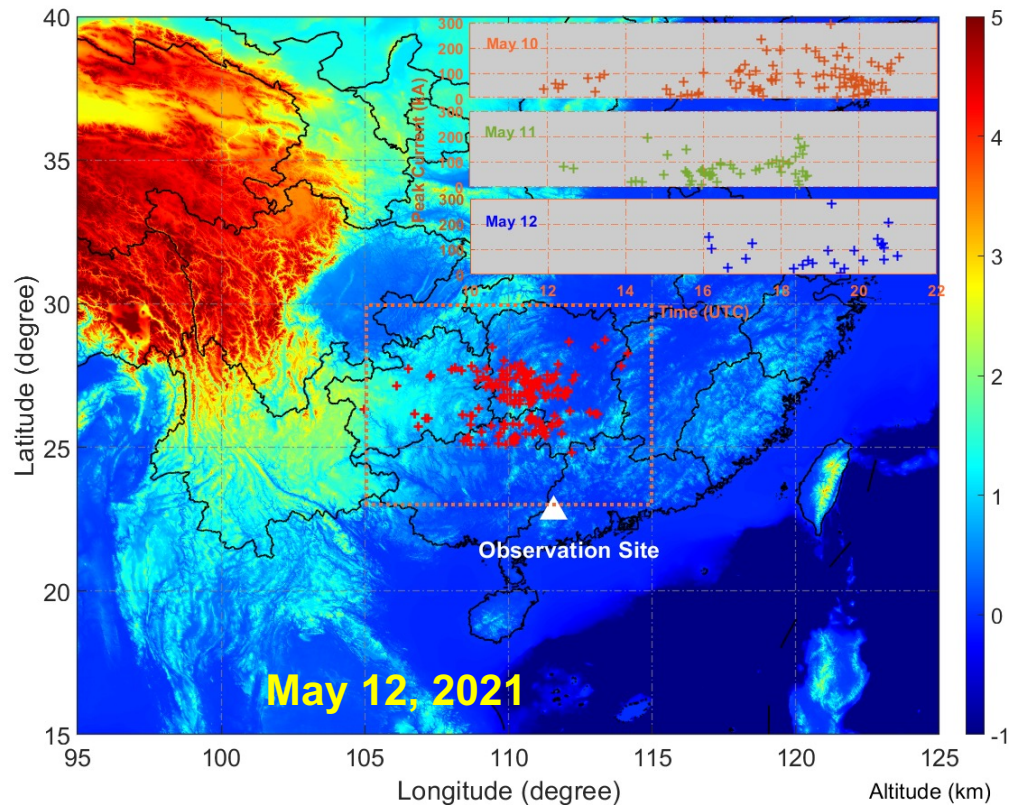


- 20余次巨大喷流
- 20余次负极性红色精灵
- 4次淘气精灵
- 2次光晕

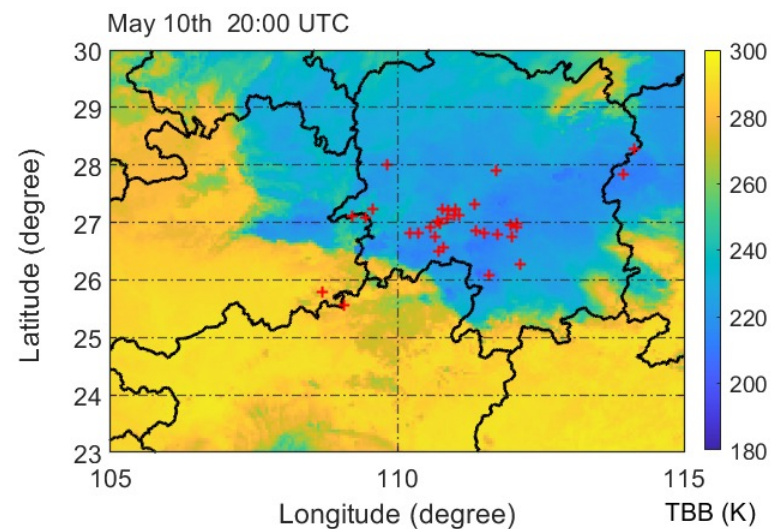
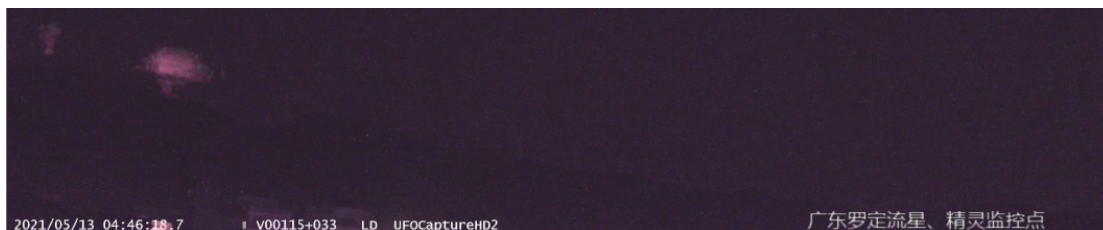


# 2021年5月10-12日特大精灵群事件

➤ 迄今为止东亚地区记录到的最大规模的红色精灵发生

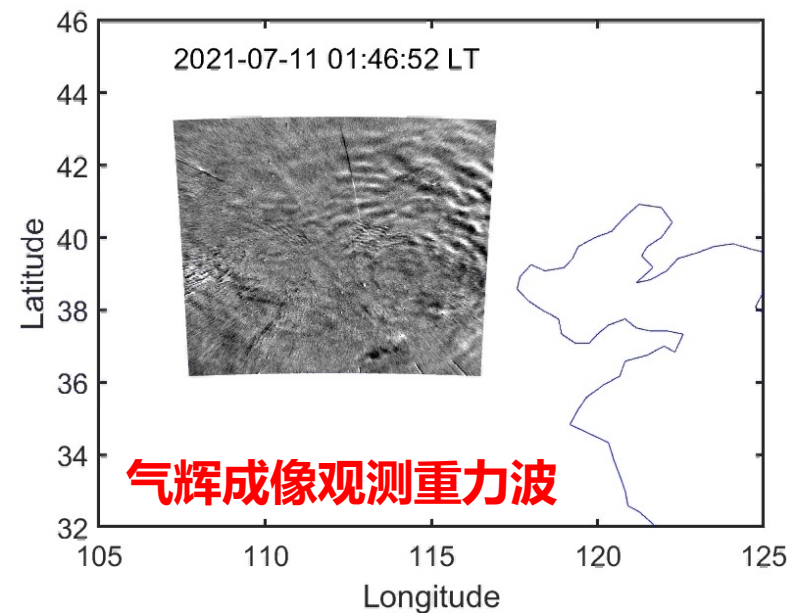
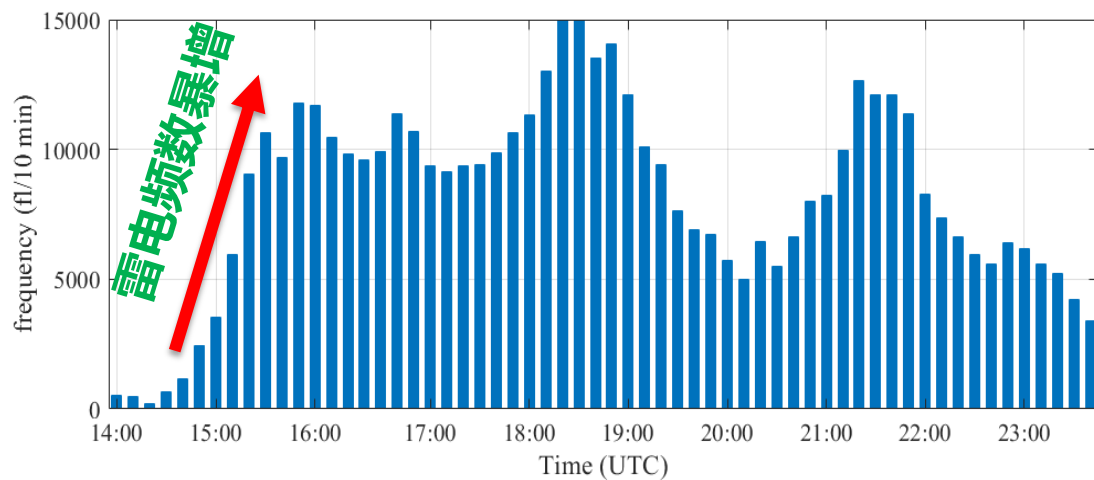
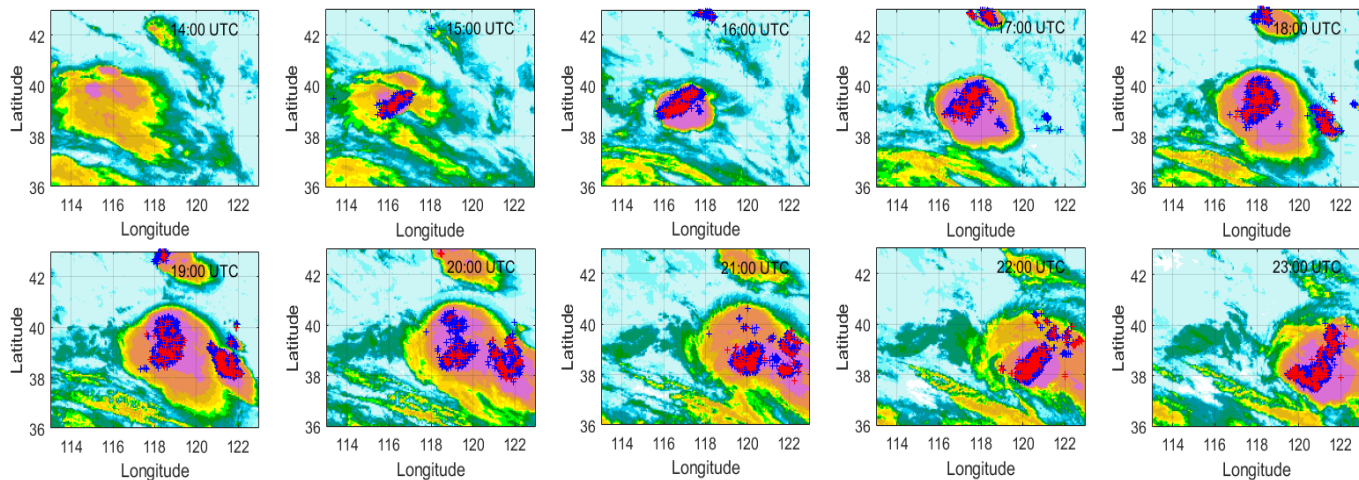


- 166次 精灵事件
- 持续三天精灵捕捉



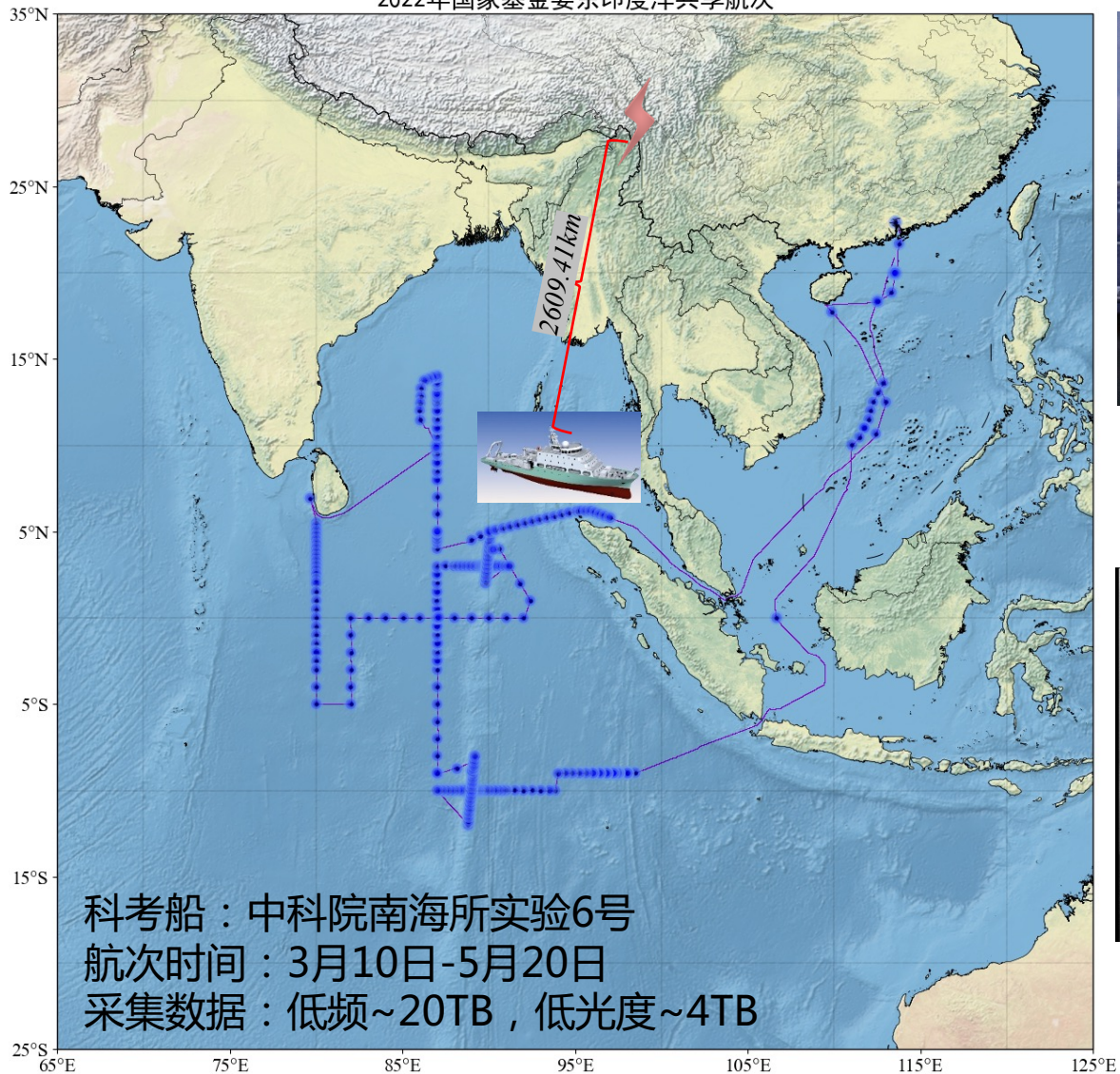
# 基于雷电探测的重力波事件预测

## 2021年7月11日凌晨京津冀地区一次强对流过程



# 2022年参加基金委东印度洋共享航次科考

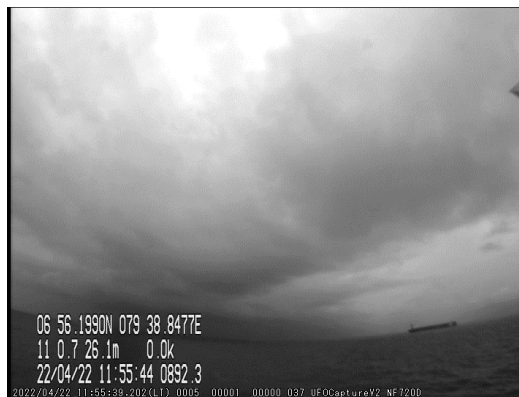
2022年国家基金委东印度洋共享航次



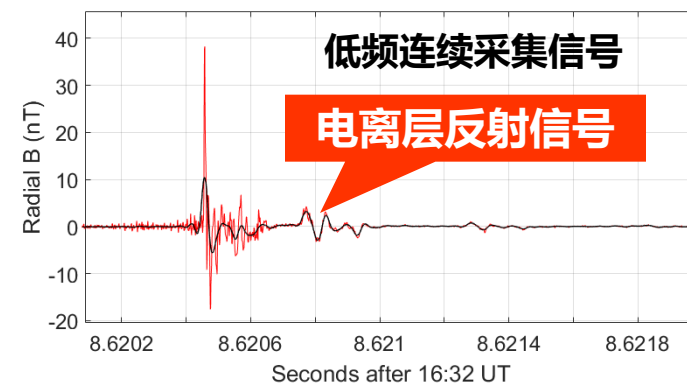
低频磁场+低光度光学



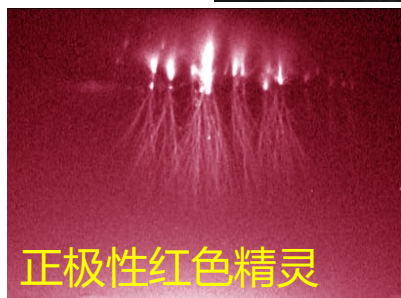
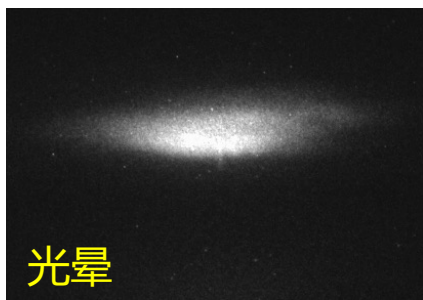
数据采集



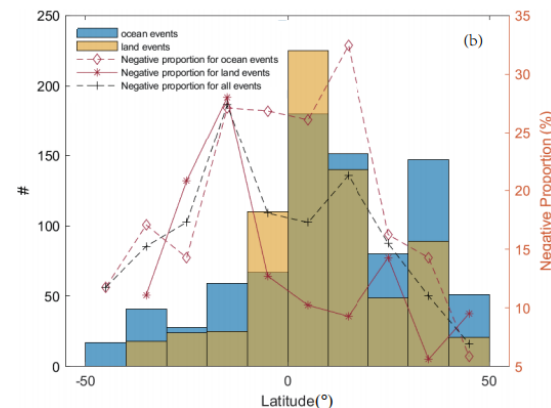
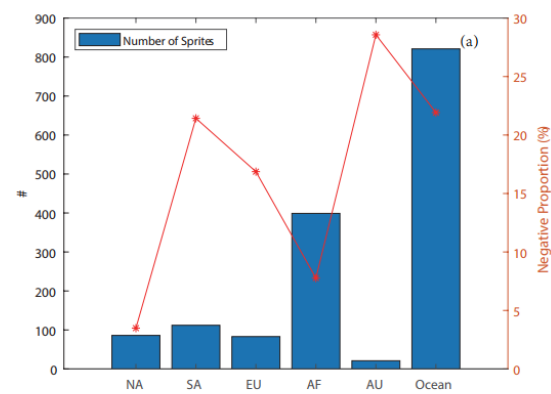
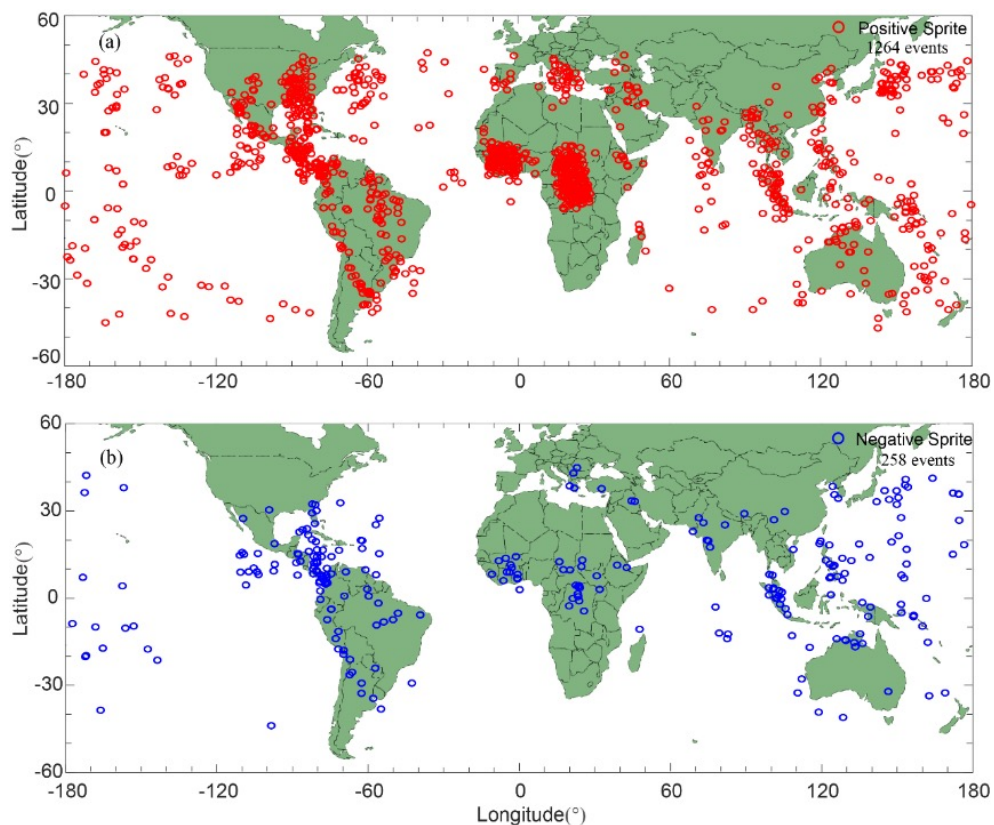
低光度相机记录的海洋雷暴



# 近期成果：人工智能方法获得正负红色精灵空间分布特征



- 以北美地区观测为训练数据集，利用机器学习方法对全球红色精灵观测进行极性判断，发现正、负极性红色精灵全球空间分布特征受到动力学和热力学两方面对雷暴特征的影响。

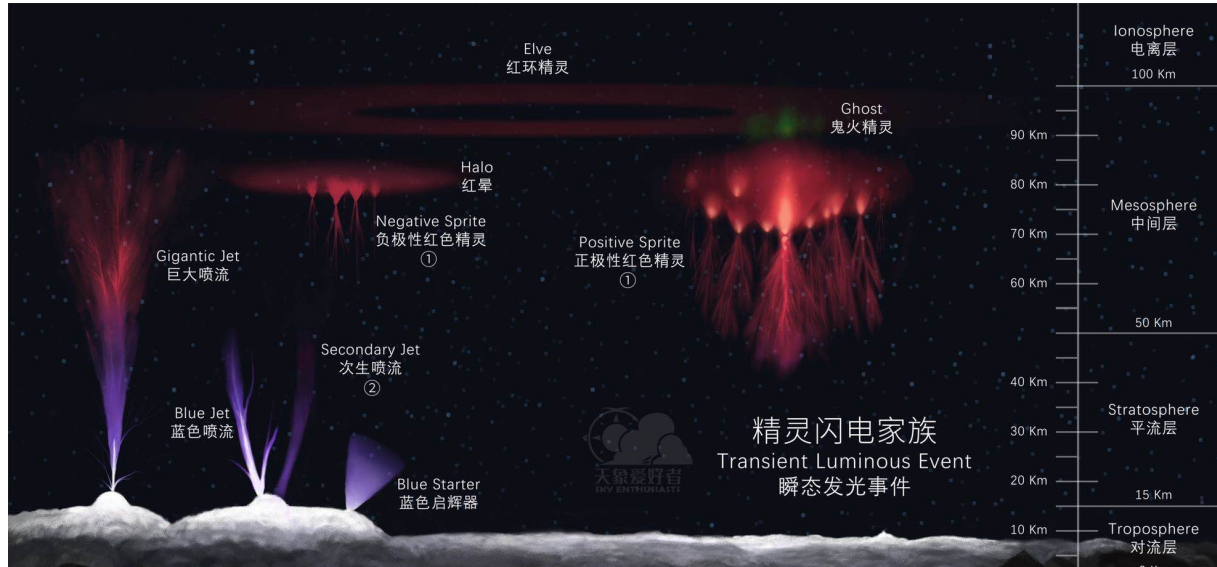


Wang et al. (submitted)

- 共识别了1522个事件，其中258个 (约17%) 为负极性
- 从红色精灵形态上，能实现近94%的极性识别准确率

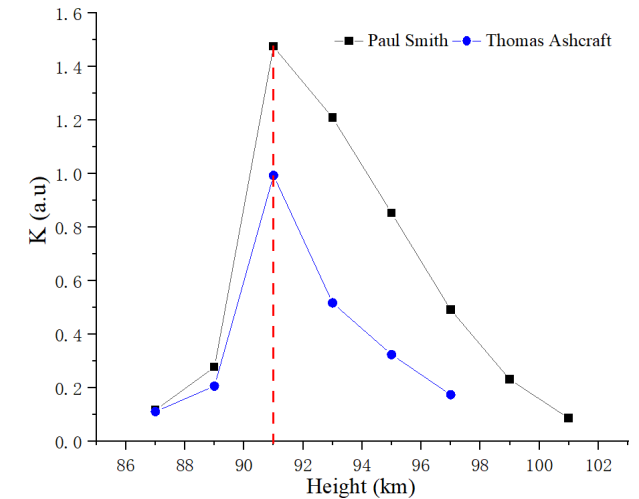
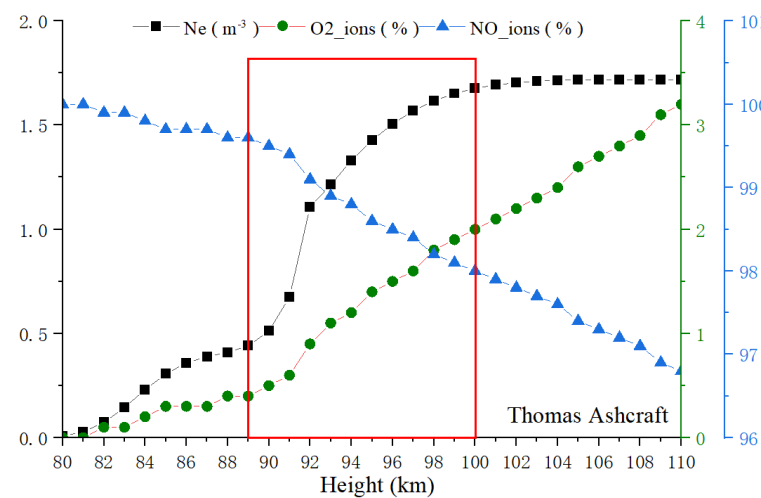
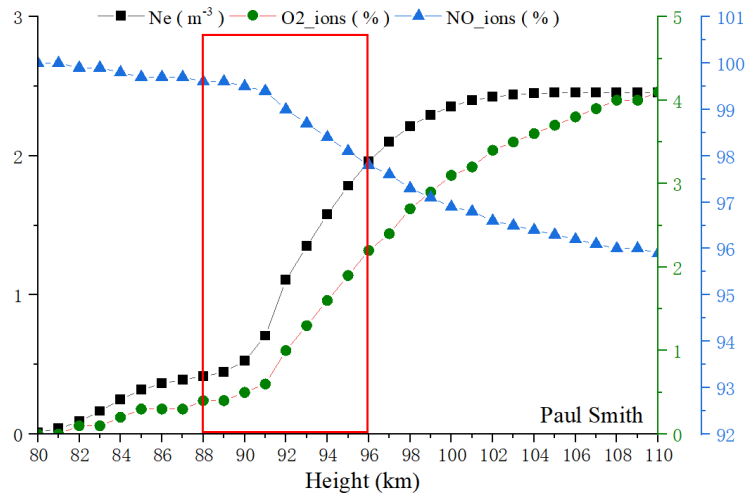


# 近期成果：中高层大气鬼火精灵ghost的机理研究



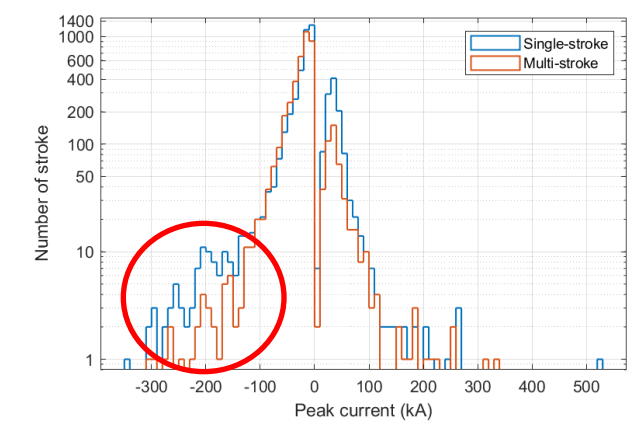
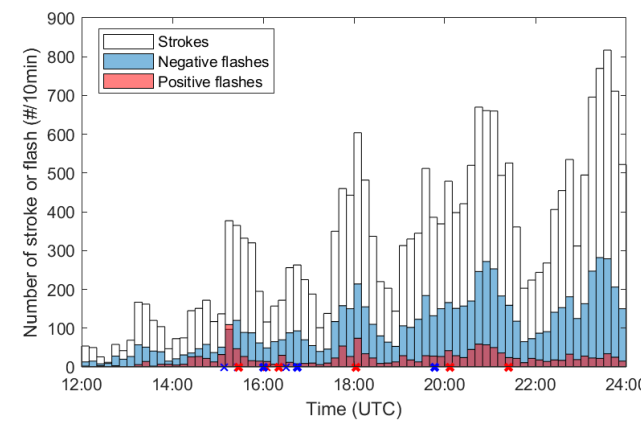
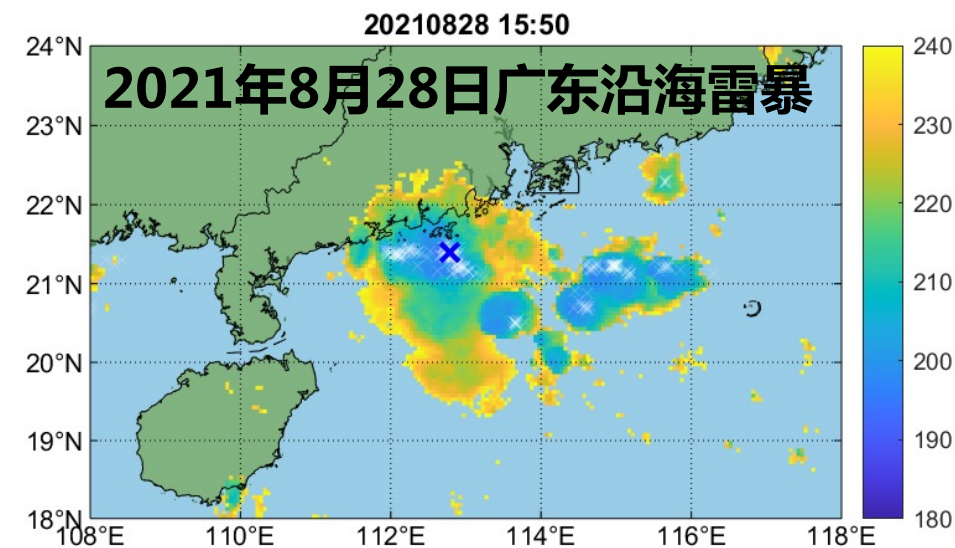
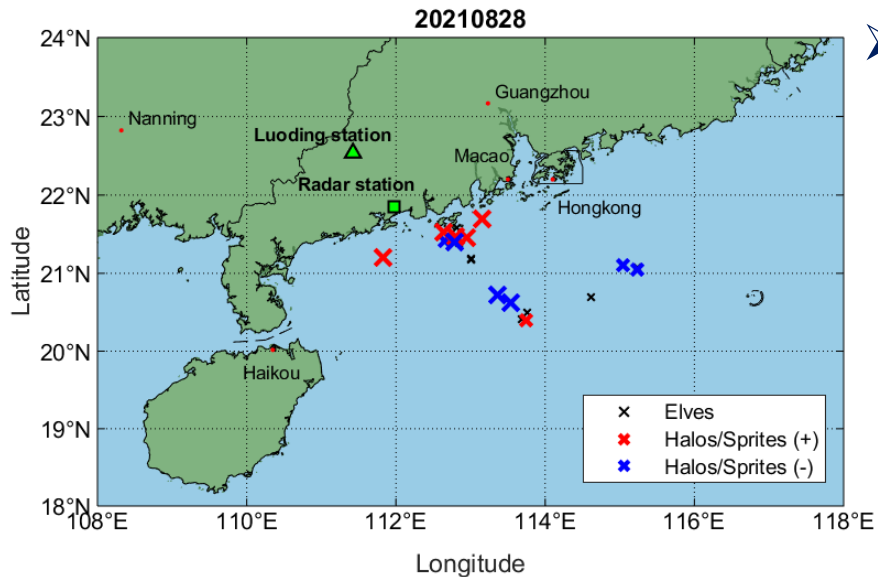
➤ 针对两个个例，根据背景星场确定绿闪现象中心高度约为91公里，并结合电离层参考模型获得该高度大气成分特征，判断绿闪形成的主要物理机制是O(1S-1D)跃迁产生557.7nm波长光辐射。

Huang et al. (to be submitted)



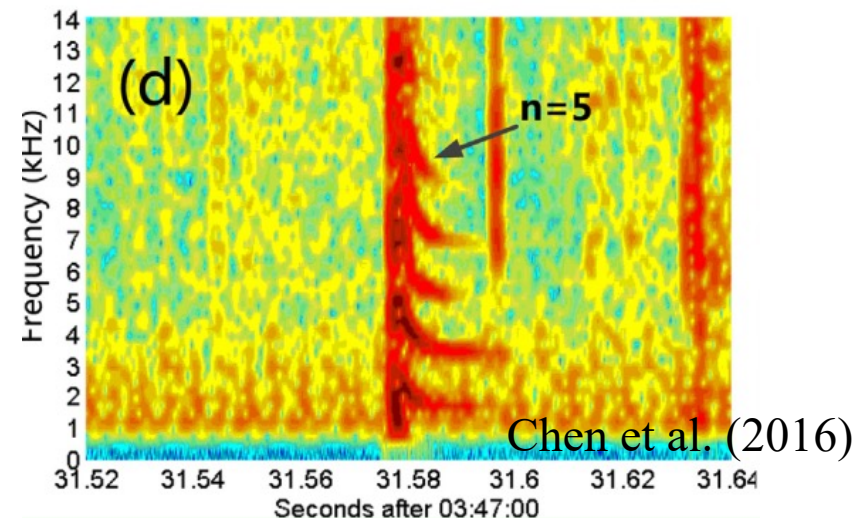
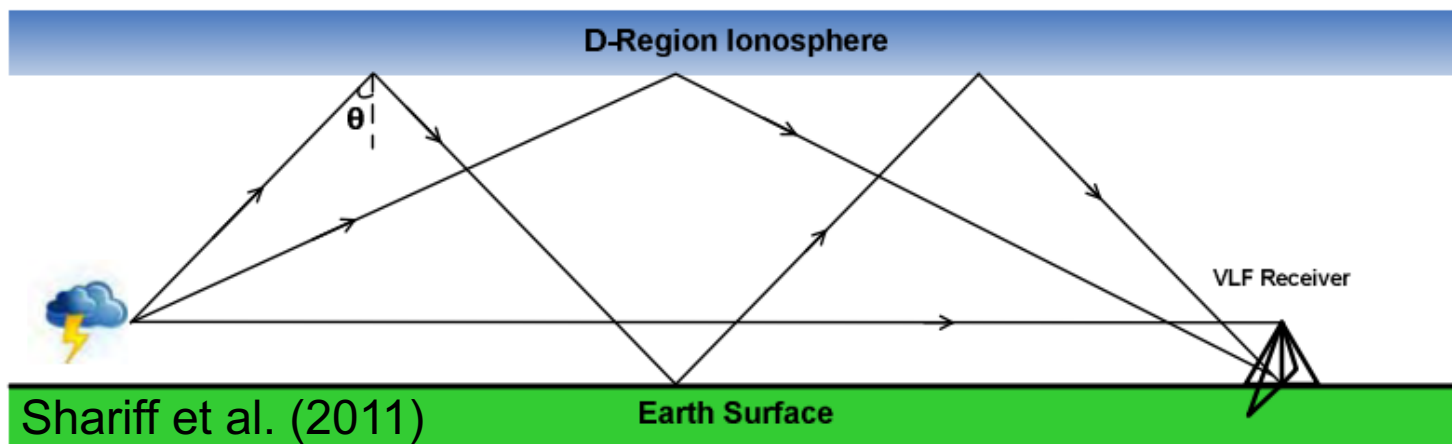
# 进展：海洋雷暴红闪和ELVES现象的地基观测

首次在中国沿海地区观测到负极性红色精灵 (6例) 和ELVES现象 (8例)，母体闪电峰值电流均超过100 kA (200 kA for elves)



海洋雷暴产生的强负地闪多由单次回击闪电产生

# 进展：地球-电离层波导吱声信号特征的人工智能提取



以往研究从频谱图中识别、提取吱声信号的时频曲线均为手动完成，因此基于吱声信号反演电离层状态实用性较差。

**技术突破：**基于深度学习实现了对吱声信号的自动识别以及频谱曲线的提取。

$$\bar{t} = \{t_l\}_L$$

$$\bar{f} = \left\{ \exp \left( \frac{\sum_m (I(t_l, f_m) \times \ln f_m)}{\sum_m I(t_l, f_m)} \right) \right\}_L$$

$$n_e (\text{cm}^3) = 1.241 \times 10^{-8} f_c f_H$$

$$h = \frac{c}{2f_c}$$

$$f(t-t_0) = \frac{f_c(t-t_0)}{\sqrt{(t-t_0)^2 - (d/c)^2}} \quad (*)$$

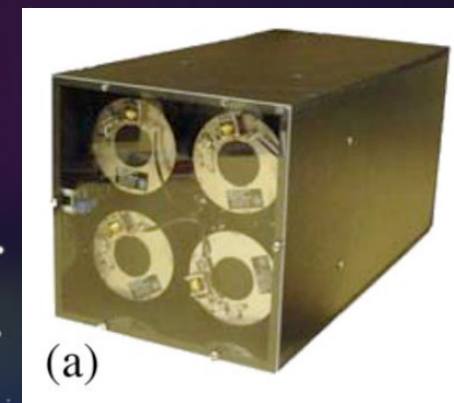
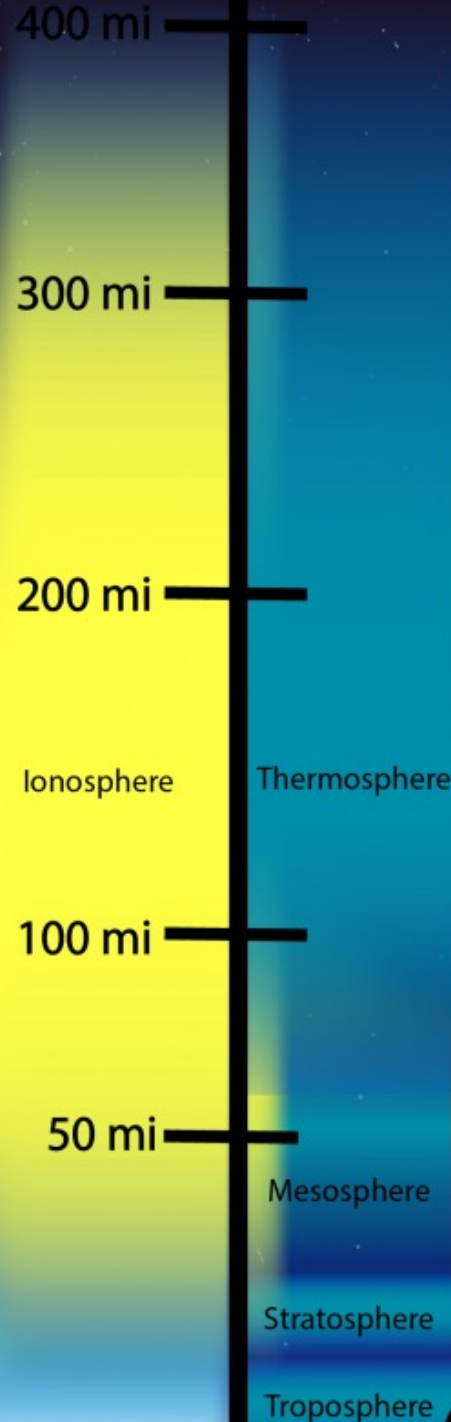
反射高度(h, km)	电子密度(N <sub>e</sub> , el/cm <sup>3</sup> )	传播距离(D, km)
87.8	28.7	2074
90.3	27.9	2310
90.4	27.8	2310
89.4	28.2	2311
89.0	28.3	2000
90.4	27.8	2320

# 极光 vs 中高层放电现象

UV airglow

Blue line airglow

Green line airglow

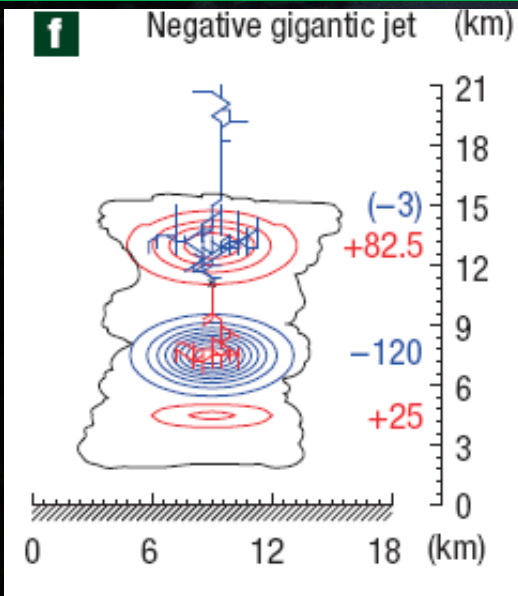


高速光度计阵列（拟研制）

# 巨大喷流-源自雷暴的电喷泉

背景星场对比确定高度

“巨大喷流”的电荷不平衡理论



巨大喷流  
Gigantic jet



Krehbiel et al. [2008]-Nature Geoscience

7/22/22

20/09/21 02:41:40 0609.0

Frankie Lucena<sup>45</sup>

# 目录

1

雷电物理及探测技术

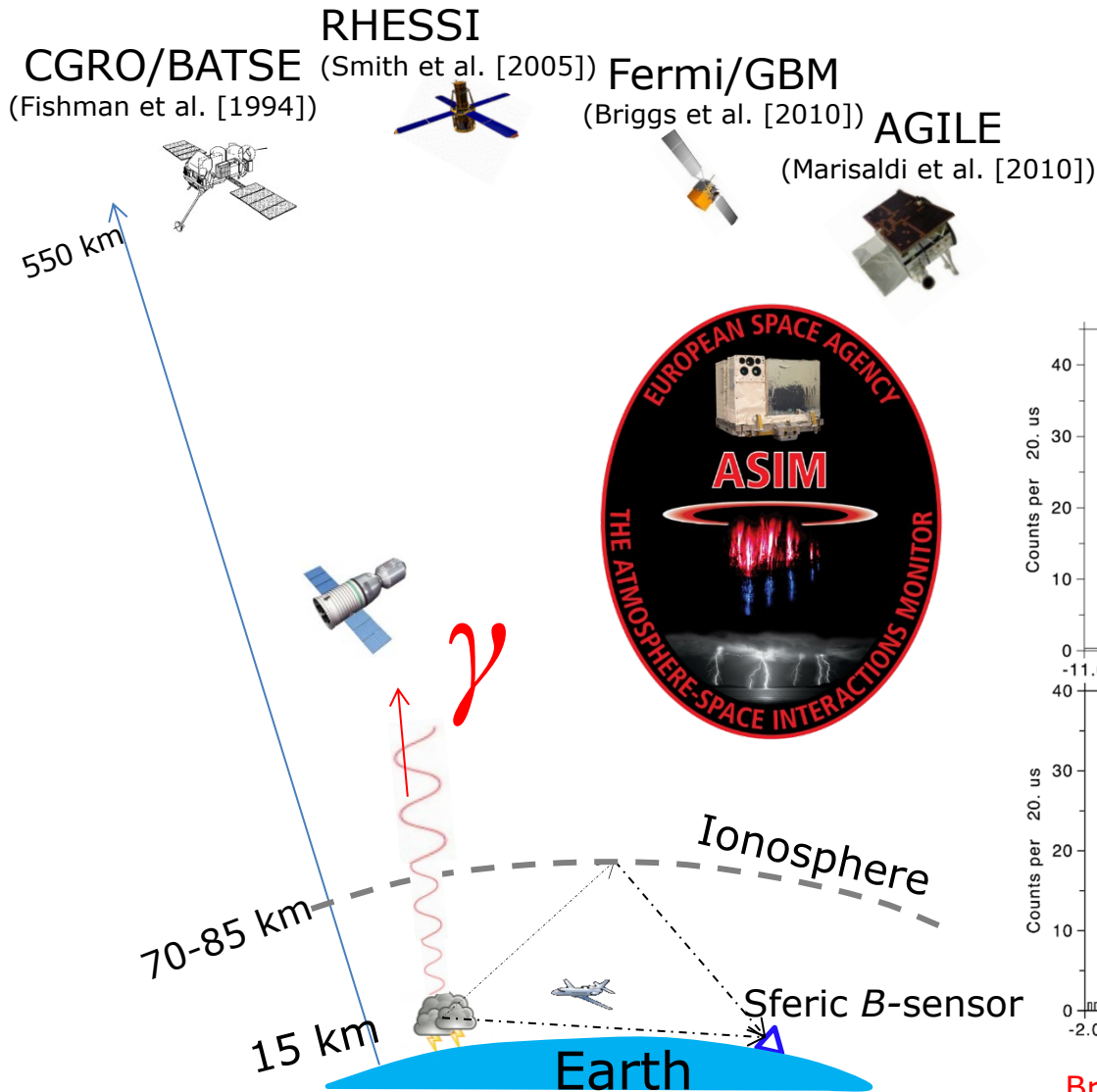
2

中高层放电现象


3

深对流雷暴强云闪过程


# 地球伽玛射线闪 (Terrestrial Gamma-ray Flashes)

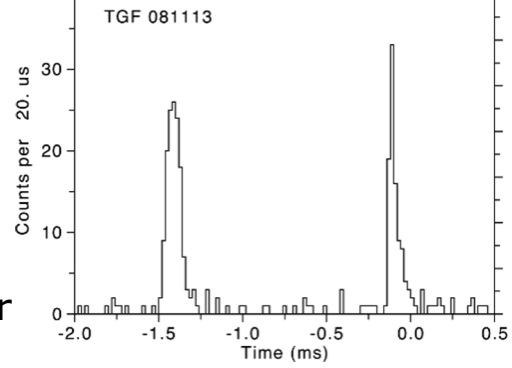
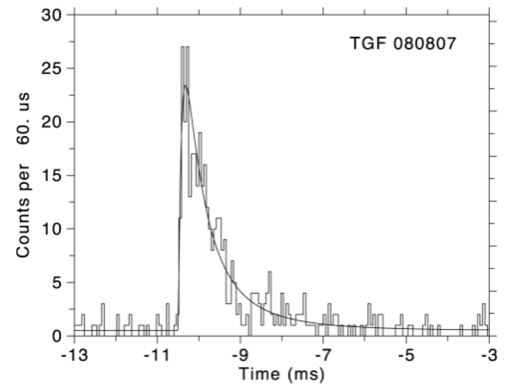
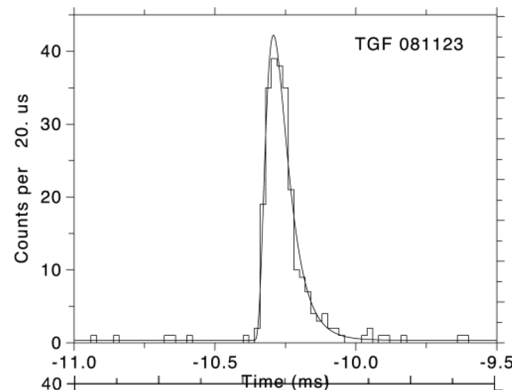


**Insight-HXMT**  
(Zhang et al. [2020])



**GECAM**  
(launched in December of 2020)

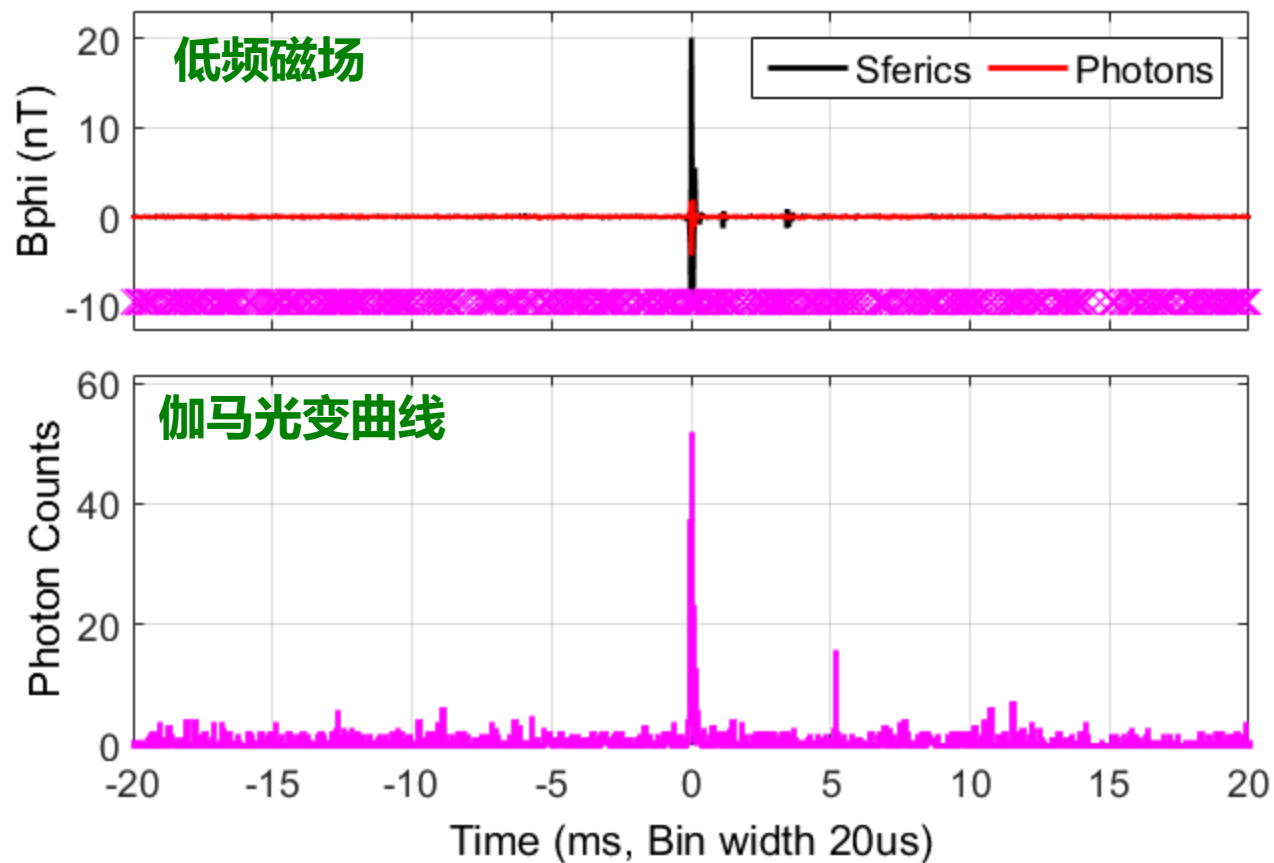




- 持续时间: 0.1 ms to a few ms
- 单脉冲或者多脉冲
- 引起航天器静电积累导致放电

Briggs et al. [2010]  
Fishman et al. [2011]

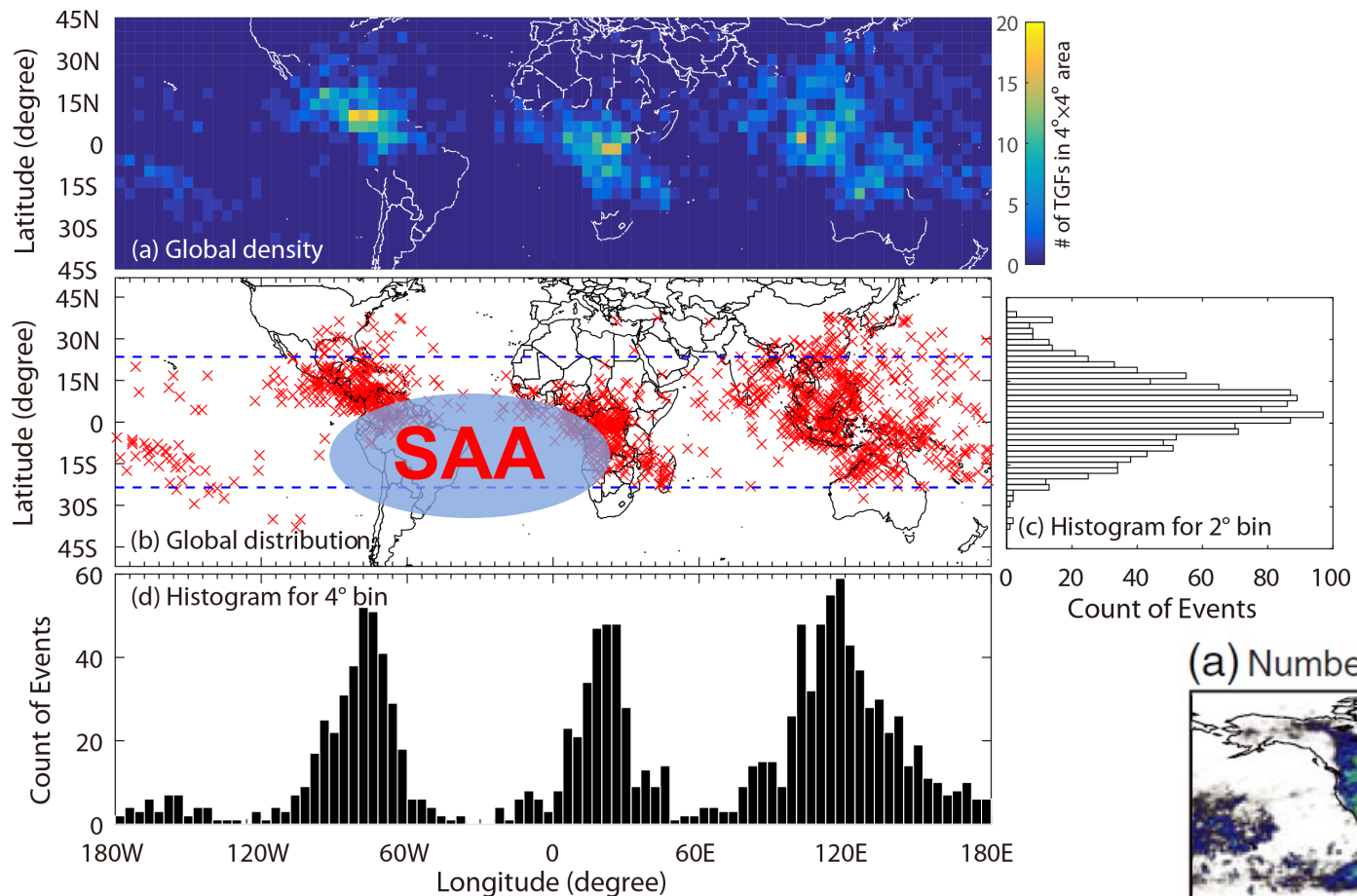
# GECAM于2021年初探测到的一次TGF事件



**GLD360: 2021/03/29 06:56:37.8299500UTC -1.7336N 103.9809E +209 kA**



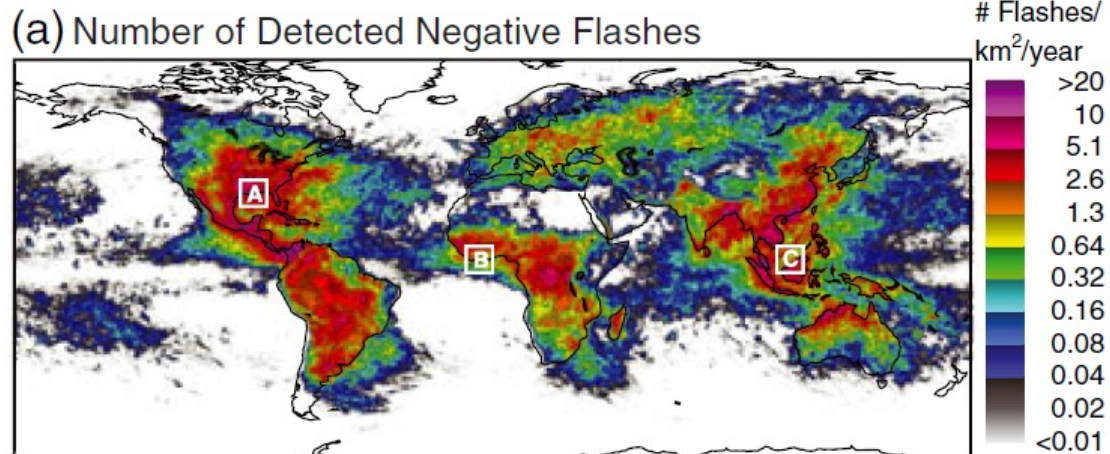
# TGF事件的全球分布 (2002-2015年RHESSI数据)



卫星名字	国家	轨道高度	轨道倾角	观测能段	运行年限
CGRO-BATSE	美国	450 km	28.5°	20keV 到 2MeV, 8MeV	1991/4/5-2000/6/4
RHESSI	美国	490-505 km	38°	3keV 到 20MeV	2002/2/5-2018/8/16
FERMI-GBM	美国	550 km	25°	150keV 到 30MeV	2008/6/11 至今
AGILE	意大利	509-533 km	2.5°		2007/4/23 至今
ISS-ASIM	欧洲	403-408 km	51.64°	15keV-400keV, 200keV-40MeV	2018/4/22 至今
HXMT	中国	550 km	43°	8keV-5MeV	2017/6/15 至今
GECAM (双星)	中国	600 km	29°	8keV-2MeV	预定 2020 年发射

陆高鹏 等 (2020)

<http://xatal.com/tgf/>



Said et al. (2013)

# Are TGFs produced by strong CG strokes?

PERSPECTIVES

ATMOSPHERIC SCIENCE

## Gamma Rays Made on Earth

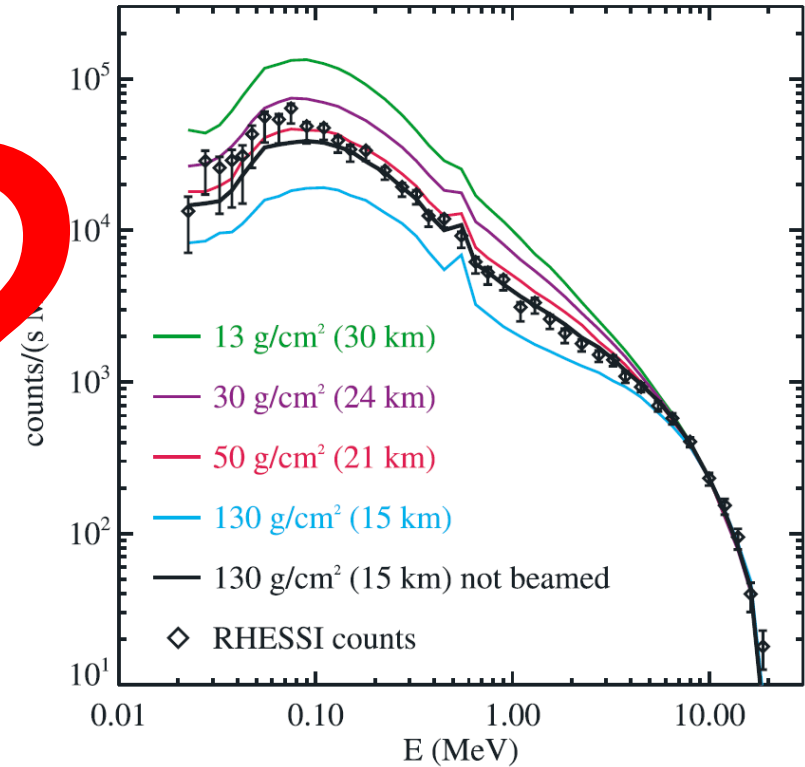
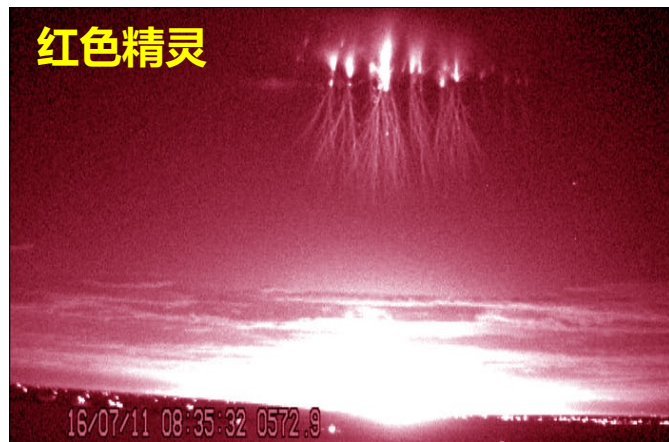
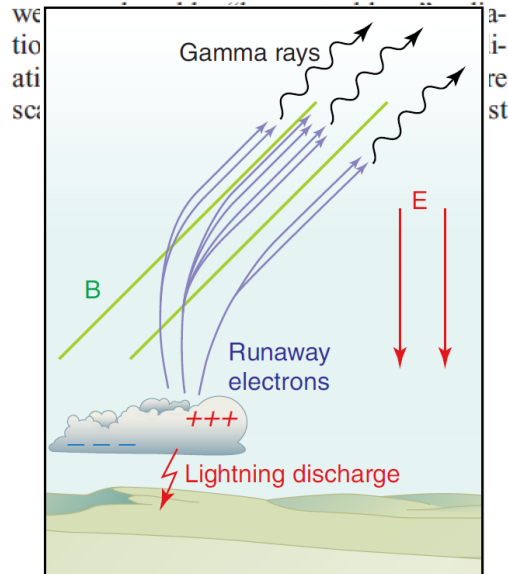
Umran Inan

Inan [2005]-Science

In 1994, Fishman *et al.* observed brief ( $>1$  ms) bursts of intense gamma rays, called terrestrial gamma-ray flashes, with the Compton Gamma-Ray Observatory (CGRO) (1). Prior to this observation, intense transient bursts of gamma rays were only known to occur in an astrophysical context. The observed photon energies of more than 1 MeV suggested that the gamma rays

were trapped in the Earth's magnetic field). Here, some electrons may become trapped. A fraction of them may then precipitate in regions that are geomagnetically conjugate to intense lightning discharges (for example at the Southern Hemisphere termination of the magnetic field line that originates from a Northern Hemisphere thunderstorm). Here they interact with molecules in the increasingly dense atmosphere to produce optical emissions and x-rays, which are ultimately caused by the release of energy in a lightning discharge in the parent hemisphere.

A total of  $\sim 76$  terrestrial gamma-ray



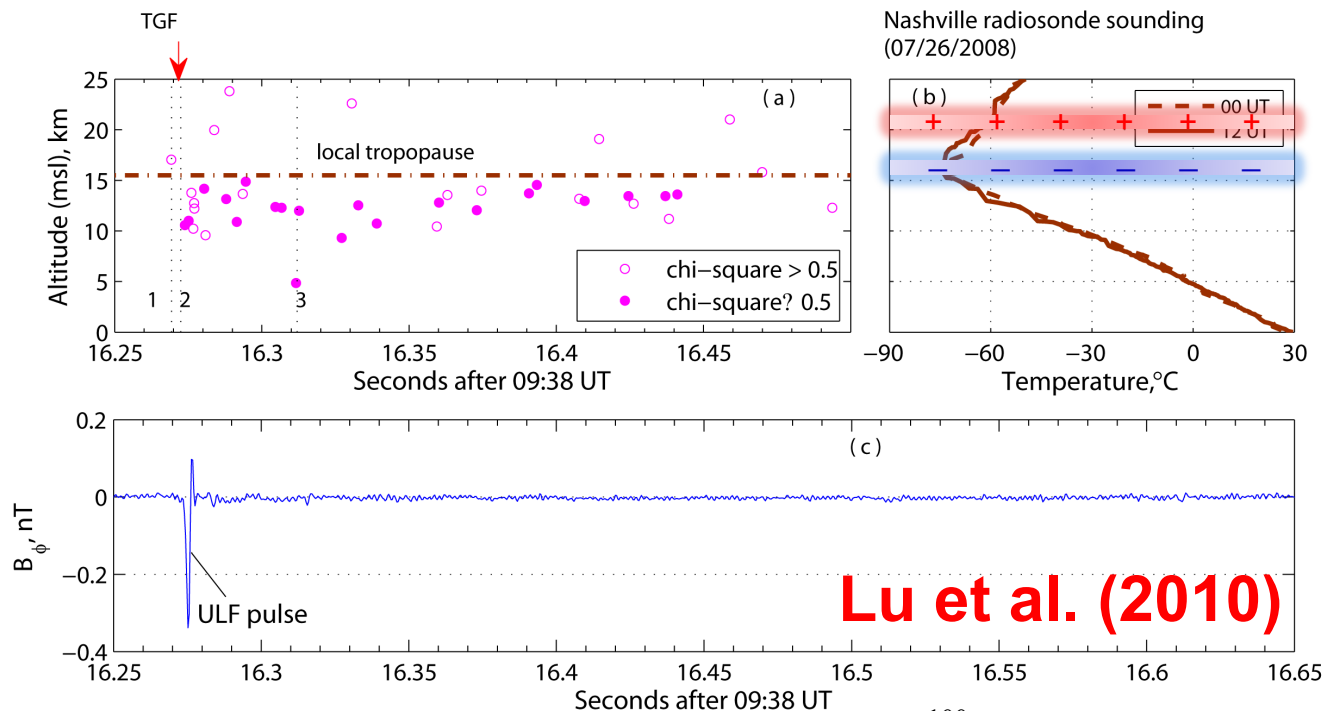
Dwyer et al. (2005)

➤ 能谱分析将TGF源限定在21 km以下高度

# TGF母体闪电的三维成像观测

Ostgaard et al. (2013)

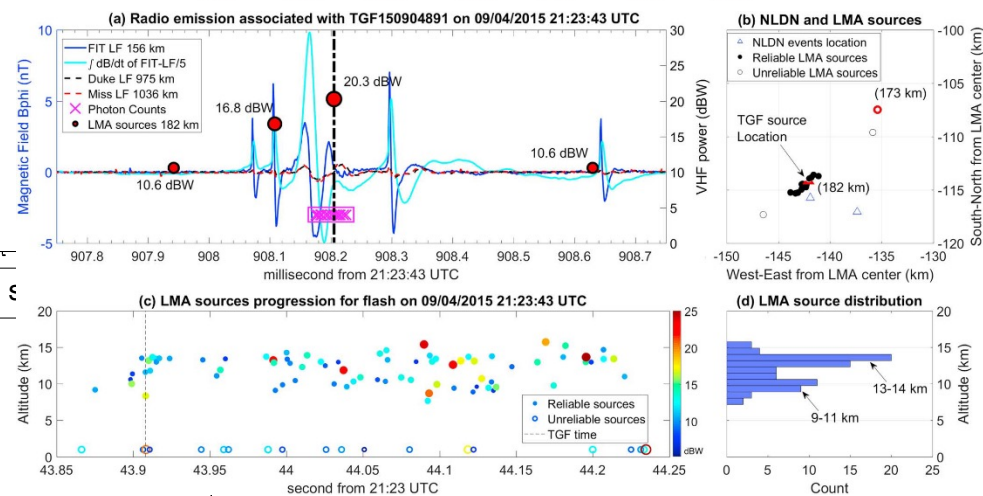
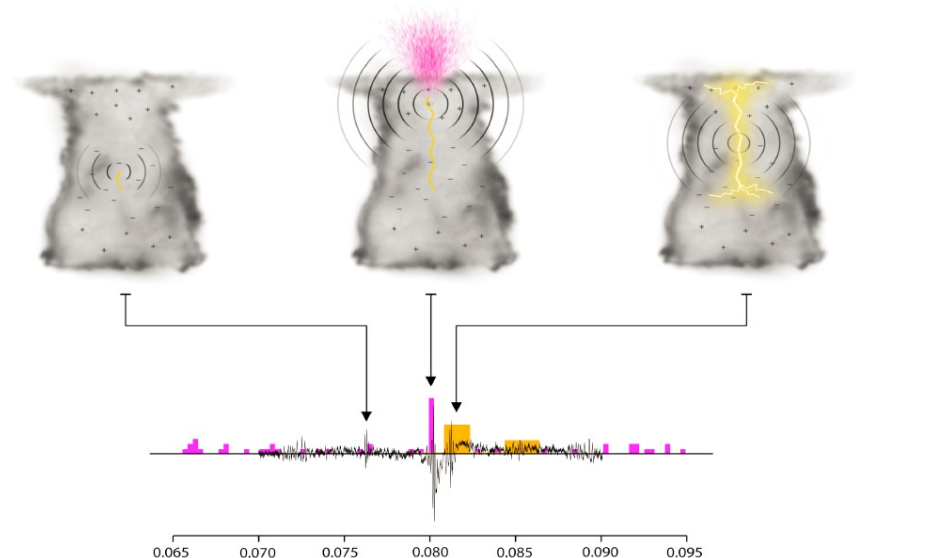
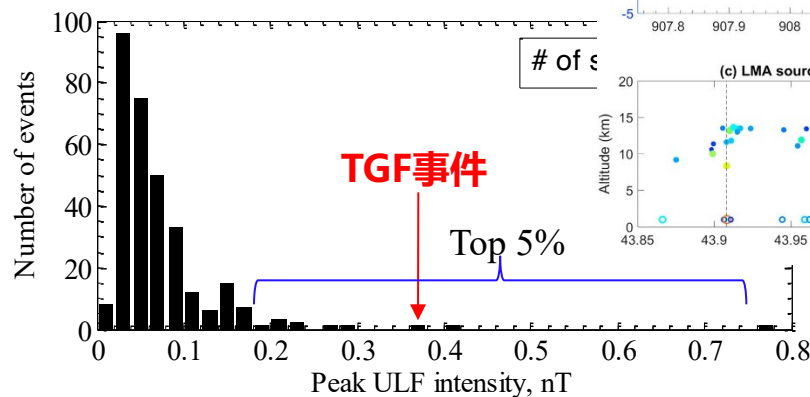
➤ TGF由云闪初始阶段的上行正先导产生



Lu et al. (2010)

➤ TGF在云闪初始上行正先导阶段产生

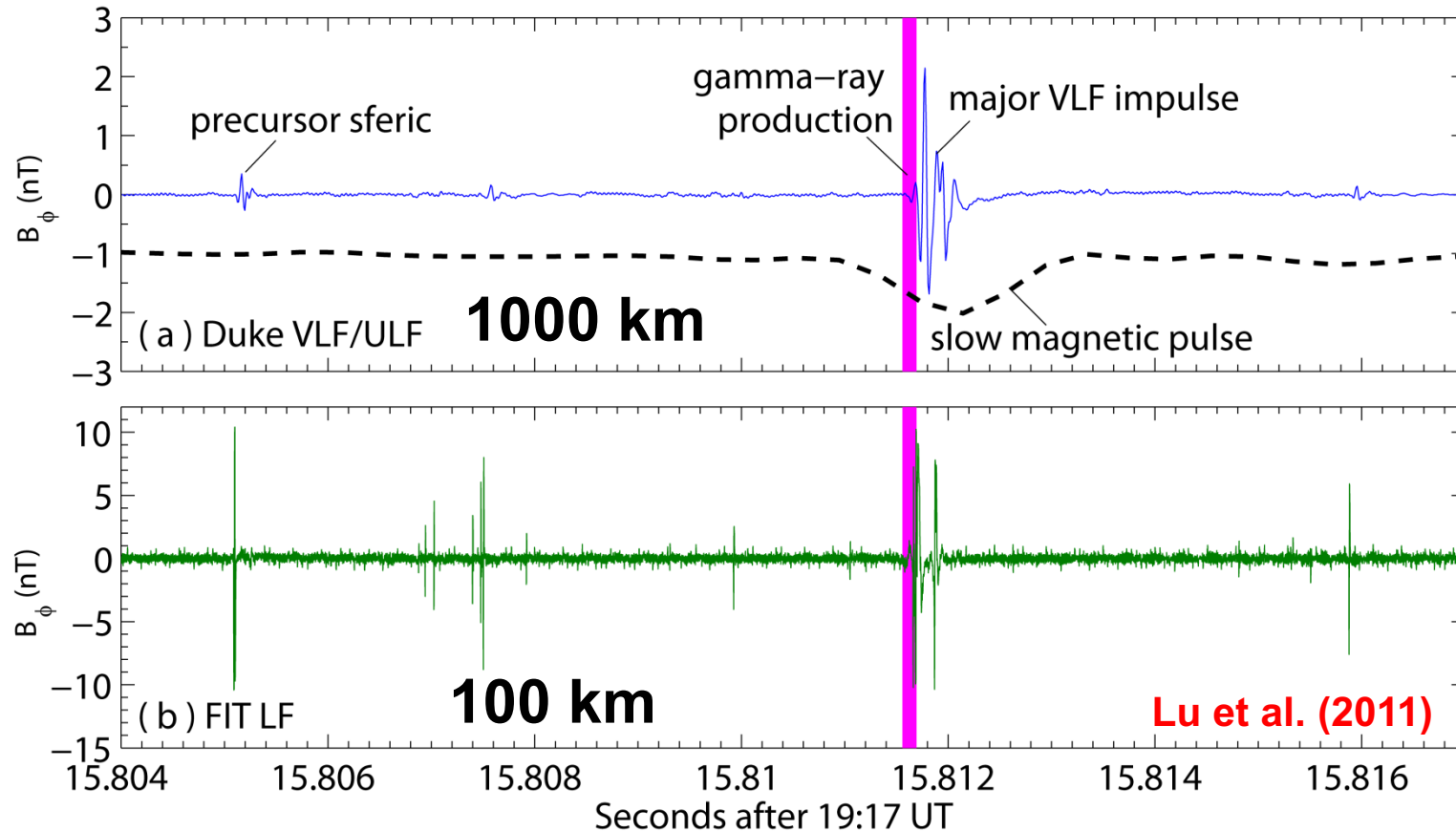
➤ 类似的过程在该雷暴中较为普遍



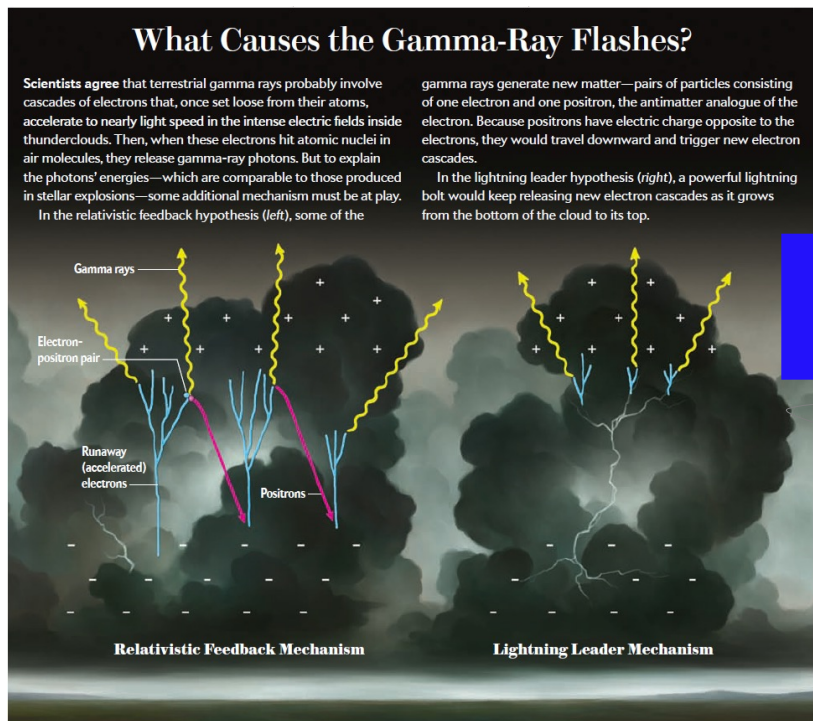
Lyu et al. (2018)

# TGF闪电射频信号的典型特征

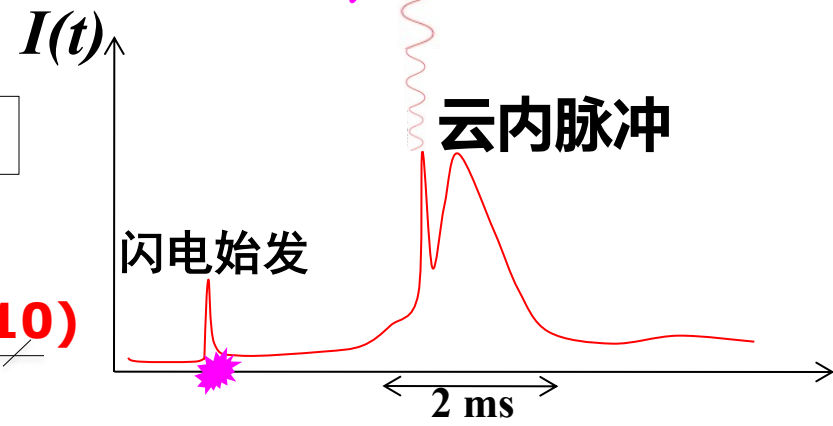
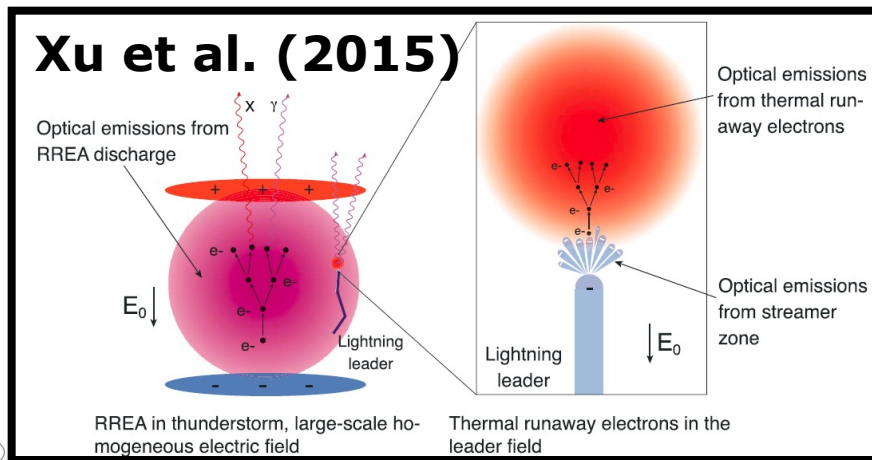
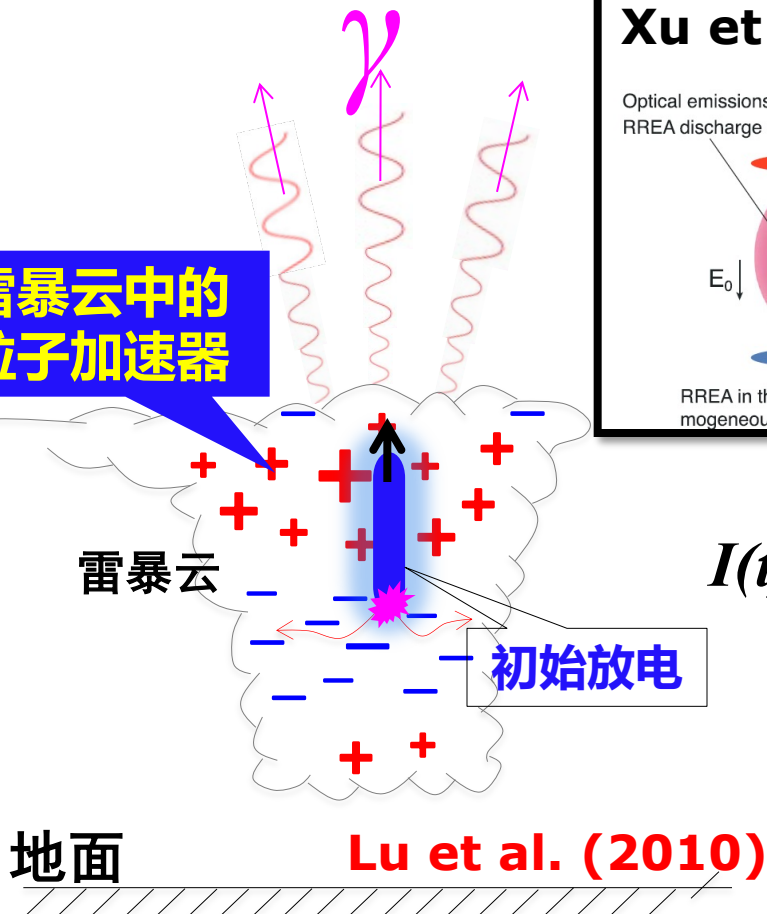
- precursor sferic
- slow magnetic pulse
- fast impulse
- flash initiation
- leader progression
- gamma-ray production



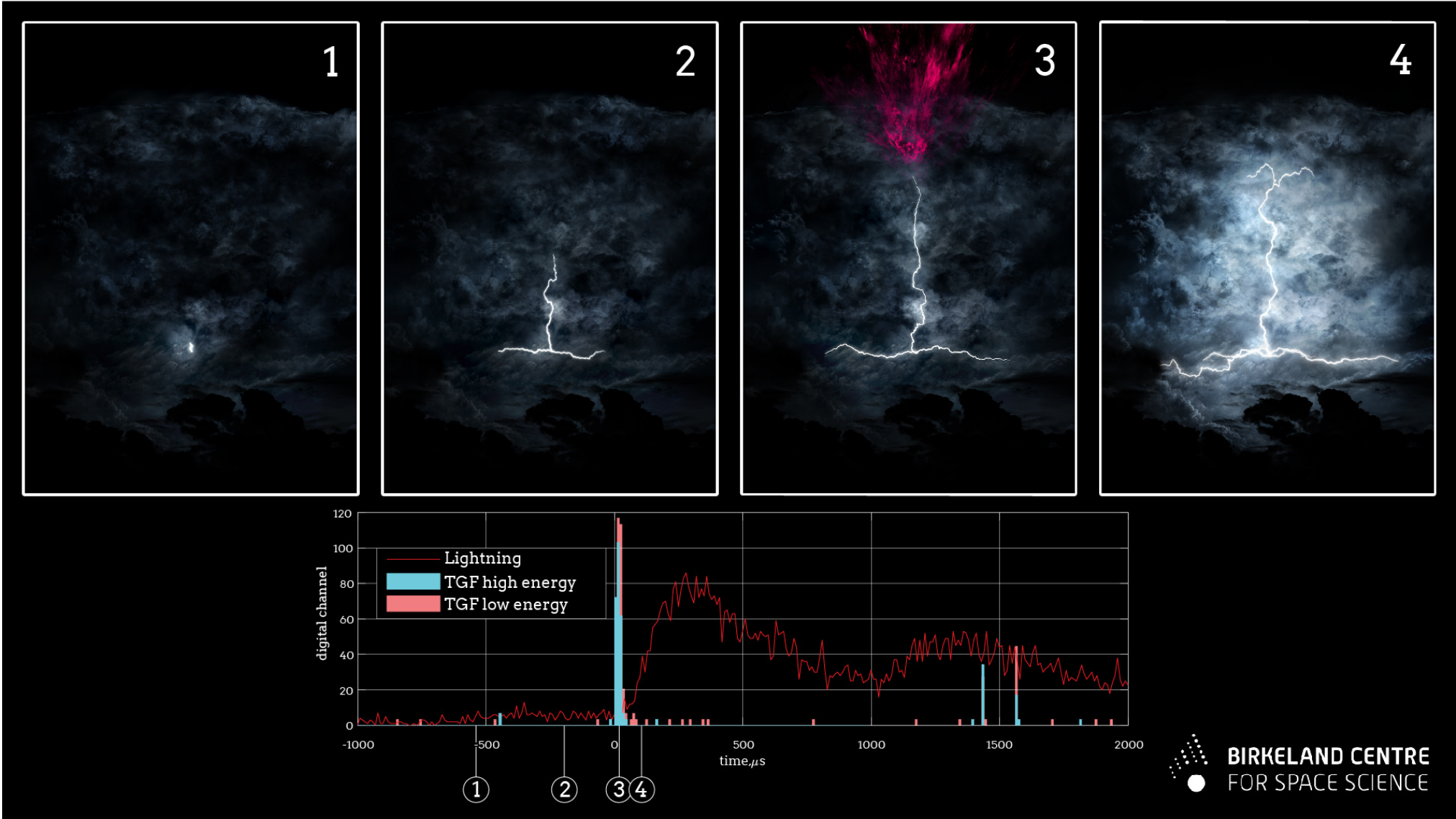
# 雷暴和闪电的高能辐射效应



雷暴云中的  
粒子加速器

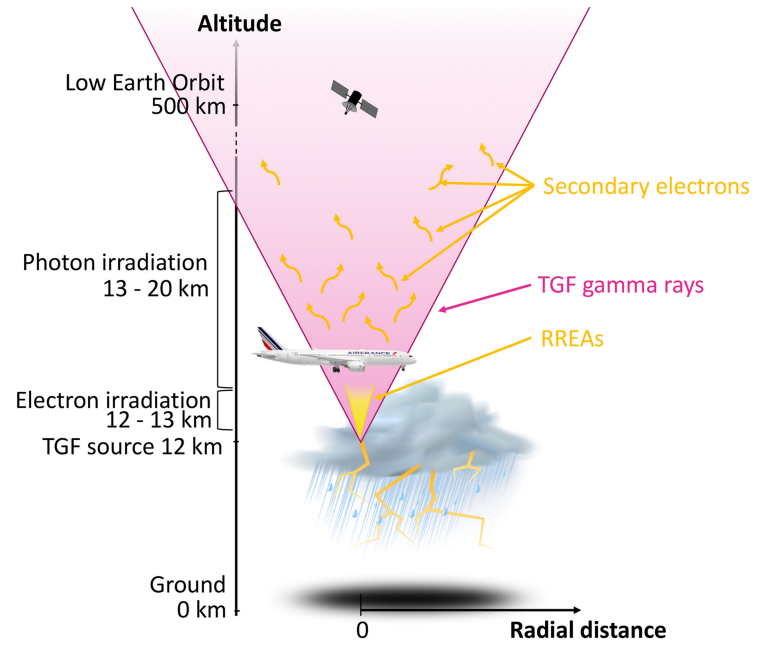
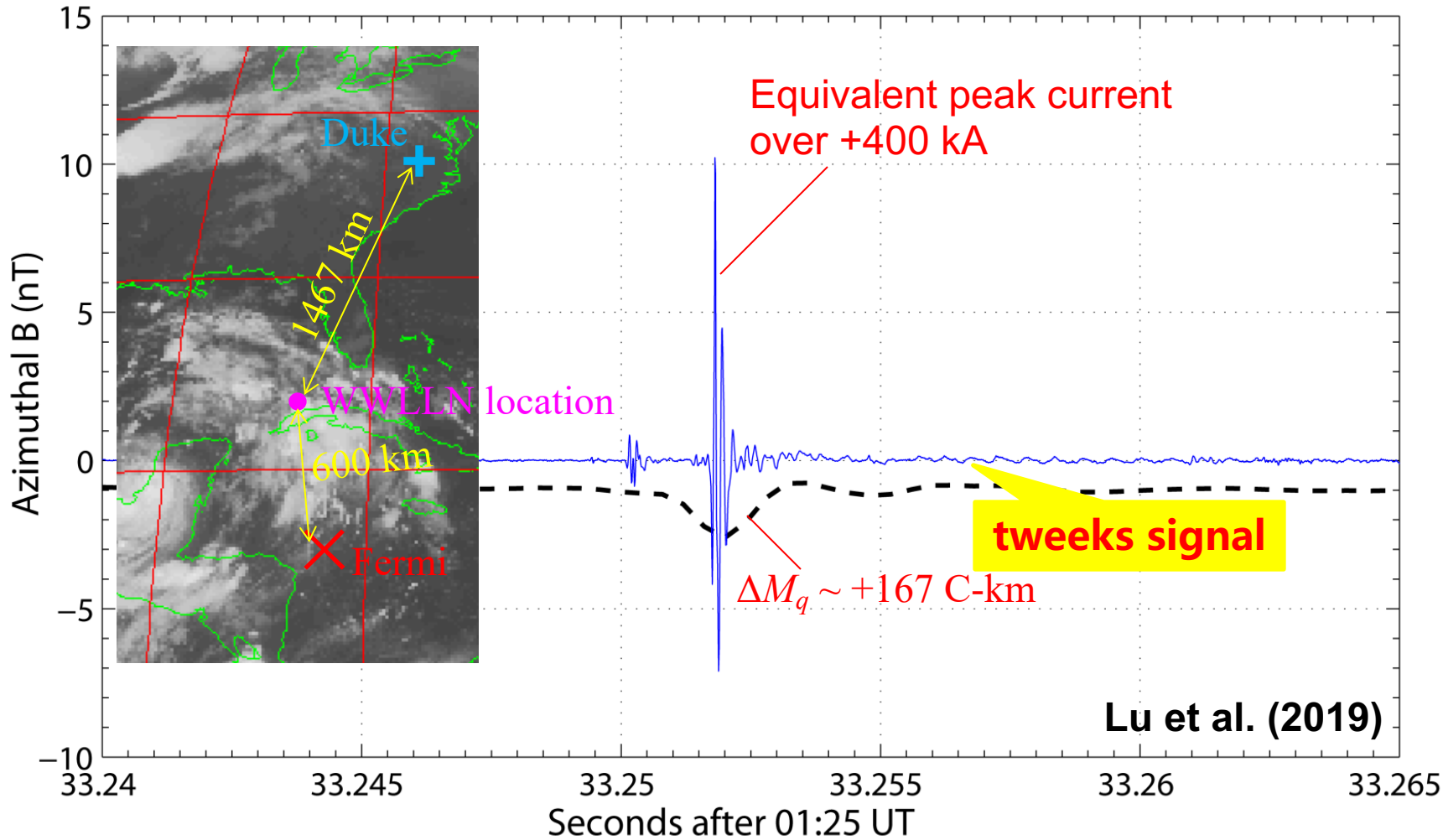


I-相对论反馈机制 II-闪电先导机制



# 一次强度极高的TGF闪电个案

Associated with a Fermi/GBM ground-search TGF on September 16, 2010.

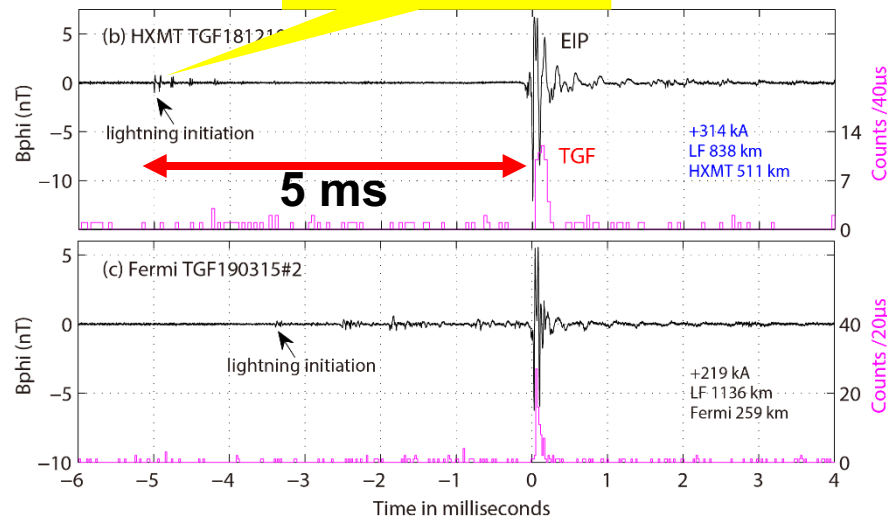
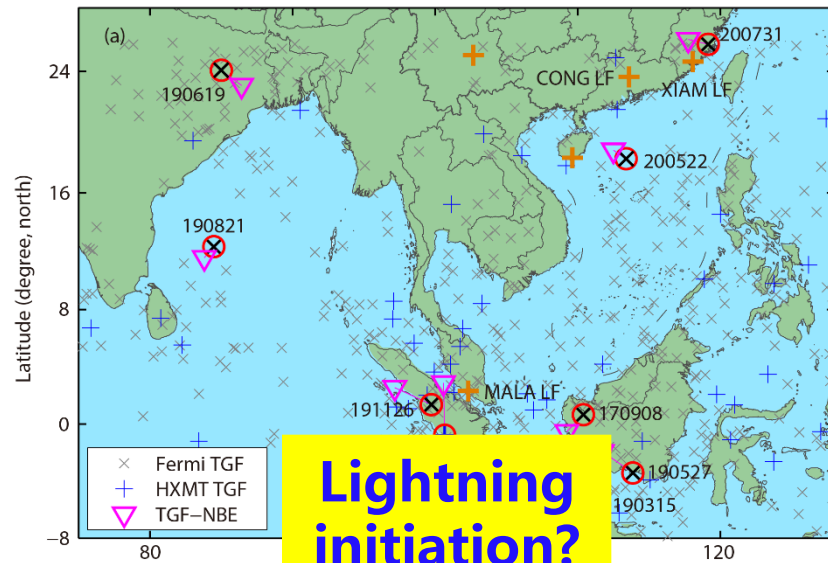


闪电高能辐射是否对航空乘客有健康影响？

# 2017至今的地基闪电信号数据集



慧眼Insight-HXMT卫星



➤ >30次“慧眼”卫星TGF的协同地基闪电电磁场信号

➤ 多数情况下均存在TGF脉冲同闪电主脉冲的同步性（证实了TGF的授时精度）

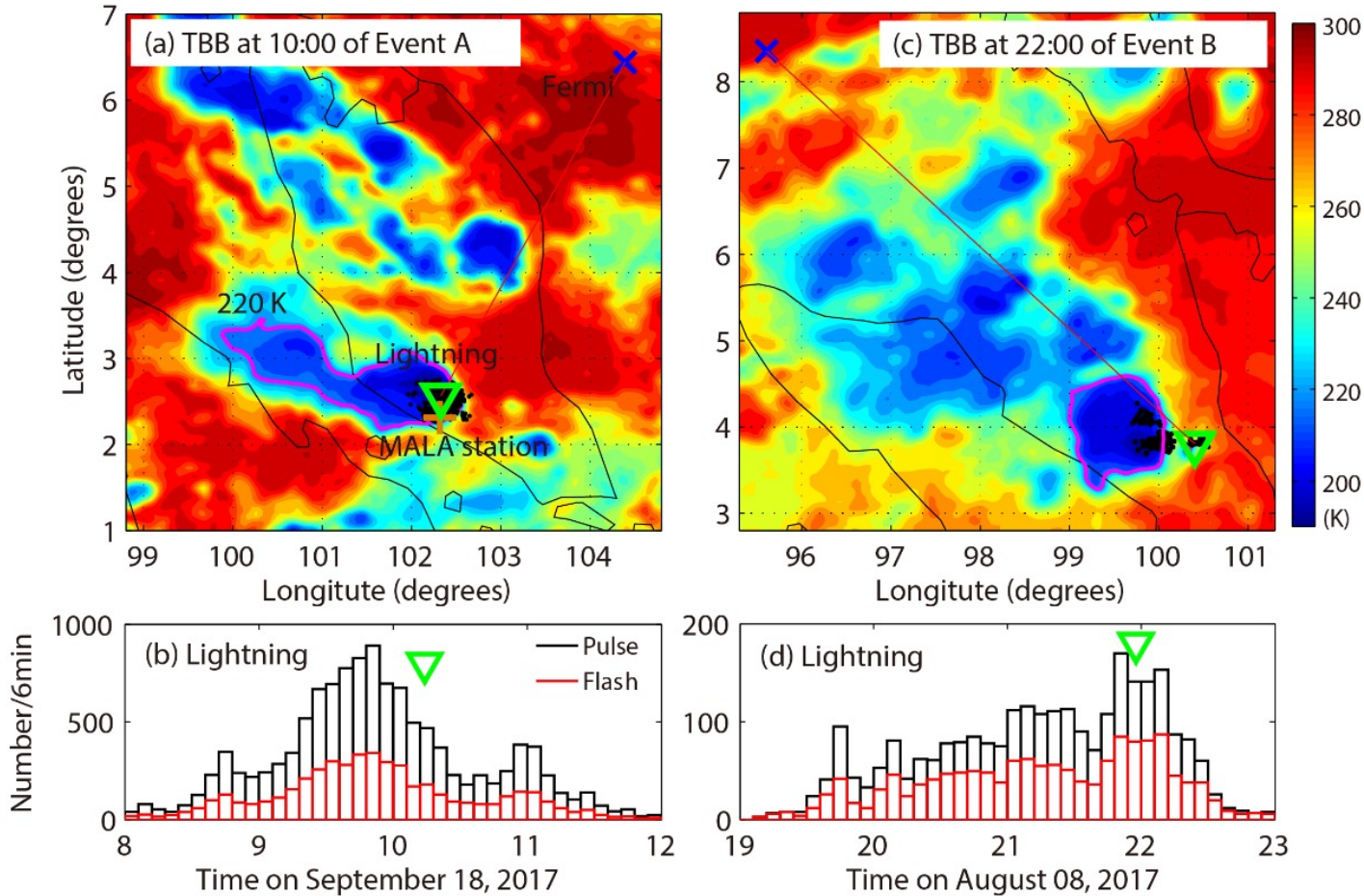
➤ 同Fermi GBM形成互补观测

12/10/2018 12:31:43.371800 8.4190 103.2730 550 km

Zhang, Lu et al. (2021)



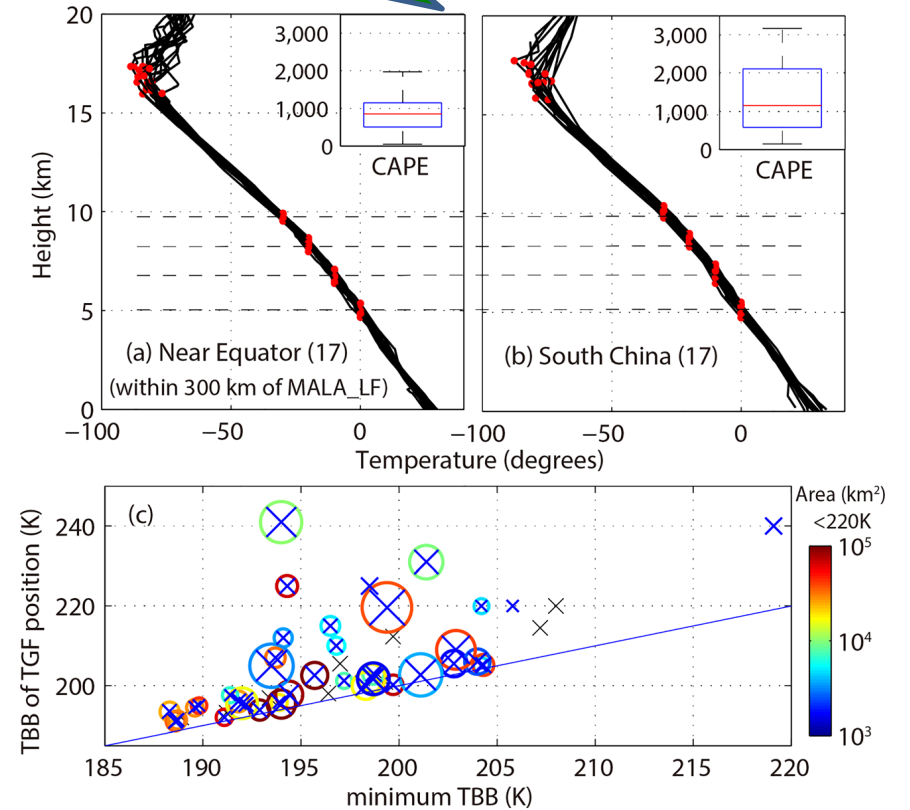
# 赤道地区TGF母体雷暴特征分析



成熟阶段、TBB强中心

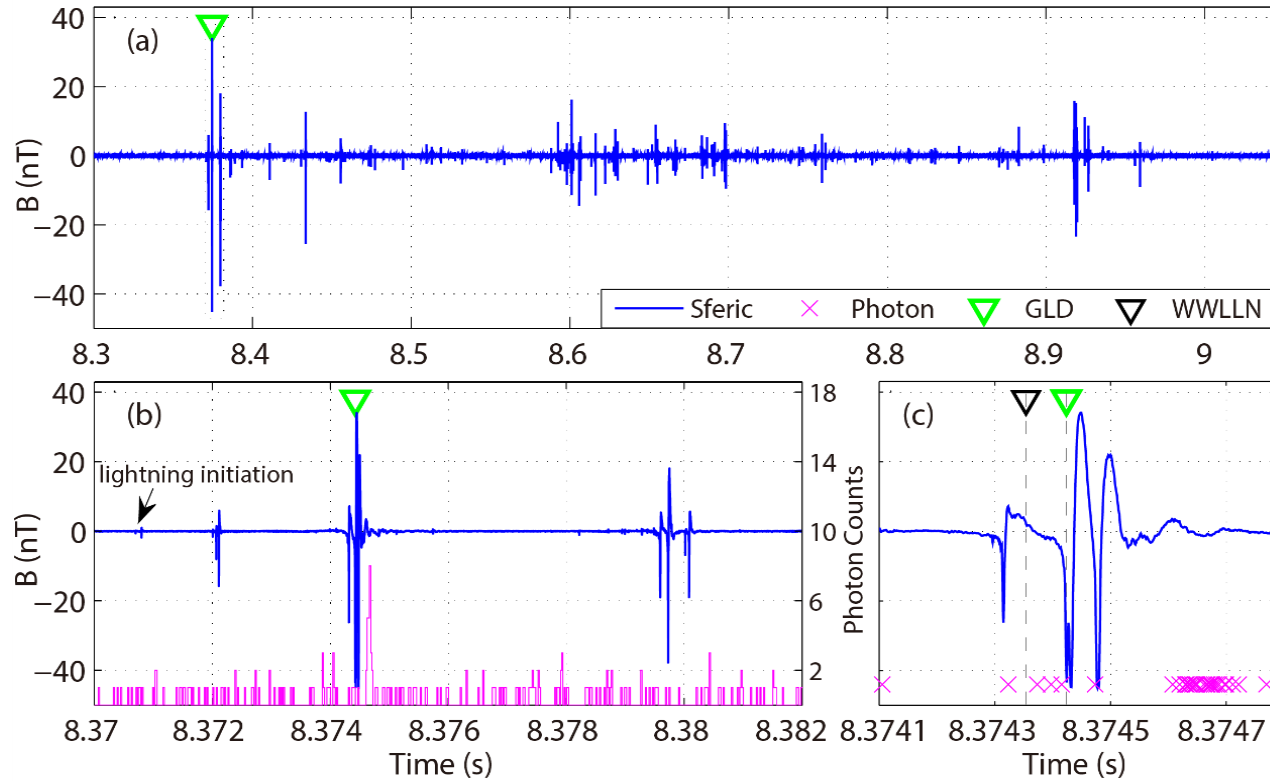
成熟阶段、TBB强中心边缘

## 赤道和华南地区TGF雷暴对流层顶高度比较

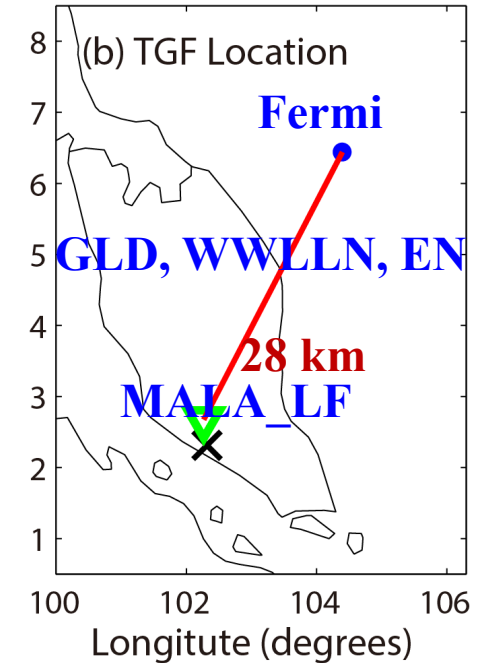


Zhang, Lu et al. (2020)

# 个例1-迄今为止最近距离地基观测 (28公里)



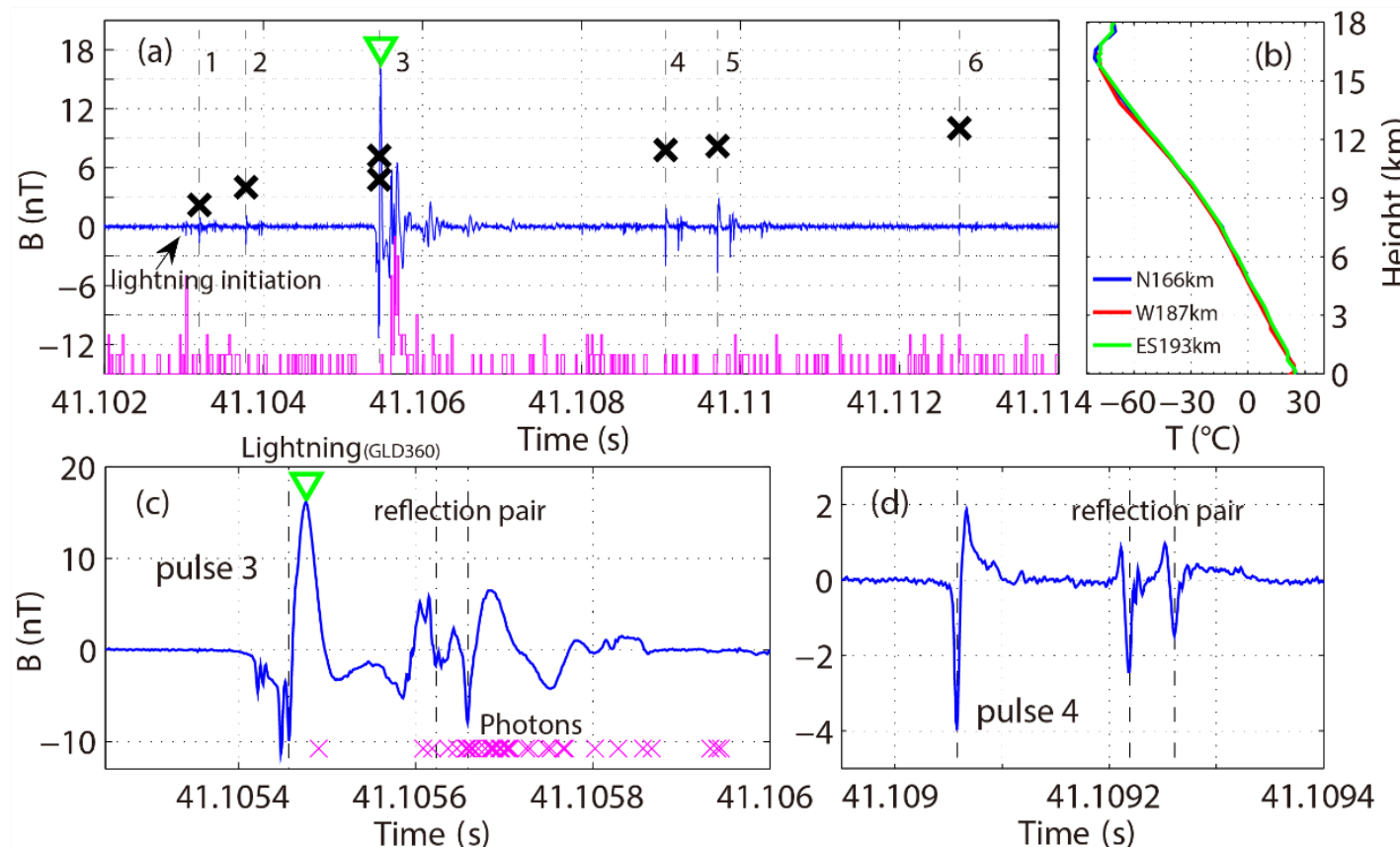
TGF170918426



➤ 云闪发展期间(3.7 ms) 最强脉冲

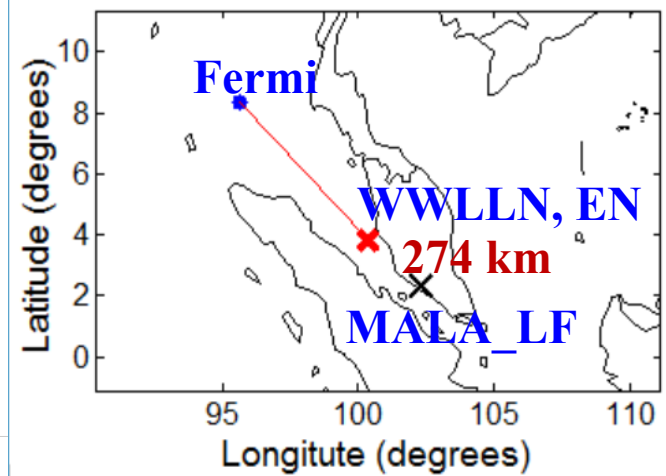
Zhang, Lu et al. (2020)

# 个例2-明显电离层反射信号用于定位辐射源高度



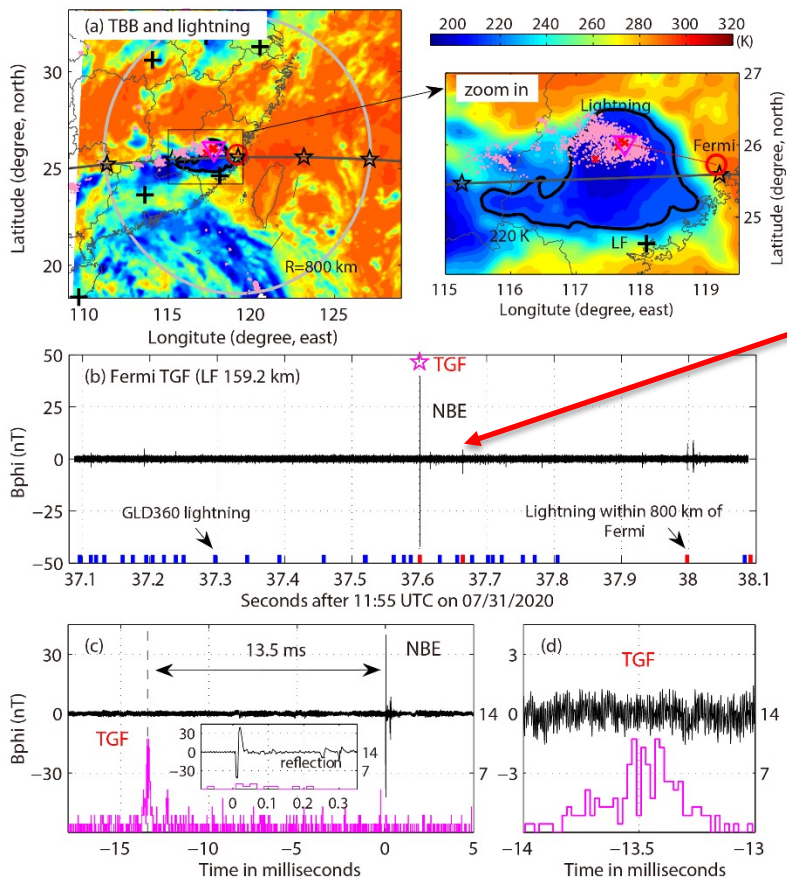
TGF170808915

Zhang, Lu et al. (2020)



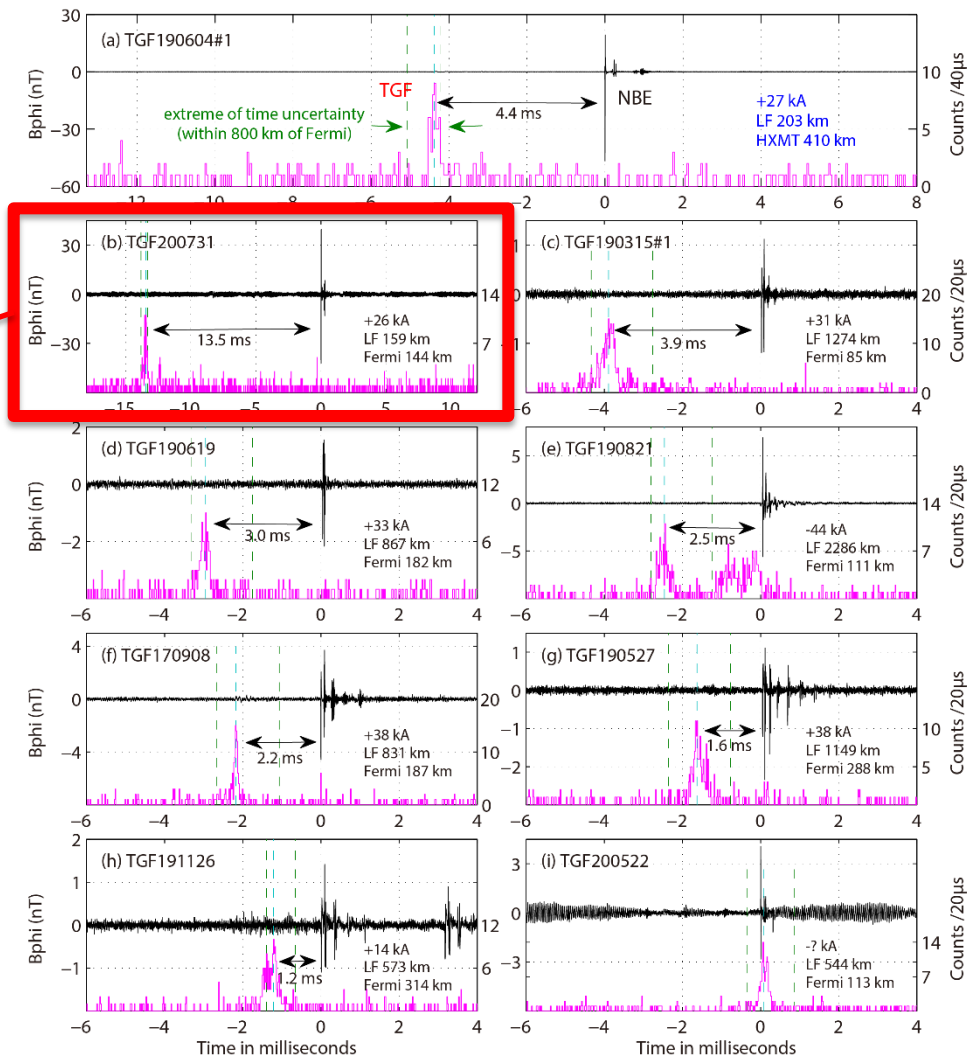
➤ 云闪向上发展期间(2.3 ms), 高度范围10-11 km

# 赤道地区与NBE相关的TGF观测



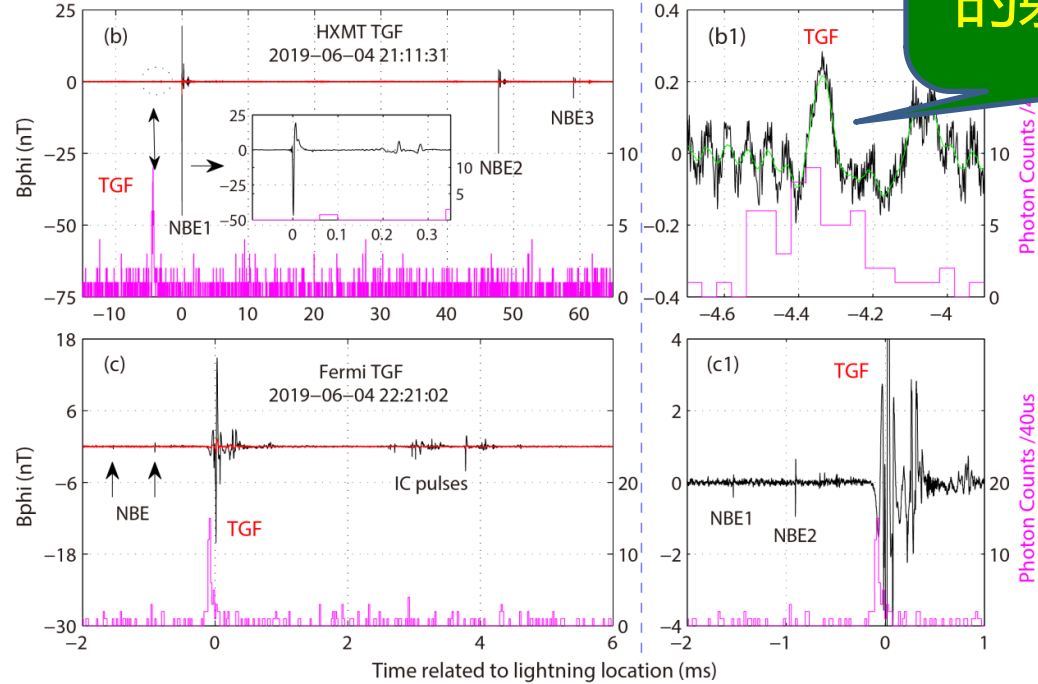
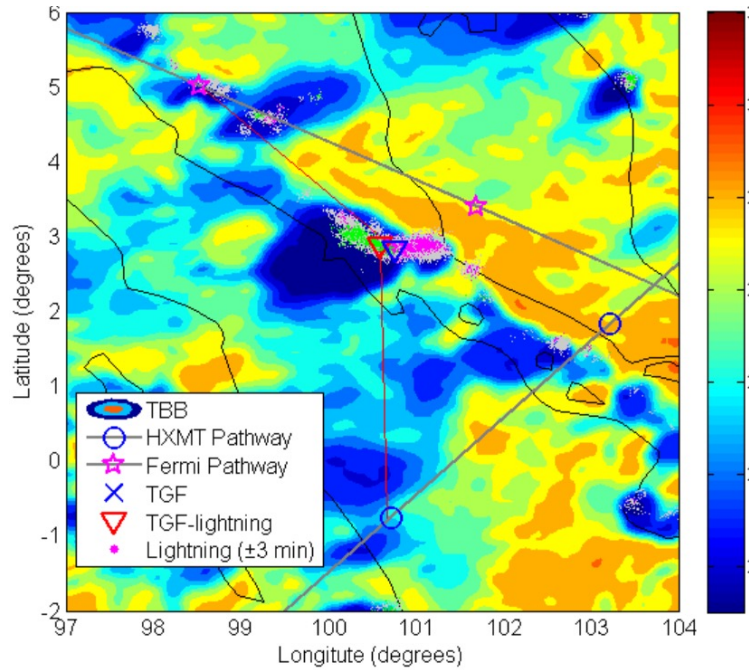
Zhang, Lu et al. (2021)

- TGF提前NBE事件1-14 ms发生
- TGF之后的NBE事件强度普遍较小



# HXMT和FERMI卫星对同一次雷暴的TGF探测

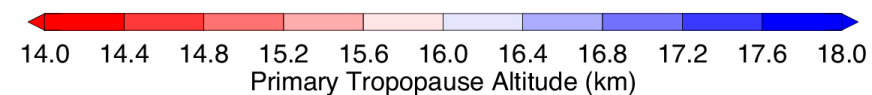
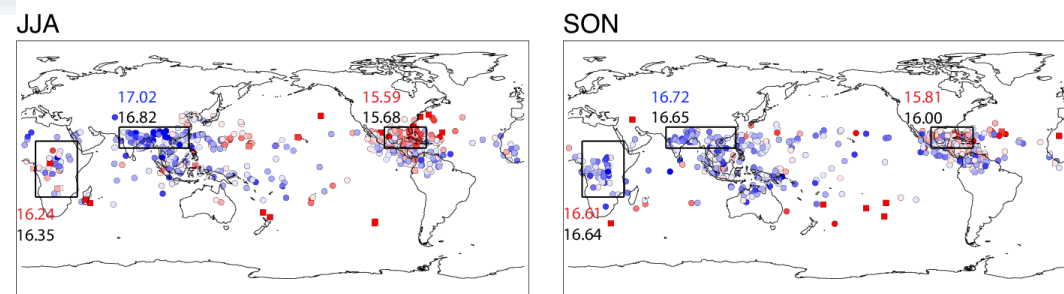
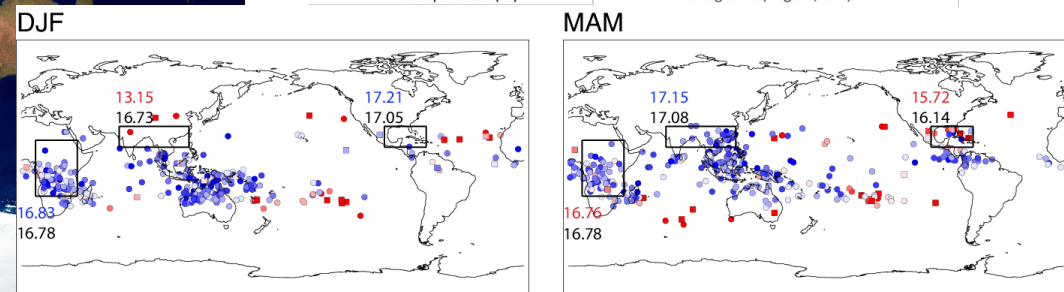
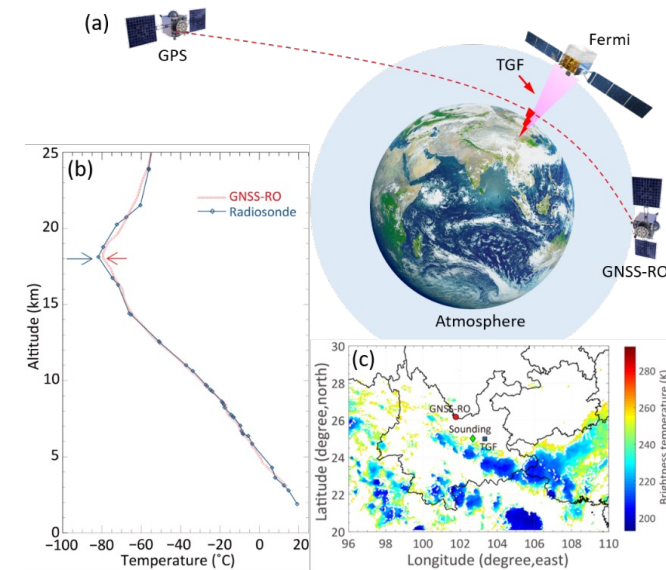
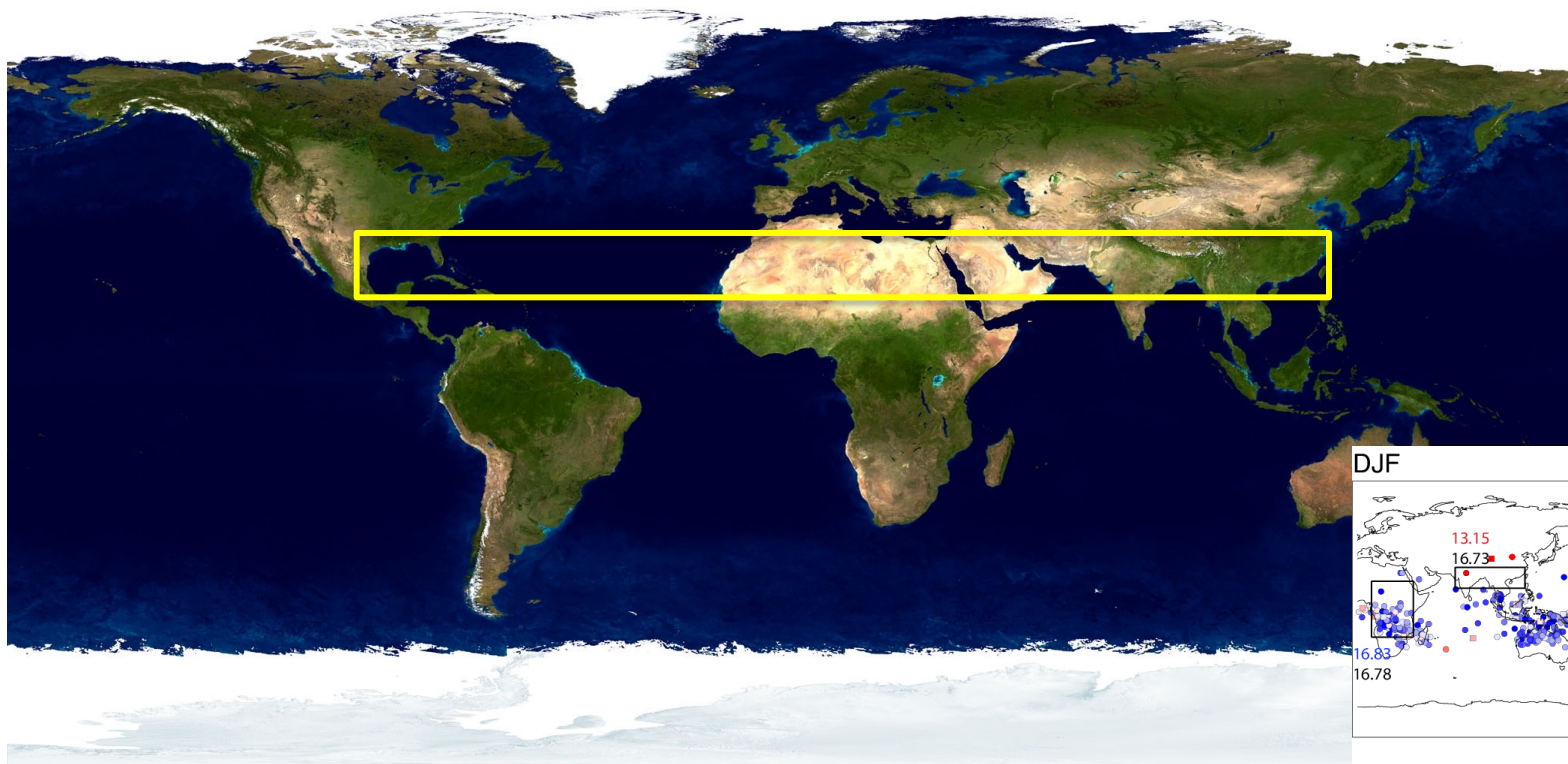
TGF放电过程的射频信号？



Zhang, Lu et al. (2021)

- 赤道地区TGF-闪电相关性同其它地区基本一致
- 近距离观测对于一些TGF相关的弱放电过程非常重要

# TGF观测区对流层顶高度统计特征

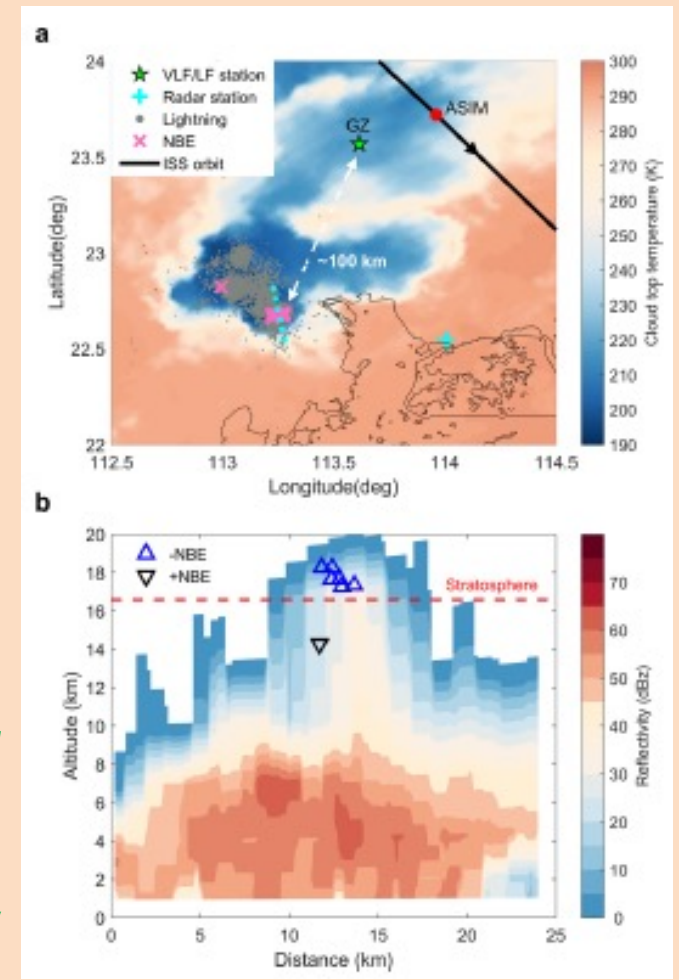
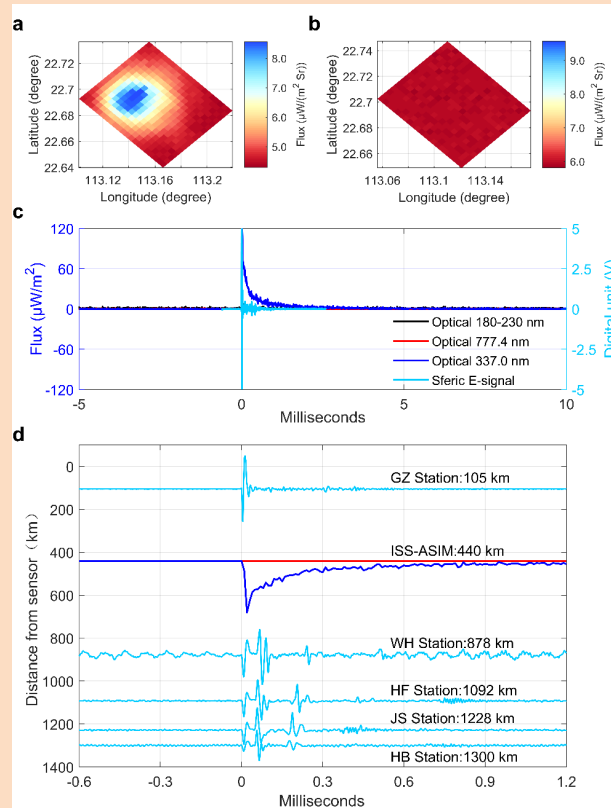
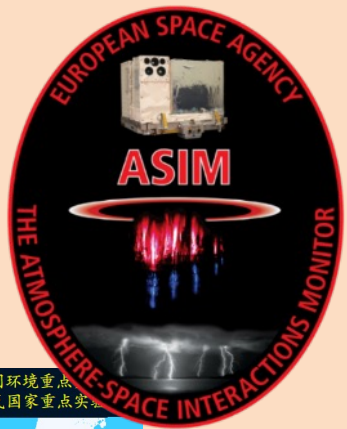
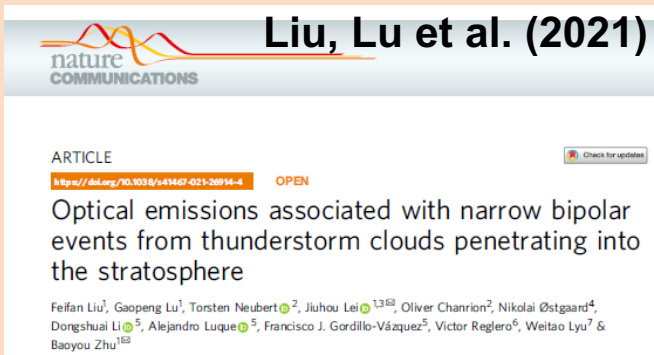


- GNSS掩星技术用于反演TGF雷暴区域的对流层顶高度
- 南亚/华南地区的TGF雷暴对流层顶高度比加勒比海地区平均高1.4公里

Xian, Lu et al. (2021)

# 雷暴云顶蓝色放电现象的光辐射特征

## 地空学院跨学科合作成果



中国科大地空学院/中科院近地空间环境重点实验室  
 中科院灾害天气国家重点实验室

<http://222.195.83.28:8081>

中国科大江淮闪电定位网

对流层雷暴-中高层大气环境耦合过程研究

- 空间-地基联合观测证实雷暴云顶蓝色发光现象同负极性NBE之间的相关性
- 发现蓝色发光亮度同NBE辐射强度之间存在较好的相关性

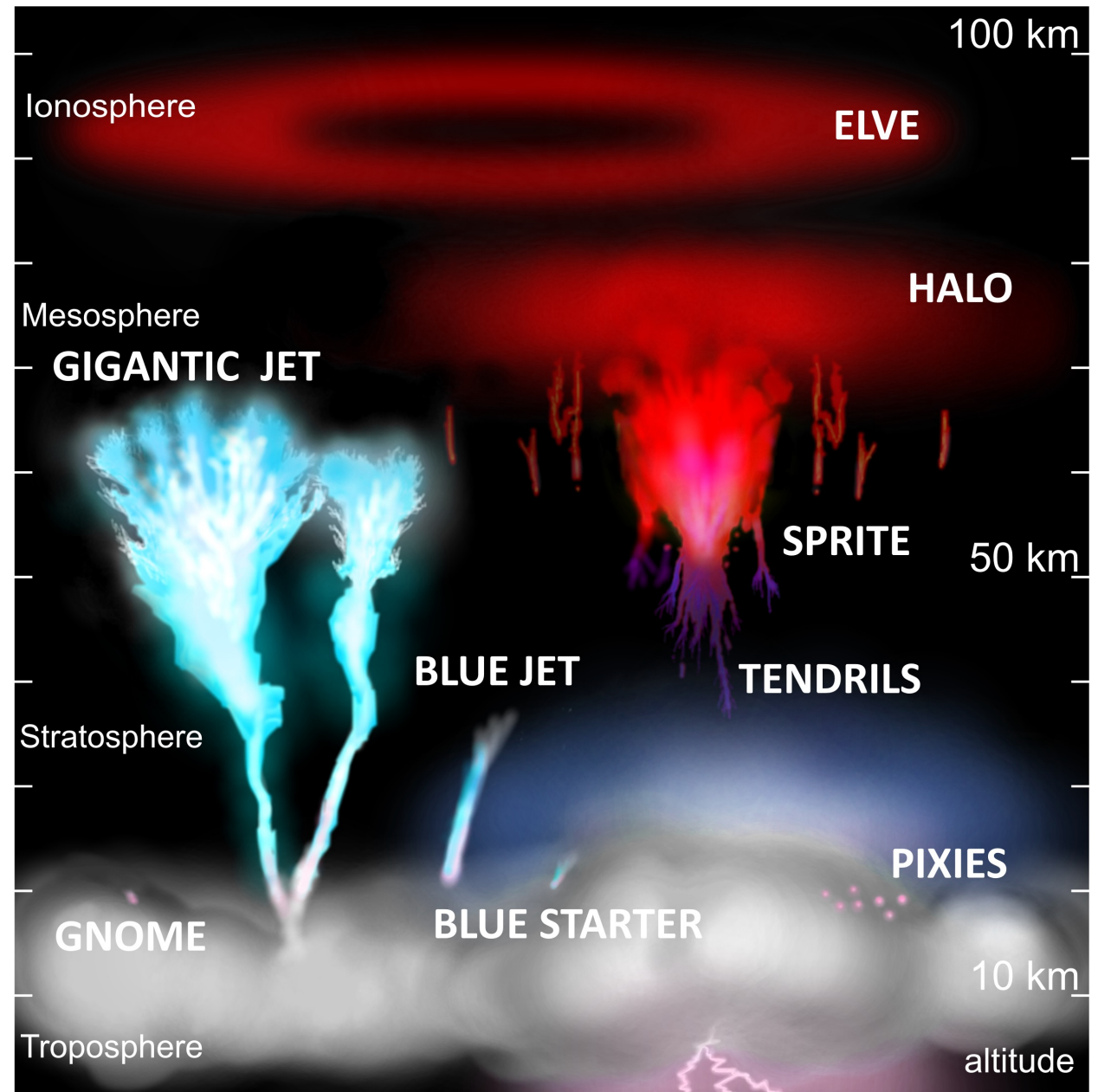
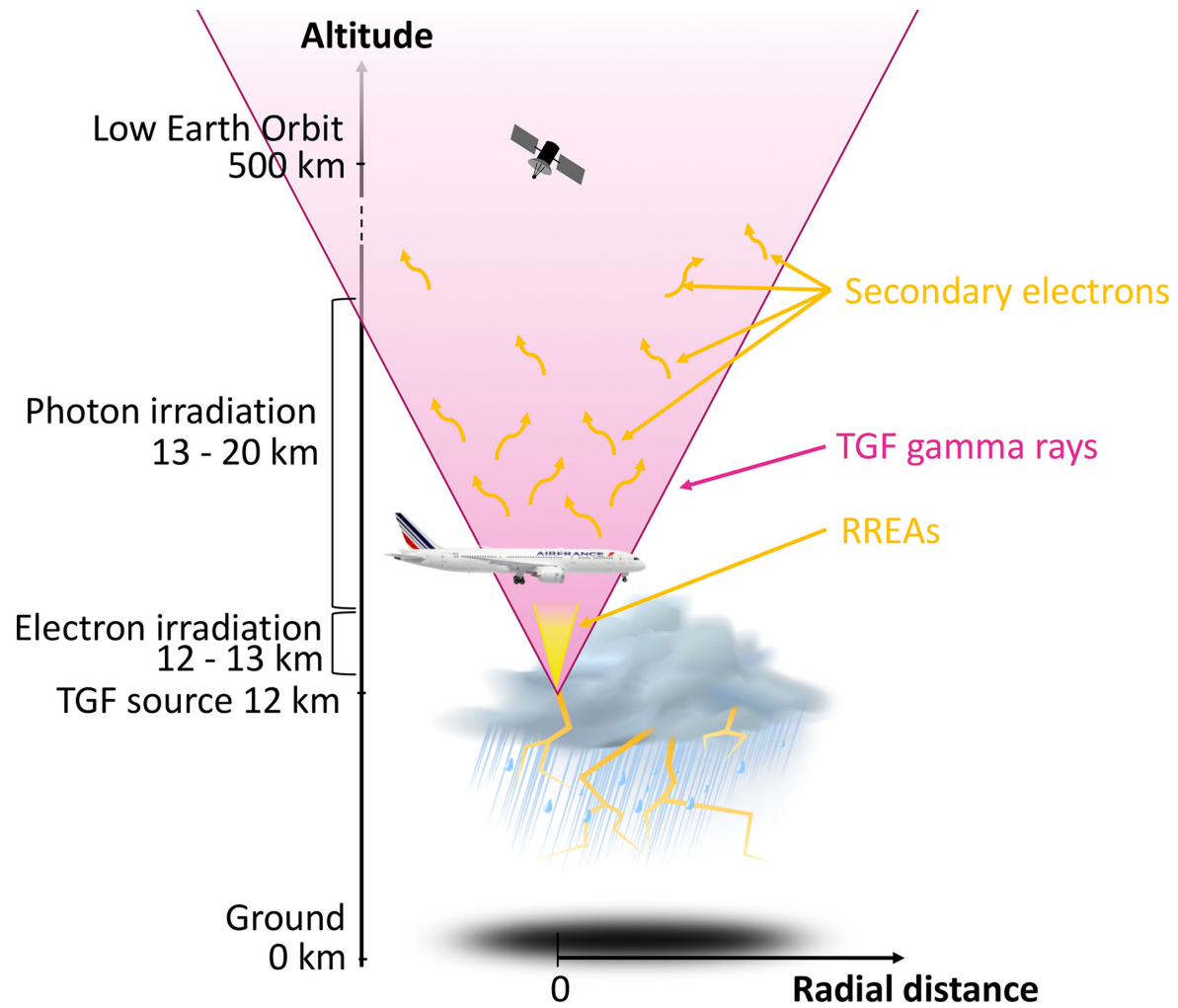
*Thank You!*

雷电研究

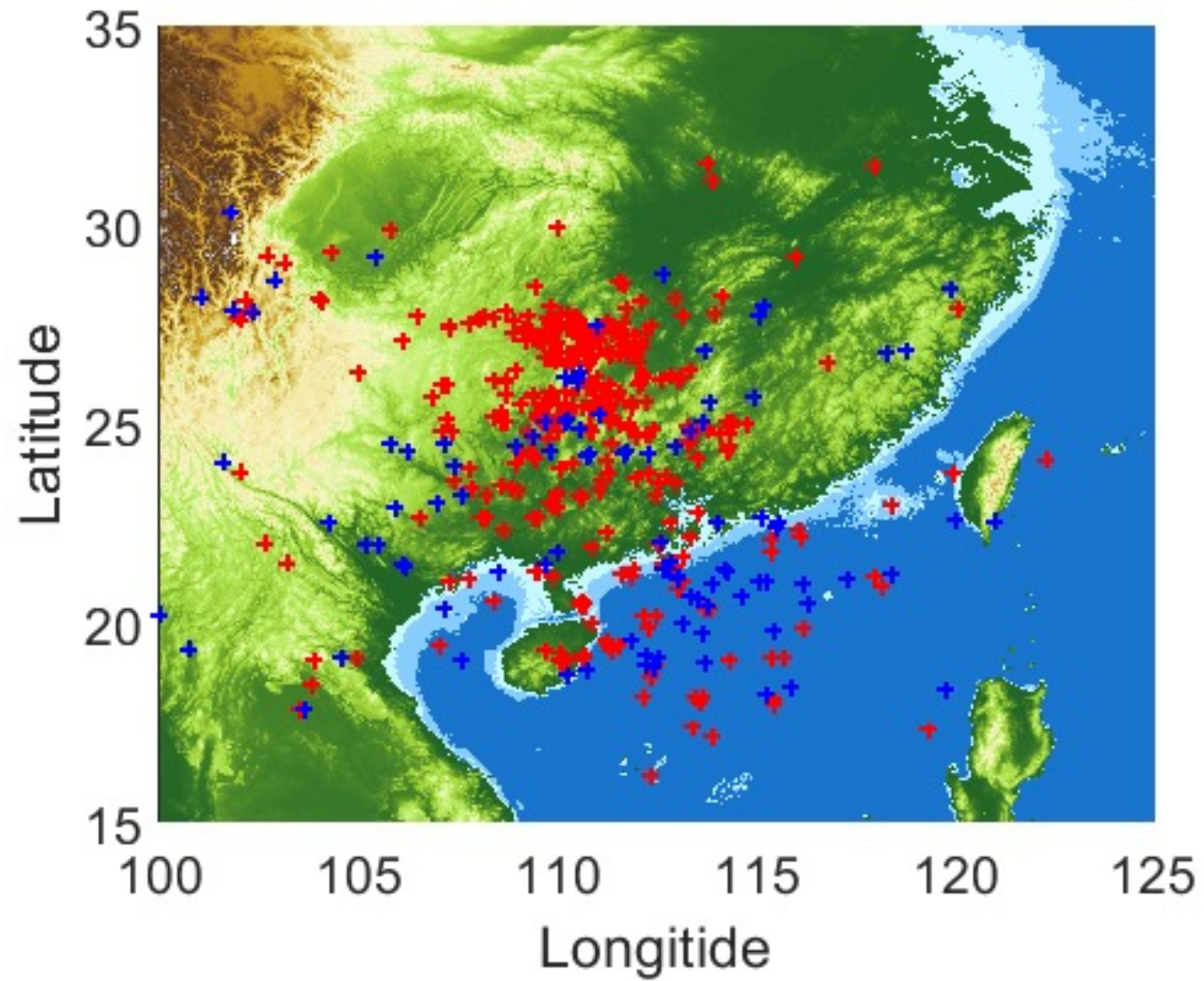
-带你上天入海





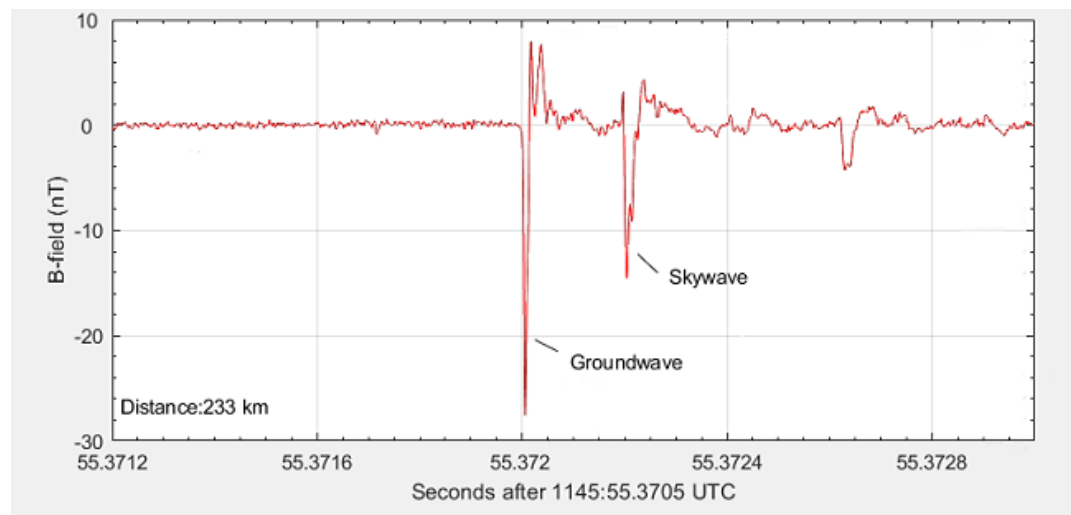
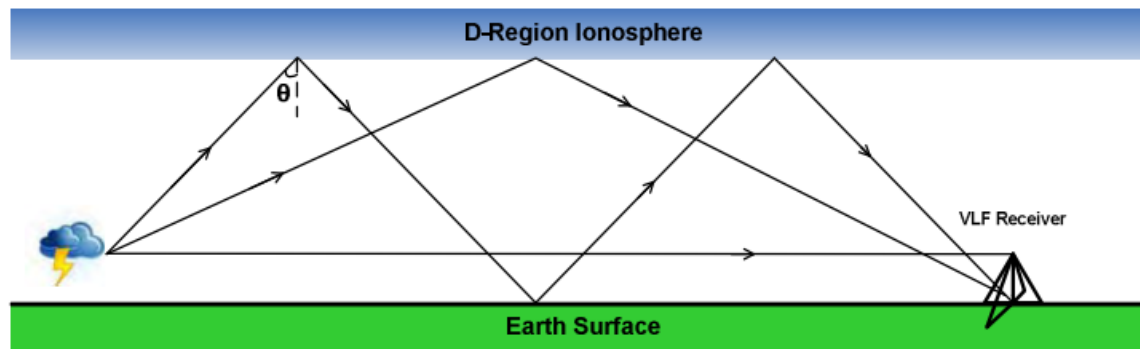
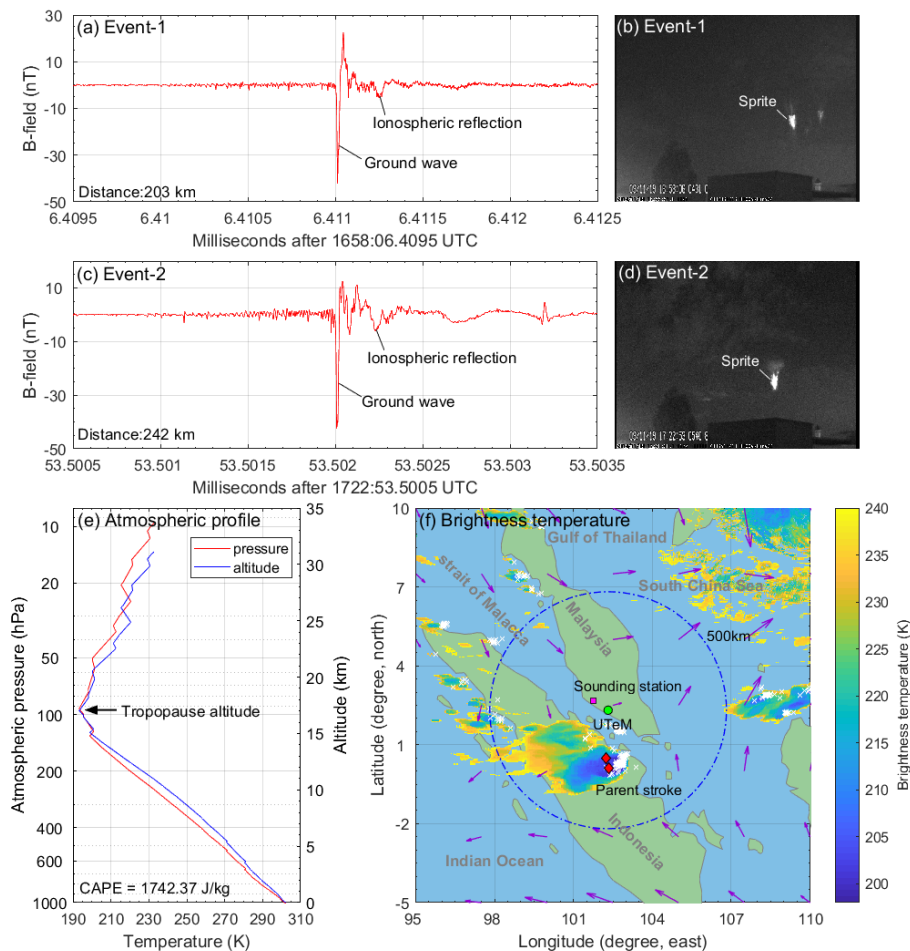


# 合作情况



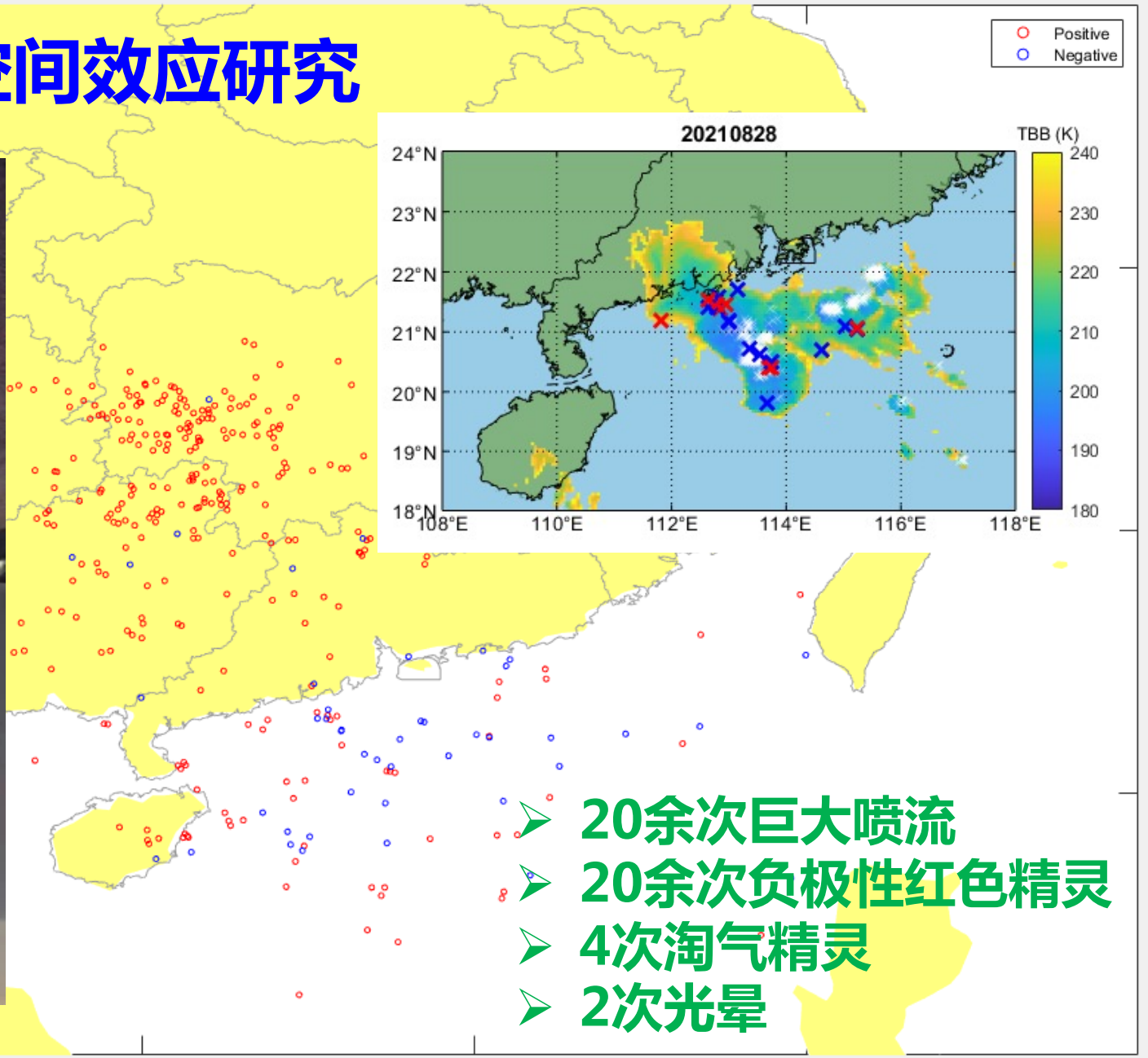
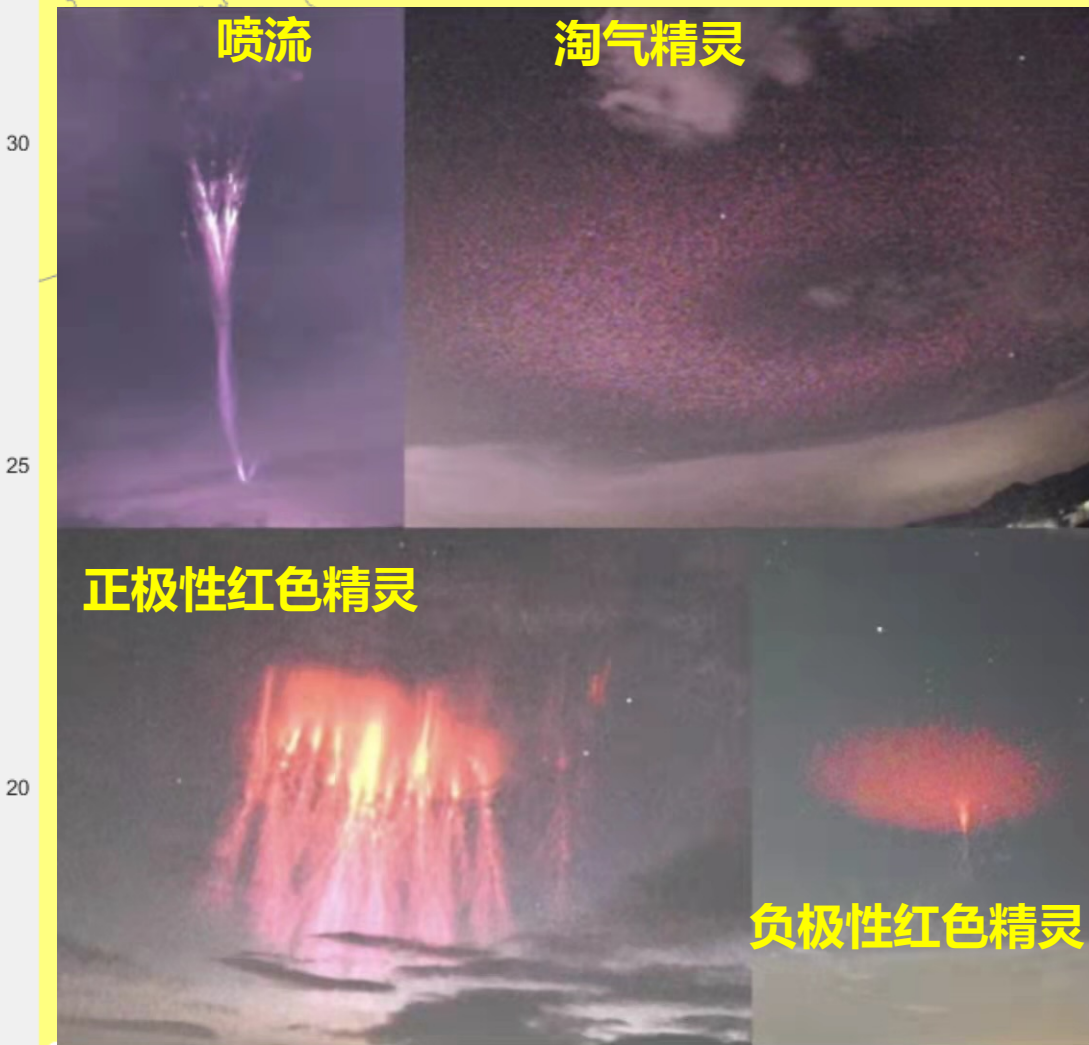
# 赤道地区红色精灵观测

- 观测受多云天气影响
  - 赤道地区红色精灵较弱
  - 雷暴单体普遍尺度较小
- 王庸平等(2021)



目前仅观测到7例红色精灵，均为正极性。

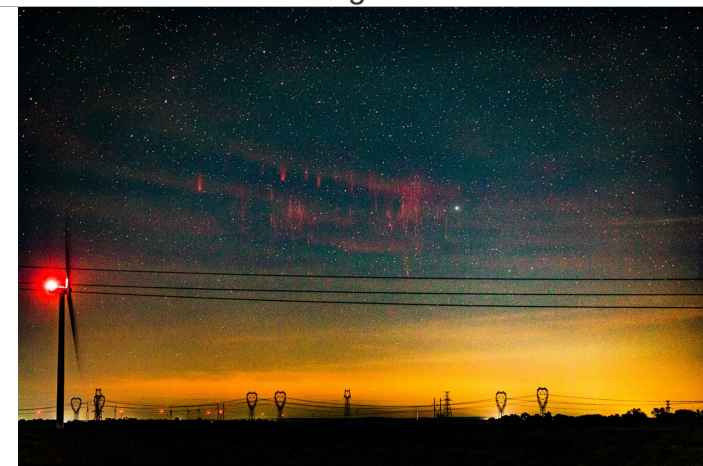
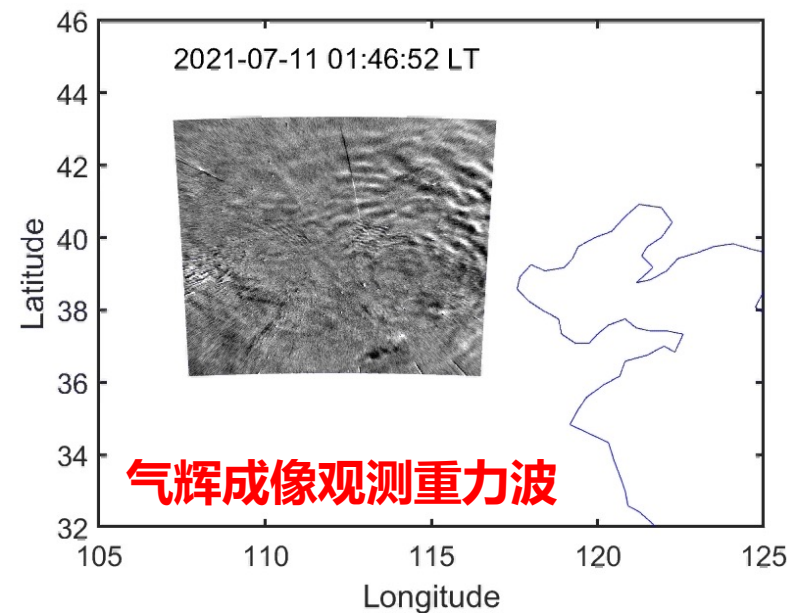
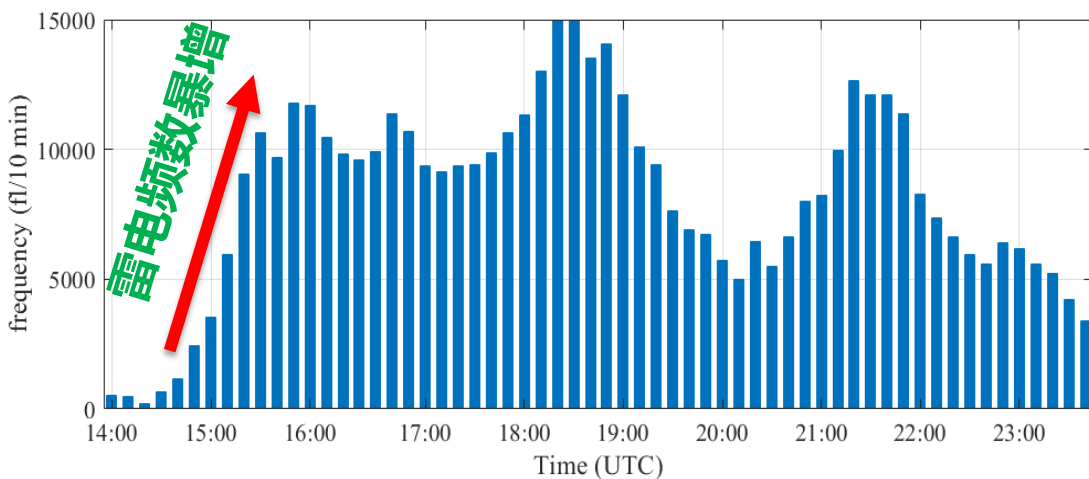
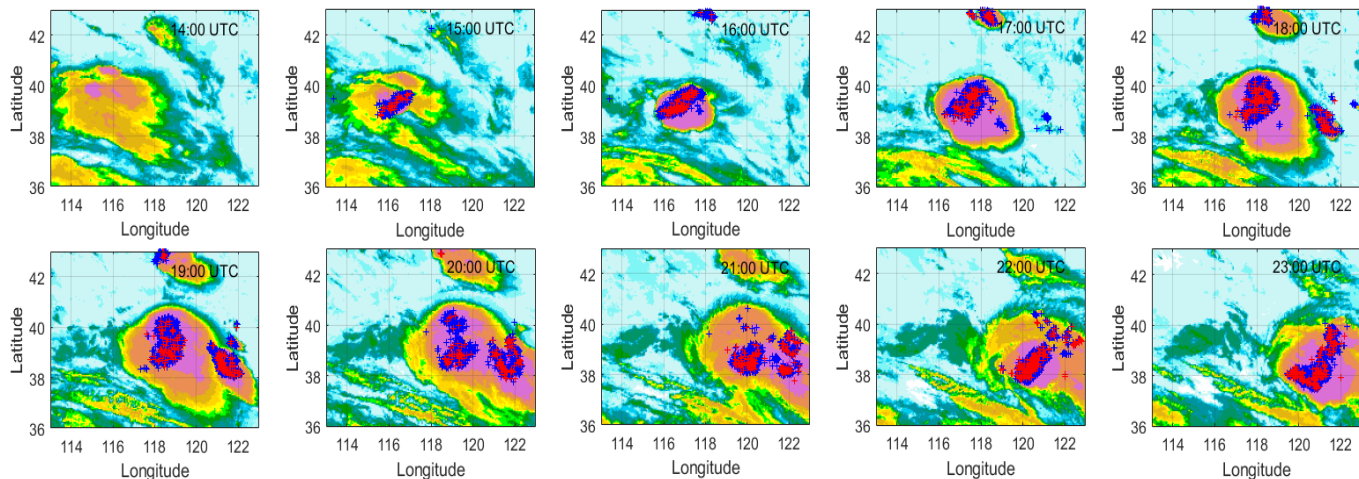
# 基于爱好者观测的雷暴临近空间效应研究



- 20余次巨大喷流
- 20余次负极性红色精灵
- 4次淘气精灵
- 2次光晕

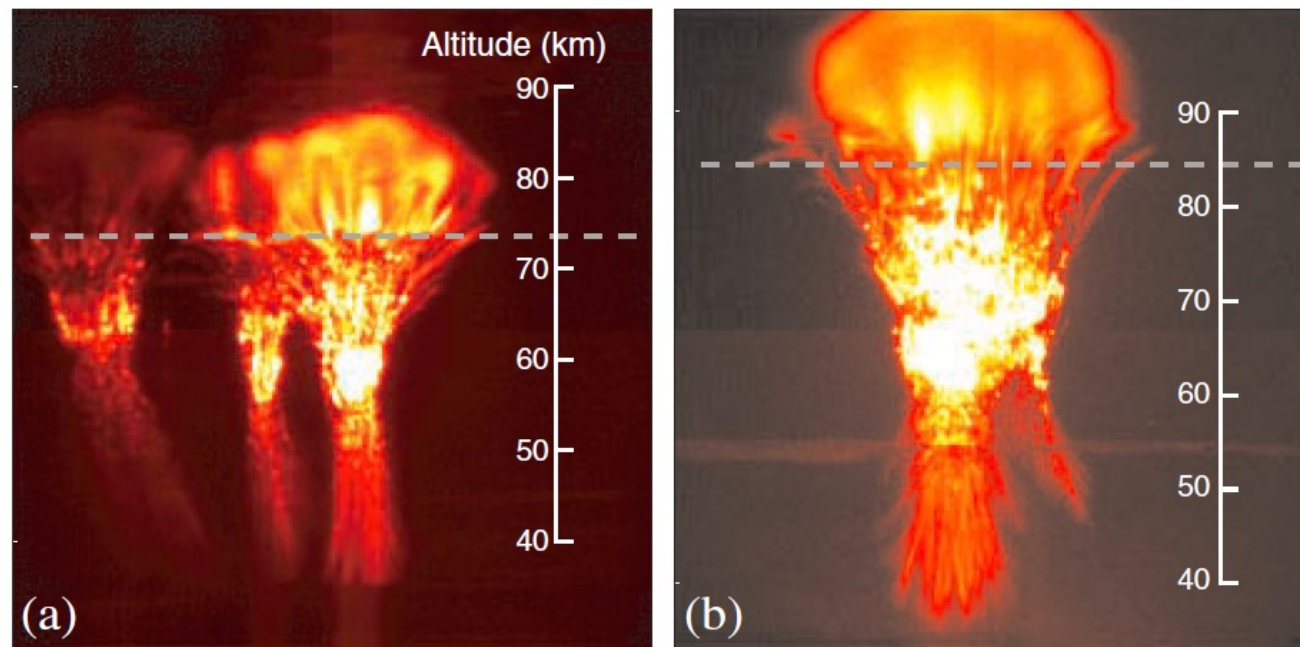
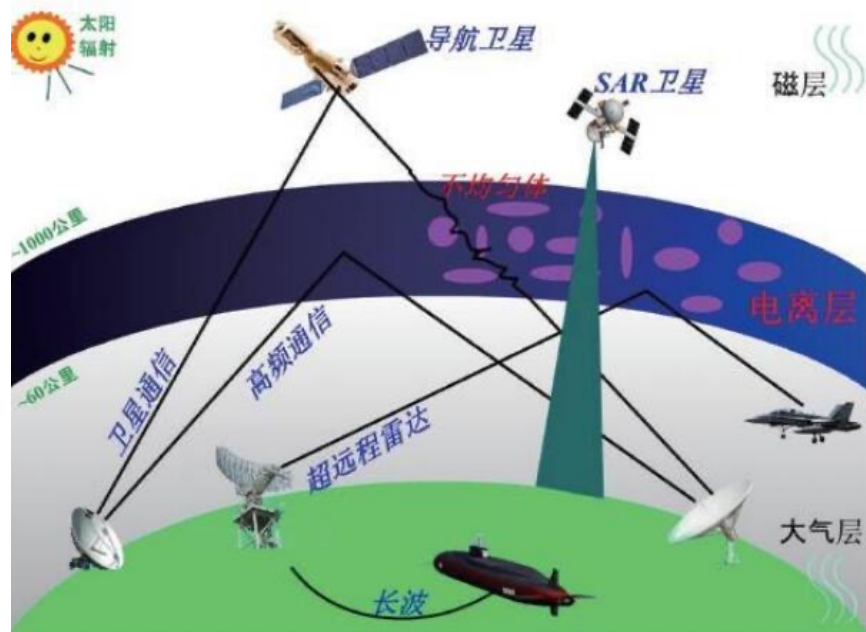
# 基于雷电探测的重力波事件预测

## 2021年7月11日凌晨京津冀地区一次强对流过程



长时曝光观测重力波

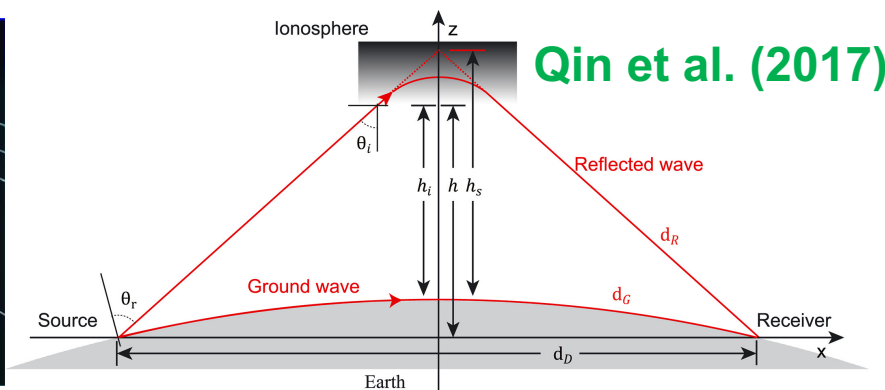
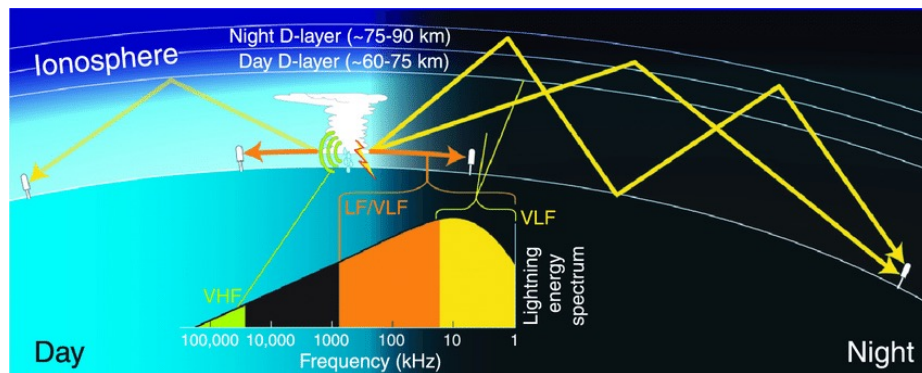
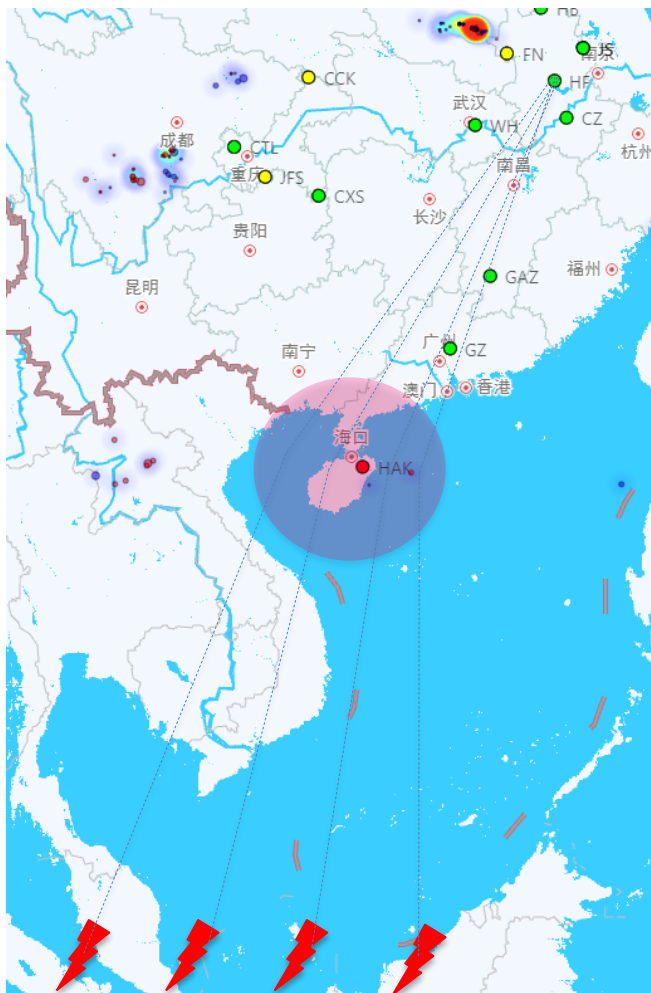
# 中高层放电事件是否会导致电离层不规则体？



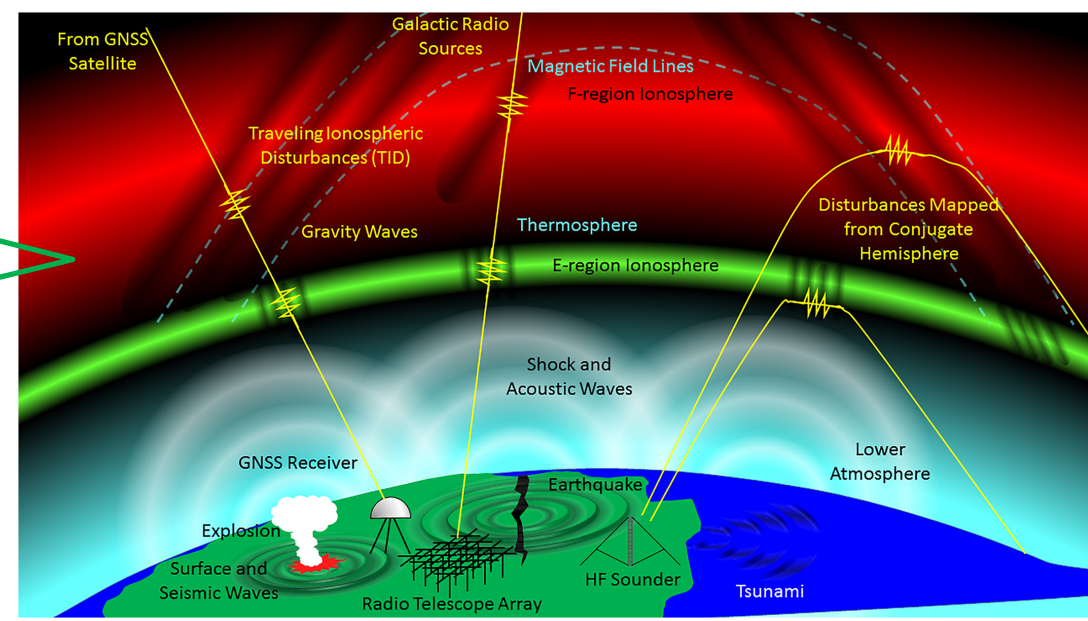
Stenbaek and Pakso (2002)

- 中高层放电现象引起的电离层底部扰动是否有可能成为电离层不规则体形成的种子？
- 中高层放电现象引起的电离层D区电子浓度增加能够持续多久？会导致哪些可观测效应？

# 基于雷电信号的电离层态势感知

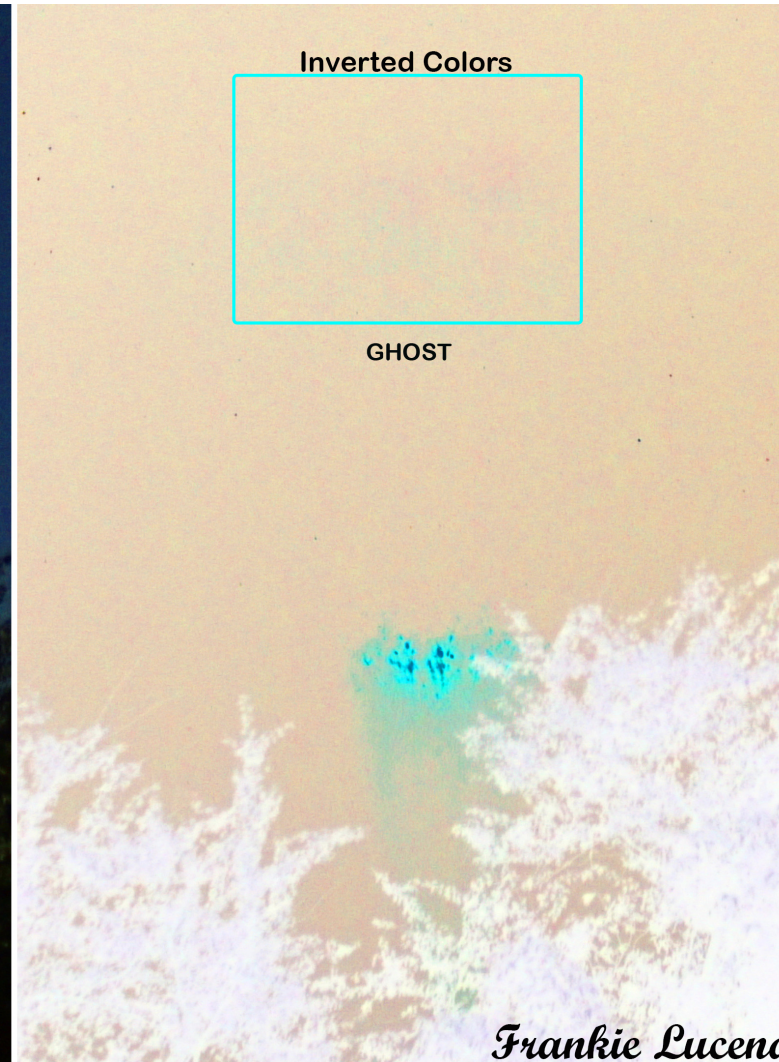


地震、深对流等  
低层扰动引起的  
电离层状态变化  
(TEC)、卫星信号  
中断等



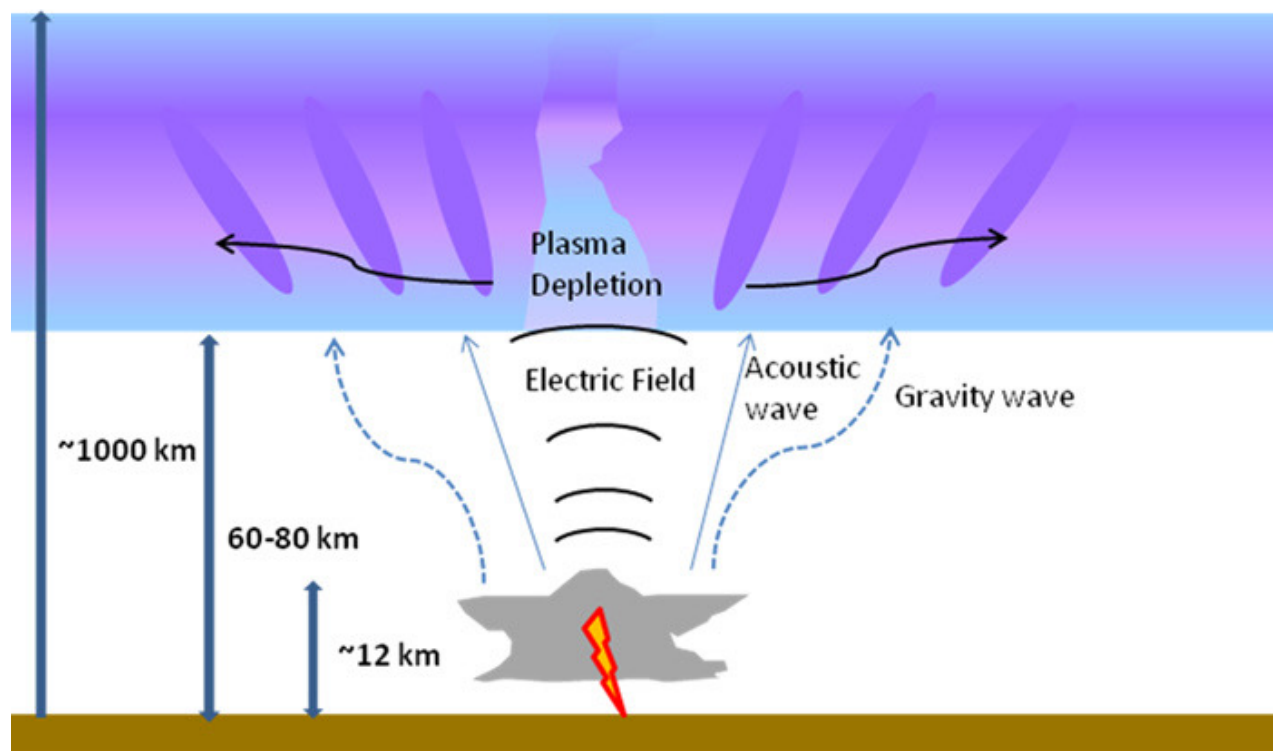
➤ 是否能够利用闪电电波测量探测地震及其他扰动源引起的电离层底部扰动？

# 疑似的GHOST现象

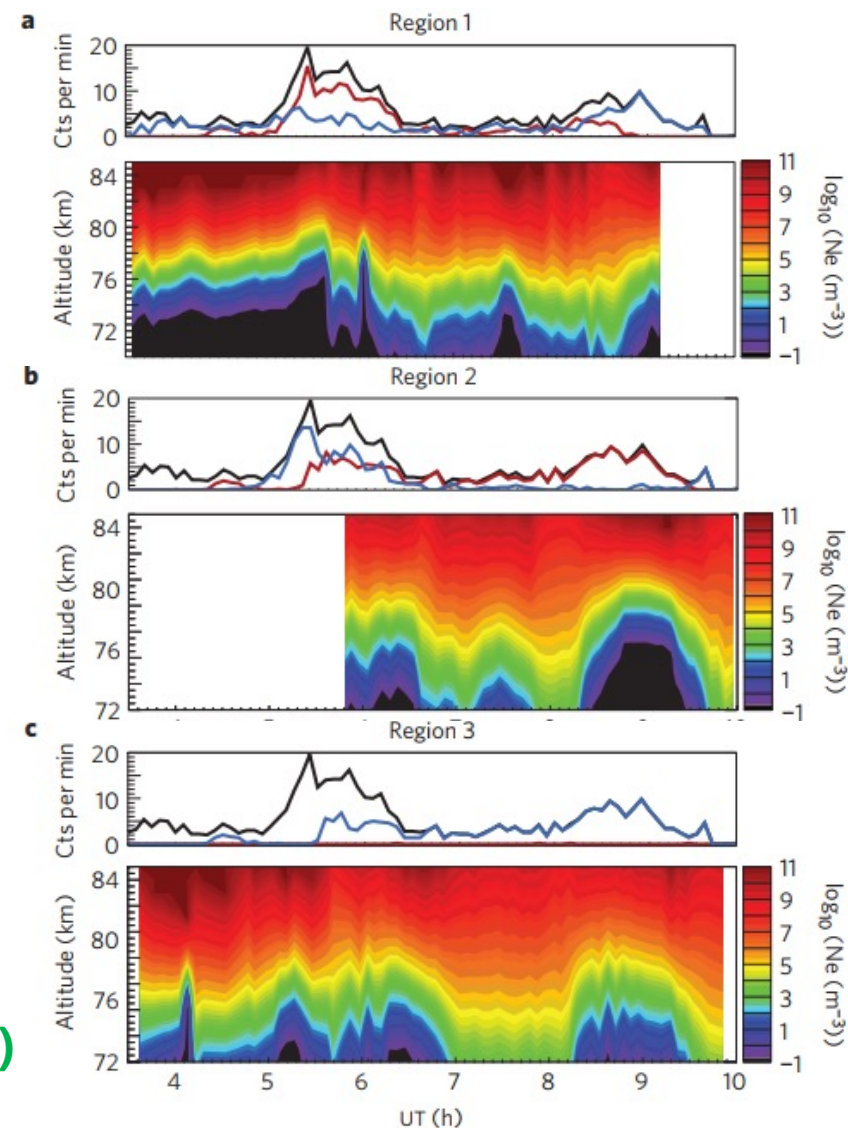




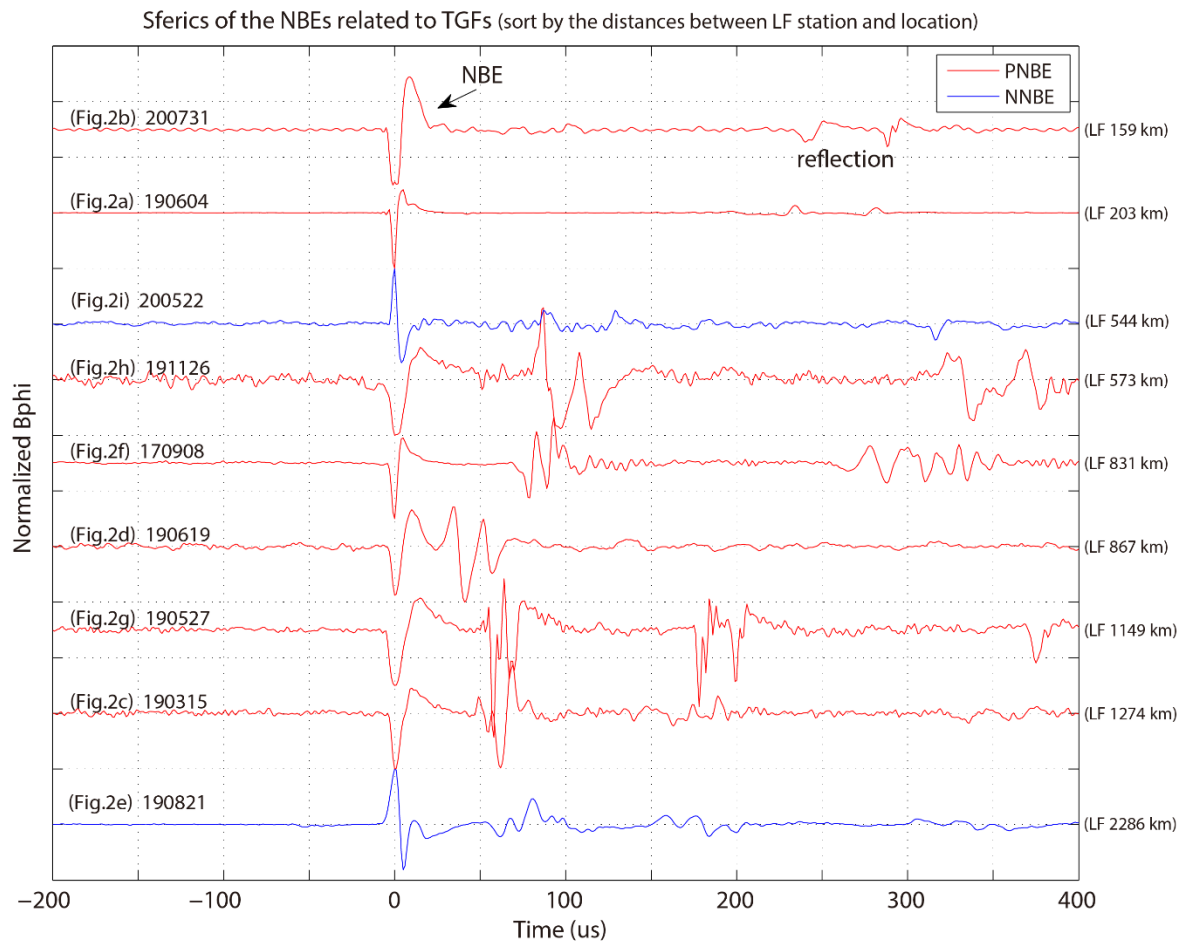
# 雷暴是否能够引起电离层扰动？



Shao et al. (2012)



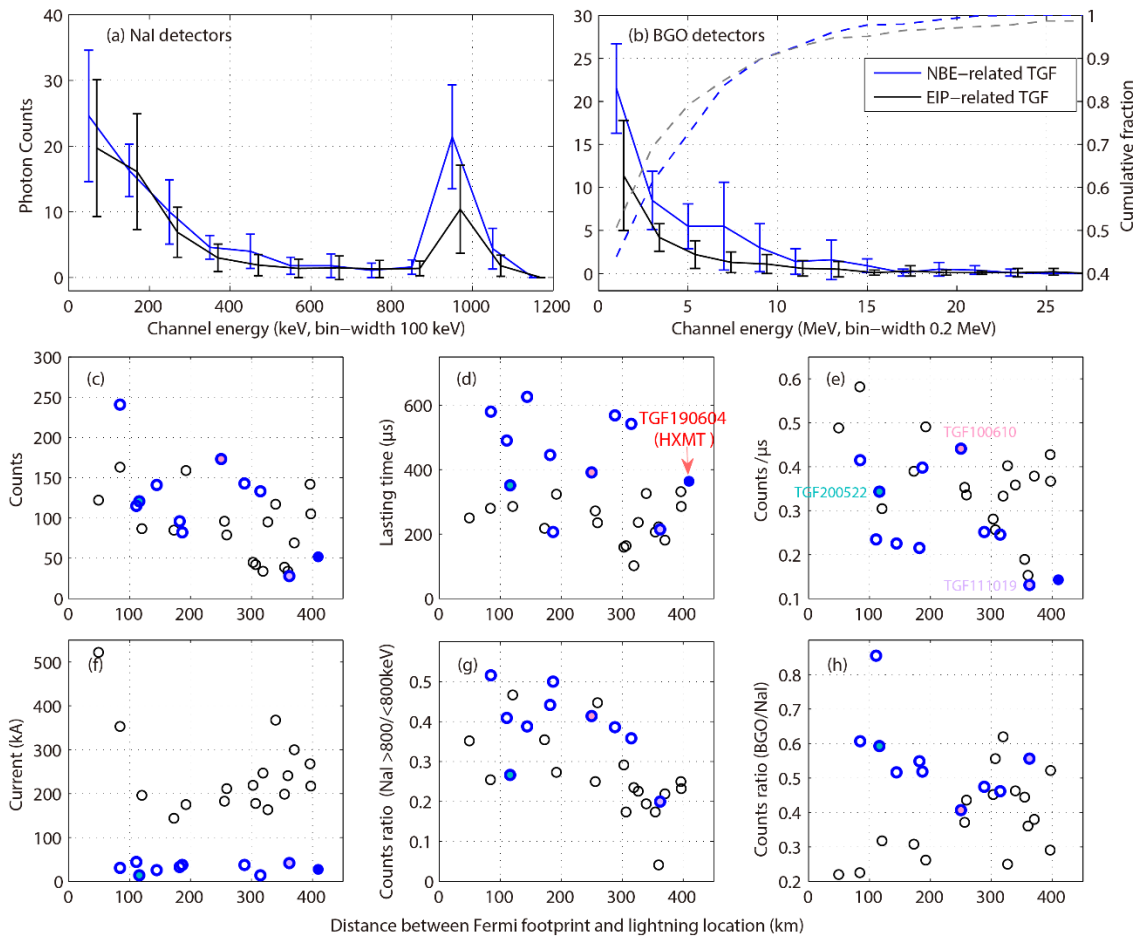
# 热带地区NBE前置的TGF事件



➤ 不同事件的低频磁场波形

Zhang, Lu et al. (2021)

7/22/22



➤ NBE-TGF中高能伽马辐射比较较高

➤ TGF源区高度更低？