

天关卫星时代的恒星X射线耀发研究 2025.05.25-28 北京

天关时代的太阳多波段观测和磁场测量

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怀柔太阳观测基地
中国科学院国家天文台

2025-05-27

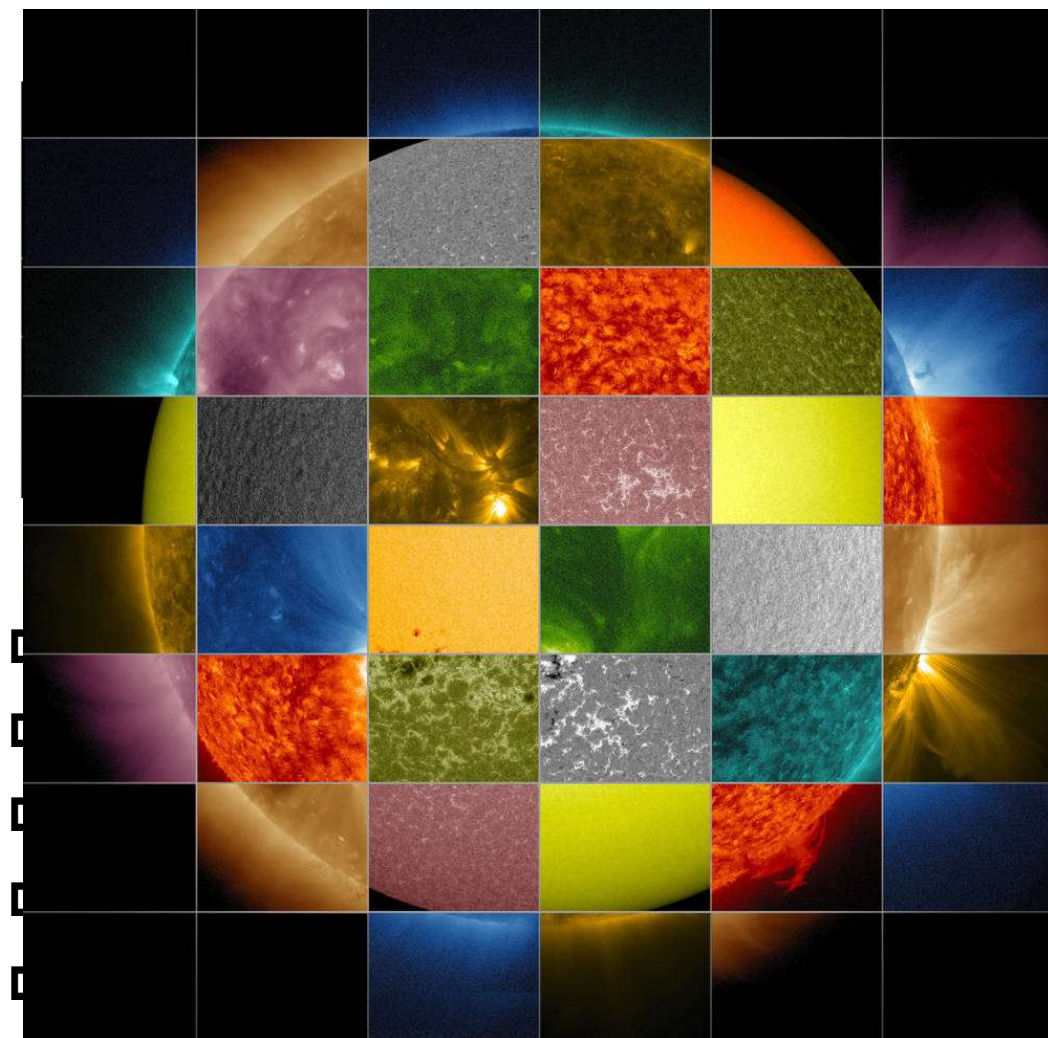
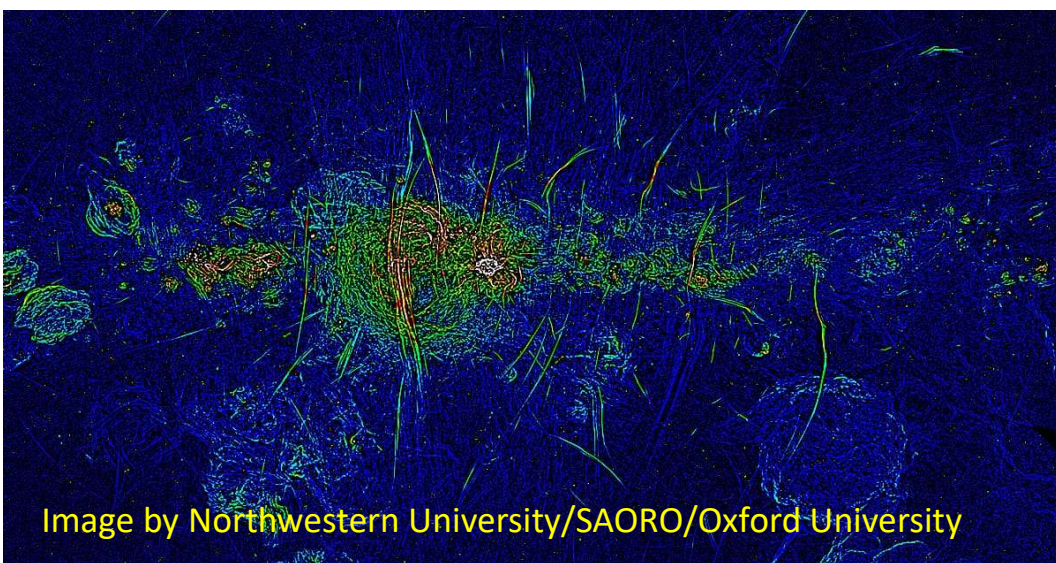
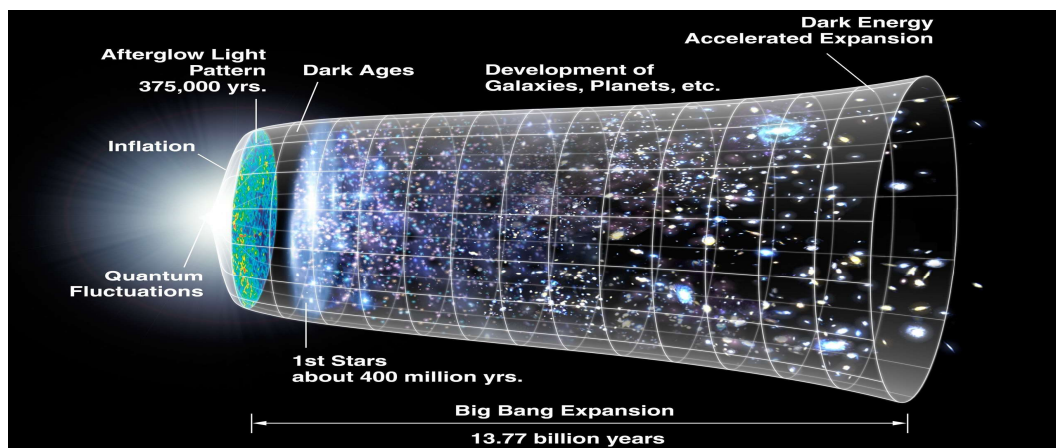


Outline

- 背景和意义
- 太阳多波段观测
- 太阳磁场测量（研究、技术、方法）
- 恒星磁场研究的一些尝试
- 展望



爱因斯坦探针揭开了探索宇宙活动性的新时代



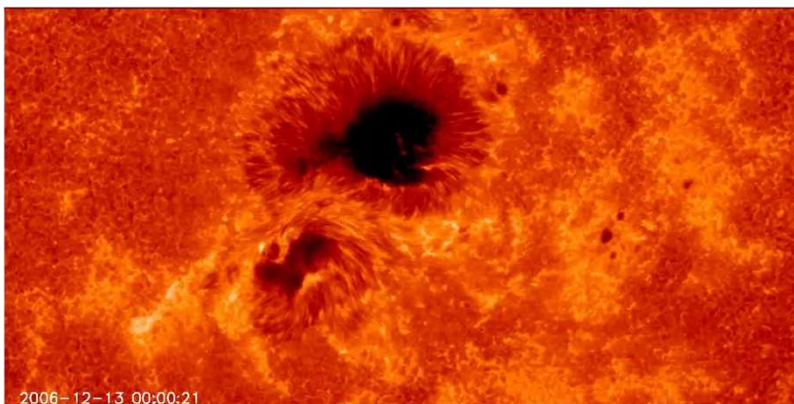
则)



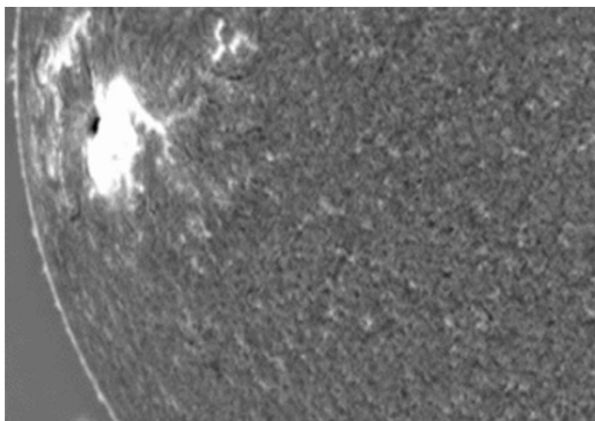
太阳多波段观测-多时间尺度

太阳的多时间尺度：可以展示从**毫秒**到**周年**尺度量级的动态演化过程

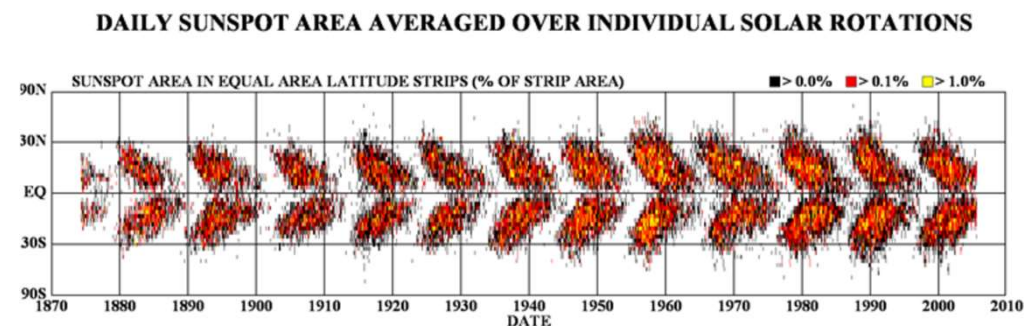
太阳耀斑



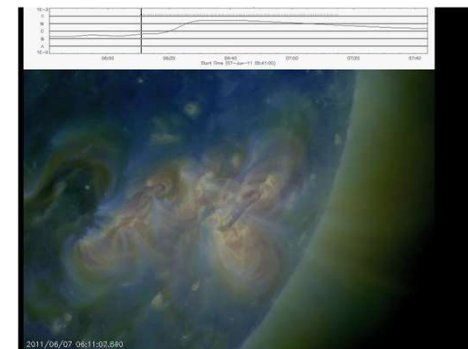
太阳上的“海啸”



太阳活动周



日冕物质抛射



天文领域多是展示静态图片，但太阳物理可以展示的动态电影！！！！

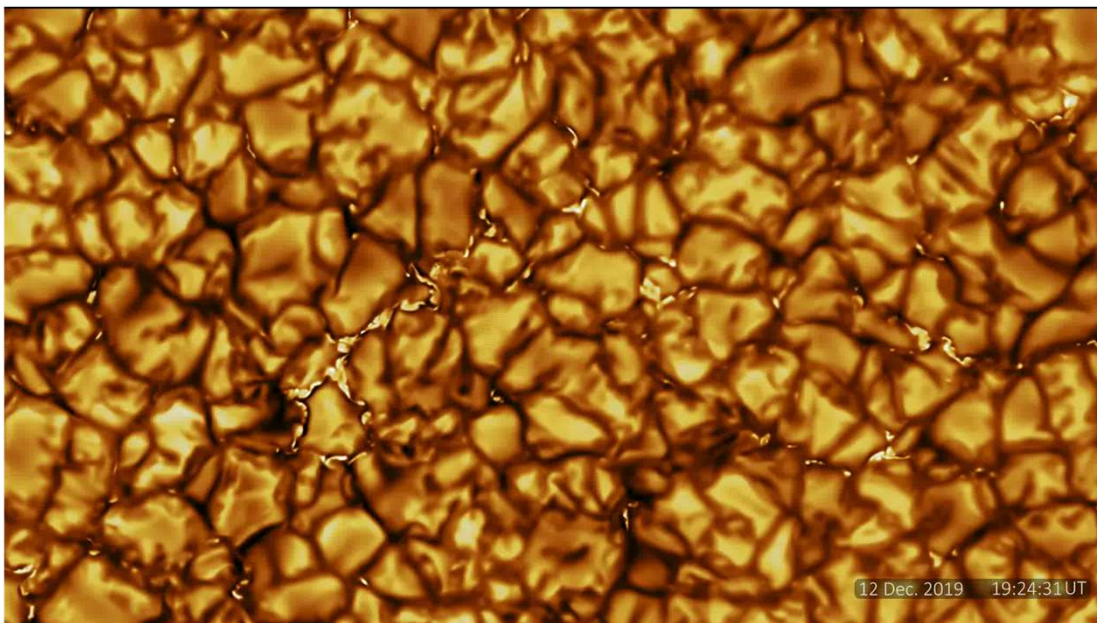


太阳多波段观测-多空间尺度

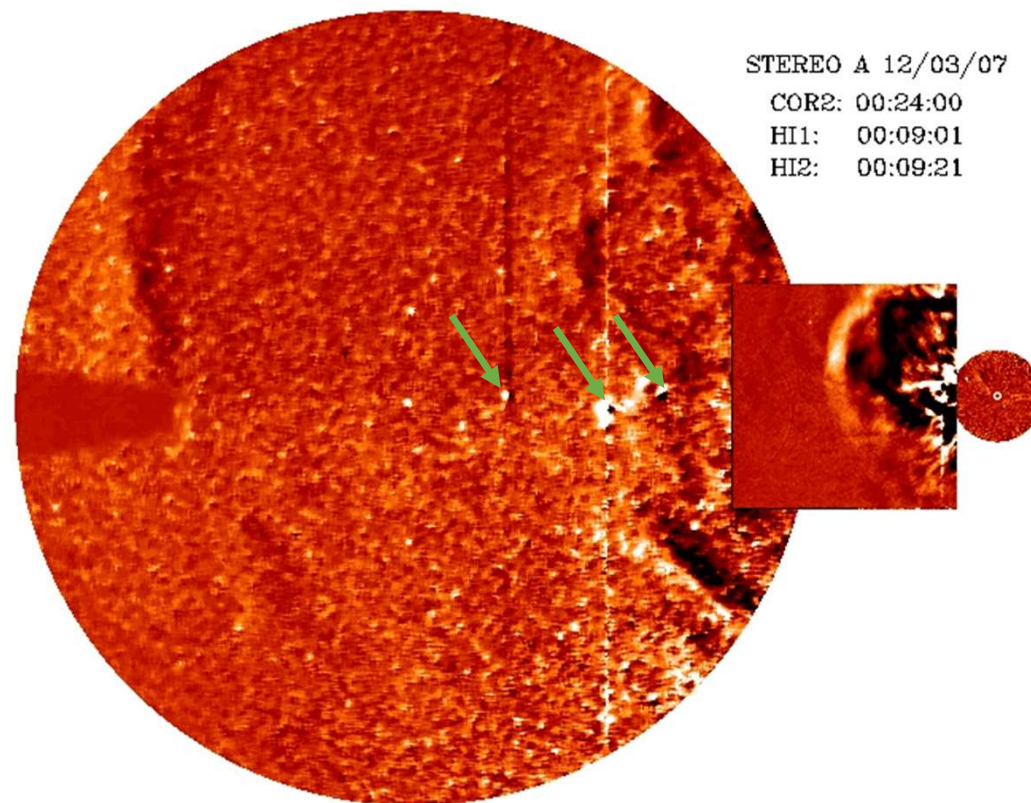
太阳的多空间尺度： 可以展示从**公里**到**AU**尺度量级的动态演化过程



DKIST 初光动态电影 (20 Km)

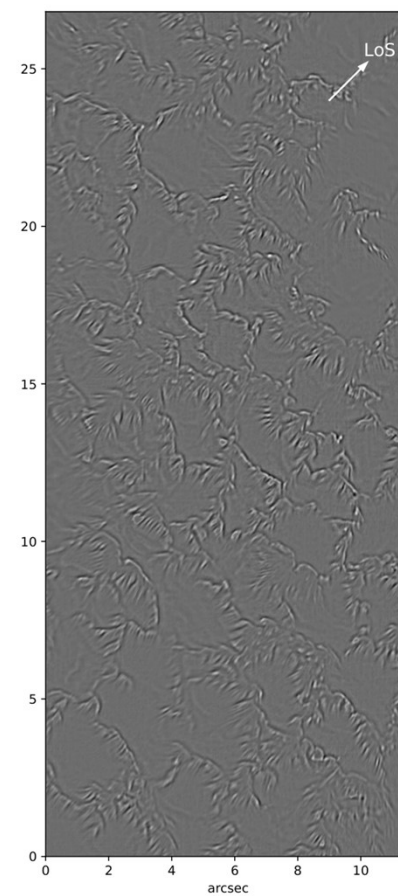
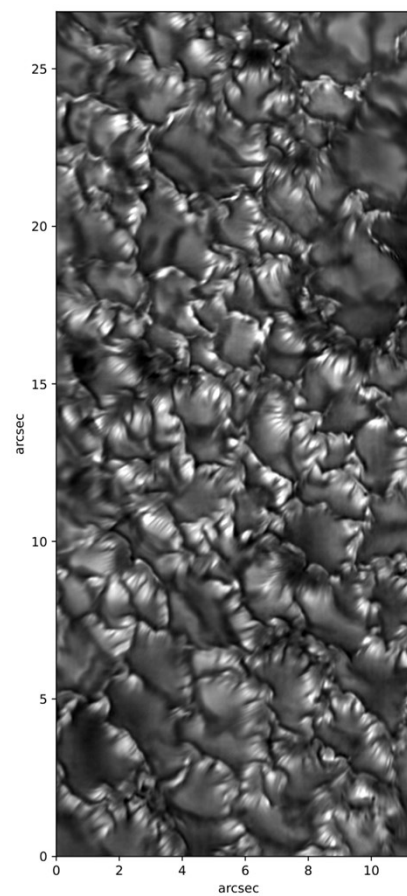
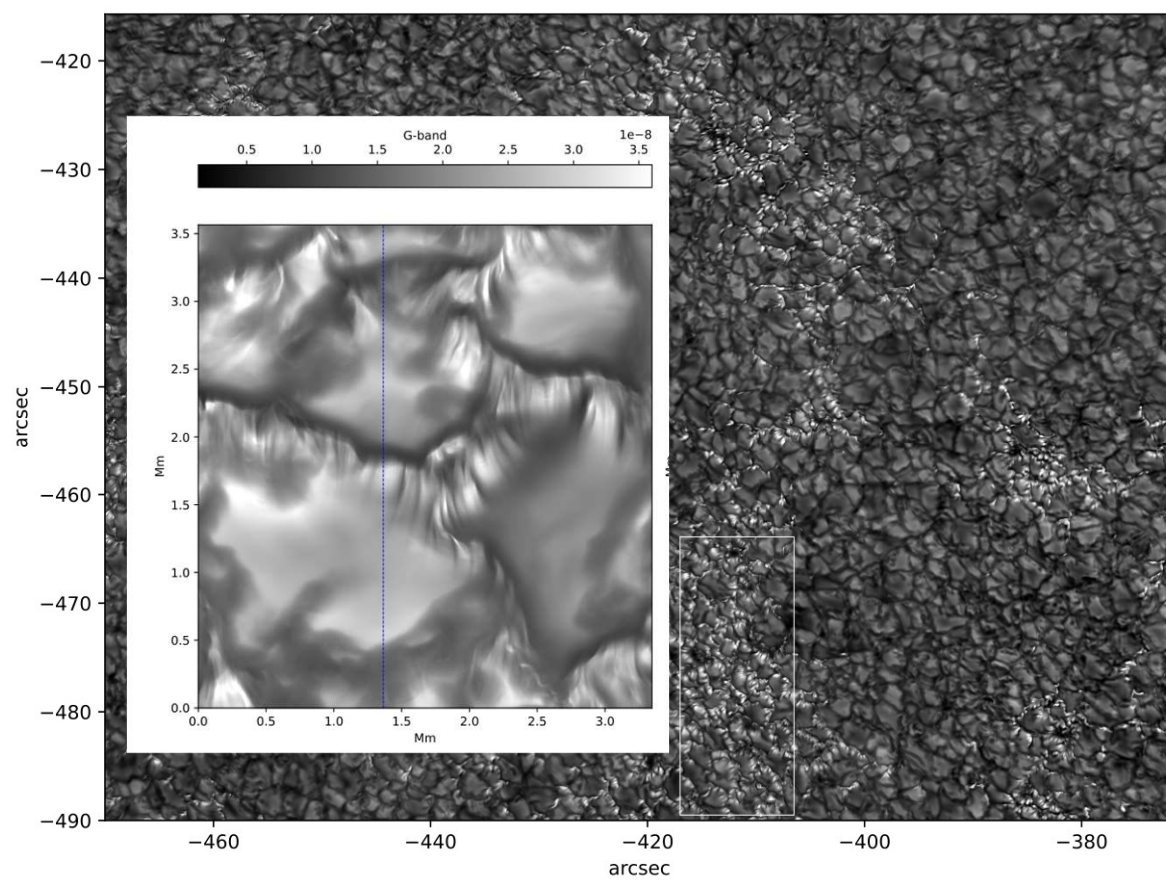


日冕物质抛射在行星际的传播 (AU)





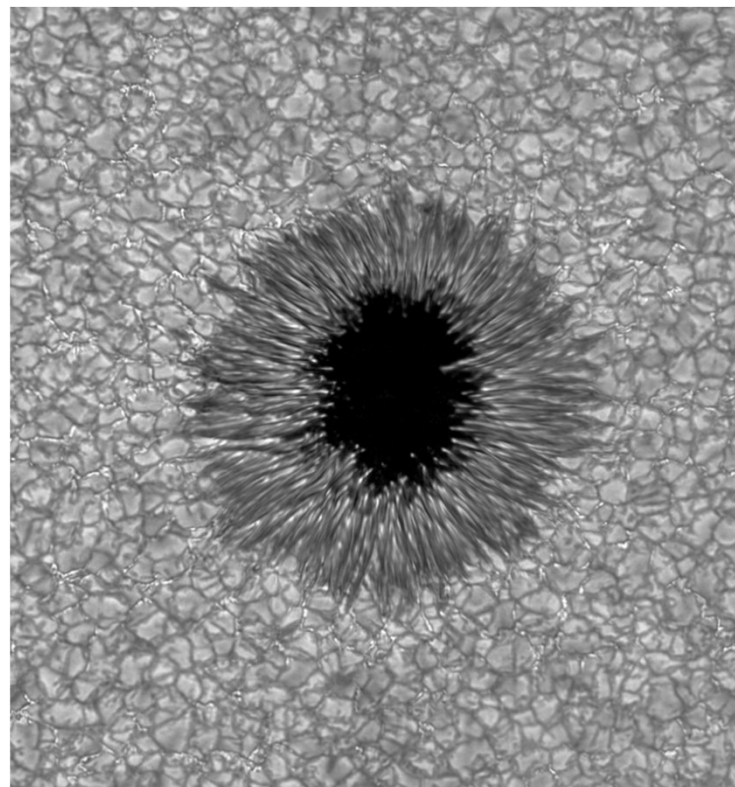
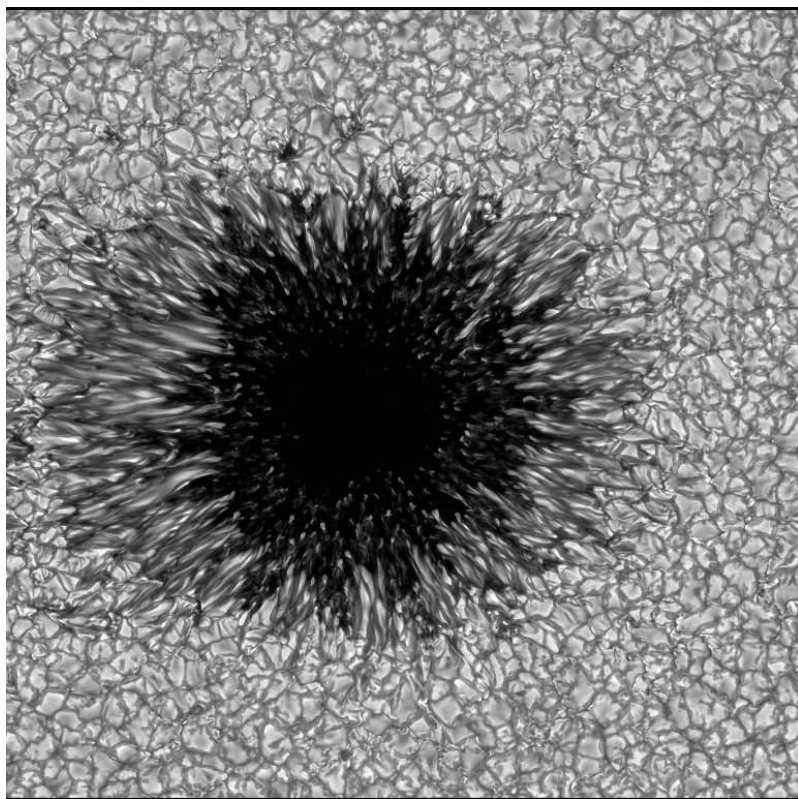
太阳多波段观测-多空间尺度





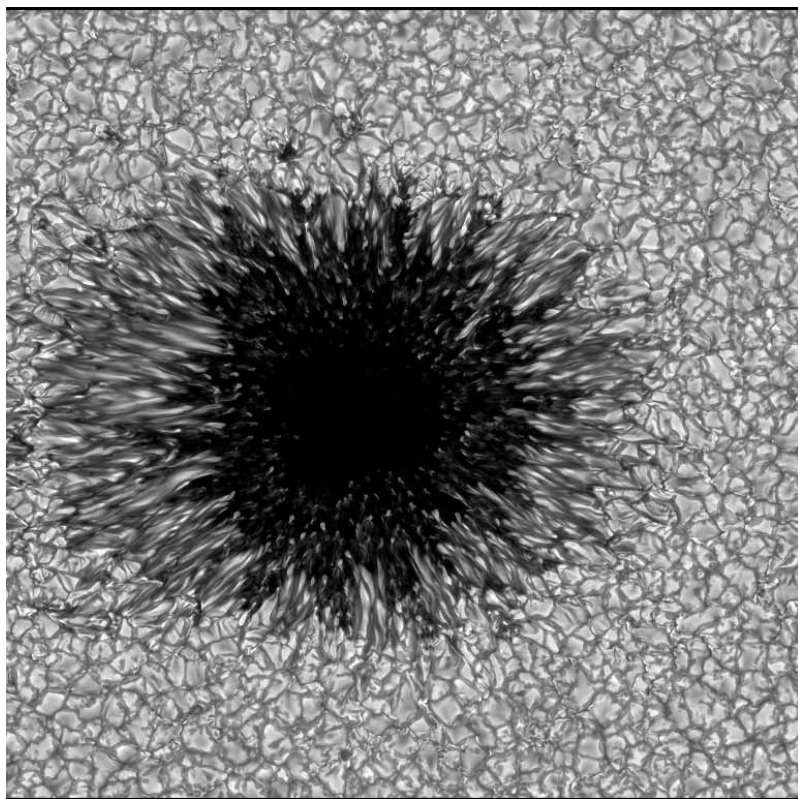
太阳多波段观测-模拟和观测齐头并进

请大家选一选，哪一个是观测的，哪一个是模拟的？

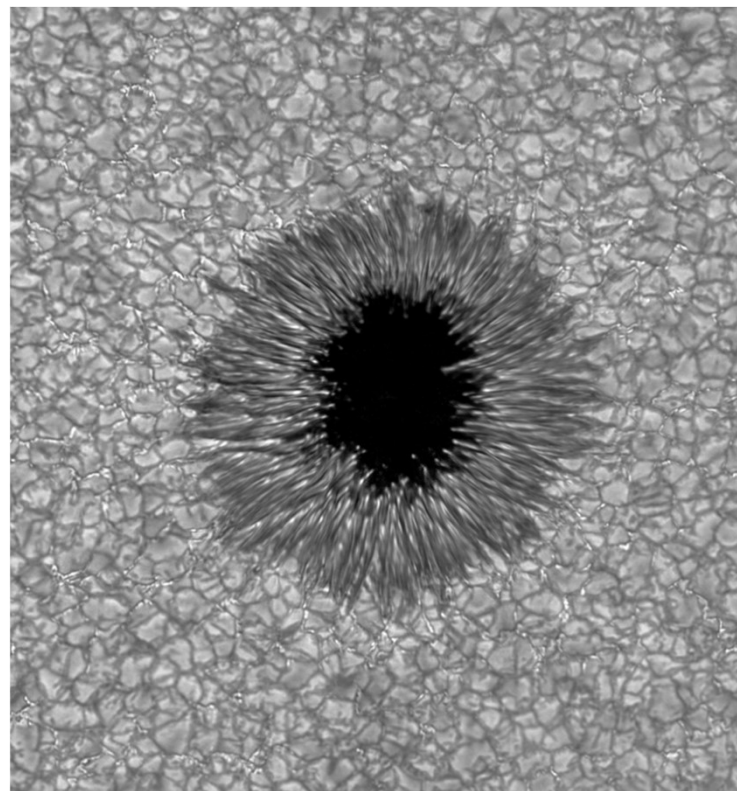


太阳多波段观测-模拟和观测齐头并进

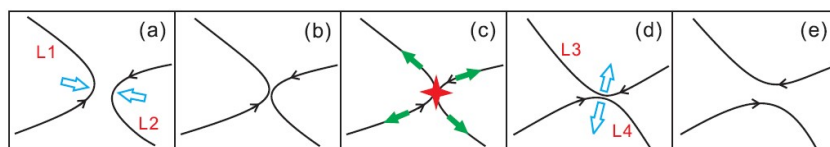
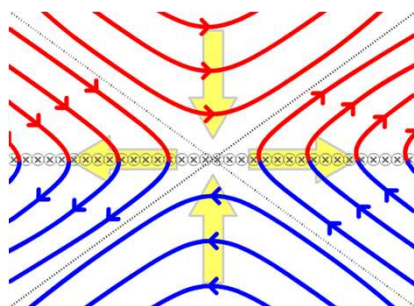
模拟
(Rempel 2009)



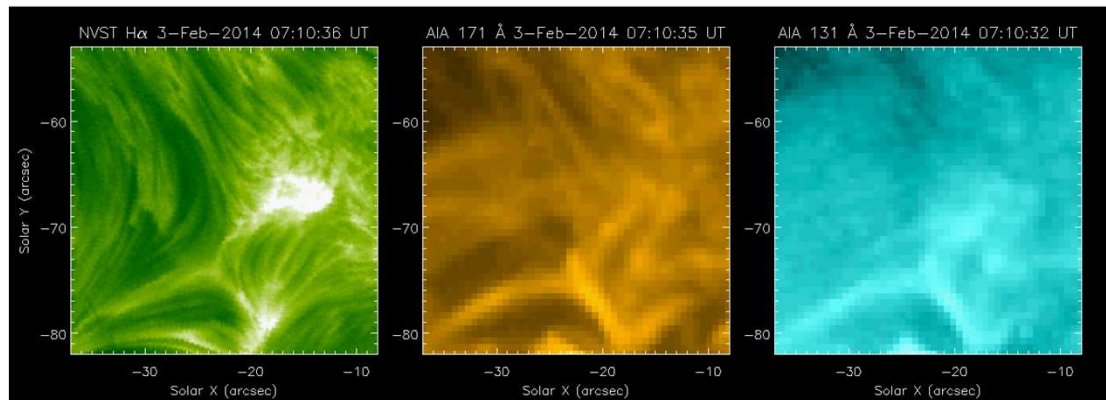
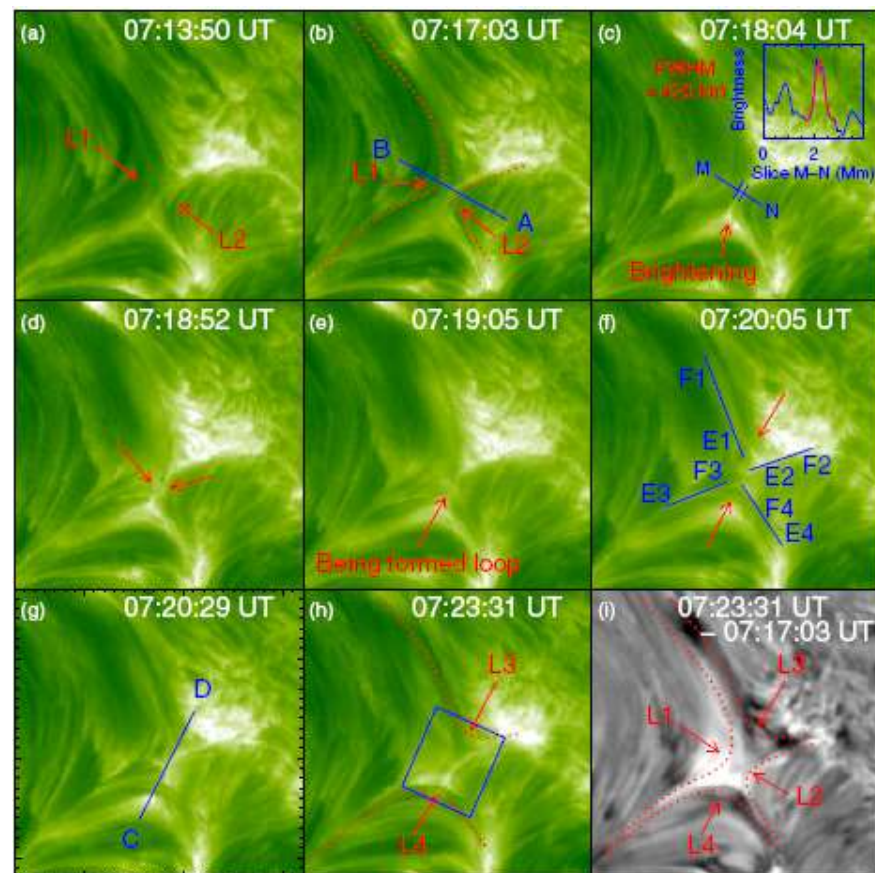
观测
GST/BBSO 1.6M



太阳多波段观测研究-小尺度低层大气磁重联



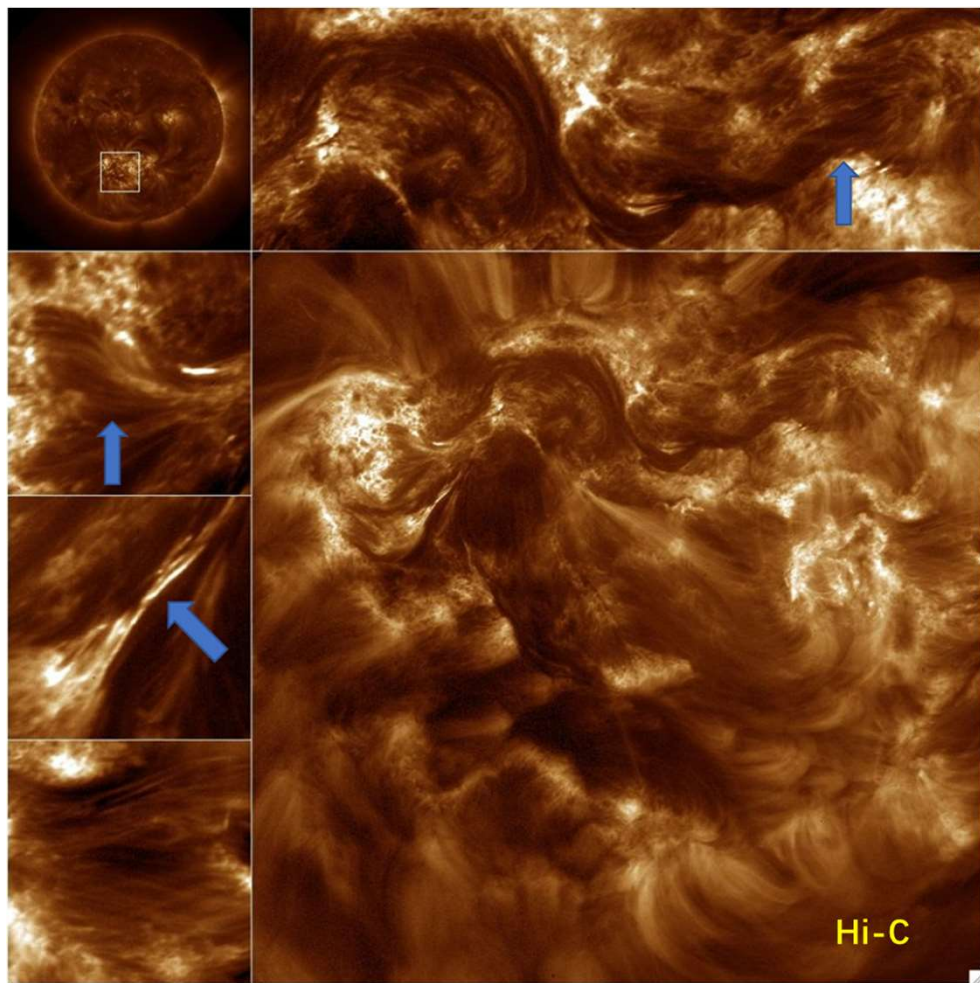
根据观测数据所刻画出的磁重联过程



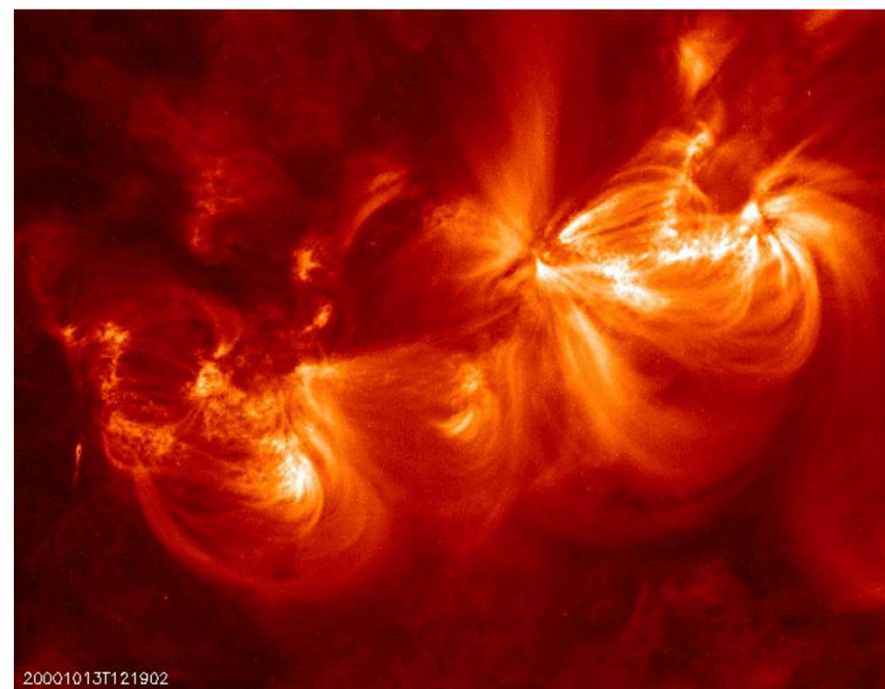
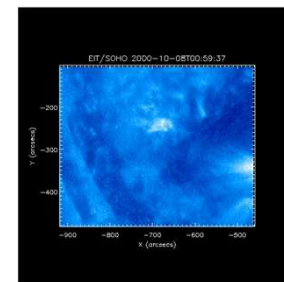
Yang Shuhong et al. 2015, ApJL, 798, L11



太阳多波段观测研究-日冕磁环的超精细结构



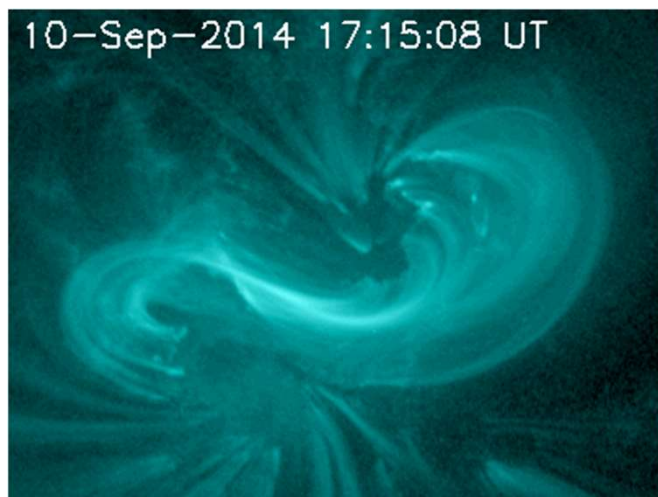
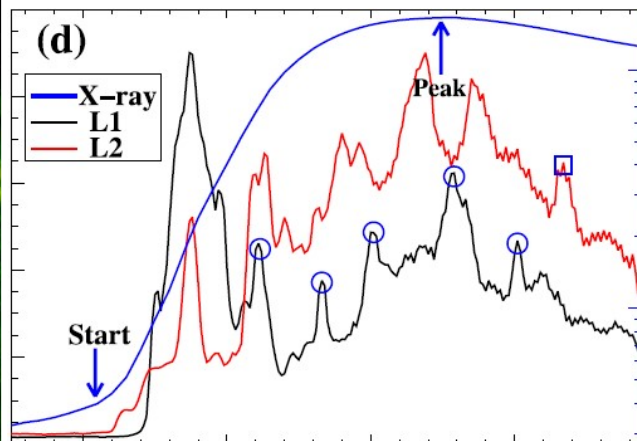
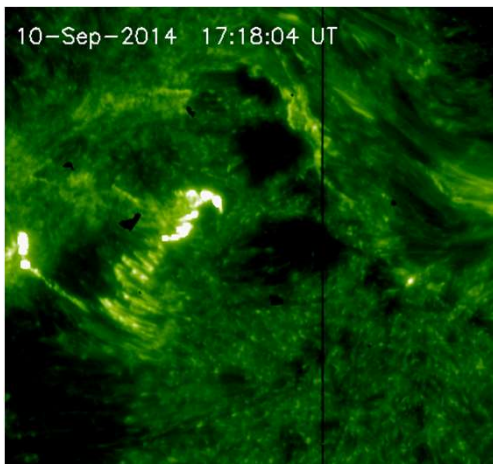
2018 Hi-C



Yang Shangbin et al. 2009 ApJL (磁螺度交换证据)

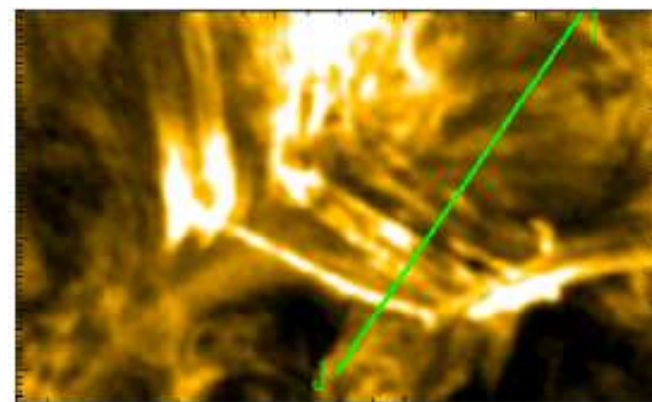
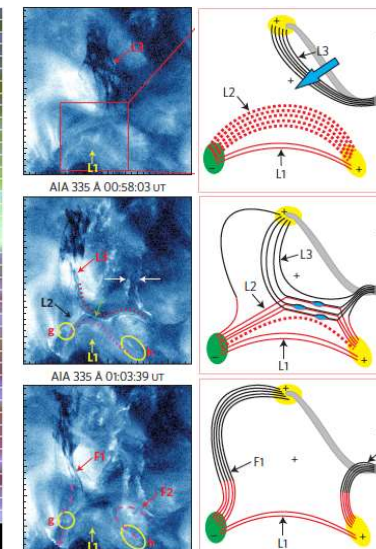
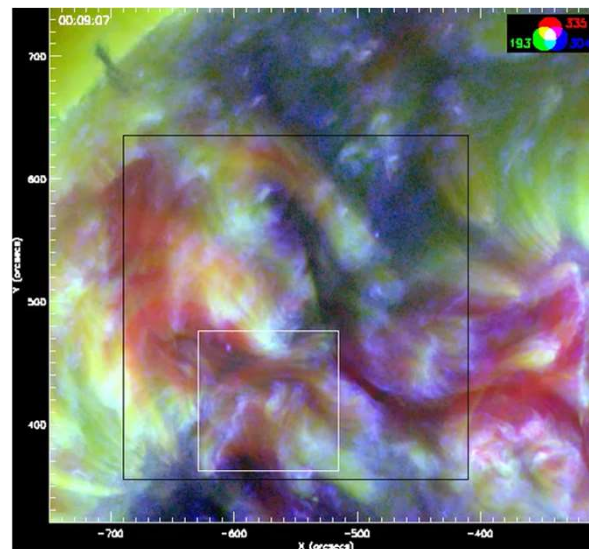


太阳多波段观测研究-刻画三维磁重联结构



时域特征: 准周期性
空域特征: 耀斑环和耀
斑带精细结构的滑动
运动

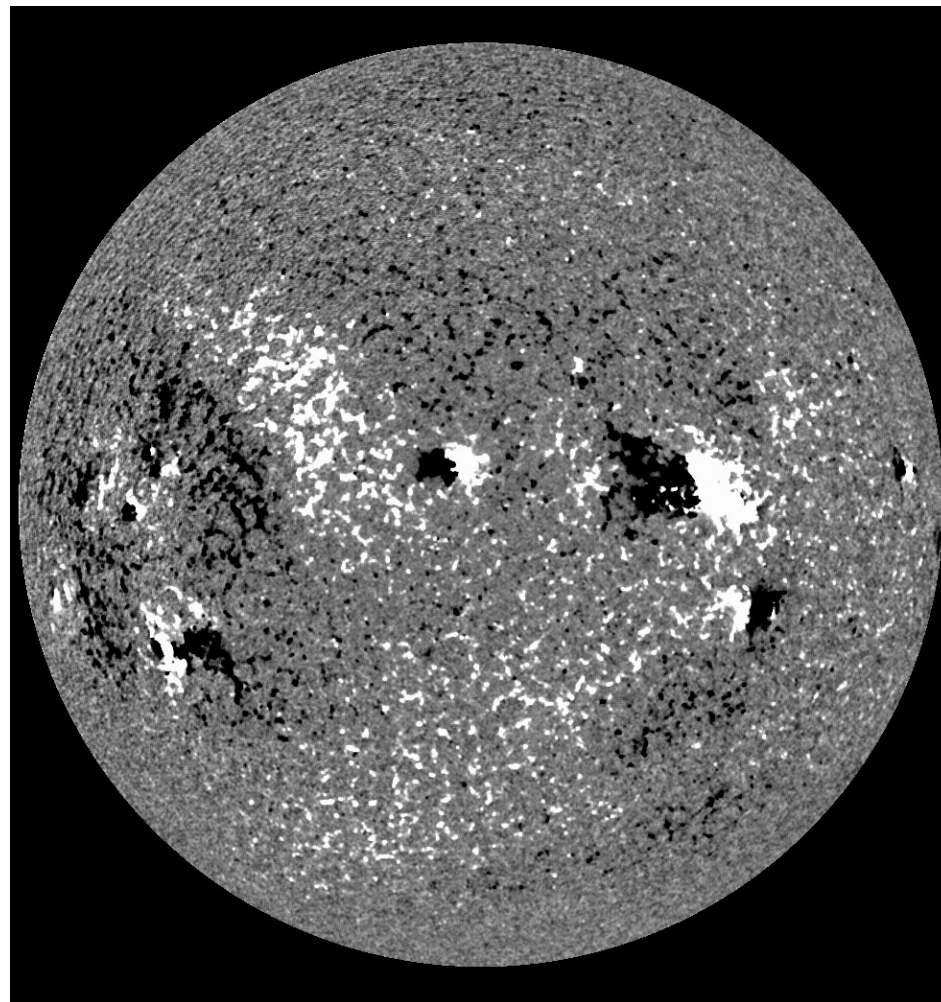
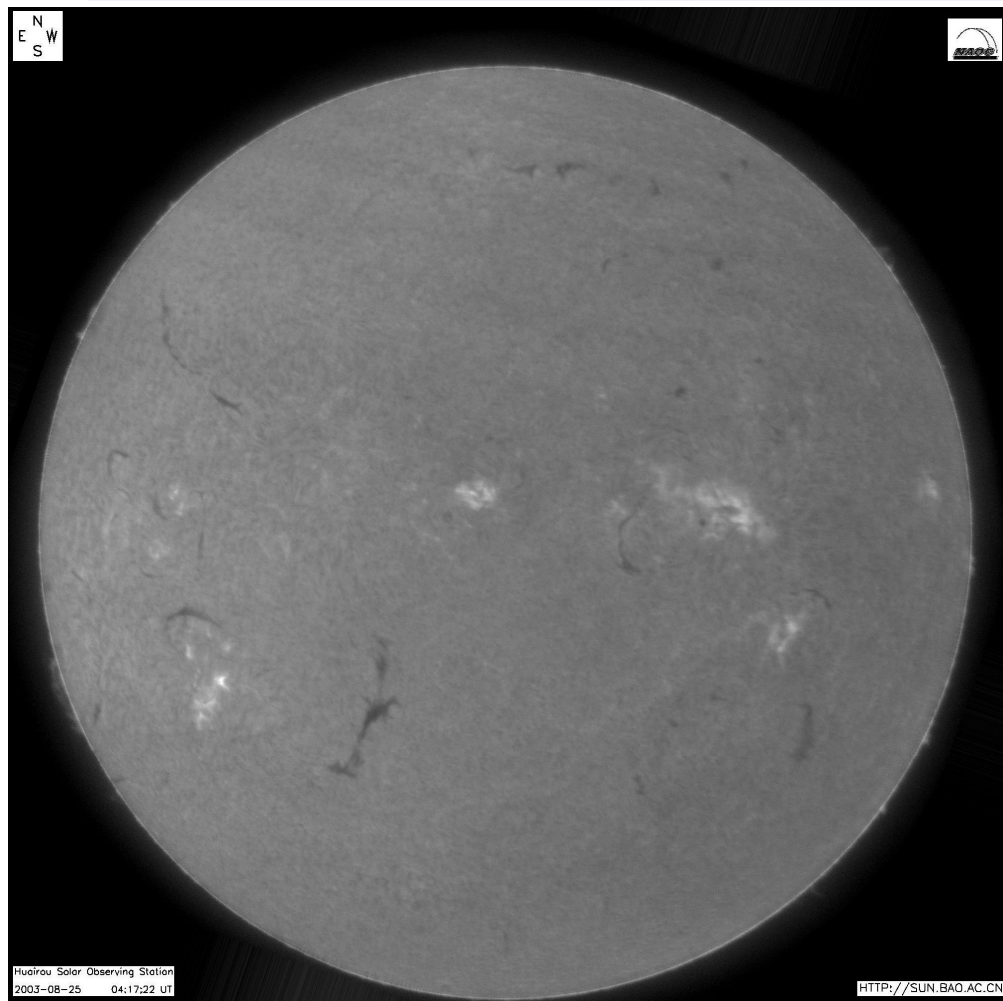
Li & Zhang (2015)



Li Leping et al. 2016 Nature Physics

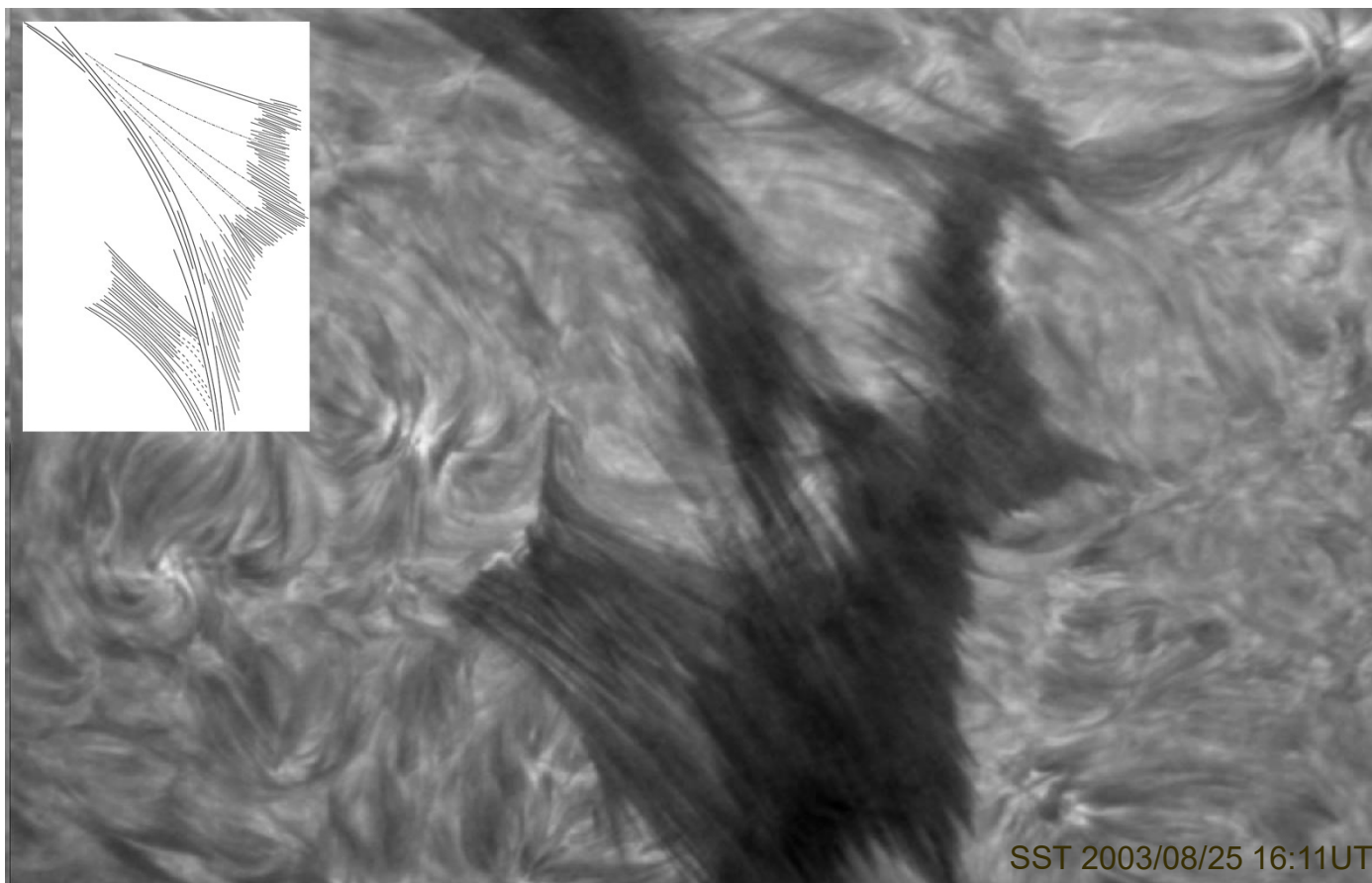


太阳多波段观测研究-刻画三维磁场结构



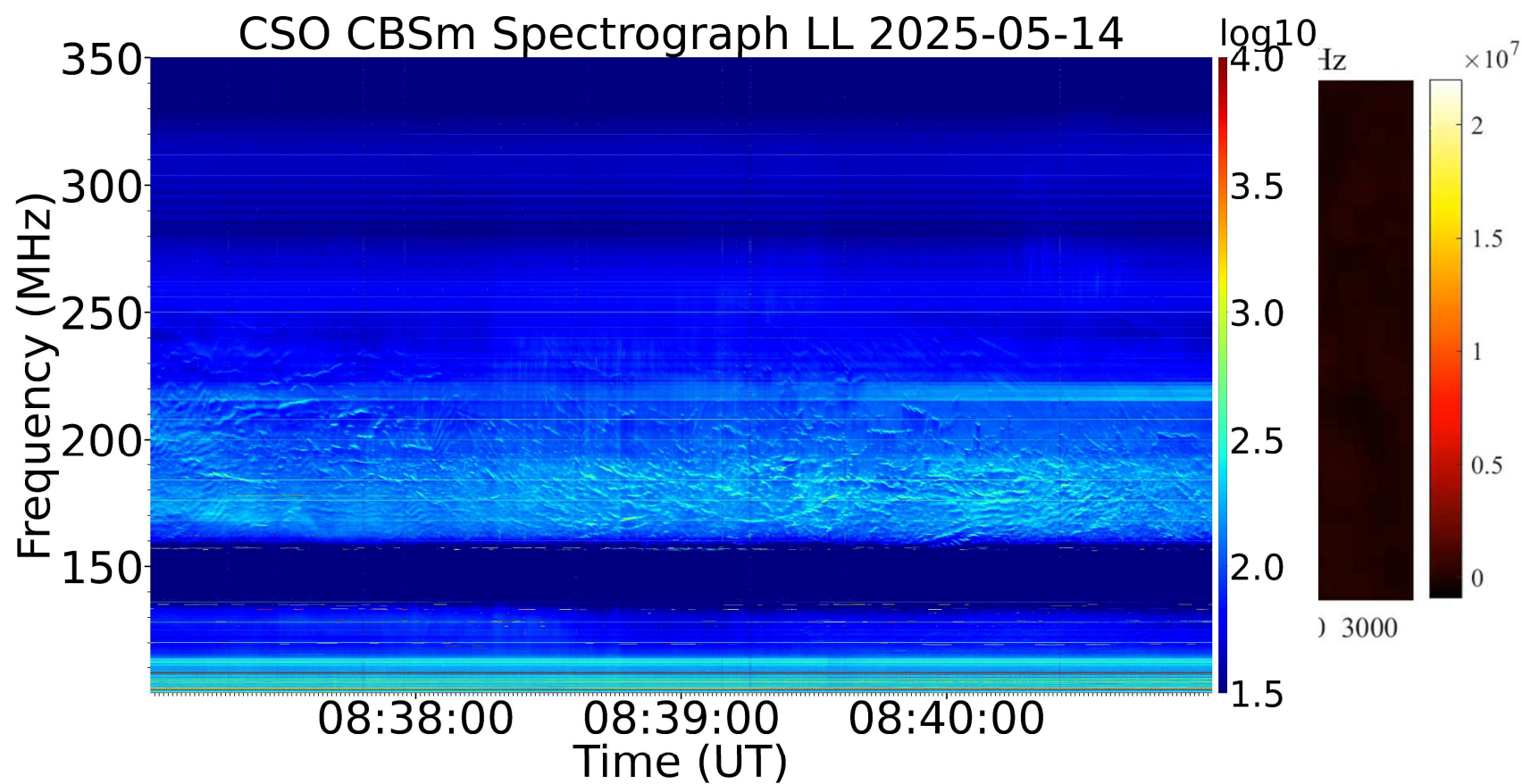
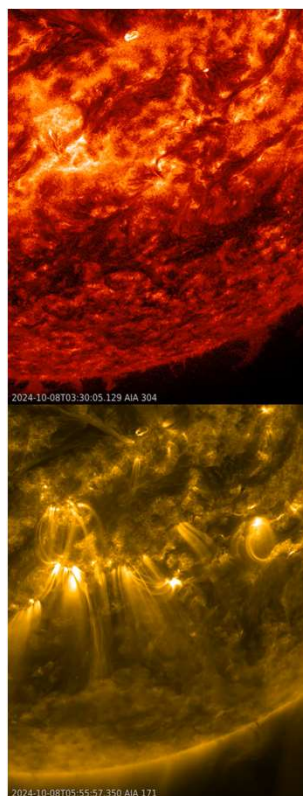


太阳多波段观测研究-刻画三维磁场结构



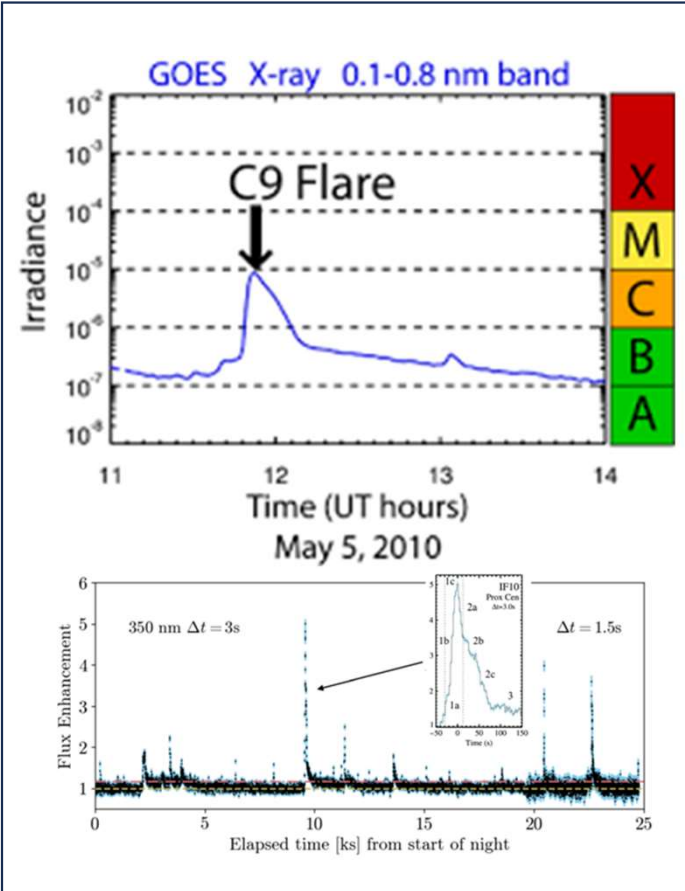


太阳多波段观测研究-射电诊断

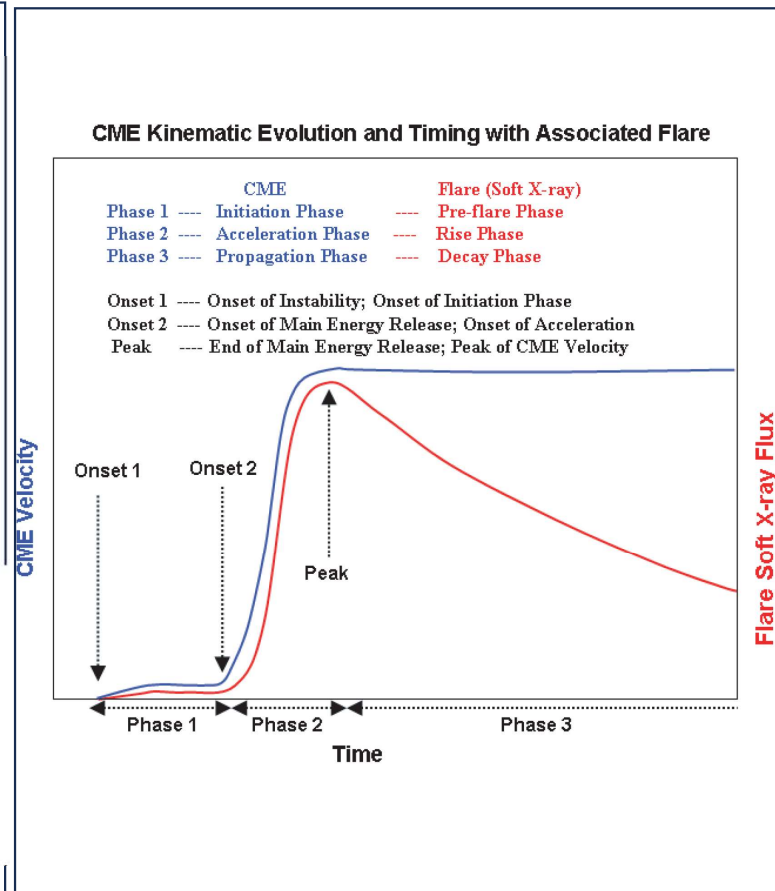




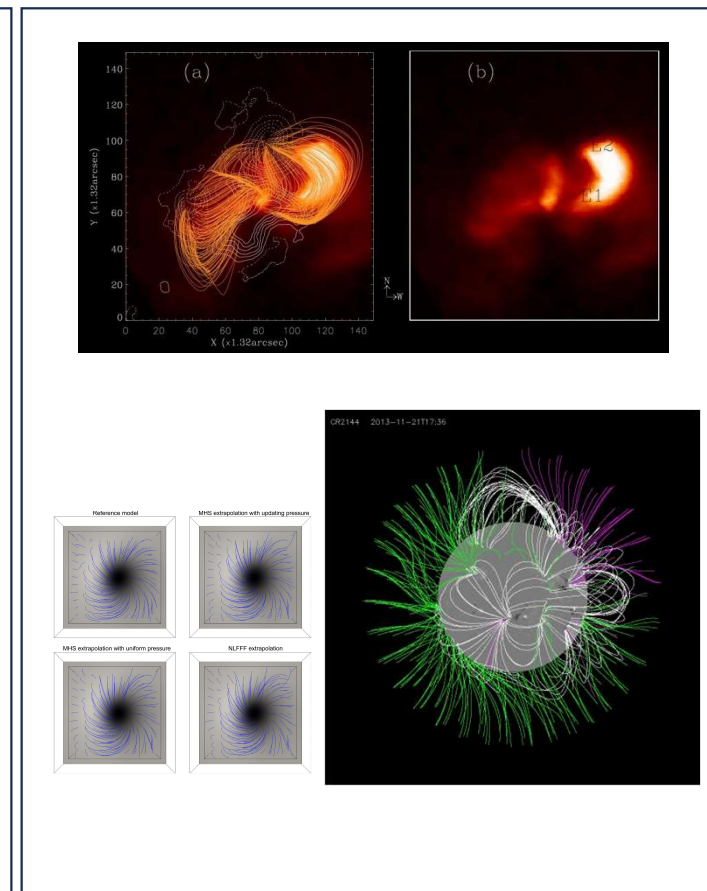
太阳多波段观测研究-检验三维磁场模型



Low (1973, 1974)



Zhang and Dere (2006)



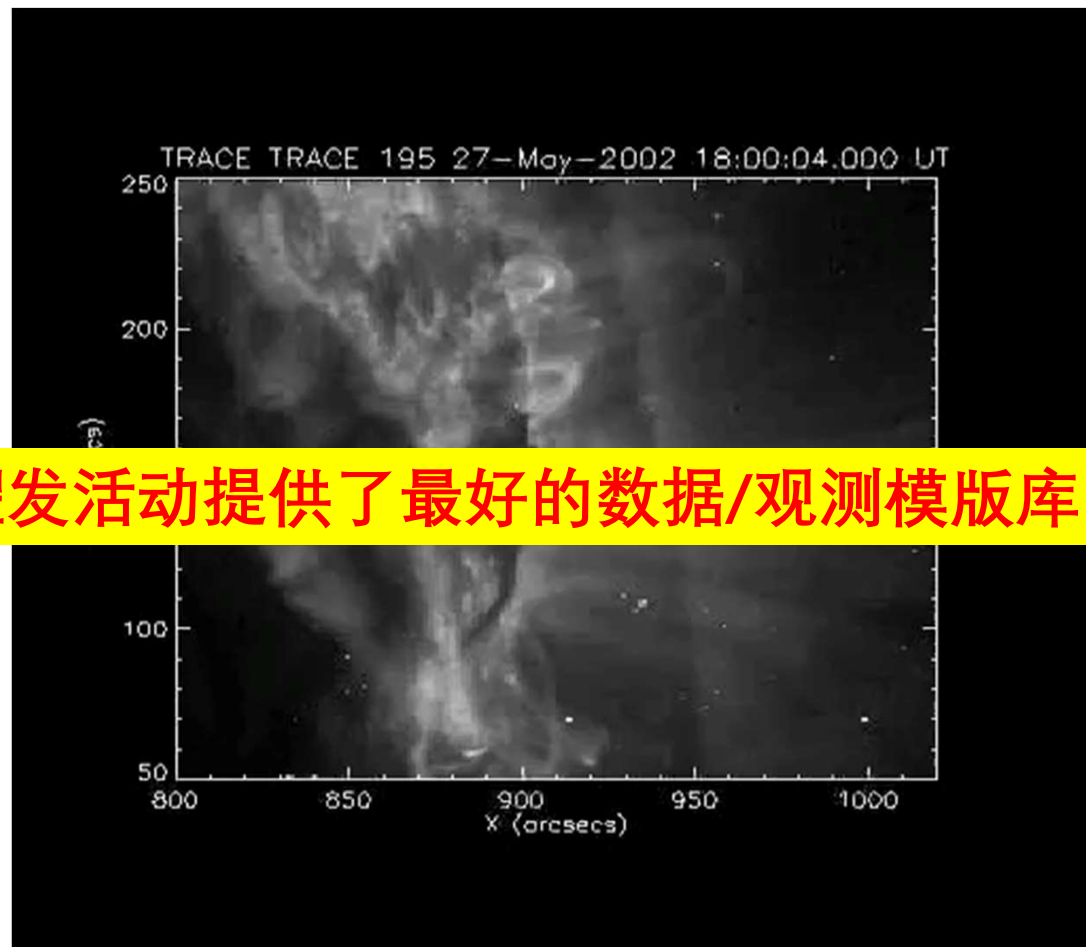
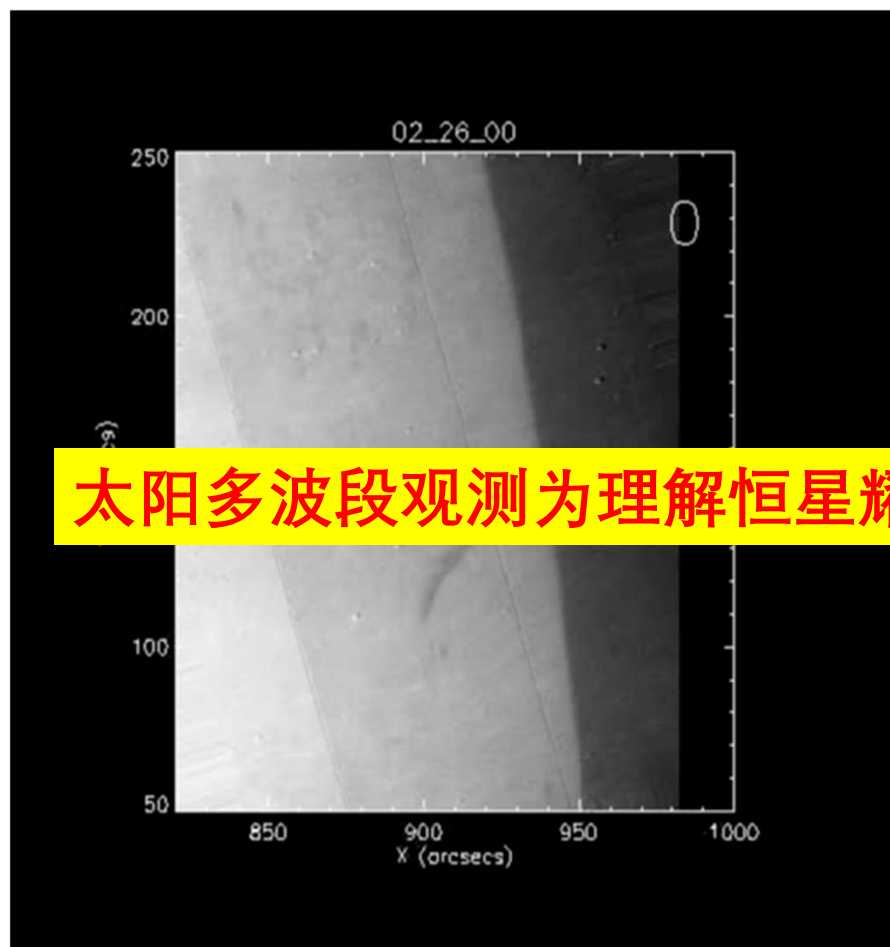
Wang et al. 2000

Hayashi, Yang, Deng (2016)

Zhu et al. 2018



太阳多波段观测研究-失败暗条爆发



太阳多波段观测为理解恒星耀发活动提供了最好的数据/观测模版库

Ji et al. 2003 ApJL



太阳磁场测量-怀柔基地发展史

1984



-怀柔-
35厘米太阳
磁场望远镜

2006



-怀柔-
全日面太阳光学
和磁场望远镜

2022



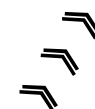
-空间-
46.5mm极紫外
线太阳成像仪
(SUTRI)

2023



-赣榆-
子午工程Ⅱ期
全日面矢量磁像仪
(SFMM)

SPO
2029

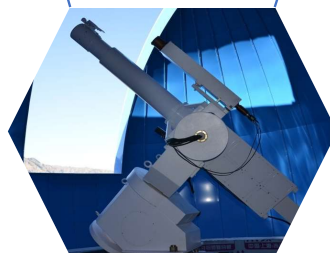


1996



-怀柔-
多通道太阳望远镜

2013



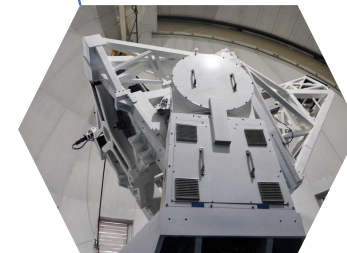
-温泉-
全日面太阳磁场望远镜

2022



-空间-
全日面矢量磁像仪
(FMG)

2024



-冷湖-
太阳磁场中红外观测系统
(AIMS)





太阳磁场测量-怀柔基地发展史

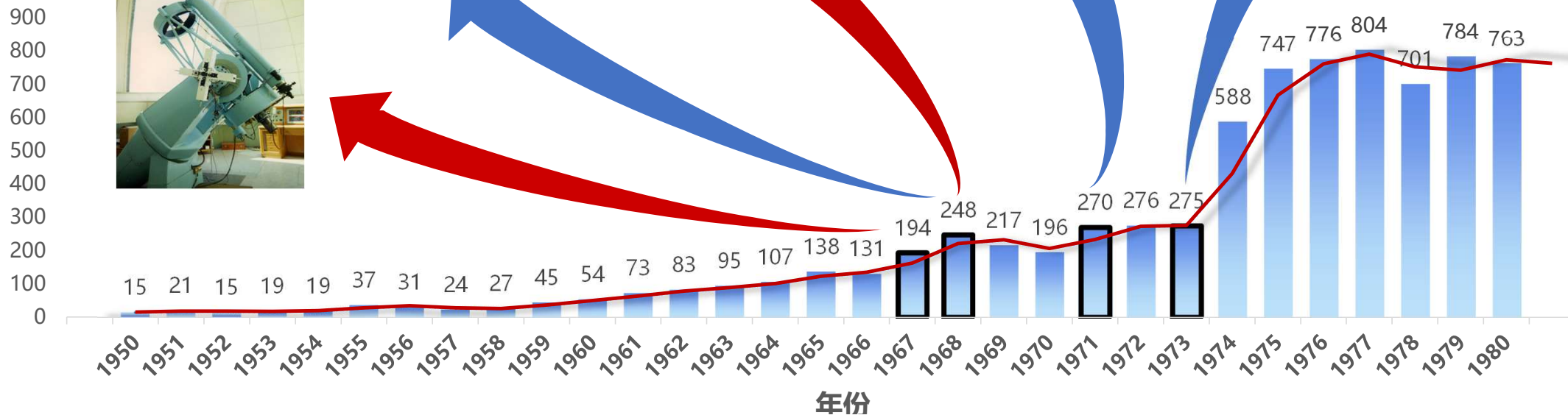
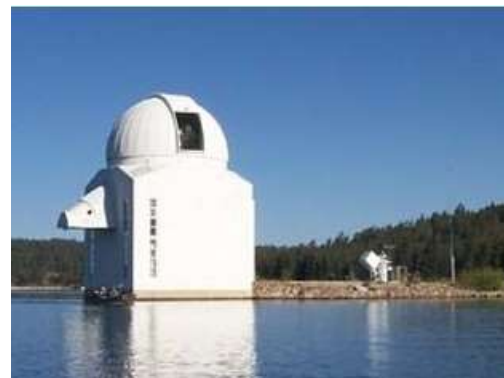
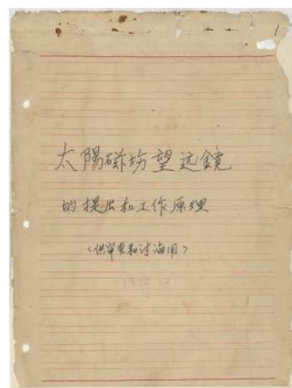
Zhong, Li, Yang et al. 2025

HIGH-RESOLUTION MEASUREMENTS OF PHOTOSPHERE AND SUNSPOT VELOCITY AND MAGNETIC FIELDS USING A NARROW-BAND BIREFRINGENT FILTER

J. M. BECKERS
*Sacramento Peak Observatory,
Air Force Cambridge Research Laboratories, Sunspot, N.M., U.S.A.*

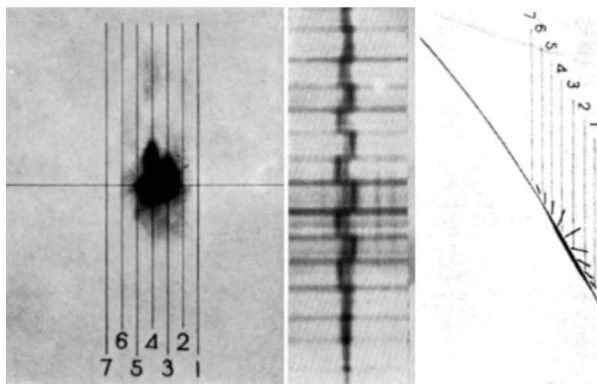
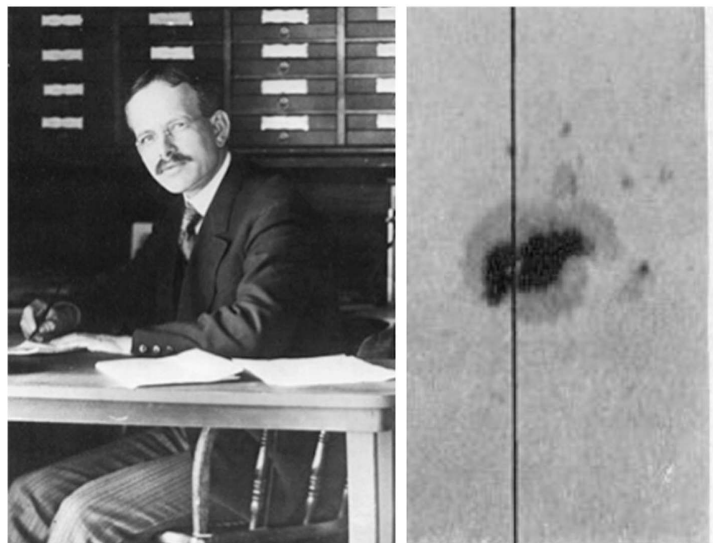
(Received 21 July, 1967)

Abstract. Modifications to a Zeiss $\frac{1}{2}$ Å filter are described which allow high spatial resolution observations of the line-of-sight velocities and magnetic fields in the photosphere and in sunspots. First results show: (1) the granular velocity field to be very strong; differences in upward motions in the granules and downward motions in between are as much as 6 km/sec; (2) the Evershed effect in sunspots to originate primarily in the dark regions between bright penumbral filaments.

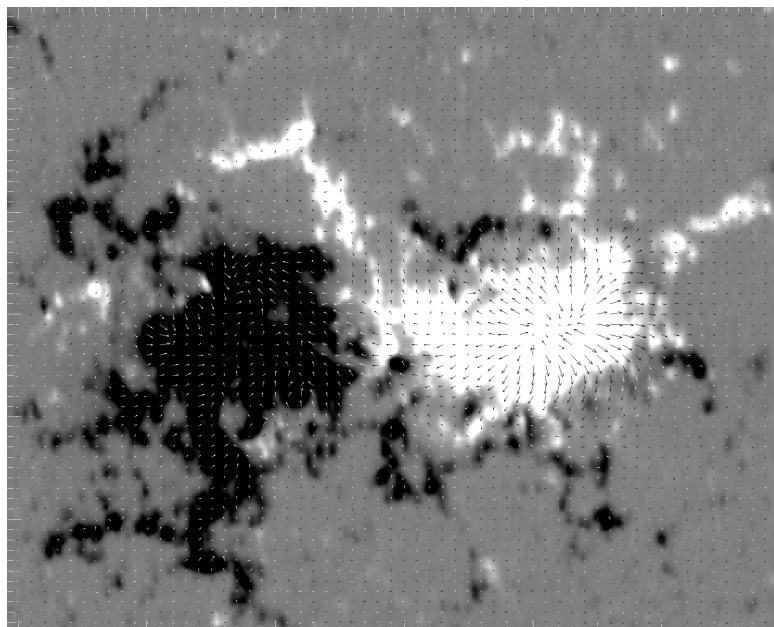
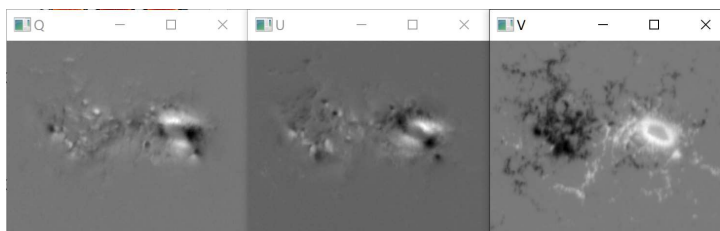




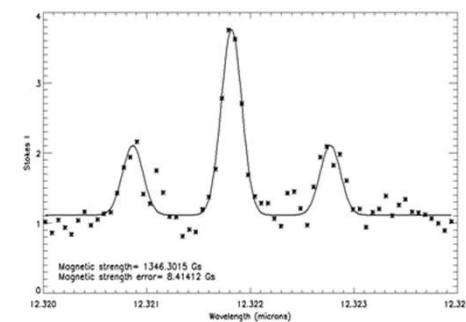
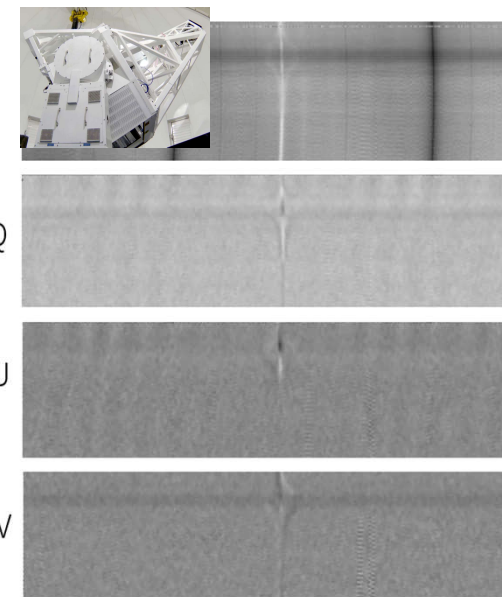
太阳磁场测量-发展脉络



Hale & Ellerman, 1919, ApJ, 49, 153



弱场近似和Stokes参数反演

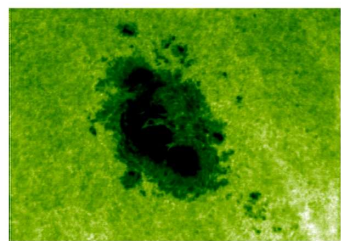
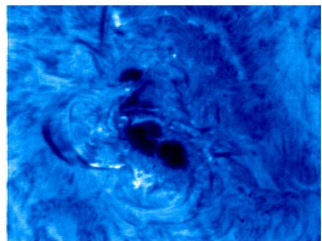
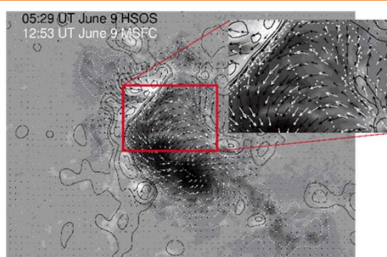


单像元三分裂光谱及磁场精度

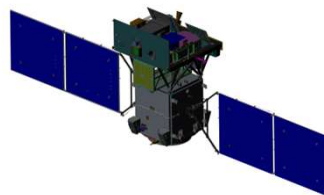


怀柔太阳观测基地磁场测量现状

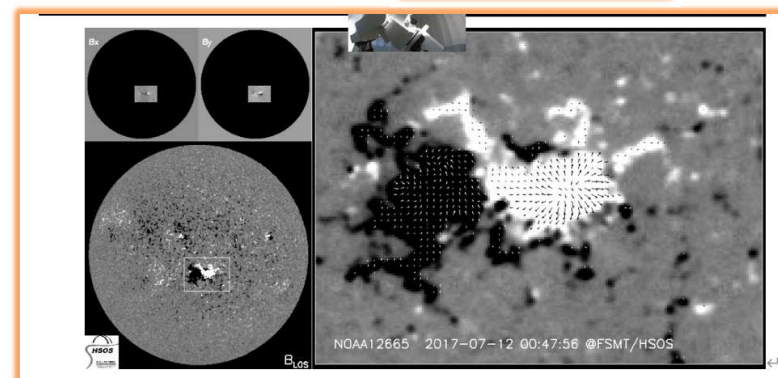
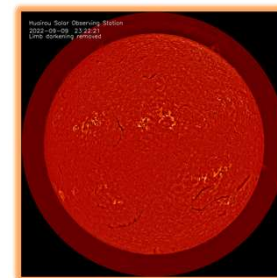
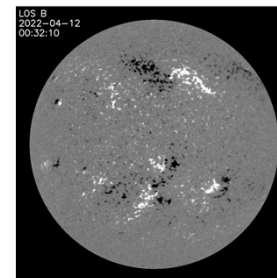
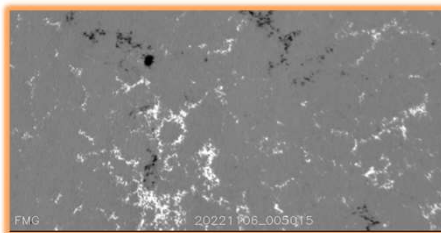
- 从光球到色球不同高度的太阳磁场 (**多层次**)
- 全日面太阳磁场和太阳活动的完整观测 (**大视场**)
- 太阳磁场的中红外波段的精确测量 (**高精度**)
- 空间太阳磁场测量 (**全时段**)
- 多层次全日面太阳磁场和速度场观测 (**多层次、大视场**)



怀柔太阳观测基地-太阳多通道磁场望远镜 (**多层次**)



空基ASO-S/FMG (**全时段**)



怀柔全日面太阳活动监测望远镜 (**大视场**)



多层次、全日面
赣榆



青海冷湖AIMS望远镜 (**高精度**)

太阳磁场研究-发展脉络

研究对象

观测仪器（方式）

实测维度

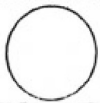
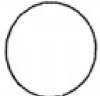
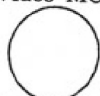
磁梯度 ∇B

磁剪切 $B - P$

电流 $\nabla \times B$

电流螺度 $B \cdot J$

磁螺度 $A \cdot B$

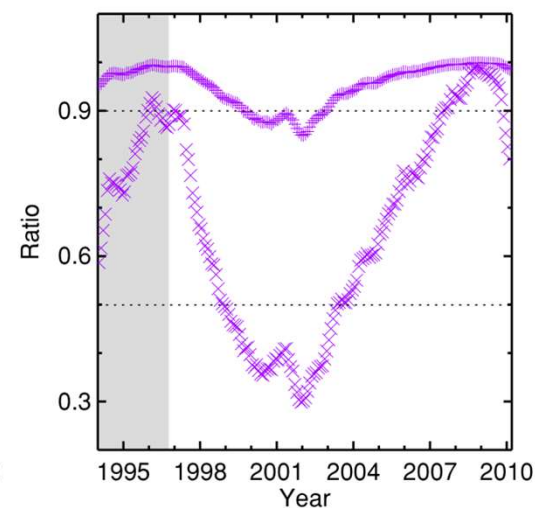
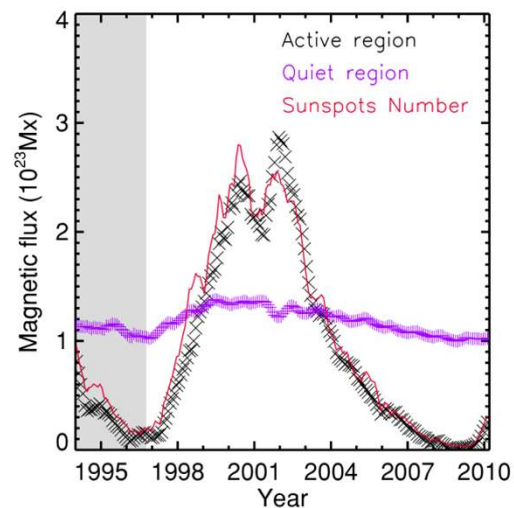
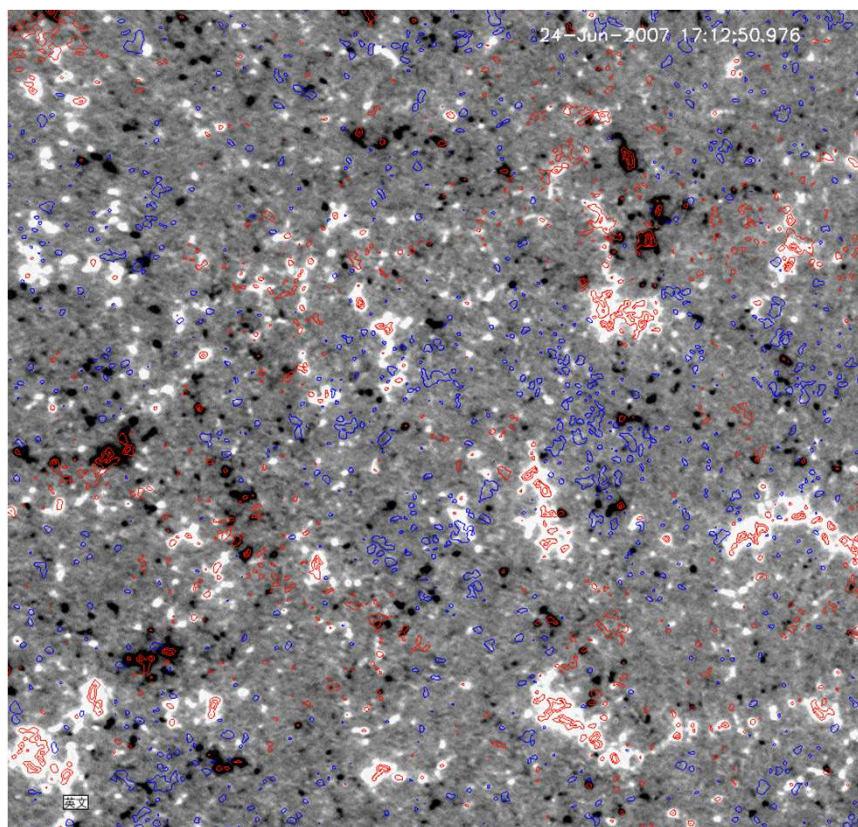
simultaneous field of view	points	points (line)	line (scanning plane)	plane	cube
white light				1611 Galilean Telescope 	
spectrum or monochromatic		1814 grating spectrograph 	1887 heliospectrograph 	1938-1944 Lyot-Öhman filter 	
polarized monochromatic (magnetic fields)	1908 Hale magnetograph stronger field 	1953-1962 Babcock-Severny MG weak field 	1971 Kitt.Peak MG 	1980s Video MG 	1990s Multichannel MG 
Stokes profile B, V_{11}		Fourier spectrograph 	gratings 	filters 	2-D real time with few lines 

点
↓
线
↓
面
↓
体

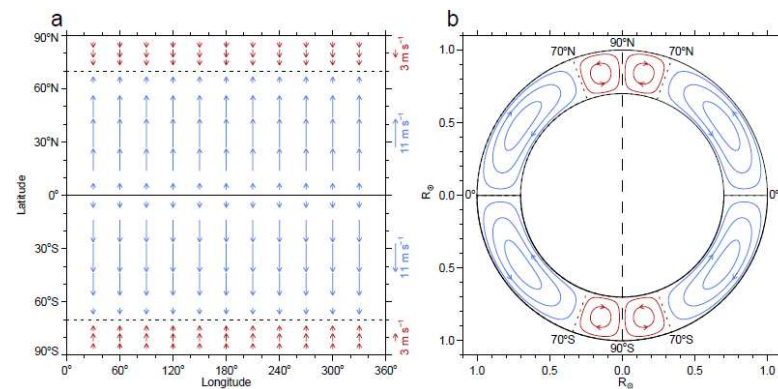
核心问题：太阳大气磁场的三维结构是什么？

太阳磁场研究-从大尺度到小尺度

小尺度磁场的通量和运动追踪



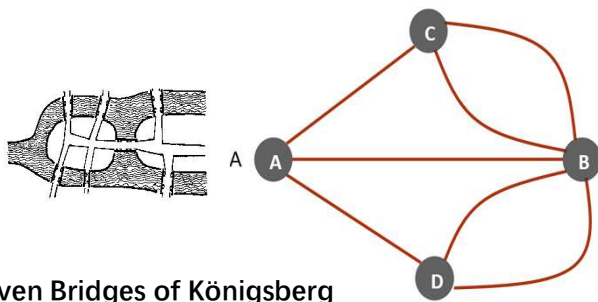
Jin C. L.; Wang J. X., Song Q. et al. 2011 ApJ



Yang et al. 2023 极区流场结构



磁螺度研究的意义 $H_m = \int \mathbf{A} \cdot \mathbf{B} d^3x$

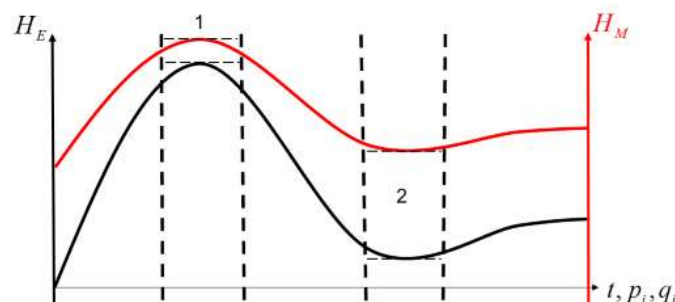


Seven Bridges of Königsberg



$H=0$ $H=T\Phi^2$ $H=\pm 2\Phi_1\Phi_2$

Topological Description of 3D B



$$\dot{H}_m = \{H_m, H\} = 0$$

$$-C^{-1}|E_m| \leq H_m \leq C^{-1}|E_m|$$

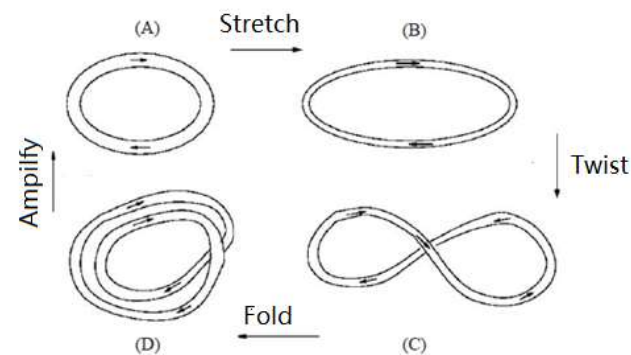
Arnold 1974 inequality



Vladimir Arnold

- Helicity bounded by energy
- Taylor Conjecture

Module Solar Dynamo Process



A schematic illustration of the stretch-twist-fold-merge dynamo.

$$\mathcal{E} = \overline{\mathbf{u} \times \mathbf{b}} = \alpha \bar{\mathbf{B}} + \gamma \bar{\boldsymbol{\Omega}} = -\frac{\tau_c}{3} \left(\langle \mathbf{u}^{(0)} \cdot \nabla \times \mathbf{u}^{(0)} \rangle \right. \\ \left. - \langle \mathbf{b}^{(0)} \cdot \nabla \times \mathbf{b}^{(0)} \rangle \right) \bar{\mathbf{B}} + \frac{2\tau_c}{3} \Omega \langle \mathbf{u}^{(0)} \cdot \mathbf{b}^{(0)} \rangle$$

Kinetic helicity

Current helicity Cross helicity

太阳磁场研究-三维磁螺度计算模型 (Coulomb-Yang method)

三维笛卡尔空间开放边界磁场、电流、磁矢势的规范、边界条件和泊松方程的同时满足



Magnetic Helicity estimations in models and observations of the solar magnetic field

*Gherardo Valori**, INAF - Osservatorio astronomico di Roma (Italy)

*Etienne Pariat***, LESIA - Observatoire de Paris Meudon (France)

Yang Guo, Nanjing University (China)

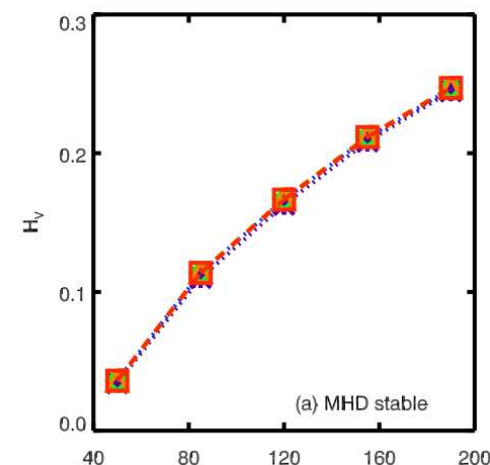
Yang Liu, Stanford University (USA)

Georgoulis Manolis, Academy of Athens (Greece)

George Rudenko, Institute of Solar-Terrestrial Physics SB RAS (Russia)

Shangbin Yang (National Astronomical Observatories, China)

Julia Thalmann, Institute of Physics/IGAM, University of Graz (Austria)

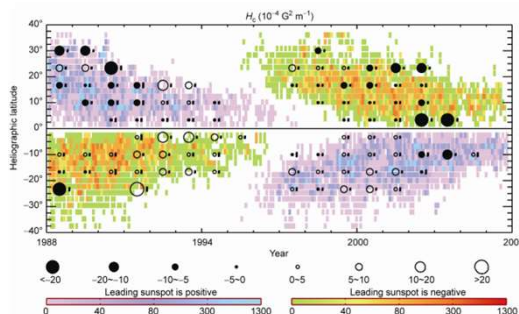


The maximul size of data is **256x256x256, less in 10 minutes.**
the data can be resized to small volume to obtain the very similar results.

Valori et al. 2016 Space Science Review

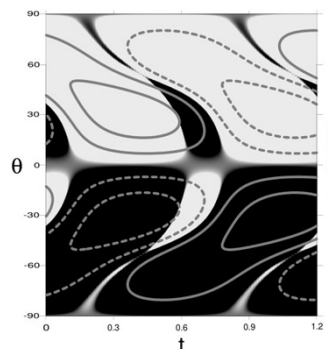
太阳磁场研究-半球螺度法则（太阳发电机模型的观测约束）

电流螺度纬度分布蝴蝶图



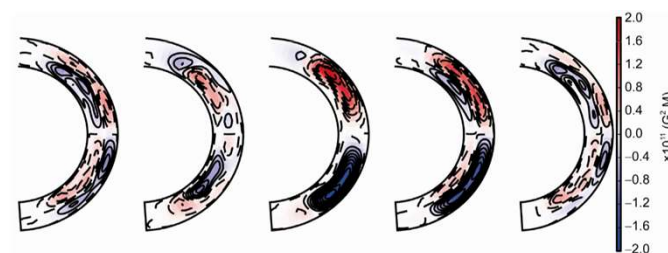
Zhang H Q et al, 2010

相位延迟与螺度起伏



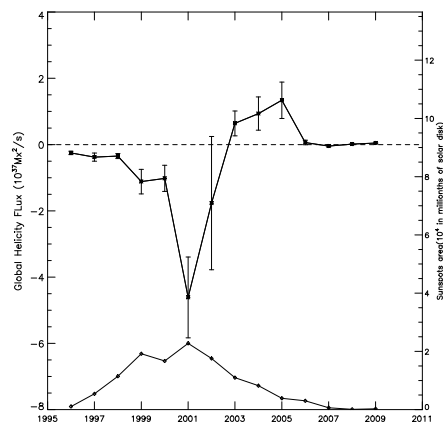
Xu et al. 2009

太阳对流区内磁场和磁螺度演化分布



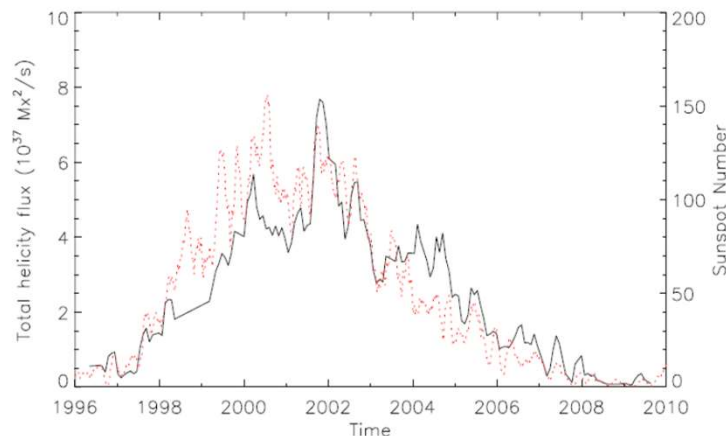
Pipin & Zhang HQ, et al, 2013

磁螺度活动周的起伏



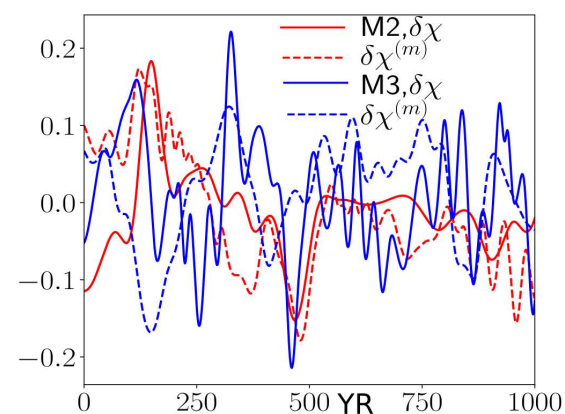
Yang et al. 2012

螺度传输峰值与磁通量峰值存在相位延迟



Zhang and Yang 2013

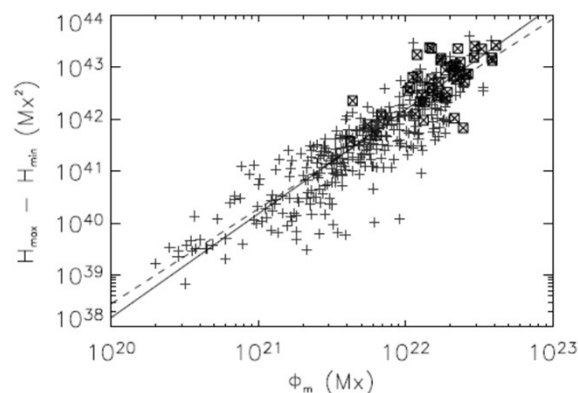
α 效应的随机振荡



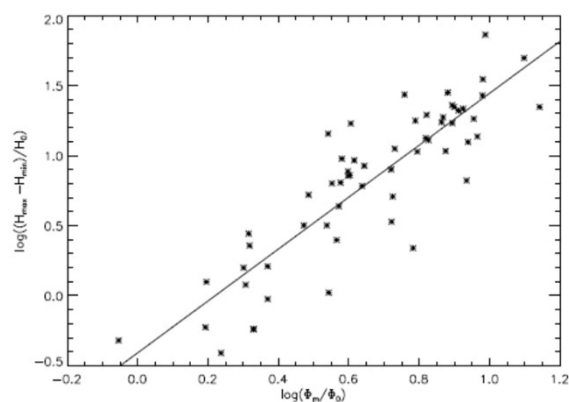
Yang et al. 2020

太阳磁场研究-磁螺度与太阳爆发的关系

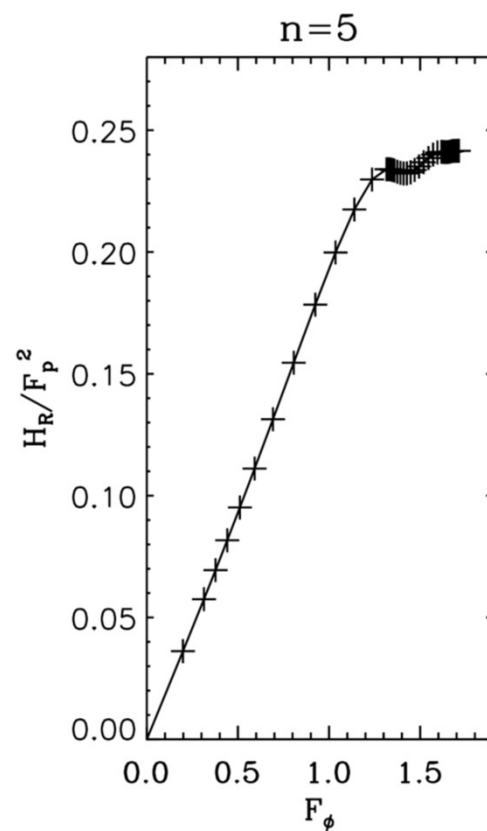
太阳活动区是自相似缠绕的磁流管



Labonte et al.2007

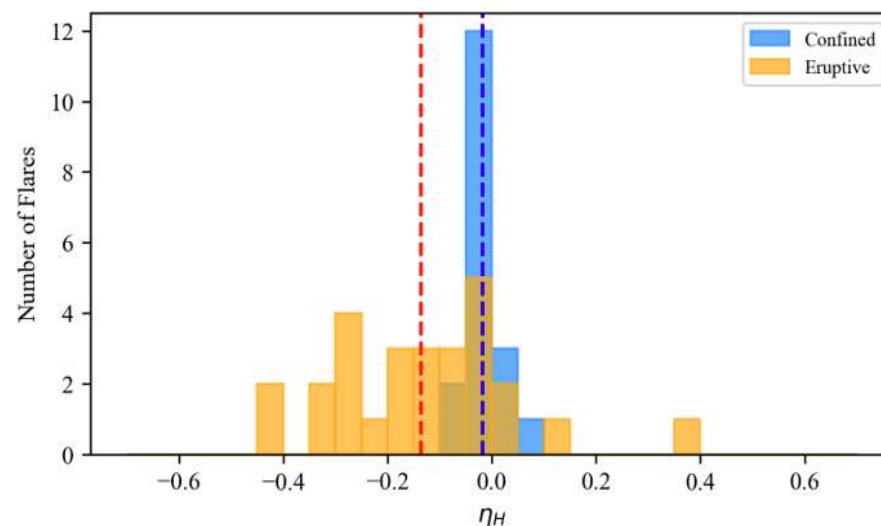


Yang et al. 2009



Zhang & Flyer 2008

受限耀斑的磁螺度耗散要明显小于有CME的耀斑



Wang, Zhang and Yang et al. 2023 RAA

太阳多波段观测研究-不稳定性触发机制

◆基于相对磁螺度概念对开放边界MHD不稳定性研究

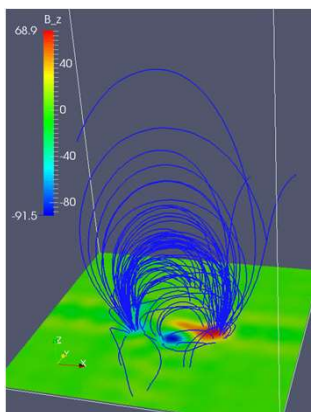
(Yang Shangbin et al. 2025, ApJ, 980.206)

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \vec{u}$$

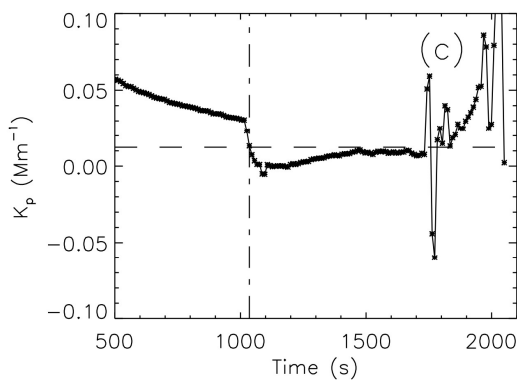
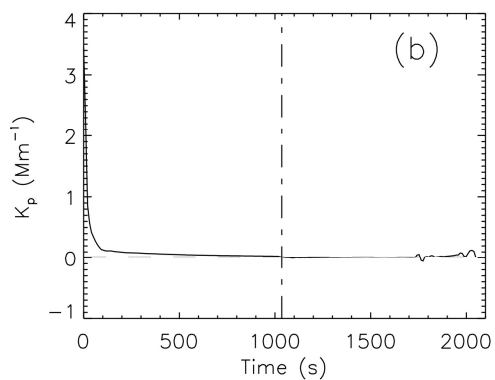
$$\frac{\partial \rho \vec{u}}{\partial t} = -\nabla \cdot \rho \vec{u} \vec{u} - \nabla p + \vec{j} \times \vec{B} - \nu \rho (\vec{u} - \vec{u}_0)$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{u} \times \vec{B} - \eta \vec{j})$$

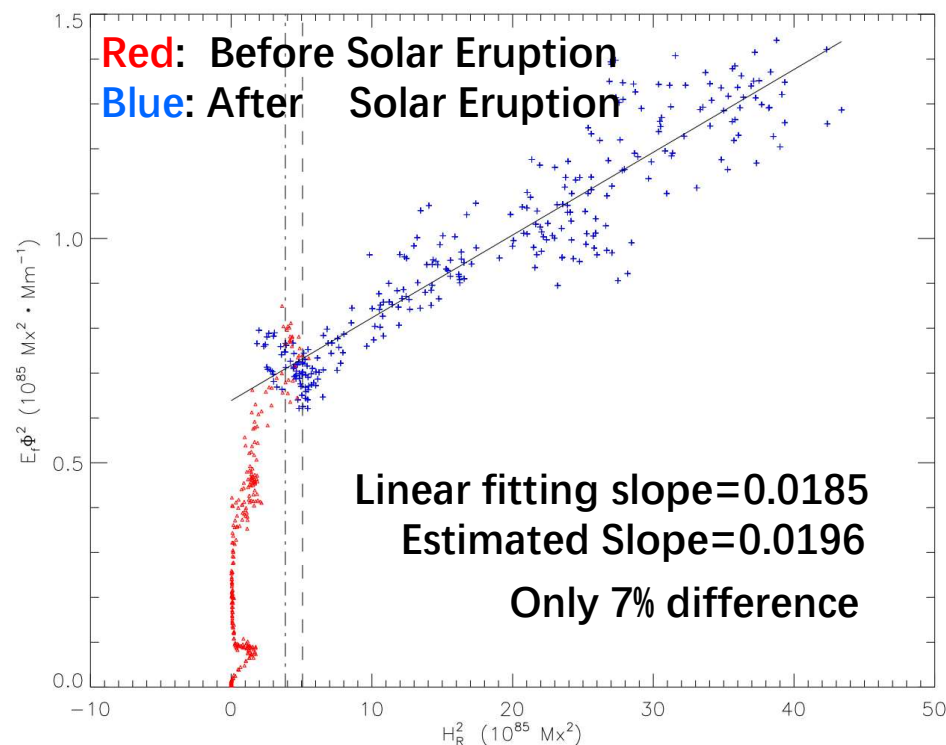
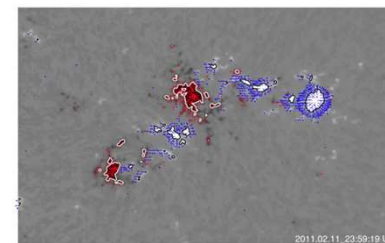
$$\frac{\partial p}{\partial t} = -\nabla \cdot p \vec{u} - (\gamma - 1) p \nabla \cdot \vec{u} + (\gamma - 1) \eta j^2$$



数值模拟的检验



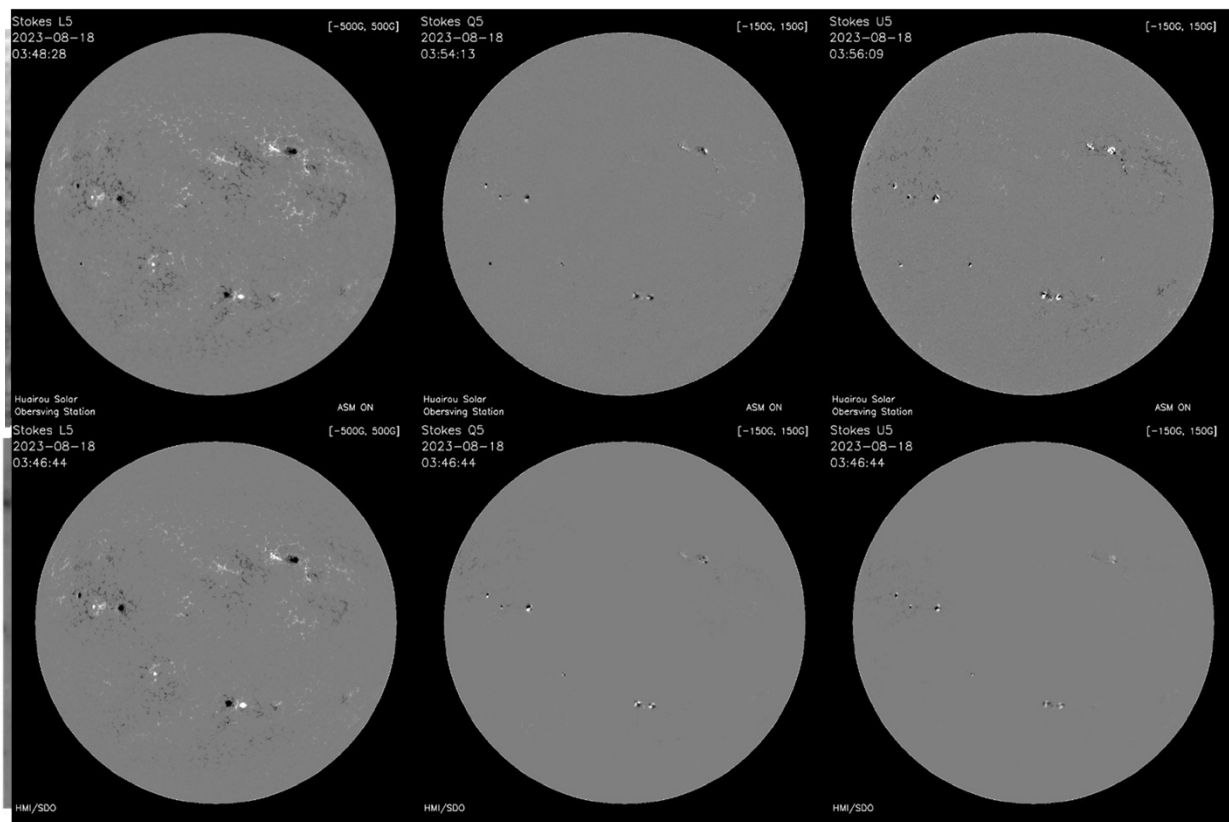
$$E_f \Phi^2 = K H_R^2$$





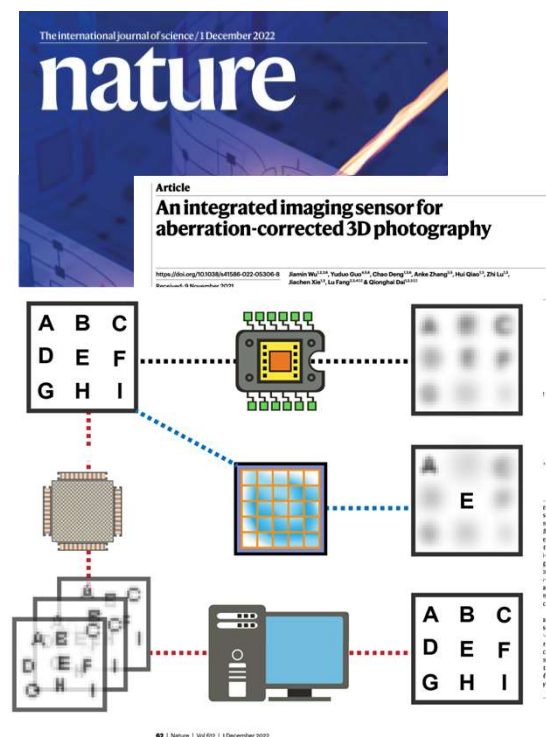
太阳磁场测量新技术-太阳矢量磁场的主动测量方法和数字自适应

□ 探索解决磁场测量分辨率和灵敏度不可得兼的问题



国家自然科学基金委原创探索项目支持

□ 探索大视场和高分辨率不可得兼的问题

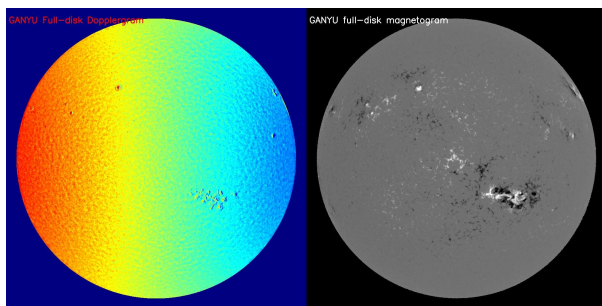


国家自然科学基金委重大仪器专项（自由申请）
清华+国台

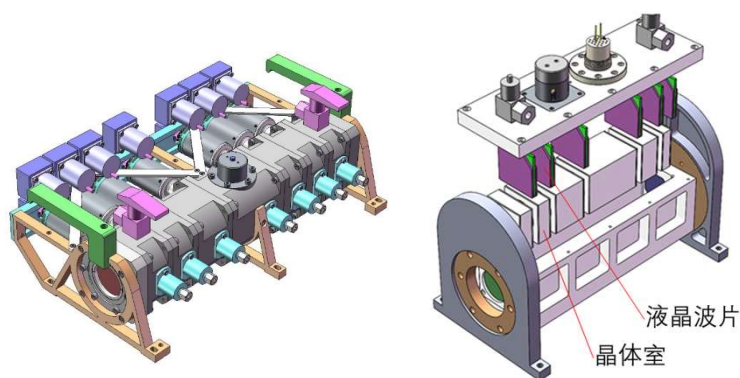


太阳磁场测量新技术-液晶窄带滤光偏振测量等新技术

液晶波片技术的应用于子午工程二期

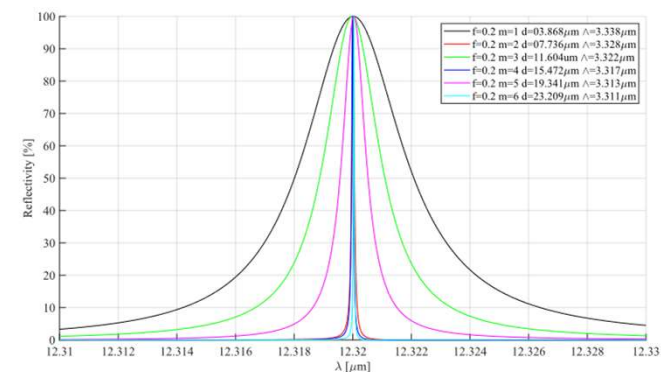
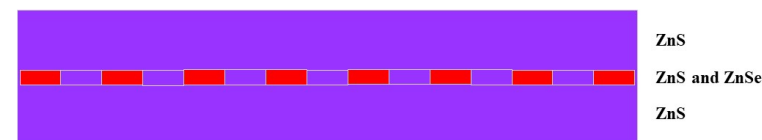


极大减轻了重量(120kg-60kg)



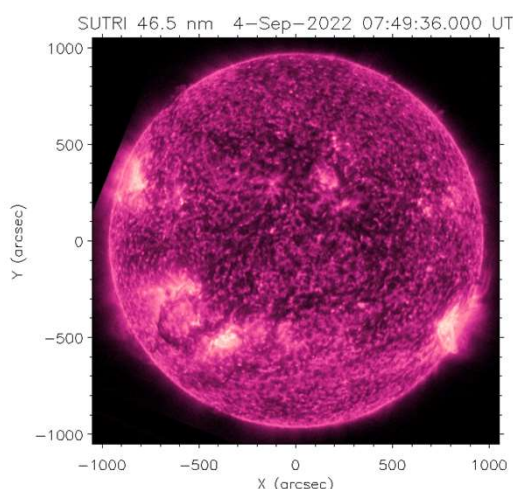
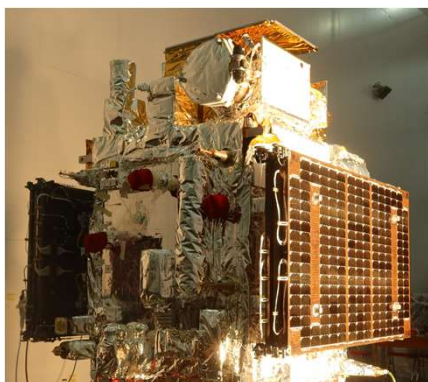
导模共振光栅滤光片

- 微纳光子学技术
- 亚波长光栅与波导耦合，实现窄带滤光成像





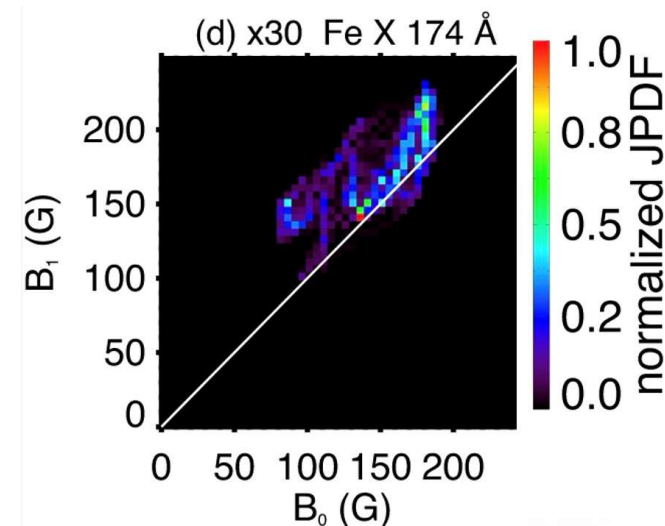
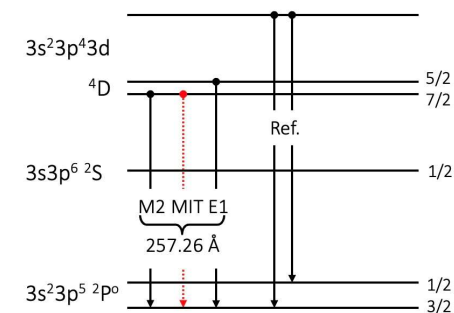
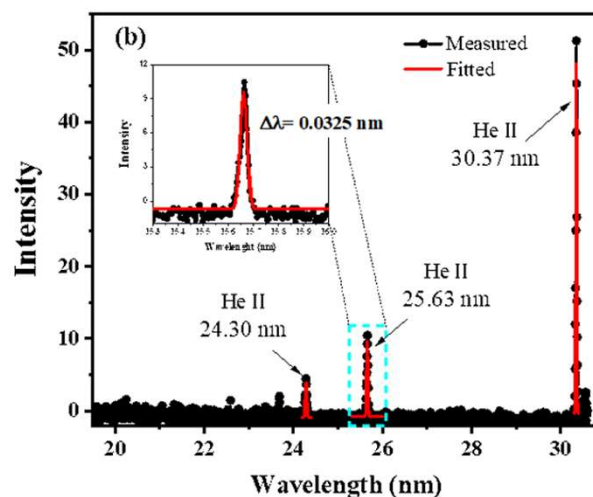
太阳磁场测量新技术-磁诱导跃迁 (MIT) 测量星冕磁场



我国首次太阳过渡区探测



极紫外光谱仪
FIS/SPO
转初样



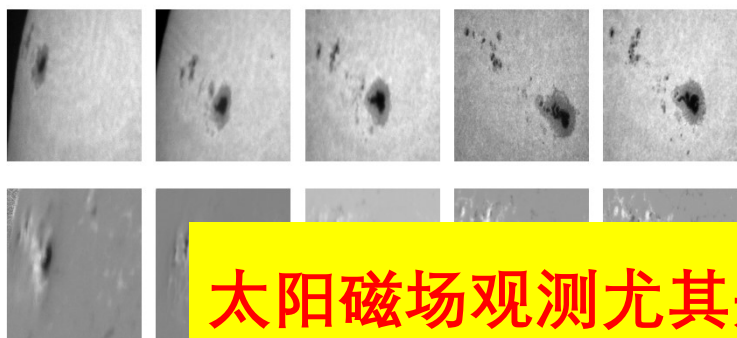
Li et al. 2015, 2016

Chen et al. 2021, 2023



太阳磁场研究新技术：先进的图像处理、深度学习模型

以自主仪器数据为主线持续构建AI数据集



太阳磁场观测尤其是矢量磁场观测（磁场和模型模版）

➤ 约束恒星大气结构、提供磁场能量边界输入

➤ 对恒星内部的发电机模型形成观测约束

✓ 太阳耀斑
✓ 太阳黑子
金乌分类
日冕物质抛射

地磁暴：JW-GeoStorm

电离层：JW-Ionosphere

文献综述：JW-DLR

太阳活动分析：JW-DSAR

具身智能望远镜：JW-Telescope

AI-太阳物理学家：JW-SolarPhysicist

基于神经网络的双折射窄带滤光器型磁像仪 观测波长点的定标

胡兴^{1,3,4}, 杨尚斌^{1,3,4*}, 季凯帆^{2,4}, 林佳本^{1,3,4}, 邓元勇^{1,3,4}, 白先勇^{1,3,4}, 朱晓明^{1,3}, 白阳^{1,3}, 王全^{1,3,4}

¹中国科学院国家天文台 北京 100101.

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OPEN ACCESS

An Automatic Approach for Grouping Sunspots and Calculating Relative Sunspot Number on SDO/HMI Continuum Images

Cui Zhao¹, Shangbin Yang^{2,3,4}, Tingmei Wang¹, Haiyan Zhao¹, Shiyuan Liu¹, Fangyuan He¹, and Zhengkun Hu¹

¹ College of Applied Science and Technology, Beijing Union University, Beijing 102200, People's Republic of China

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Received 2023 July 26; revised 2023 November 27; accepted 2023 December 1; published 2024 January 10

宁度变化

<https://doi.org/10.3847/1538-4365/adb61b>



Deep-learning Model

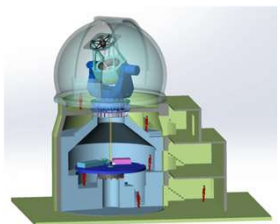
Shiyuan Liu¹, and Fangyuan He¹



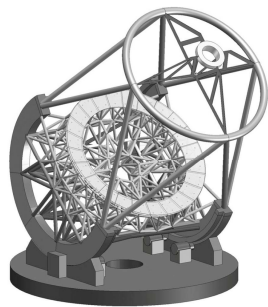
总结与展望

地基大口径

WeHost望远镜(2.5)



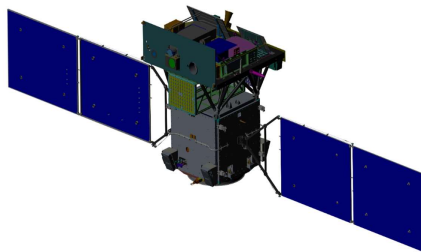
2m环, 8m 口径CGST



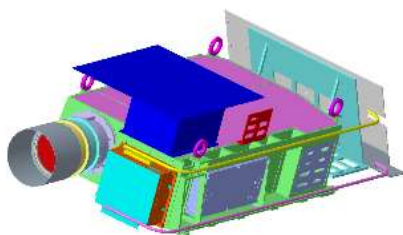
看得更清更广

空间望远镜

先进天基望远镜



全日面磁场望远镜

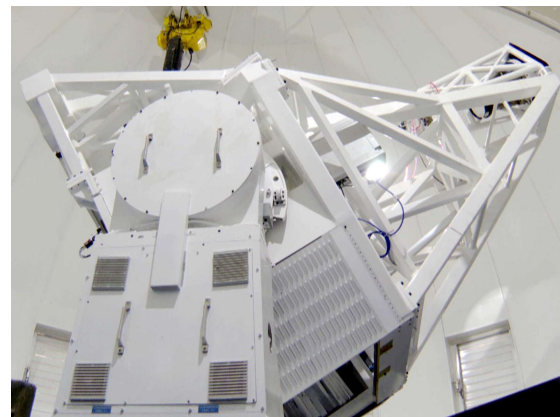


看得更稳

中红外望远镜

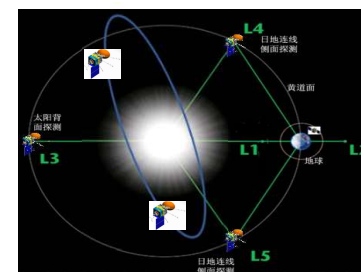
国家重大仪器专项AIMS

(青海冷湖天文观测基地)

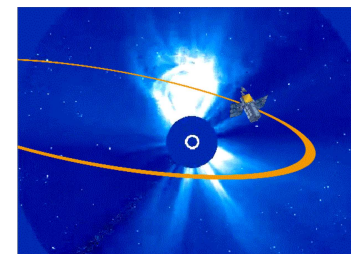


看得更准

立体探测



黄道面探测+极轨探测



抵近探测, 极紫外...

看得更全面

谢谢！
解解！

Thank you

Welcome to Beijing !!!

Call for abstracts!

Frontier in Solar and Heliospheric Physics

The 3rd China-Europe Solar Physics Meeting

15-19 September 2025, Beijing, China

On-site registration begins at September 14!

Topics:

- Solar interior, dynamo and the solar cycle
- The solar atmosphere from the solar surface into the interplanetary space: heating, cooling, dynamics, turbulence
- Solar-Heliospheric connection: energy release, triggering, prediction and impact of flares/CMEs and the solar wind on Earth
- Numerical modelling and machine learning
- Solar instrumentation and ground/space missions.

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Haisheng Ji (co-chair) (Purple Mountain Observatory)
Patrick Antolin (co-chair) (Northumbria University)
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Jörg Büchner (Berlin Institute of Technology)
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Yu Liu (co-chair) (South West Jiaotong University)
Xin Cheng (Nanjing University)
Xuan Meng (Purple Mountain Observatory)

webpage for registration:

<https://cespm2025.casconf.cn>

Abstract deadline: May 30, 2025

Registration deadline: June 30, 2025

Contact: Shangbin Yang (yangshb@nao.cas.cn)



CESPM 2025