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

杨尚斌

怀柔太阳观测基地

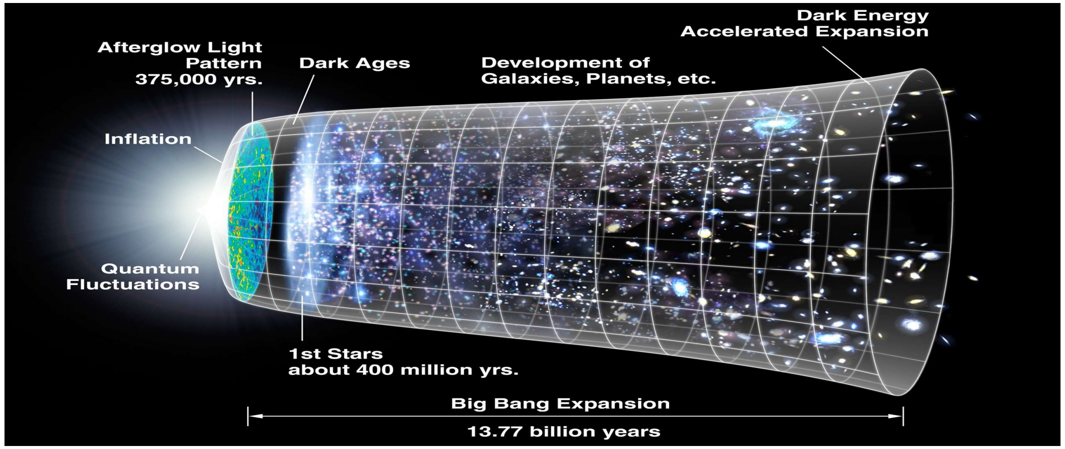
中国科学院国家天文台

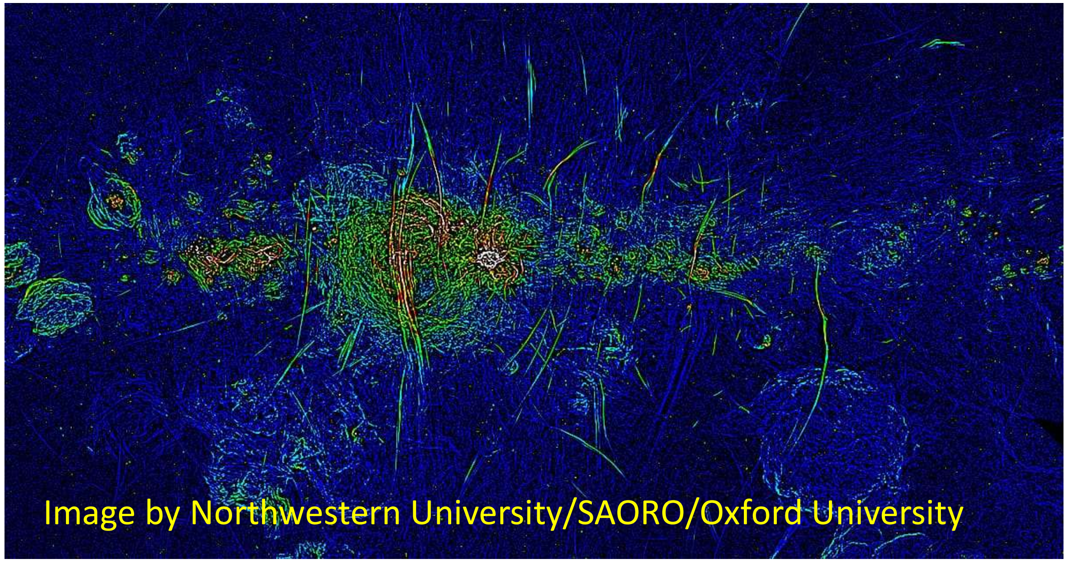
2025-05-27

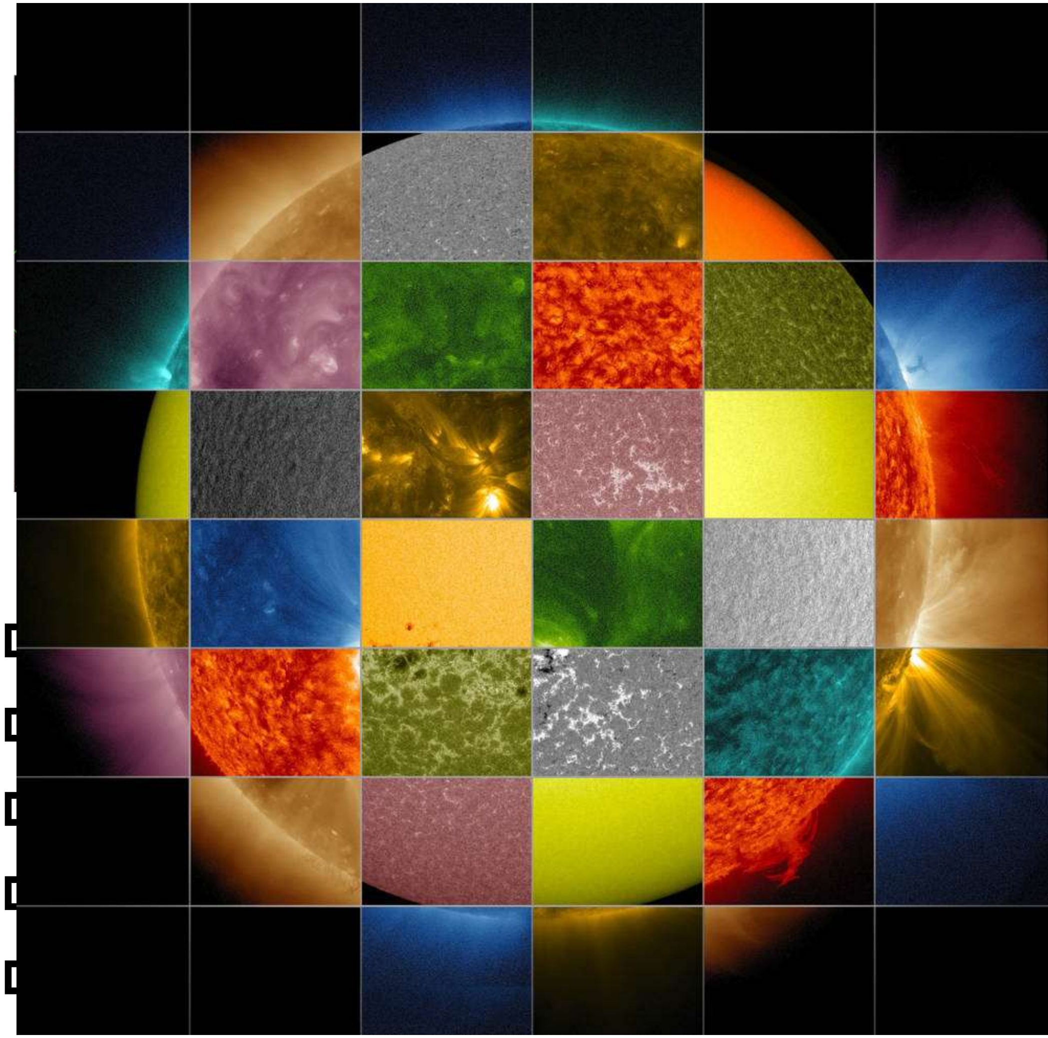
Outline

- ➢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





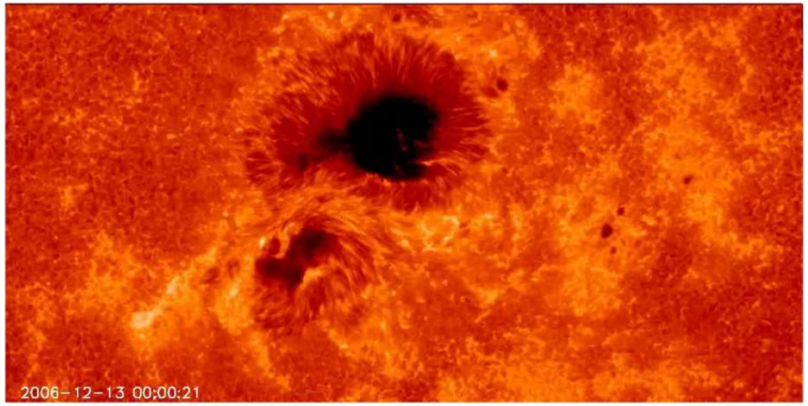


则)

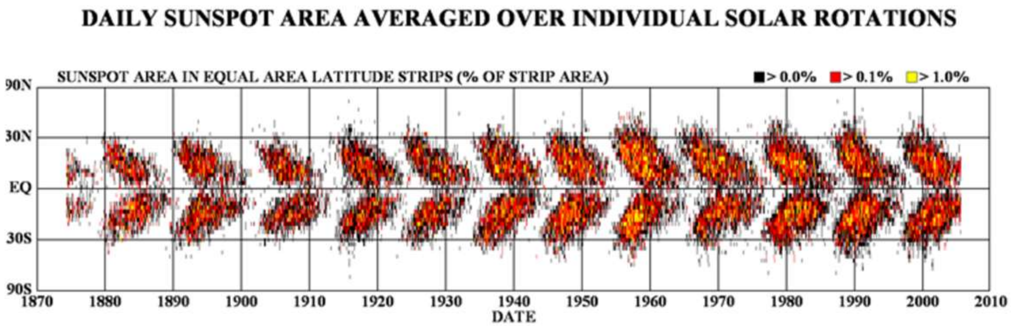
太阳多波段观测-多时间尺度

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

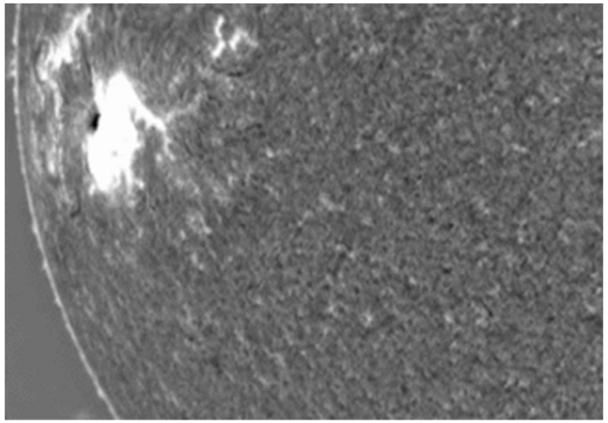
太阳耀斑



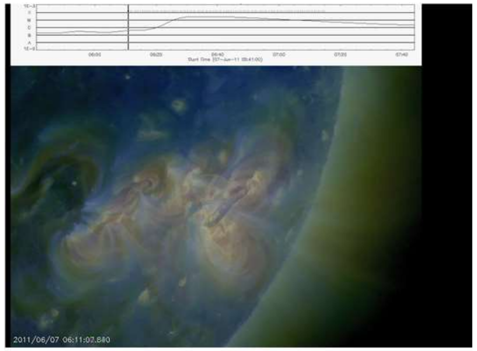
太阳活动周



太阳上的“海啸”



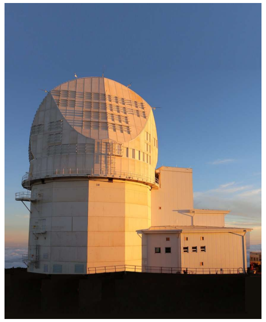
日冕物质抛射



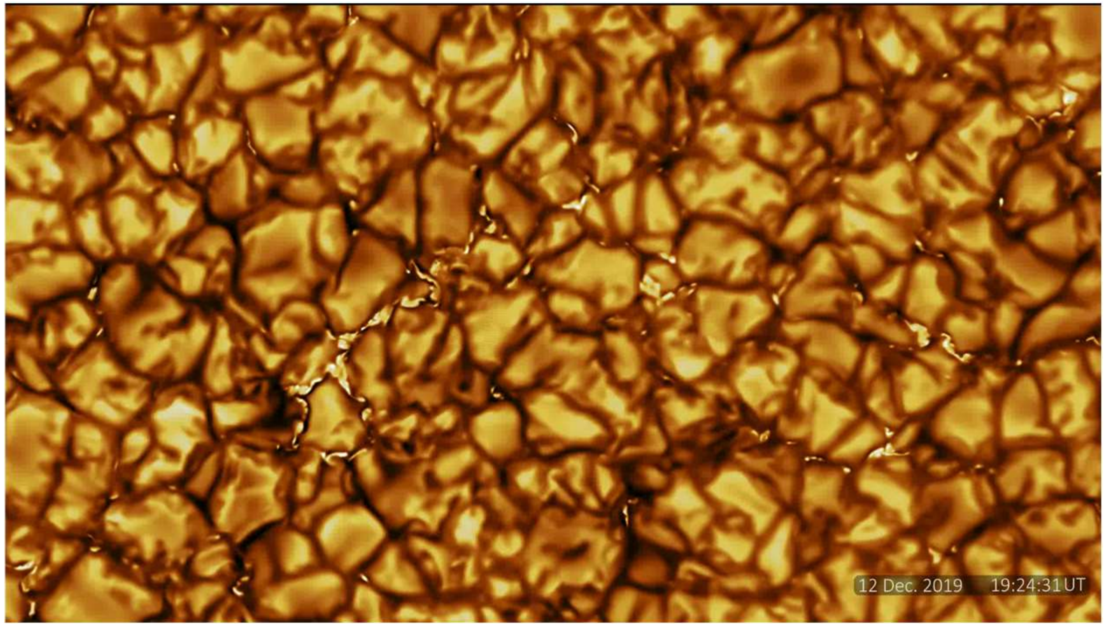
天文领域多是展示静态图片，但太阳物理可以展示的动态电影！！！

太阳多波段观测-多空间尺度

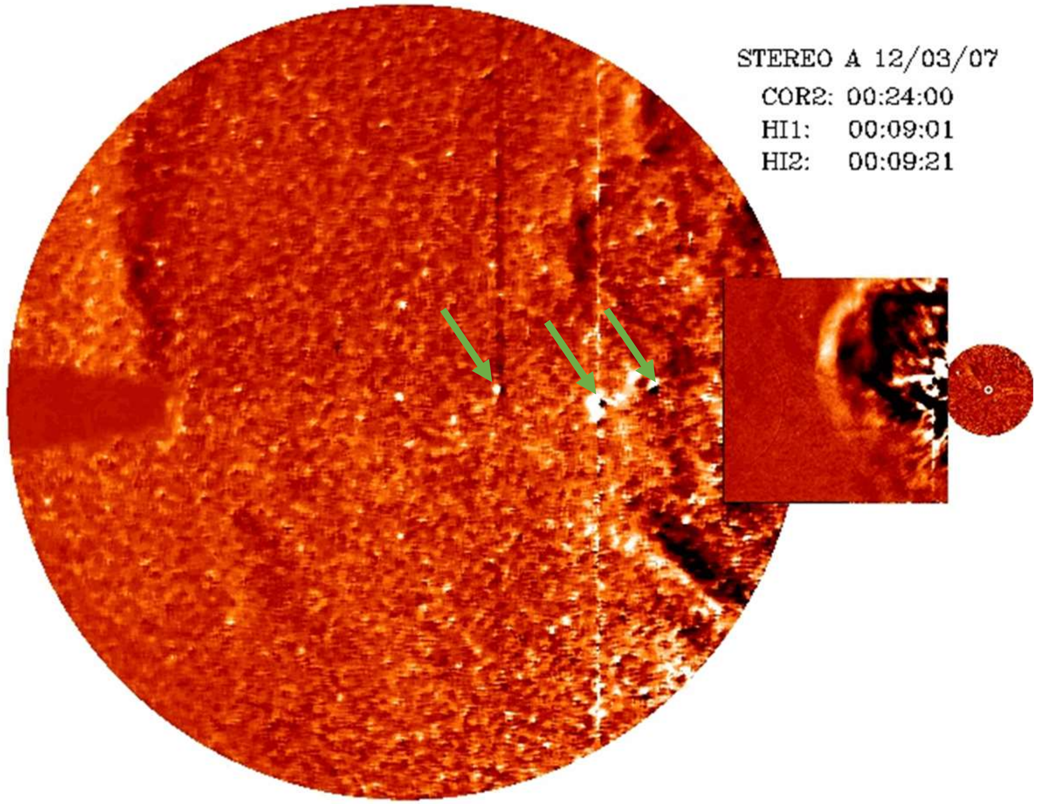
太阳的多空间尺度： 可以展示从**公里**到**AU**尺度量级的动态演化过程



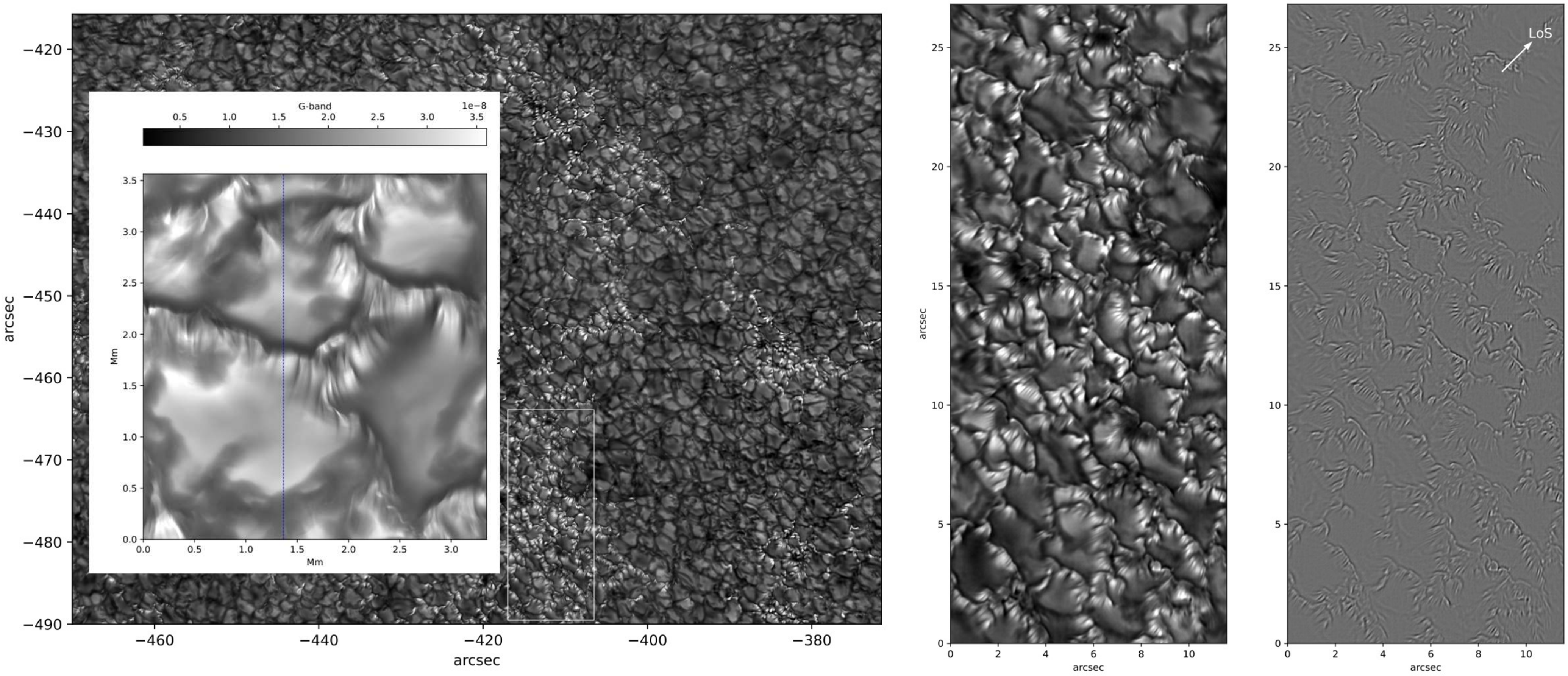
DKIST 初光动态电影（**20 Km**）



日冕物质抛射在行星际的传播 (AU)

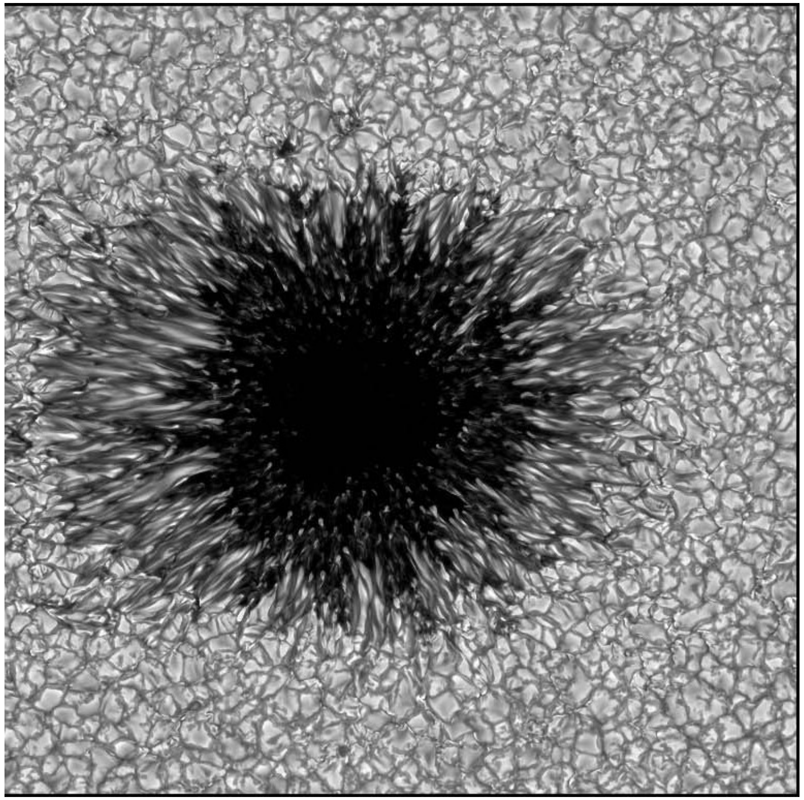


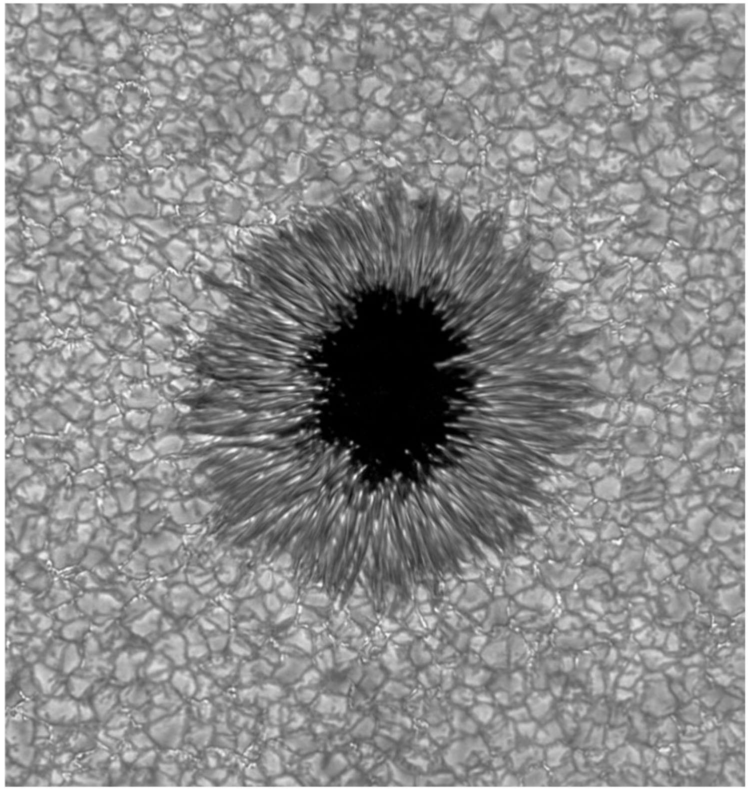
太阳多波段观测-多空间尺度



太阳多波段观测-模拟和观测齐头并进

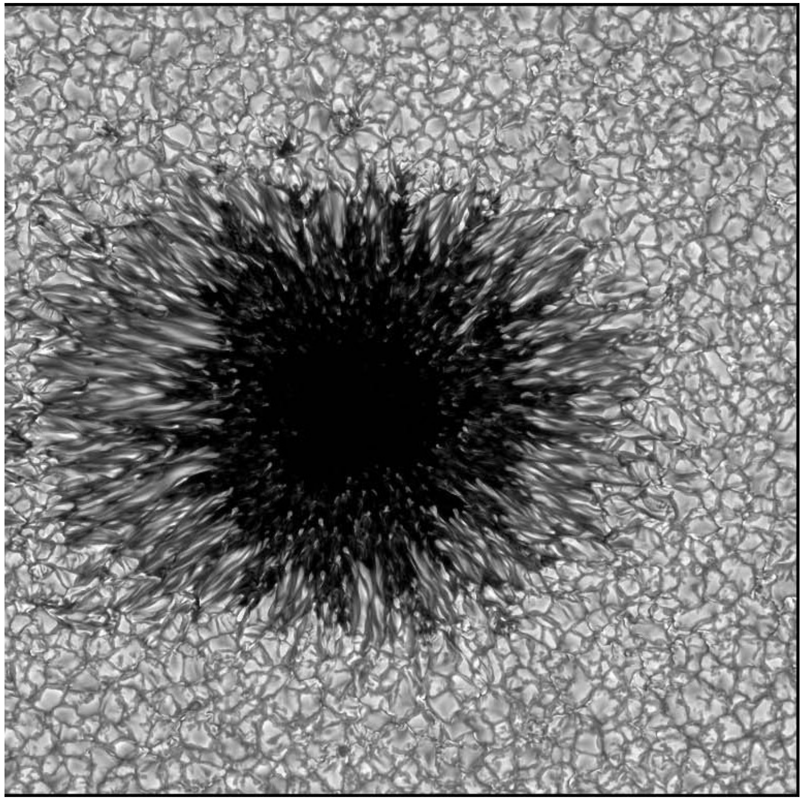
请大家选一选，哪一个是观测的，哪一个是模拟的?



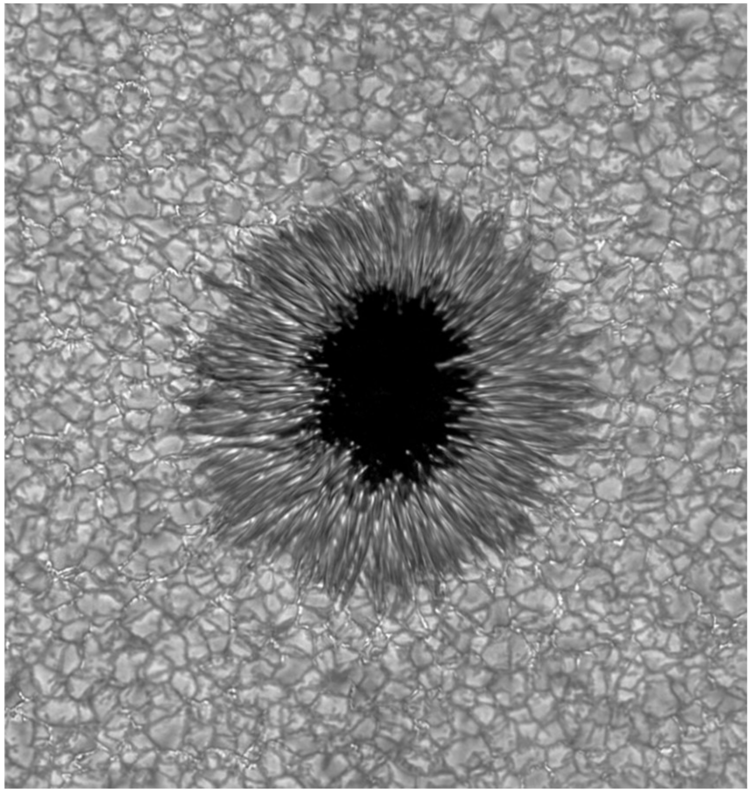


太阳多波段观测-模拟和观测齐头并进

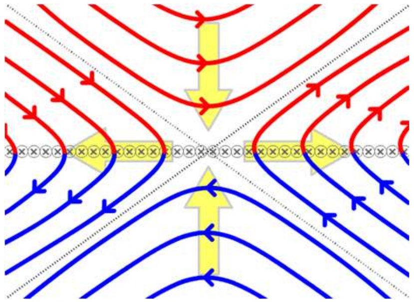
模拟
(Rempel 2009)

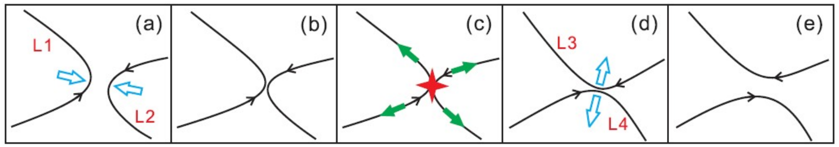


观测
GST/BBSO 1.6M

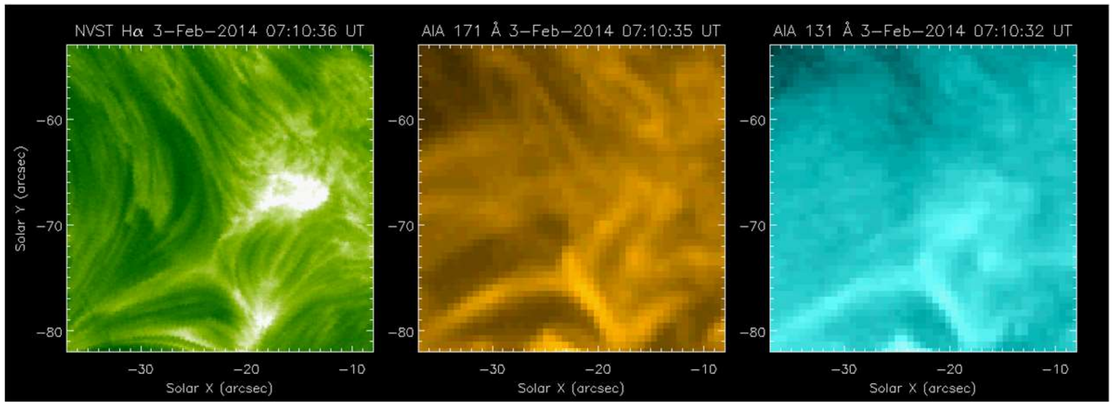


太阳多波段观测研究-小尺度低层大气磁重联

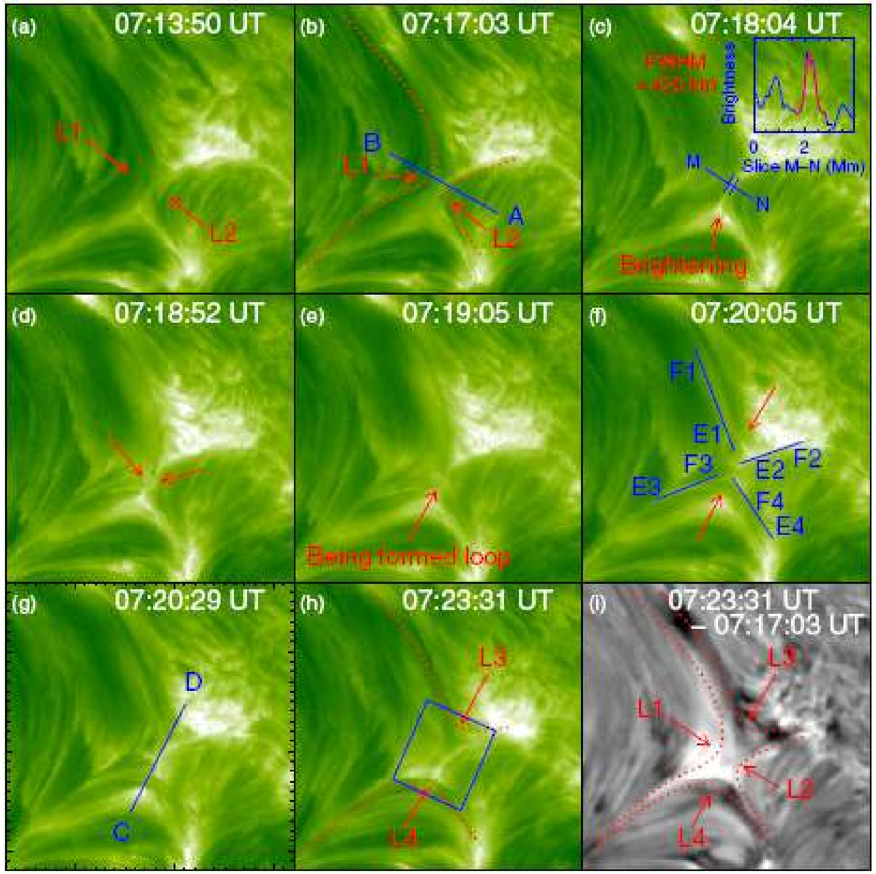




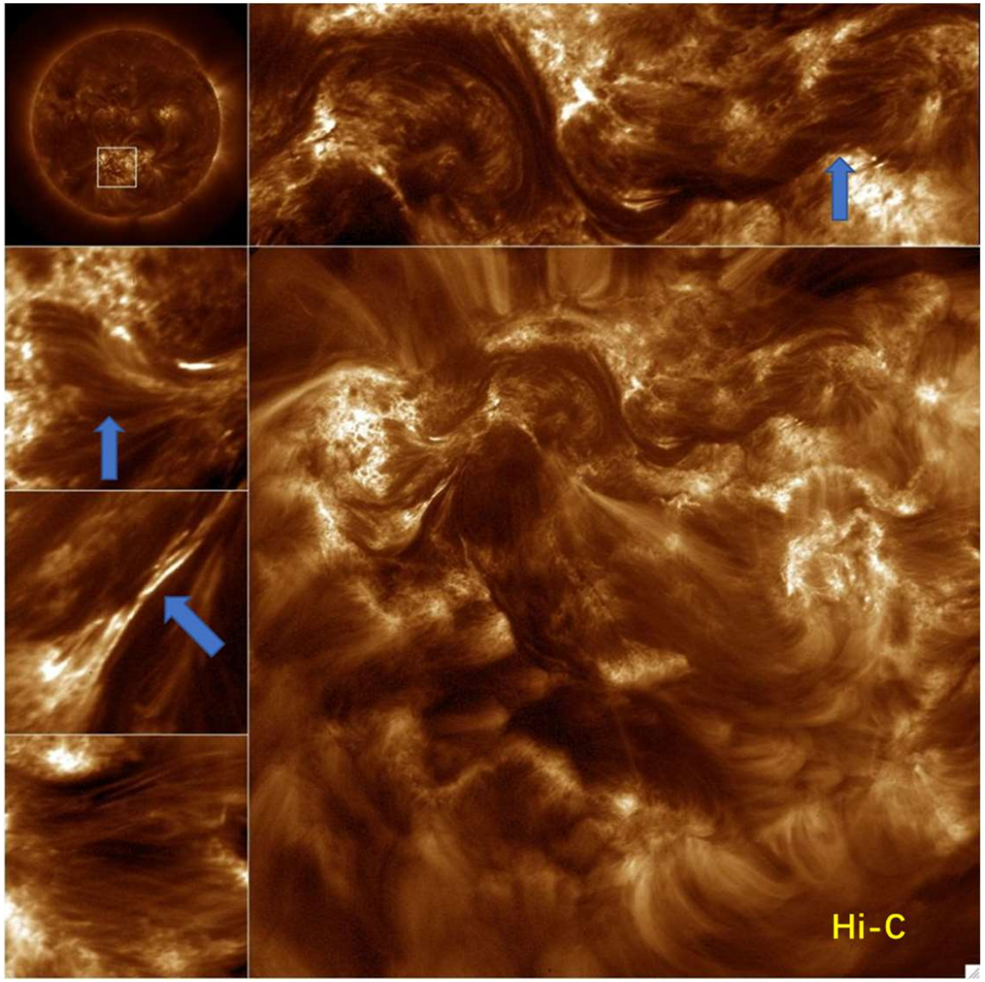
根据观测数据所刻画出的磁重联过程



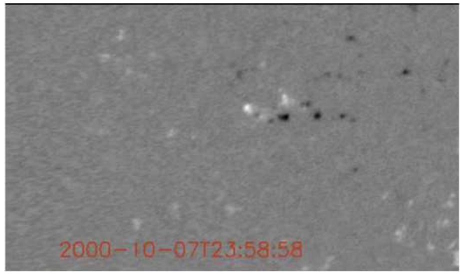
Yang Shuhong et al. 2015, ApJL, 798, L11

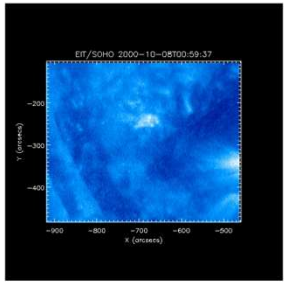


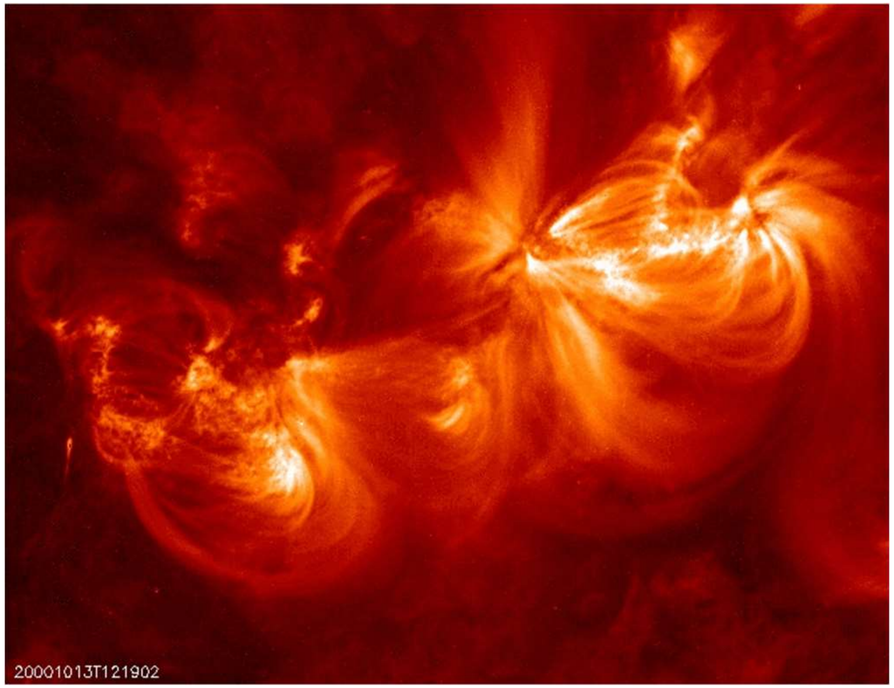
太阳多波段观测研究-日冕磁环的超精细结构



2018 Hi-C

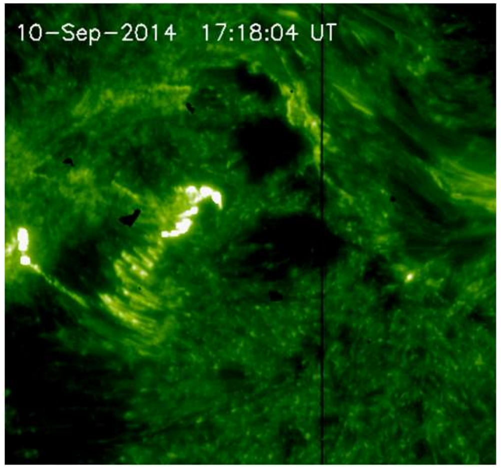


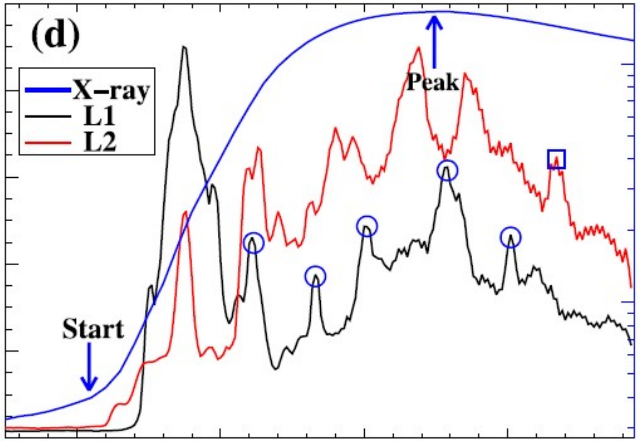


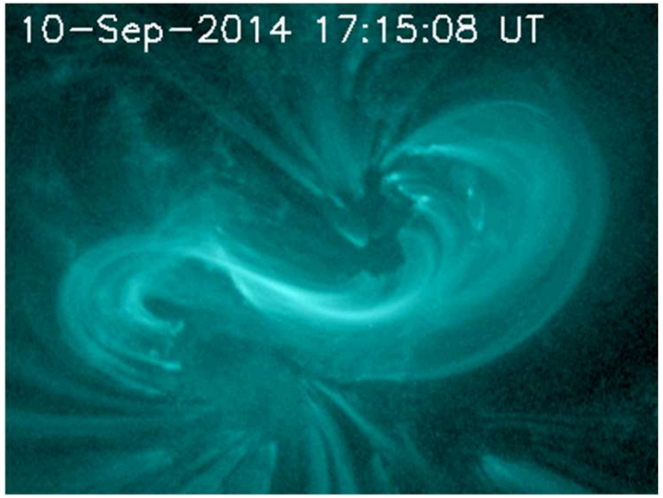


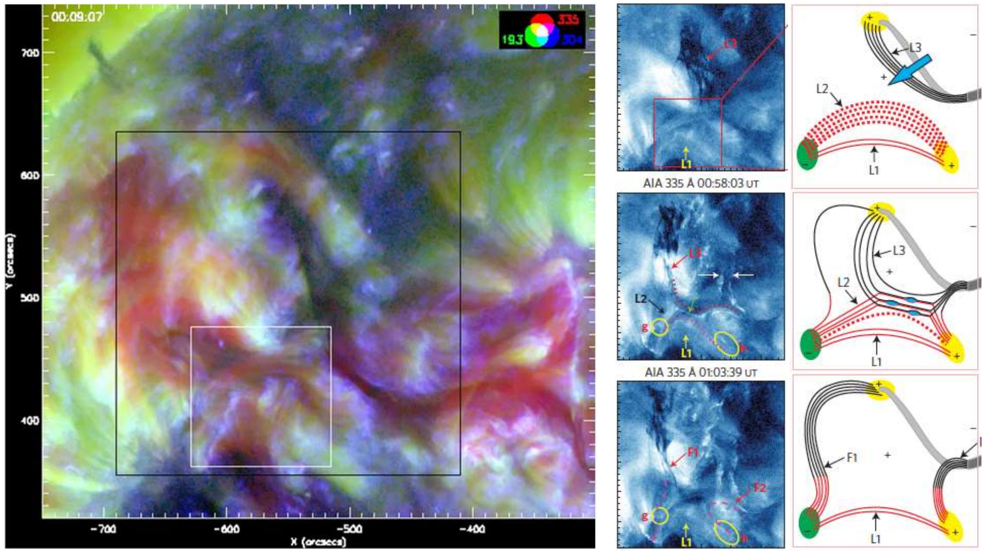
Yang Shangbin et al. 2009 ApJL（磁螺度交换证据）

太阳多波段观测研究-刻画三维磁重联结构



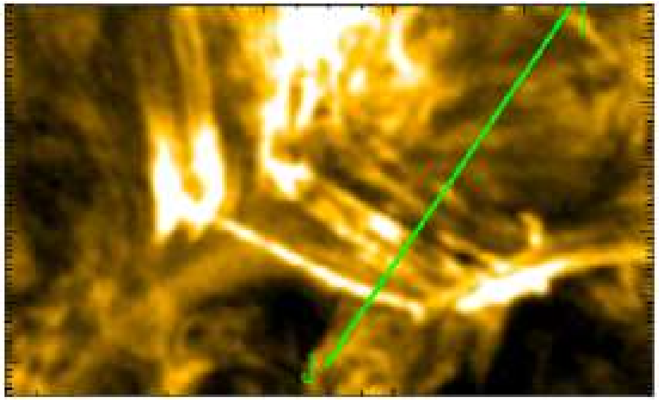






时域特征：准周期性

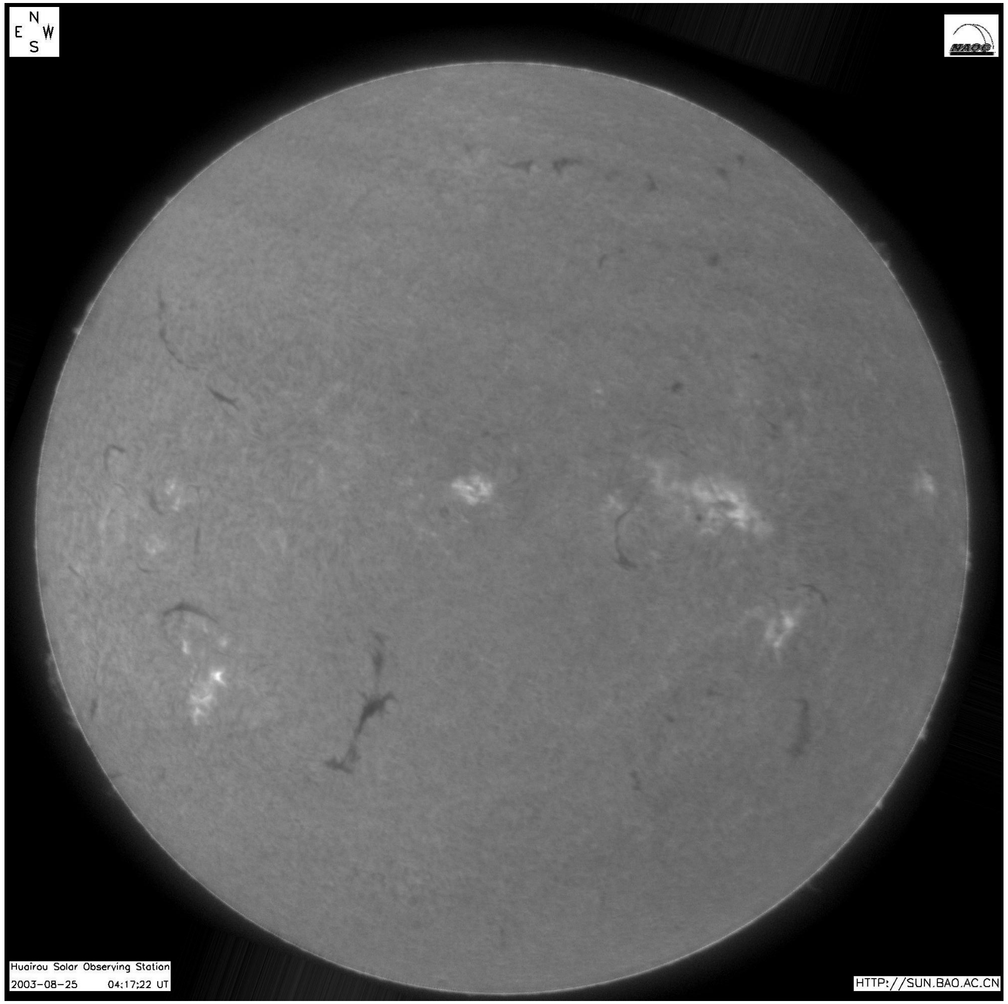
空域特征：耀斑环和耀斑带精细结构的滑动运动

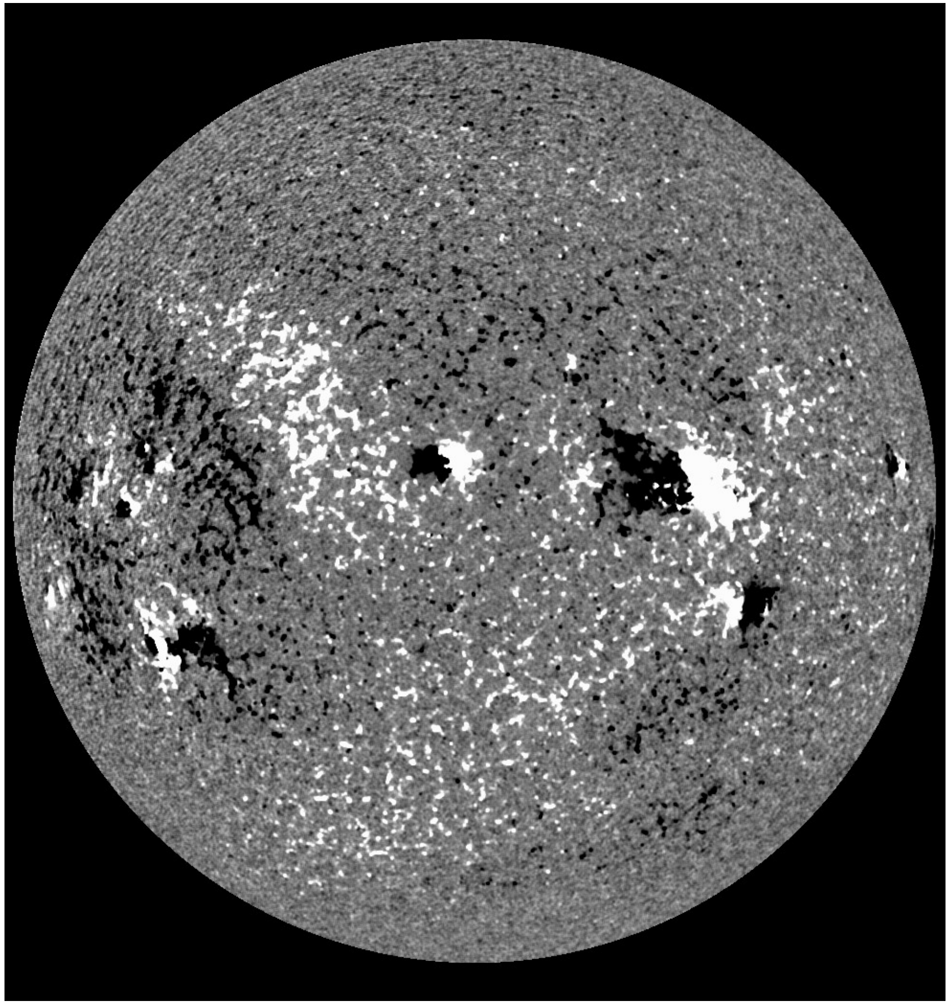


Li & Zhang （2015）

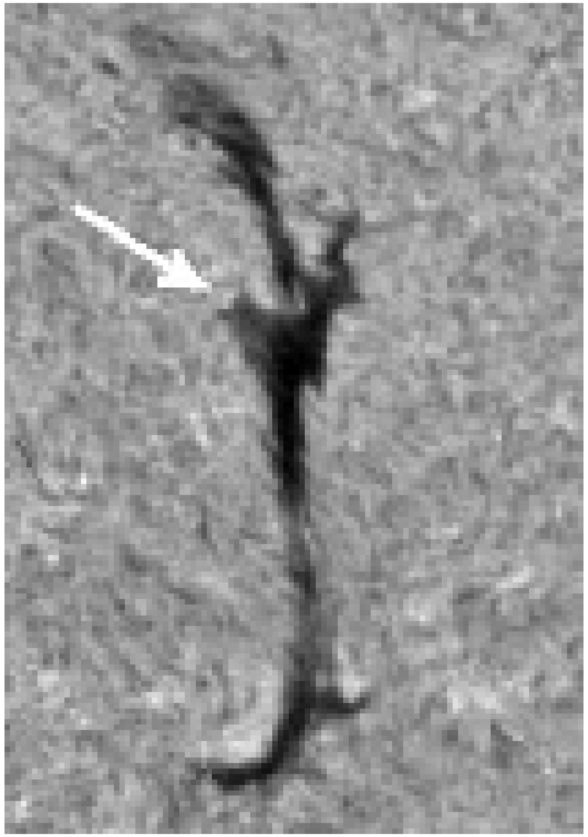
Li Leping et al. 2016 Nature Physics

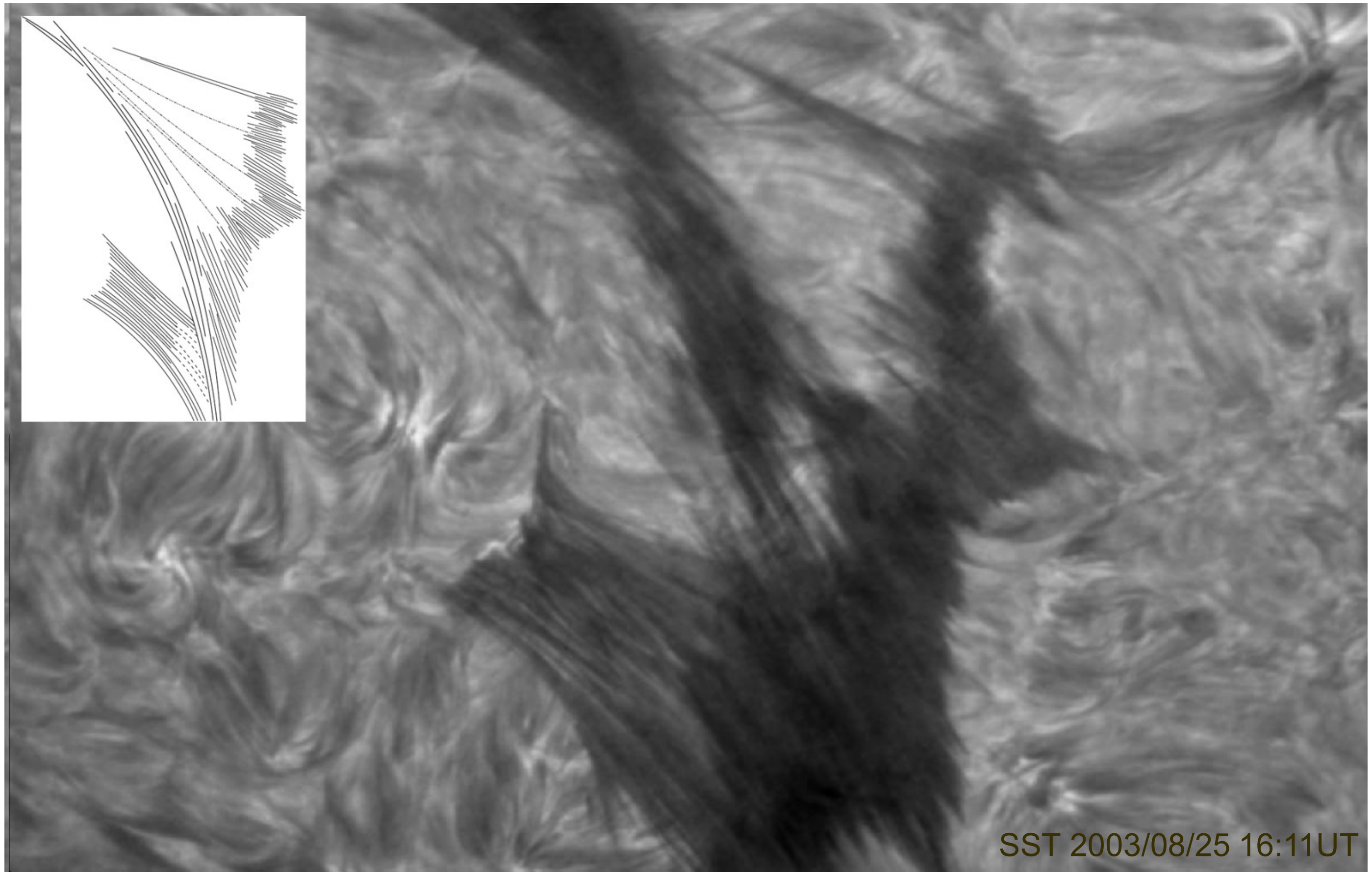
太阳多波段观测研究-刻画三维磁场结构



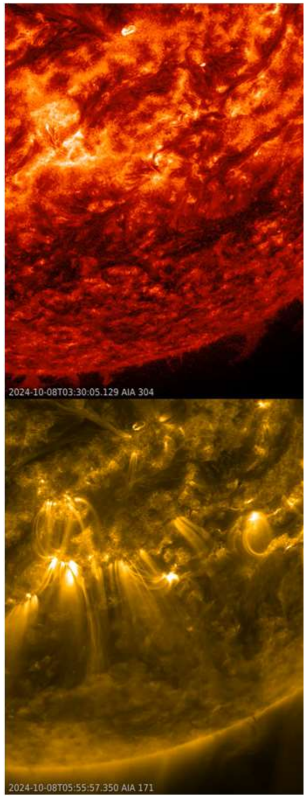


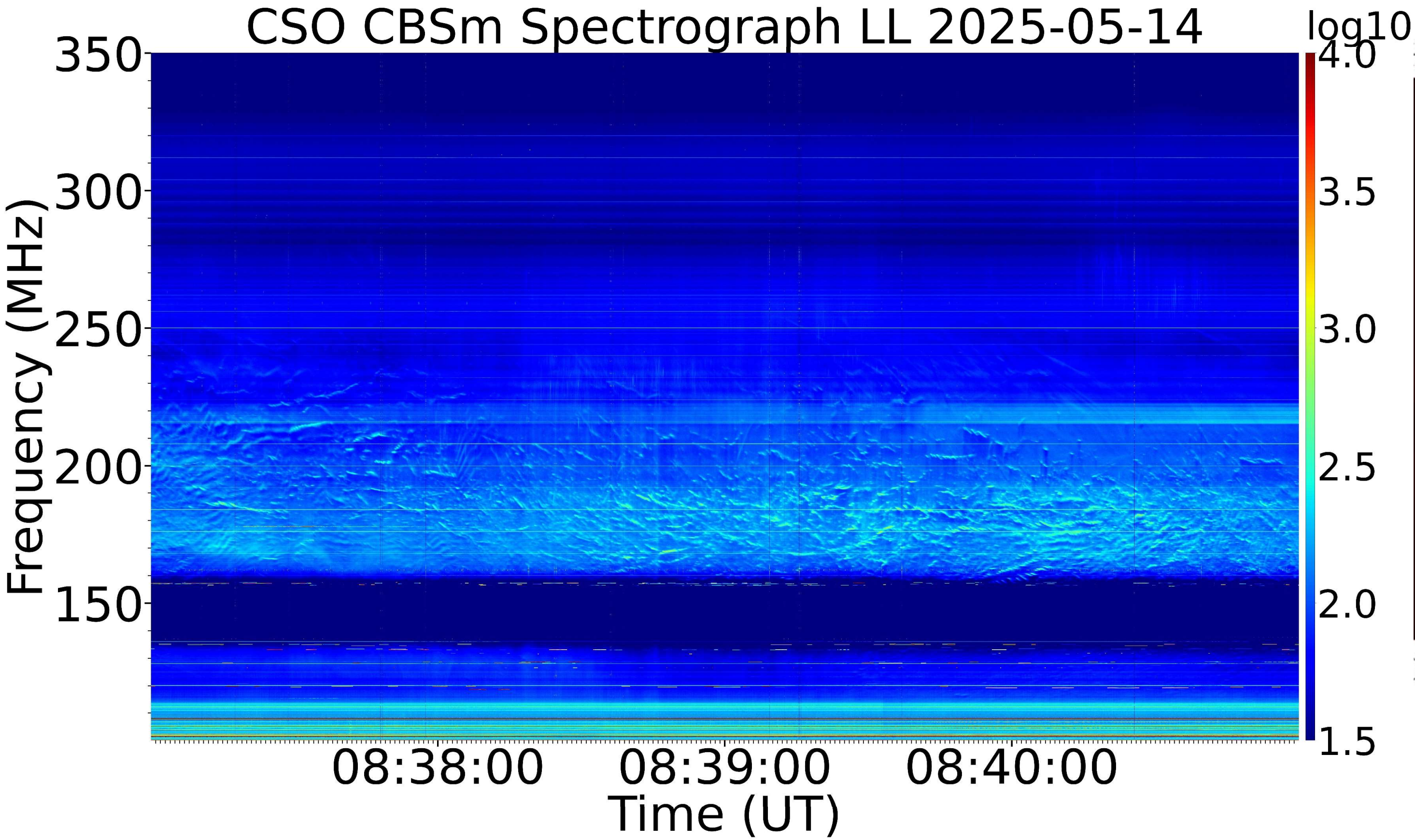
太阳多波段观测研究-刻画三维磁场结构

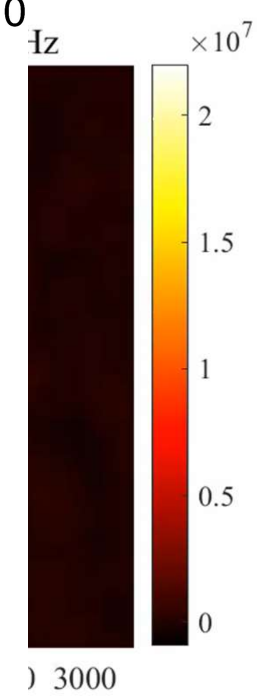




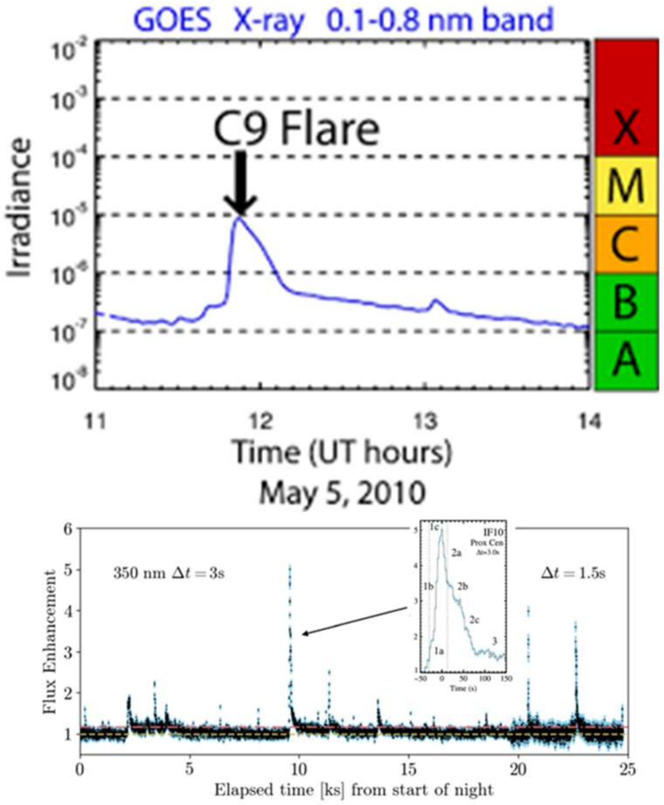
太阳多波段观测研究-射电诊断



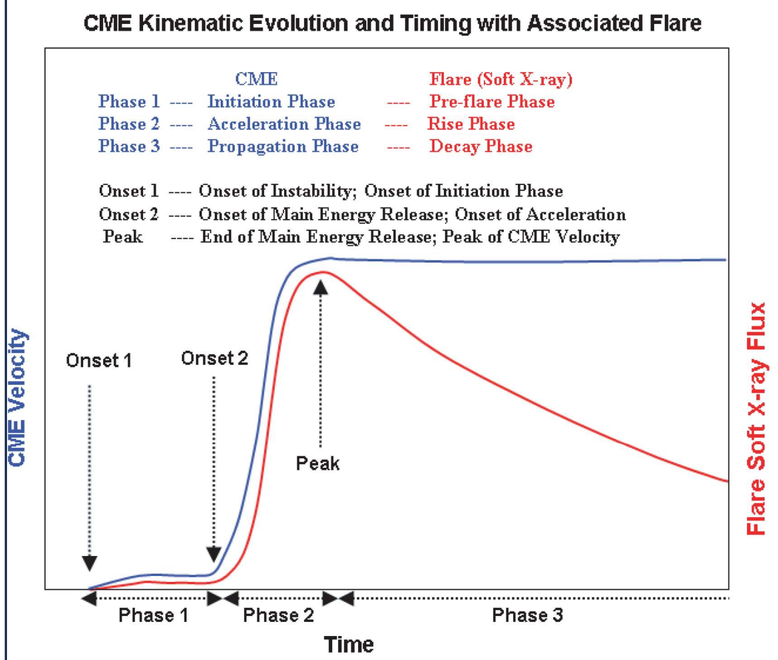




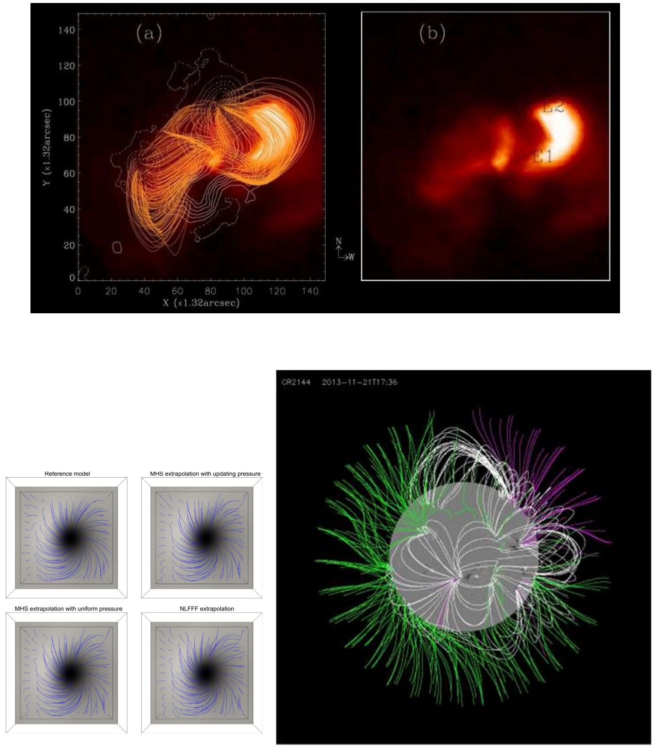
太阳多波段观测研究-检验三维磁场模型



Low (1973, 1974)

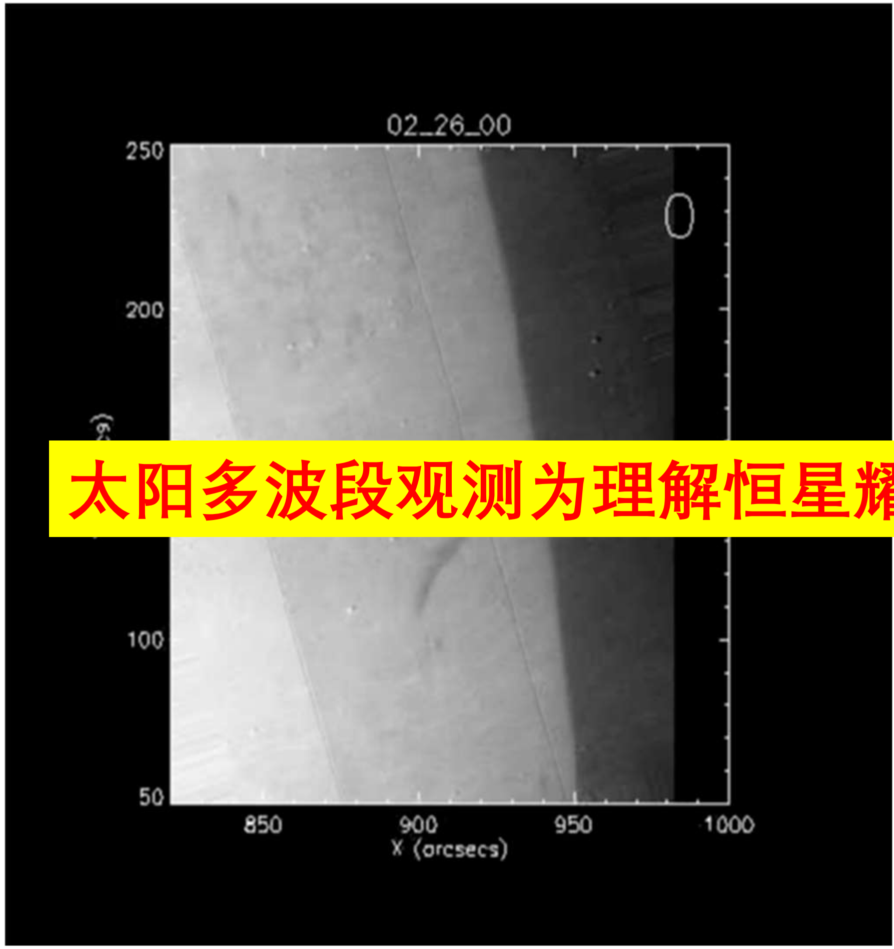


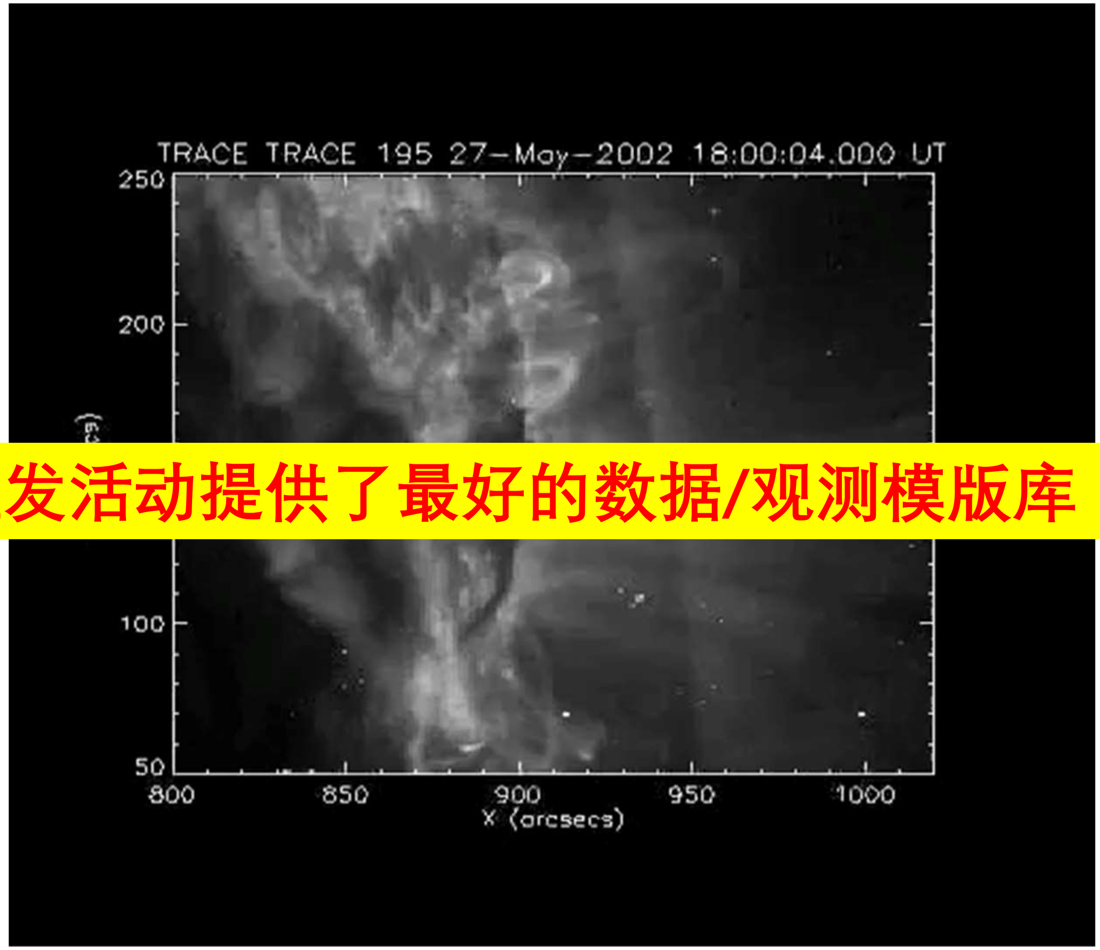
Zhang and Dere (2006)



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-

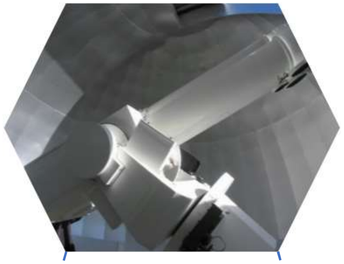
35厘米太阳
磁场望远镜

1996

-怀柔-

多通道太阳望远镜

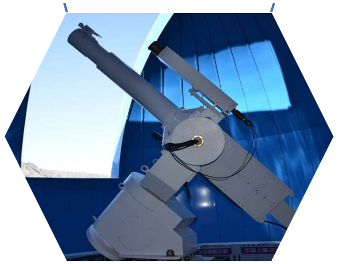
2006



-怀柔-

全日面太阳光学
和磁场望远镜

2013



-温泉-

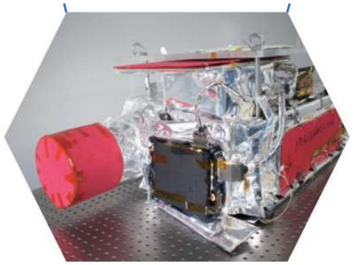
全日面太阳磁场望远镜

2022

-空间-

46.5mm极紫外
线太阳成像仪
(SUTRI)

2022



-空间-

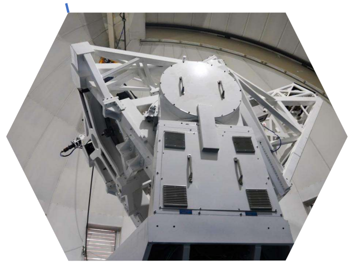
全日面矢量磁像仪
(FMG)

2023

-赣榆-

子午工程Ⅱ期
全日面矢量磁像仪
(SFMM)

2024



-冷湖-

太阳磁场中红外观测系统
(AIMS)

SPO
2029

太阳磁场测量-怀柔基地发展史

Zhong, Li, Yang et al. 2025

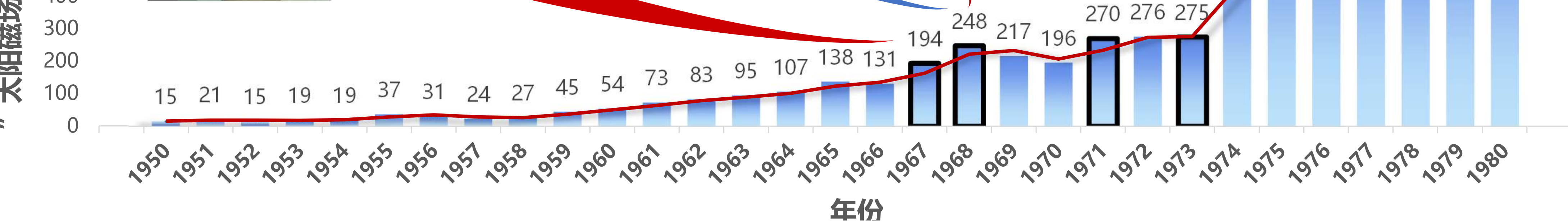
HIGH-RESOLUTION MEASUREMENTS OF PHOTOSPHERE AND SUNSPOT VELOCITY AND MAGNETIC FIELDS USING A NARROW-BAND BIREFRINGENT FILTER

J. M. BECKERS

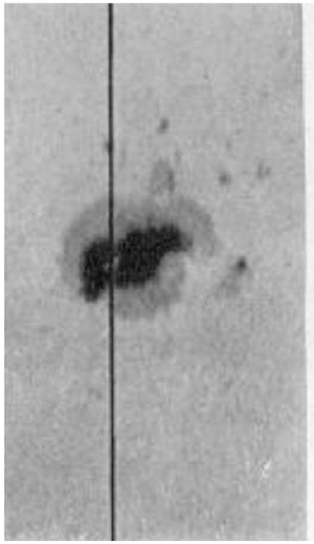
Sacramento Peak Observatory, Air Force Cambridge Research Laboratories, Sunspot, N.M., U.S.A.

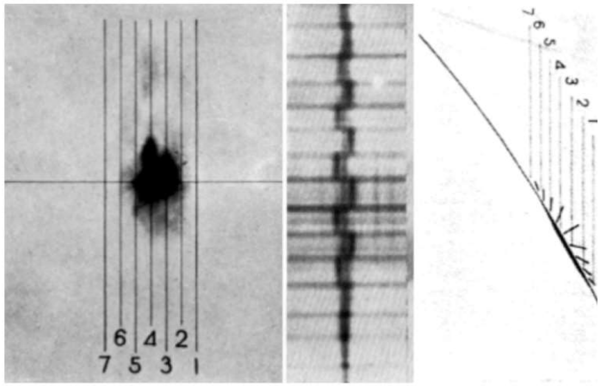
(Received 21 July, 1967)

Abstract. Modifications to a Zeiss ⅛ 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.

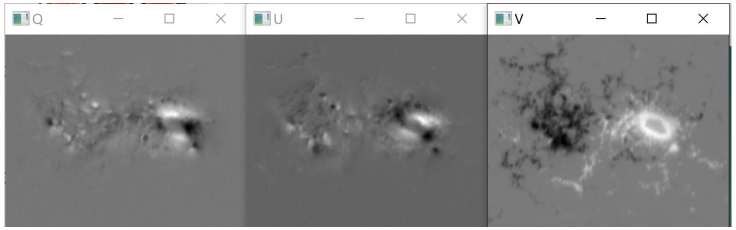


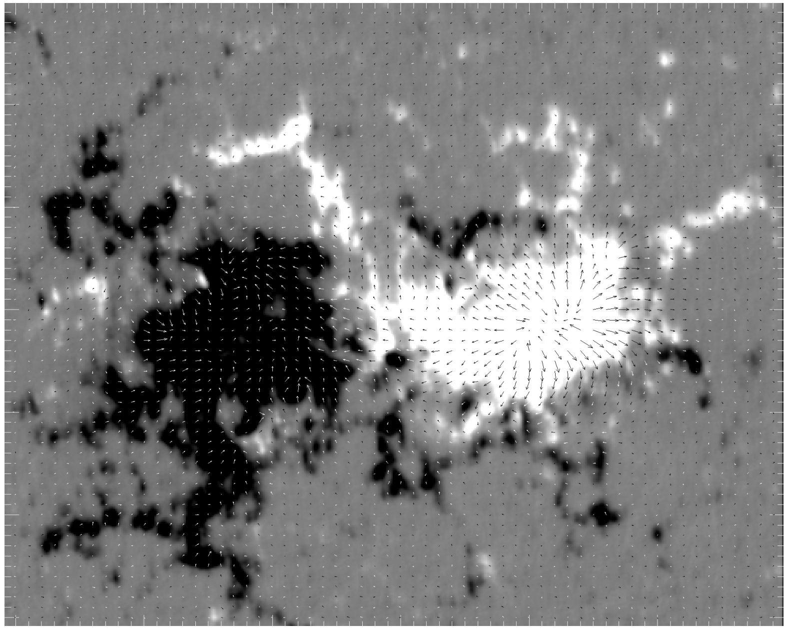
太阳磁场测量-发展脉络



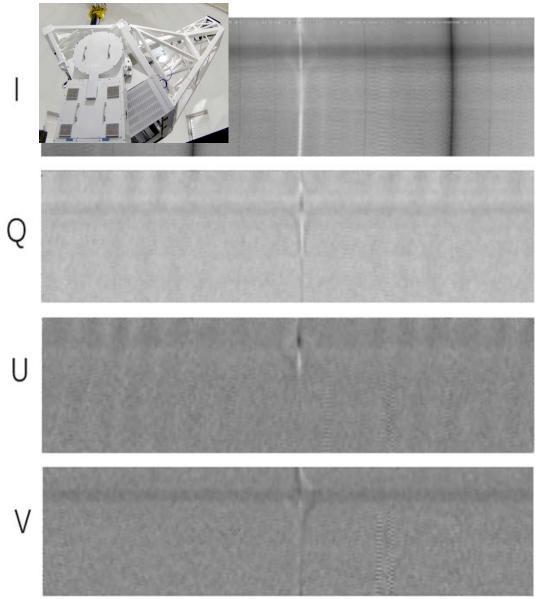


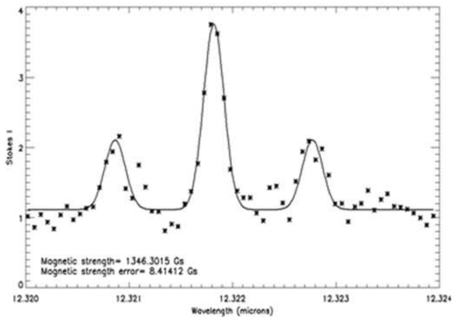
Hale & Ellerman, 1919, ApJ, 49, 153





弱场近似和Stokes参数反演

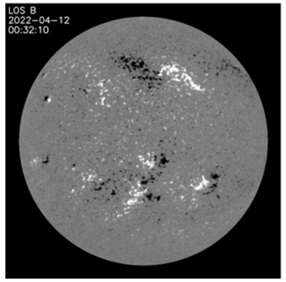


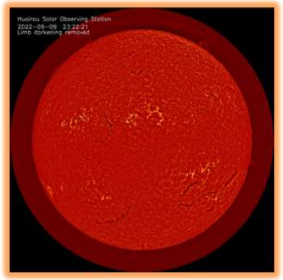


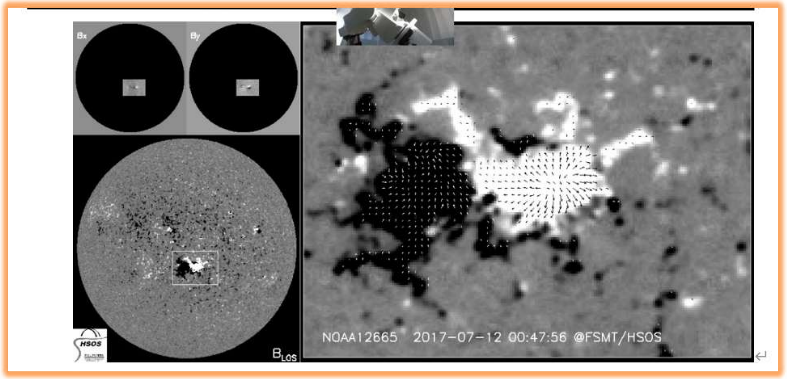
单像元三分裂光谱及磁场精度

怀柔太阳观测基地磁场测量现状

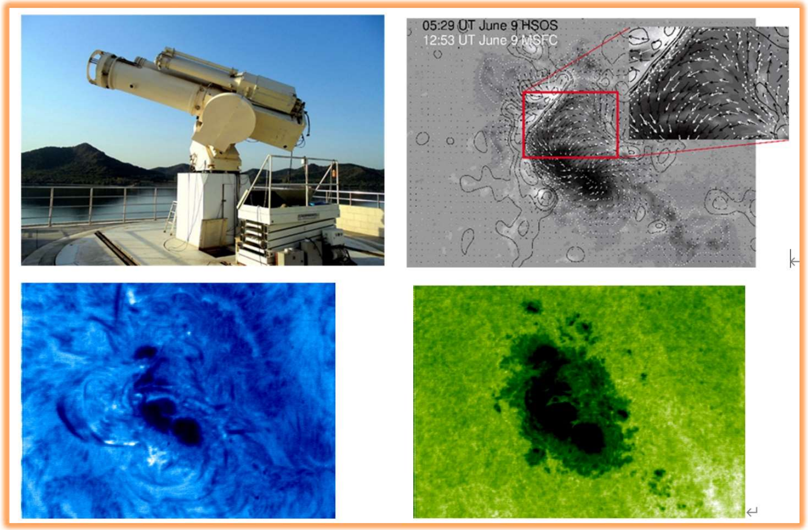
- 从光球到色球不同高度的太阳磁场（多层次）
- 全日面太阳磁场和太阳活动的完整观测（大视场）
- 太阳磁场的中红外波段的精确测量（高精度）
- 空间太阳磁场测量（全时段）
- 多层次全日面太阳磁场和速度场观测（多层次、大视场）





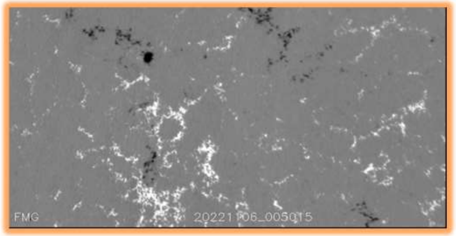


怀柔全日面太阳活动监测望远镜（大视场）



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）



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

磁梯度 $\nabla \mathbf{B}$

↓

磁剪切 $\mathbf{B} - \mathbf{P}$

↓

电流 $\nabla \times \mathbf{B}$

↓

电流螺度 $\mathbf{B} \cdot \mathbf{J}$

↓

磁螺度 $\mathbf{A} \cdot \mathbf{B}$

观测仪器（方式）

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

实测维度

点

↓

线

↓

面

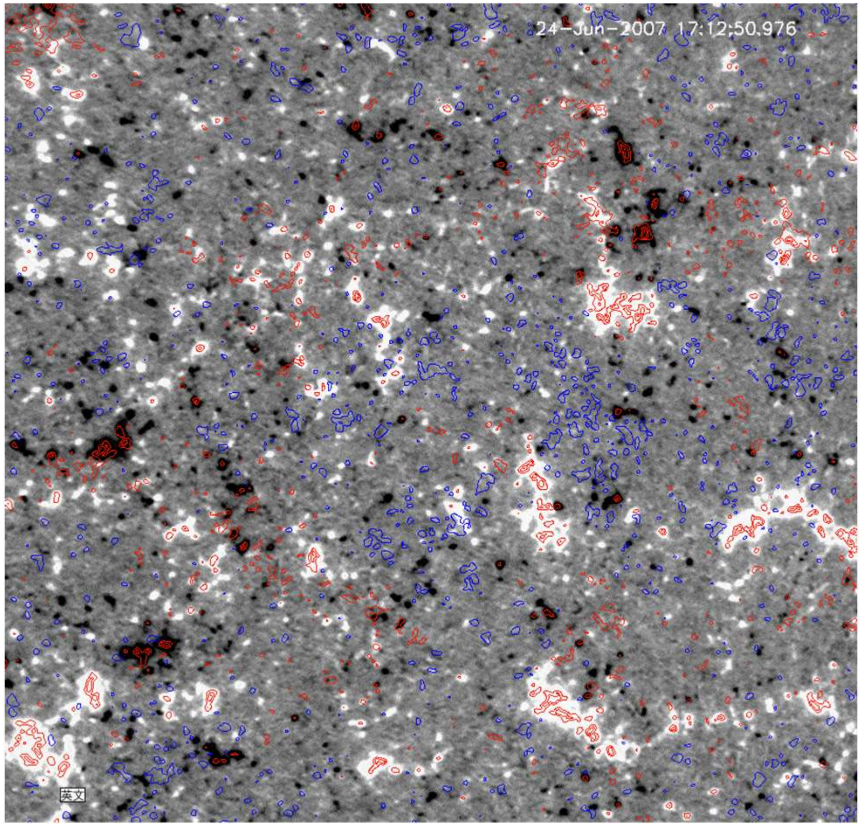
↓

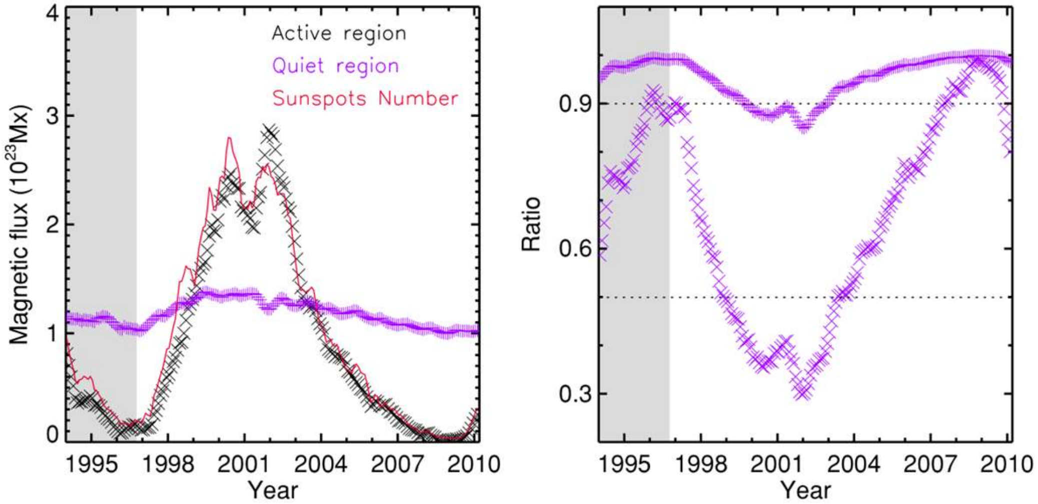
体

核心问题：太阳大气磁场的三维结构是什么？

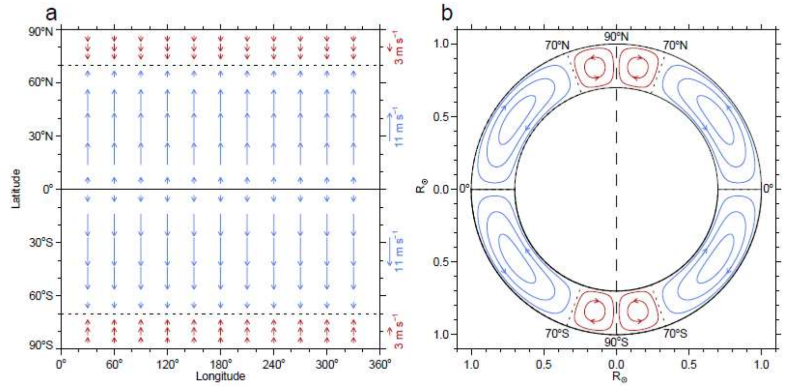
太阳磁场研究-从大尺度到小尺度

小尺度磁场的通量和运动追踪



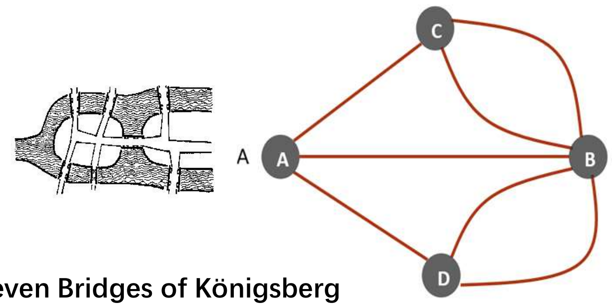


Jin C. L.; Wang J. X., Song Q. et al. 2011 ApJ



Yang et al. 2023 极区流场结构

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

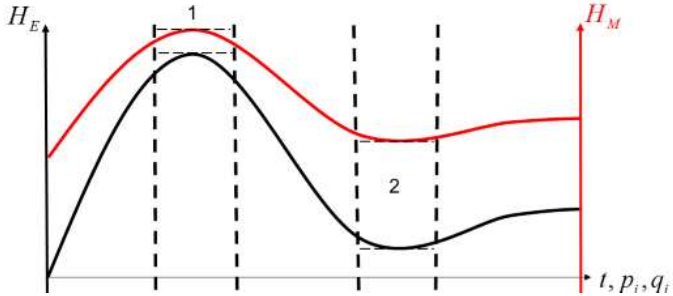


Seven Bridges of Königsberg

H＝0 H＝TΦ² H＝±2Φ₁Φ₂

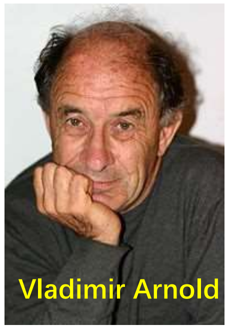
$H=0$ $H=T\Phi^2$ $H=\pm 2\Phi_1\Phi_2$

Topological Description of 3D B



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

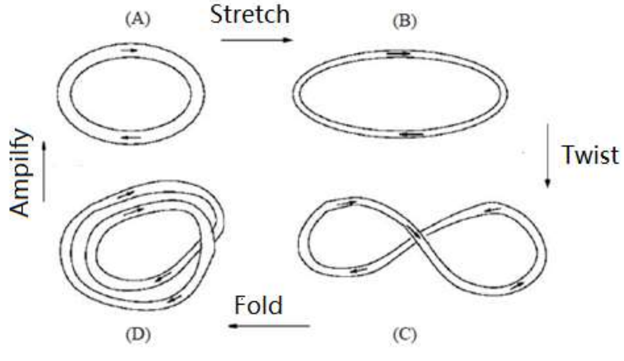
$$-C^{-1}|E_m| \le H_m \le C^{-1}|E_m|$$



Arnold 1974 inequality

- **Helicity bounded by energy**
- **Taylor Conjecture**

Module Solar Dynamo Process



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

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

Kinetic helicity

$$- \langle \mathbf{b}^{(0)} \cdot \nabla \times \mathbf{b}^{(0)} \rangle \big) \bar{\mathbf{B}} + \frac{2\tau_c}{3} \Omega \langle \mathbf{u}^{(0)} \cdot \mathbf{b}^{(0)} \rangle$$

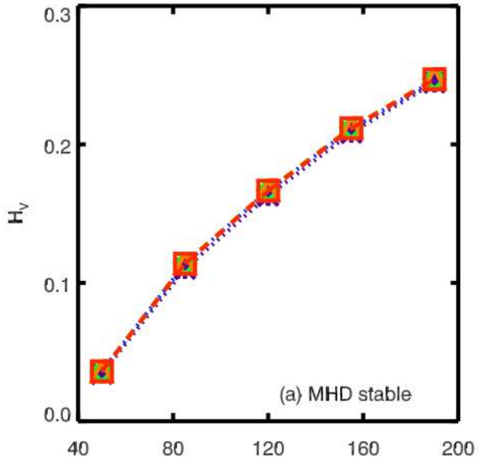
Current helicity Cross helicity

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)



INTERNATIONAL SPACE SCIENCE INSTITUTE

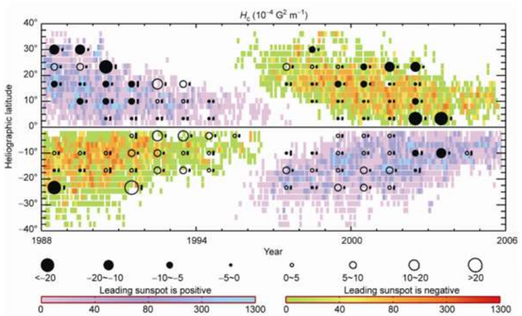
http://www.issibern.ch/teams/magnetichelicity/

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

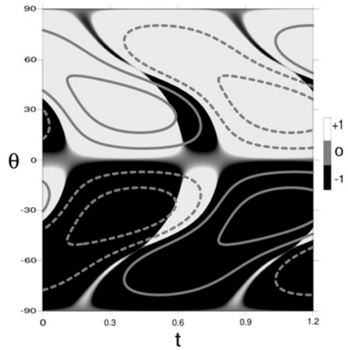
太阳磁场研究-半球螺度法则 （太阳发电机模型的观测约束）

电流螺度纬度分布蝴蝶图



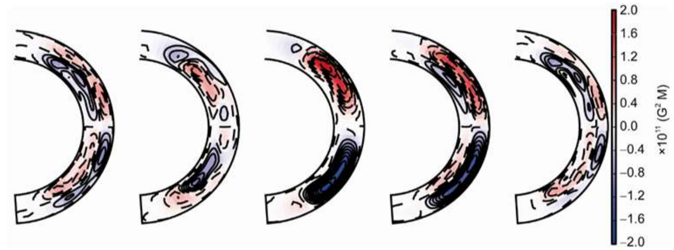
Zhang H Q et al，2010

相位延迟与螺度起伏



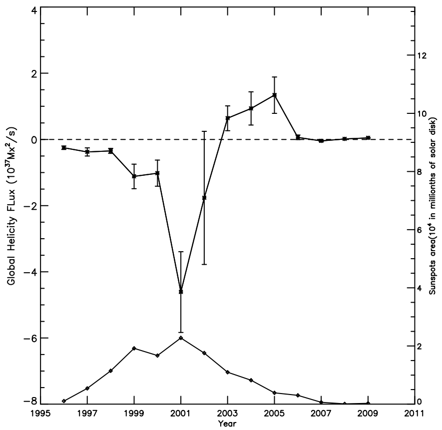
Xu et al. 2009

太阳对流区内磁场和磁螺度演化分布



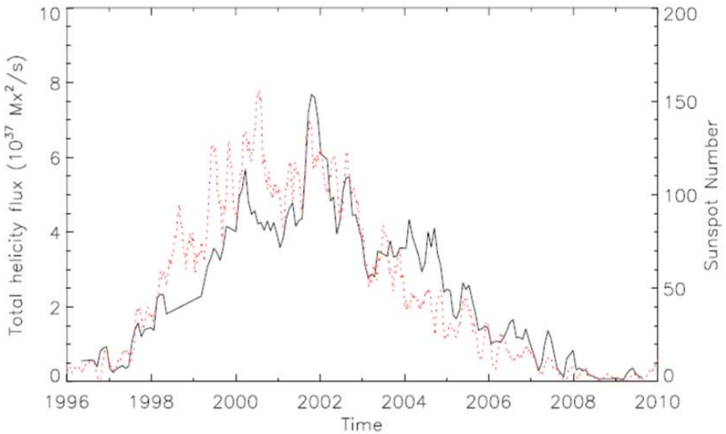
Pipin & Zhang HQ, et al, 2013

磁螺度活动周的起伏



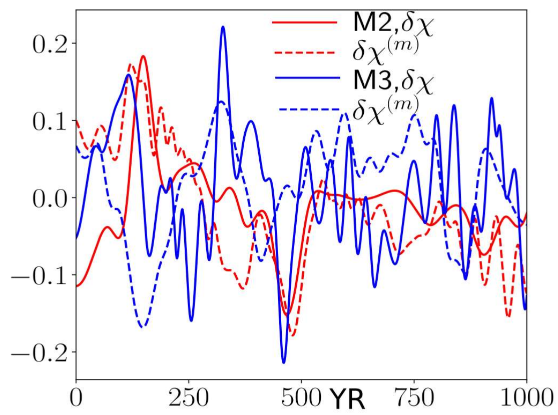
Yang et al. 2012

螺度传输峰值与磁通量峰值存在相位延迟



Zhang and Yang 2013

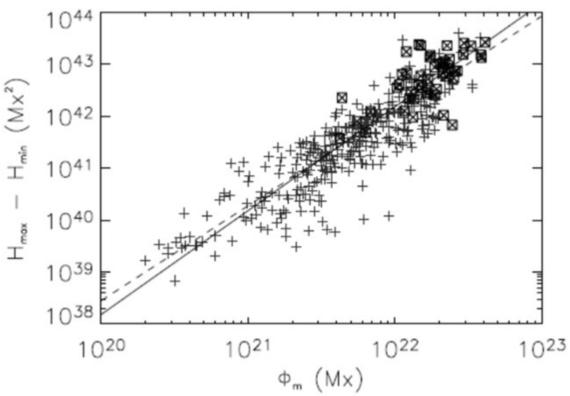
α效应的随机振荡



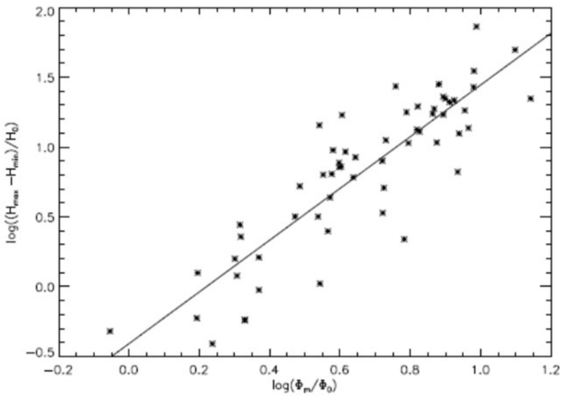
Yang et al. 2020

太阳磁场研究-磁螺度与太阳爆发的关系

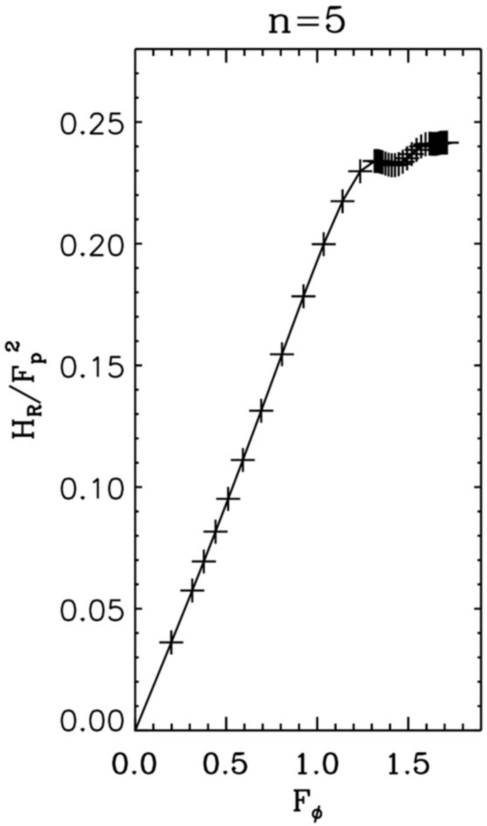
太阳活动区是自相似缠绕的磁流管



Labonte et al.2007

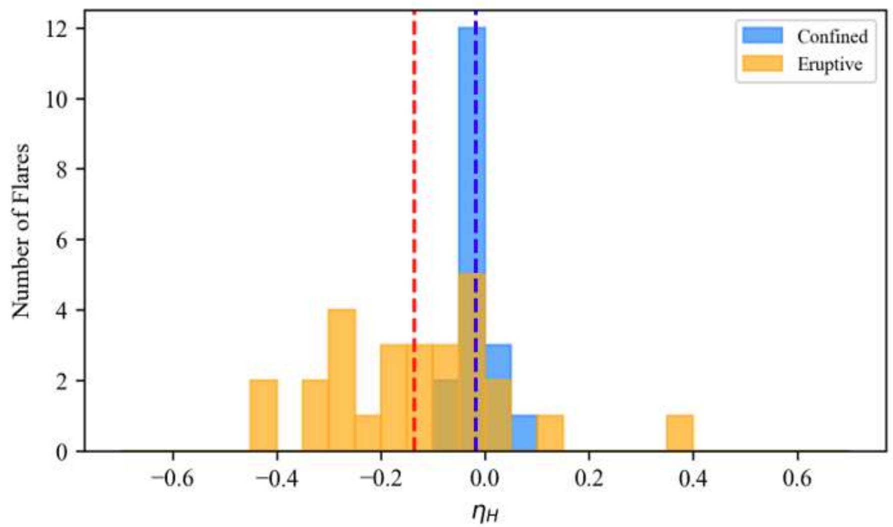


Yang et al. 2009



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

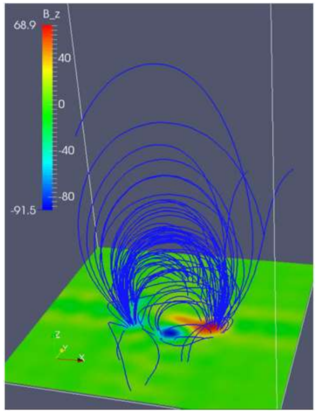
（Yang Shangbin et al. 2025, ApJ，980.206）

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

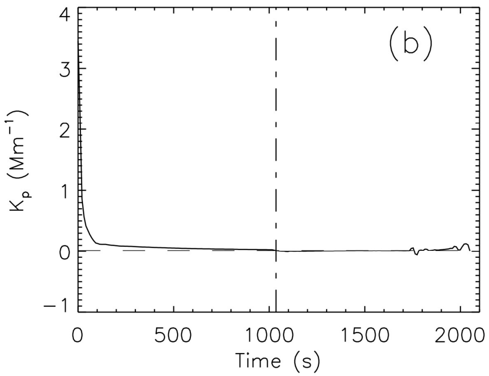
$$\frac{\partial \rho \vec{u}}{\partial t} = -\nabla \cdot \rho \vec{u}\vec{u} - \nabla p + \vec{j} \times \vec{B} - \nu \rho (\vec{u} - \vec{u}_0)$$

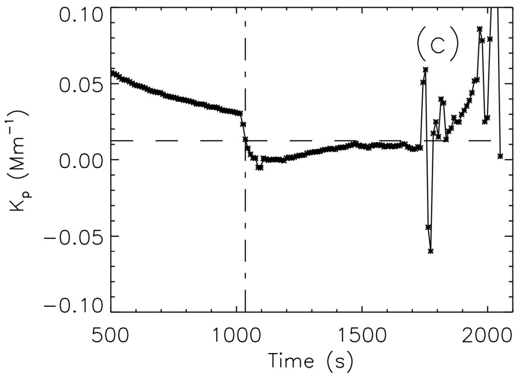
$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{u} \times \vec{B} - \eta \vec{j} \right)$$

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

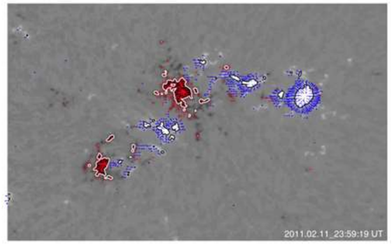


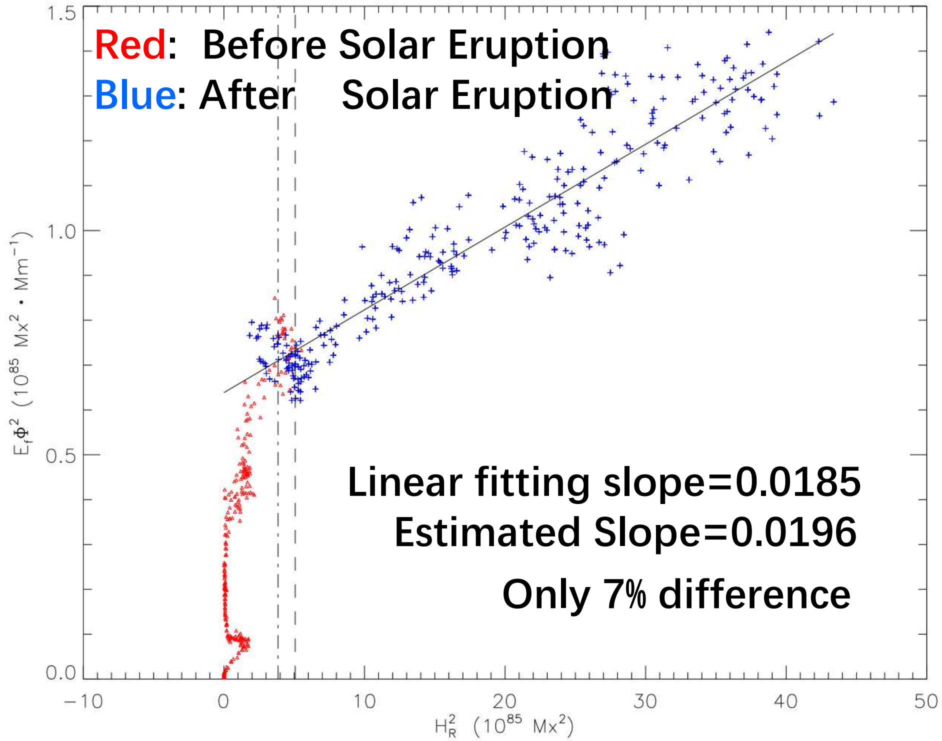
数值模拟的检验





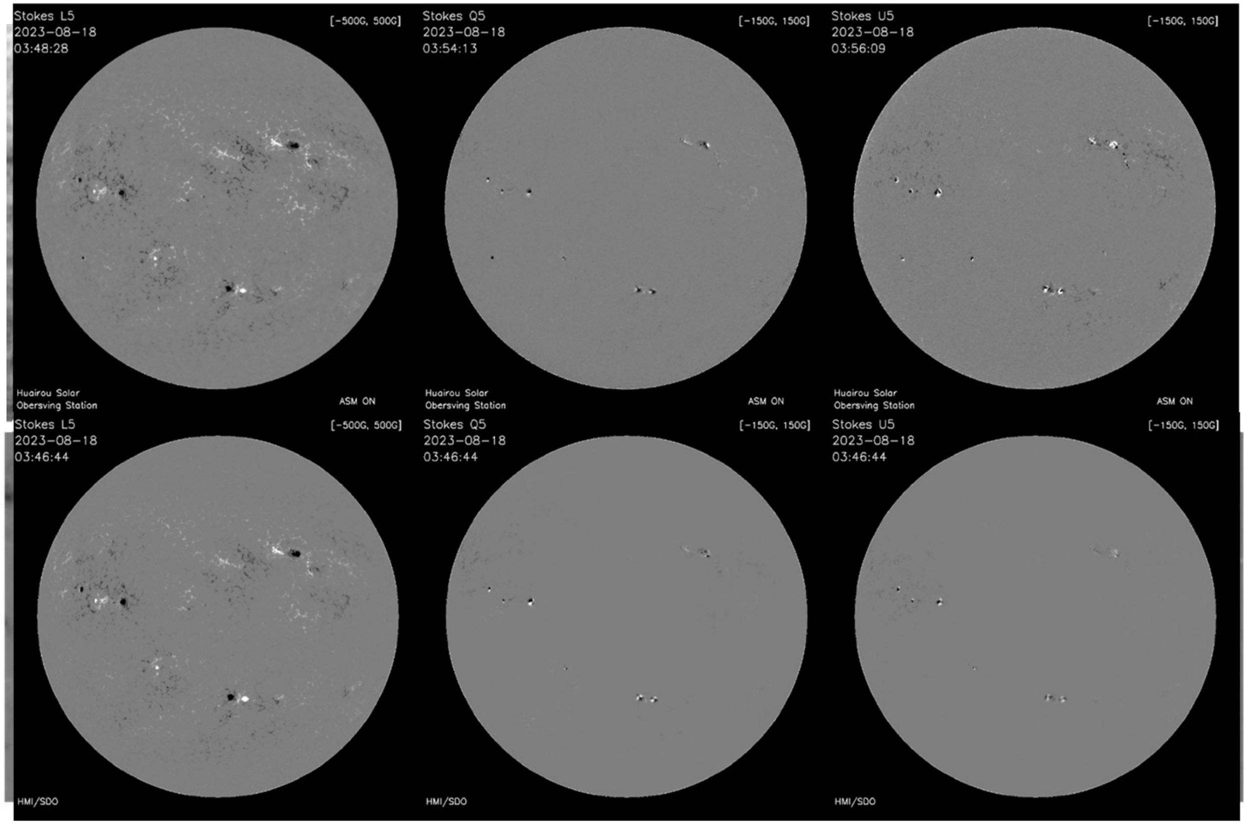
$$E_f \Phi^2 = K H_R^2$$





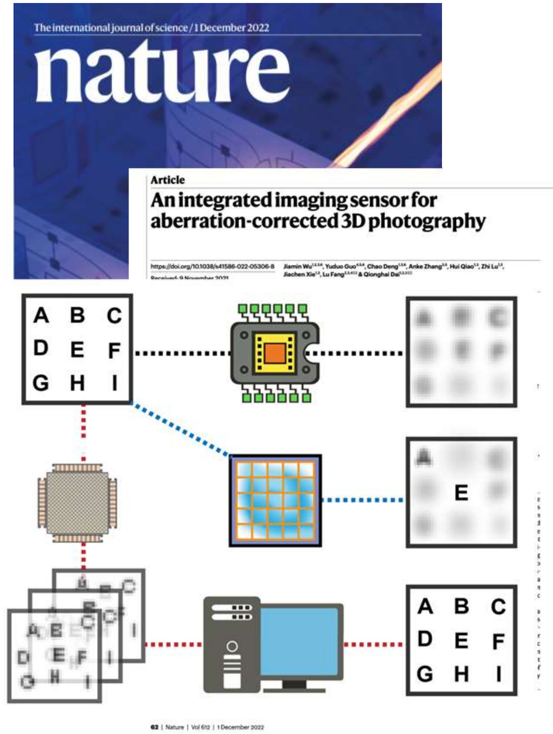
太阳磁场测量新技术-太阳矢量磁场的主动测量方法和数字自适应

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

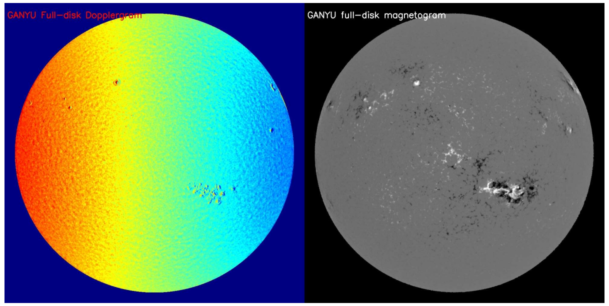
探索大视场和高分辨率不可得兼的问题



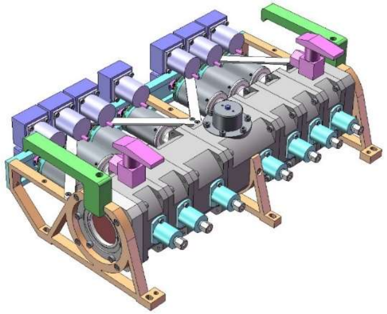
国家自然科学基金委重大仪器专项（自由申请）
清华+国台

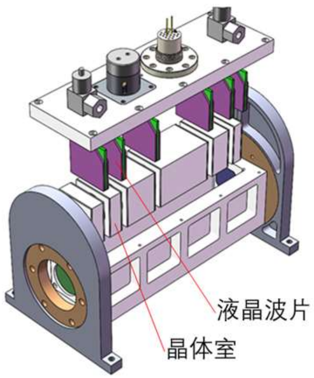
太阳磁场测量新技术-液晶窄带滤光偏振测量等新技术

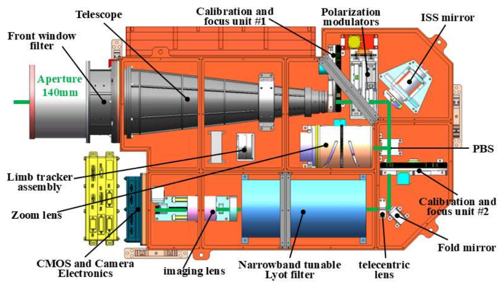
液晶波片技术的应用于子午工程二期



极大减轻了重量(120kg-60kg)

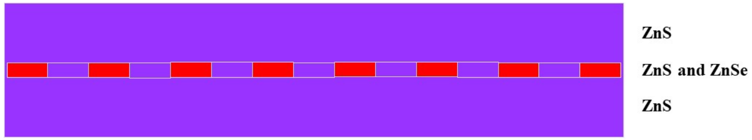


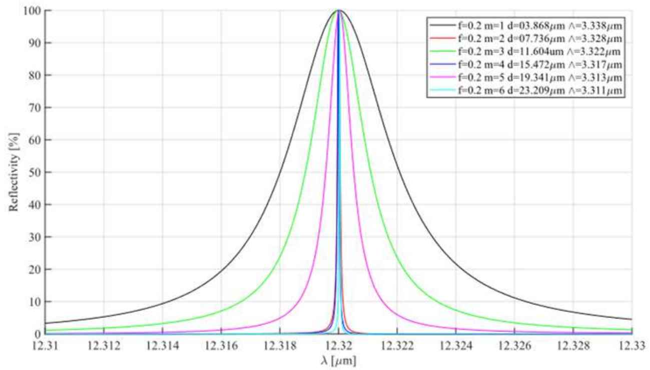




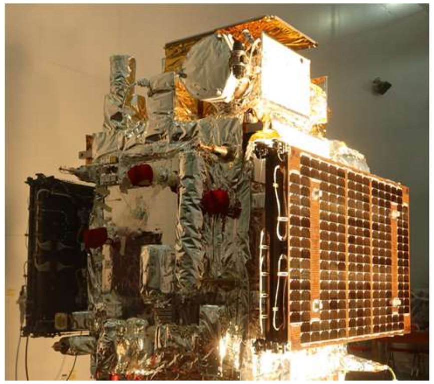
导模共振光栅滤光片

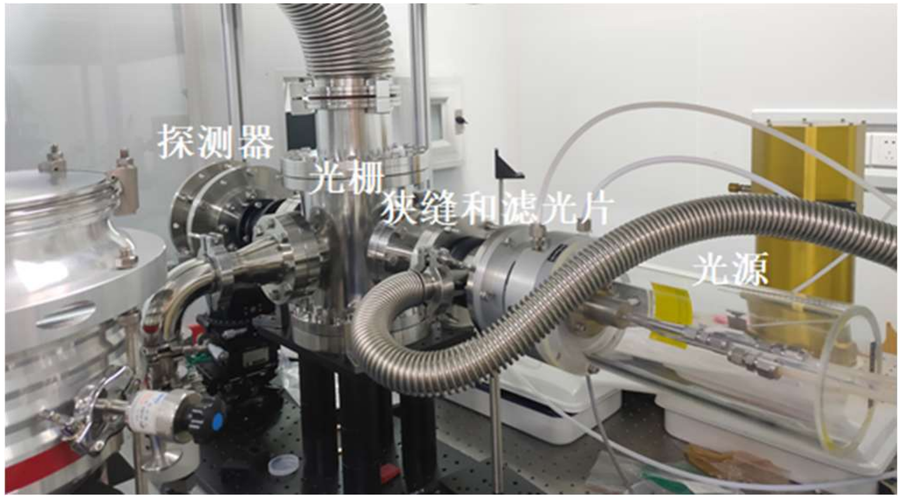
- 微纳光子学技术
- 亚波长光栅与波导耦合，实现窄带滤光成像

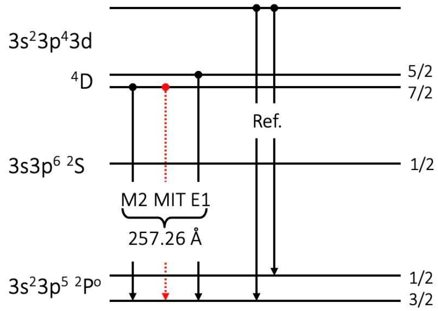


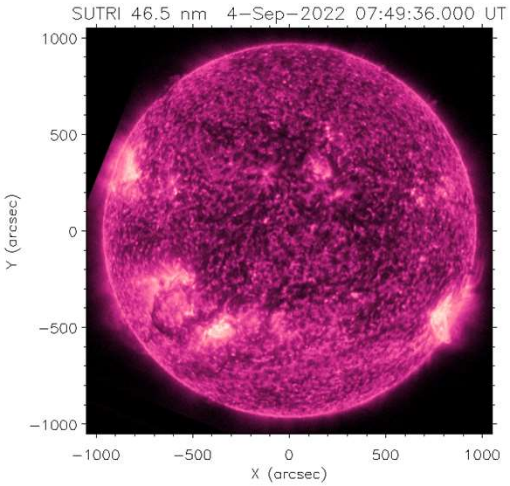


太阳磁场测量新技术-磁诱导跃迁（MIT）测量星冕磁场







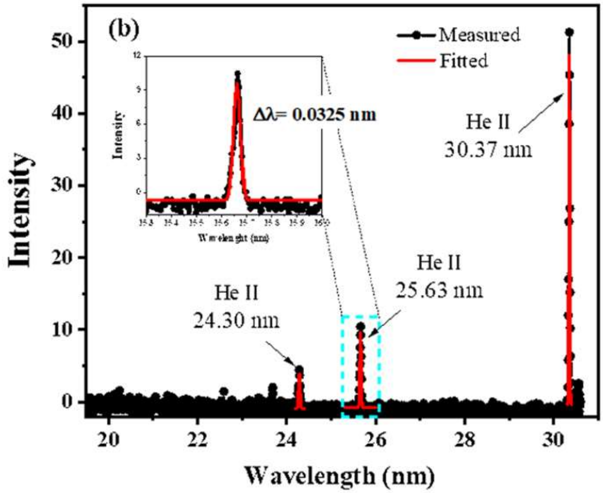


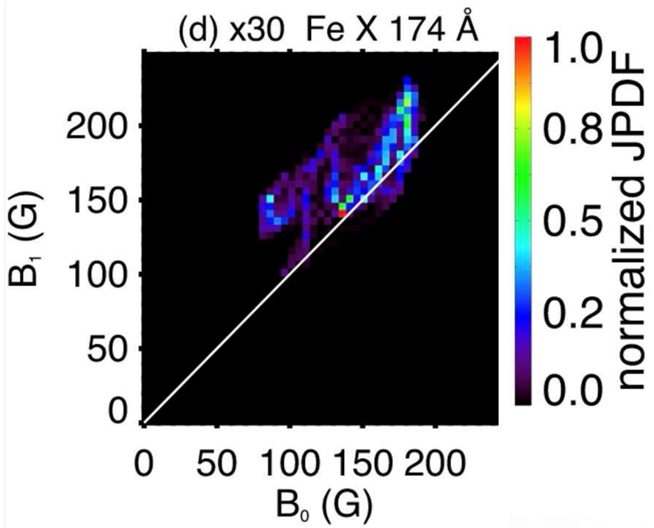
我国首次太阳过渡区探测

极紫外光谱仪

FIS/SPO

转初样



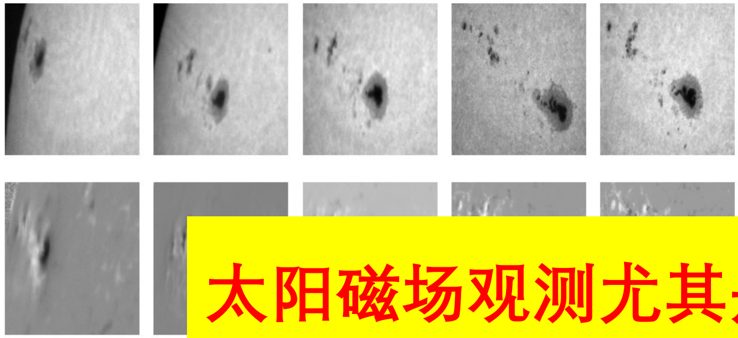


Li et al. 2015, 2016

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



√ 太阳耀

√ 太阳黑

金乌分类：

日冕物质抛

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

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

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]

第65卷 第4期 天 文 学 报 Vol. 65 No. 4
2024年7月 ACTA ASTRONOMICA SINICA Jul., 2024

宁度变化

…s://doi.org/10.3847/1538-4365/adb61b

CrossMark

… Deep-learning Model

…yuan Liu[1], and Fangyuan He[1]
[1] College of Applied Science and Technology, Beijing Union University, Beijing 102200, People's Republic of China
[2] State Key Laboratory of Solar Activity and Space Weather, Beijing 100190, People's Republic of China; yangshb@bao.ac.cn
[3] National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, People's Republic of China

The Astronomical Journal, 167:52 (7pp), 2024 February https://doi.org/10.3847/1538-3881/ad11e2

CrossMark

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

Cui Zhao[1], Shangbin Yang[2,3,4], Tingmei Wang[1], Haiyan Zhao[1], Shiyuan Liu[1], Fangyuan He[1], and Zhengkun Hu[1]
[1] College of Applied Science and Technology, Beijing Union University, Beijing 102200, People's Republic of China
[2] National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, People's Republic of China
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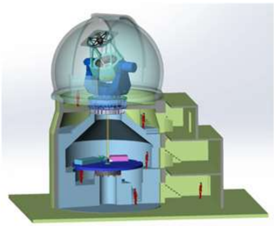
Received 2023 July 26; revised 2023 November 27; accepted 2023 December 1; published 2024 January 10

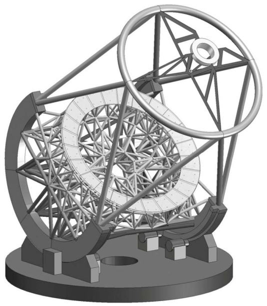
总结与展望

地基大口径

WeHost望远镜(2.5)



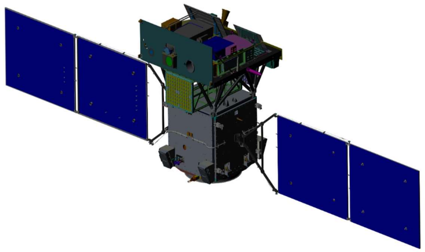
2m环，8m 口径CGST



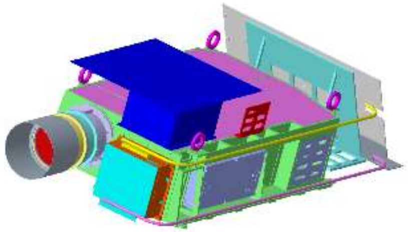
看得更清更广

空间望远镜

先进天基望远镜



全日面磁场望远镜

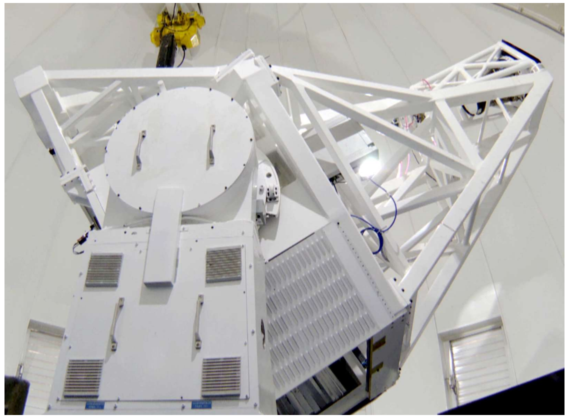


看得更稳

中红外望远镜

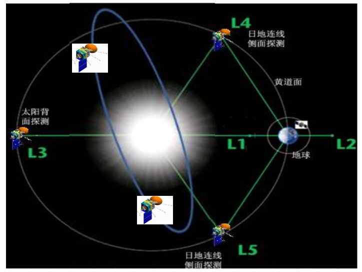
国家重大仪器专项AIMS

(青海冷湖天文观测基地)

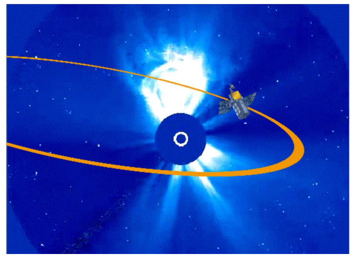


看得更准

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！

Thank you

Welcome to Beijing !!!