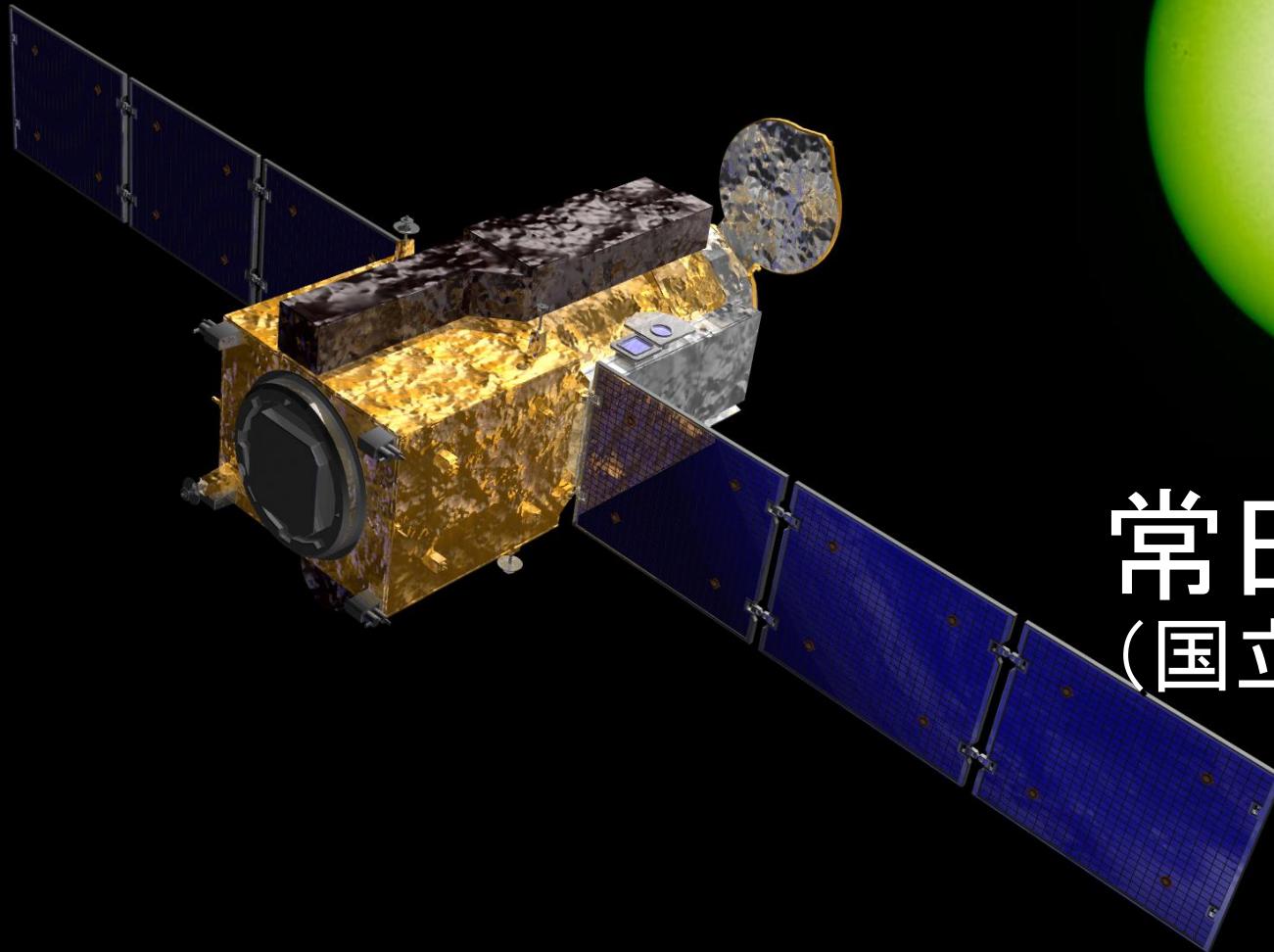


講義の内容

- 変動する太陽と太陽のダイナモ
 - 「ひので」の観測結果から
 - 太陽の短時間変動 (**1秒～1年**)
- 最近の太陽は異常か？
 - 太陽の中時間変動 (**10年～1万年**)
 - イントロダクション：変動する太陽
 - 太陽ダイナモ：標準理論とその矛盾
 - 最近の太陽活動について：最新の観測結果
 - 最近の太陽活動とダイナモ
 - 地球環境への影響？
- **46億年の太陽史**
 - The Faint Young Sun Paradox
 - 天文学的解決
 - 46億年間の太陽ダイナモ

変動する太陽と 太陽のダイナモ



第10回 森羅万象学校
「太陽の変動性と地球・惑星」
2010年2月22-24日
北海道 支笏湖

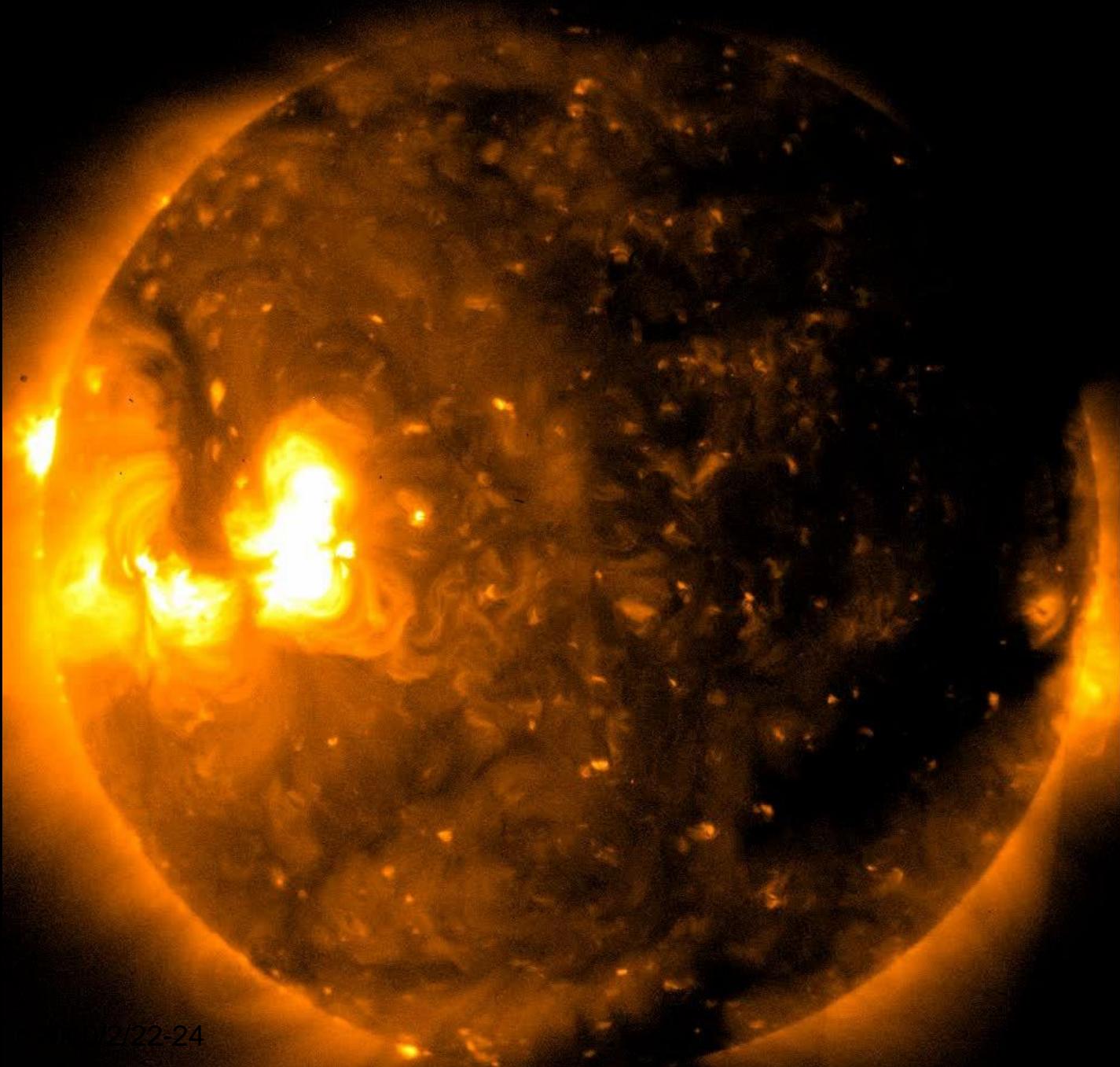


常田佐久
(国立天文台)

*A rotating solitary
star has intense
magnetic fields*

Rotation of the Sun
Convection inside the Sun





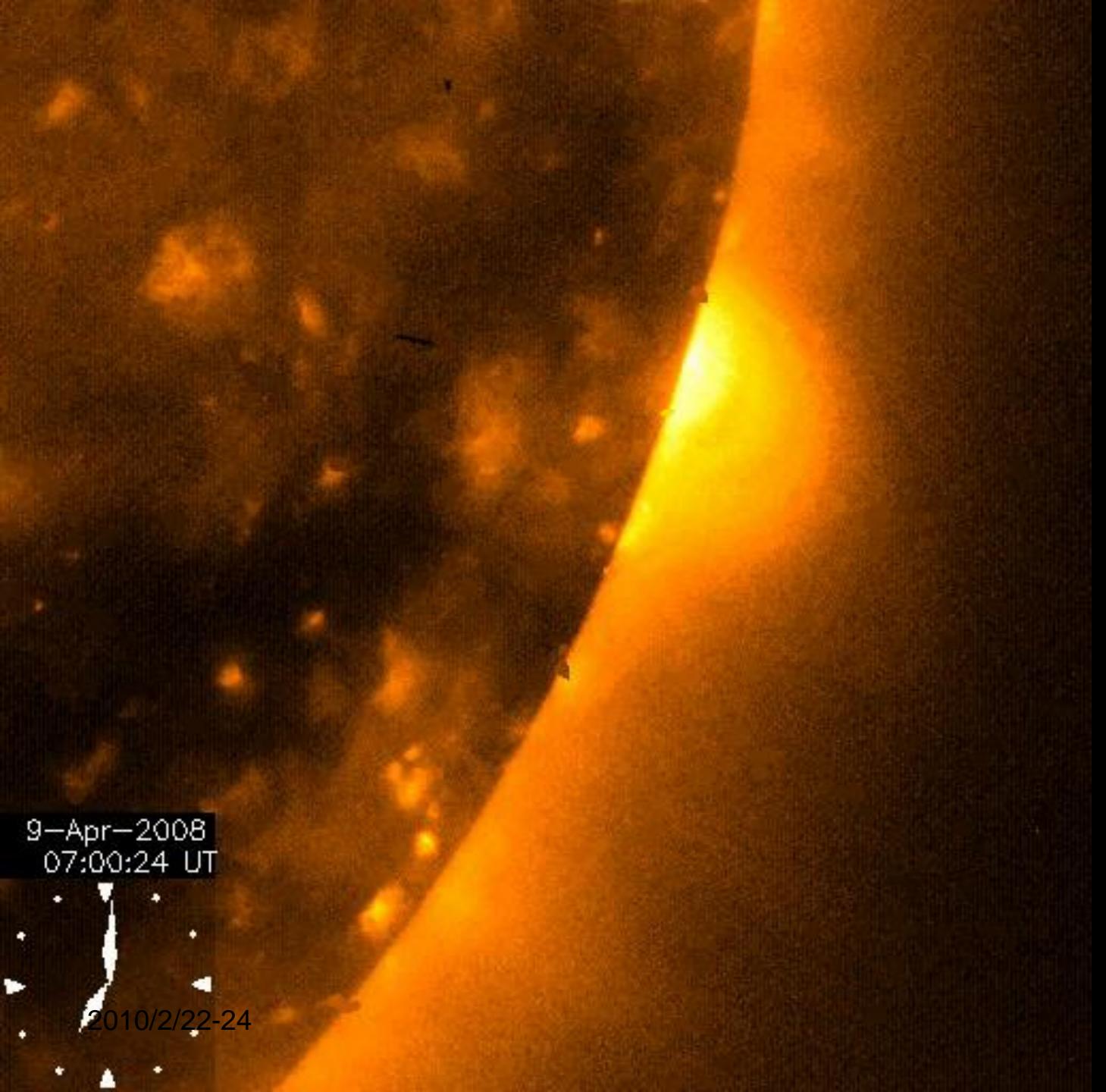
12/22-24
Hinode/XRT: 2007-01-03 16:19:03UT

*2MK Solar Corona as
observed with Hinode
2007 Oct. – 2009 Apr.*



*Gigantic solar flares due to
annihilation of magnetic field
observed with Yohkoh satellite*

2010/2/22-24



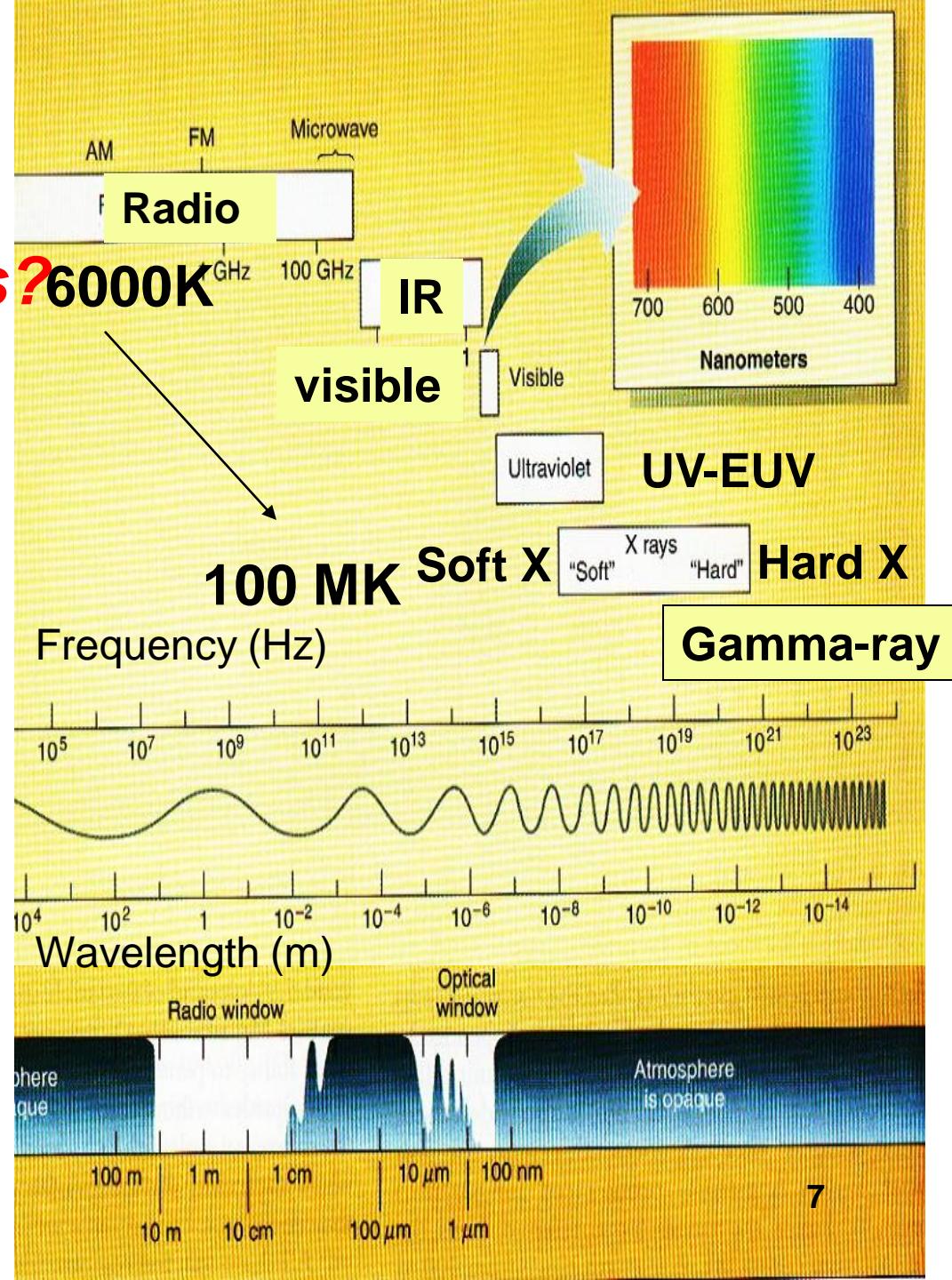
*Coronal Mass Ejection (CME)
another way to launch mass to
interplanetary space. 4.4 billion
years ago, X300 powerful CMEs
may dominate gentle solar wind.*

- **Why do we go to space in solar physics?**

- **Opaque atmosphere in UV and X-rays**
- **Severe atmospheric seeing effect even with adaptive optics**

Observations from space have been inevitable in solar astronomy since the dawn of space age!

2010/2/22-24



Importance of Solar Research from Space

- The Sun is the only astronomical object that can be resolved, and is a laboratory of astrophysical phenomena related to interplay of plasma and magnetic field. We address fundamental questions such as
 - *How is intense solar magnetic field generated and transported?*
 - *How is the magnetic energy converted to create X-ray corona, flares and eruptions?*

JAXA-NASA-UK-ESA Hinode

Solar Optical
Telescope (SOT)

High spatial resolution for
vector magnetic observations

EUV Imaging
Spectrometer (EIS)

*Hinode mission objective:
Systems approach to understand
generation, transport and ultimate
dissipation of solar magnetic fields with
3 well-coordinated advanced telescopes.*

(XRT)

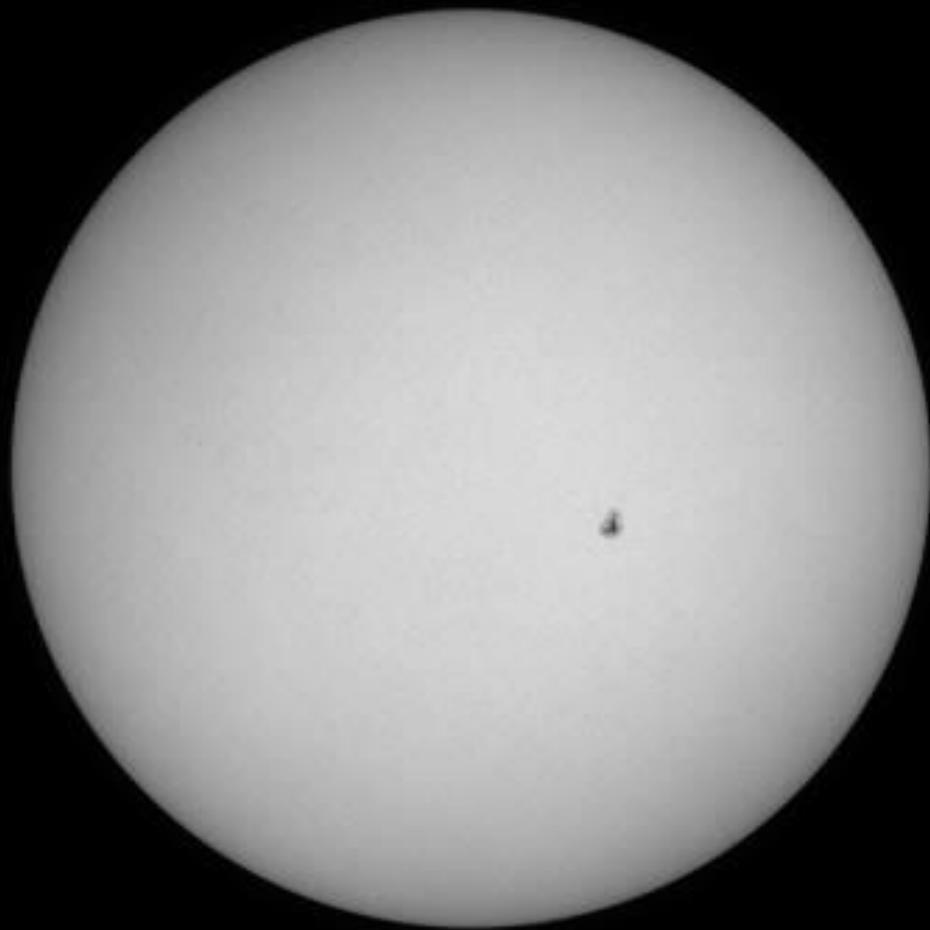
1-10MK X-ray corona

Orbit: Polar Sun Synchronous

Role of Magnetic fields in Stars and Cosmos and **Hinode**

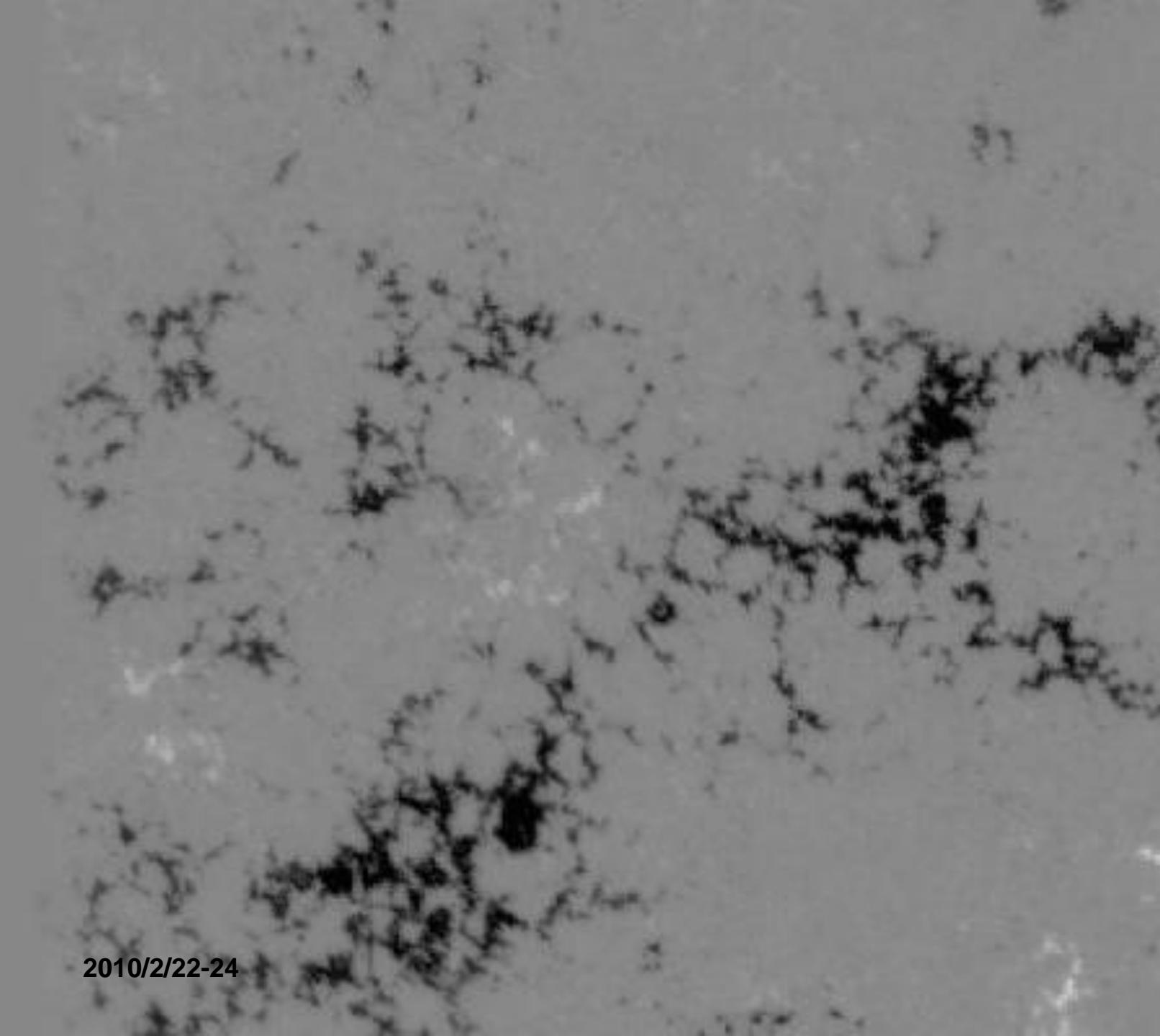
The best analogy of cosmic magnetic field is rubber band!

- Magnetic fields are created by interaction of flow and fields (**dynamo process**)
- Carry energy through **waves**
- Store energy
- Dissipate stored energy with **annihilation of anti-parallel magnetic field**
- Induce MHD instability and **eruptions**
- Suppress **cross-field transport** for mass and heat
- **Suppress convection** i.e. energy transport



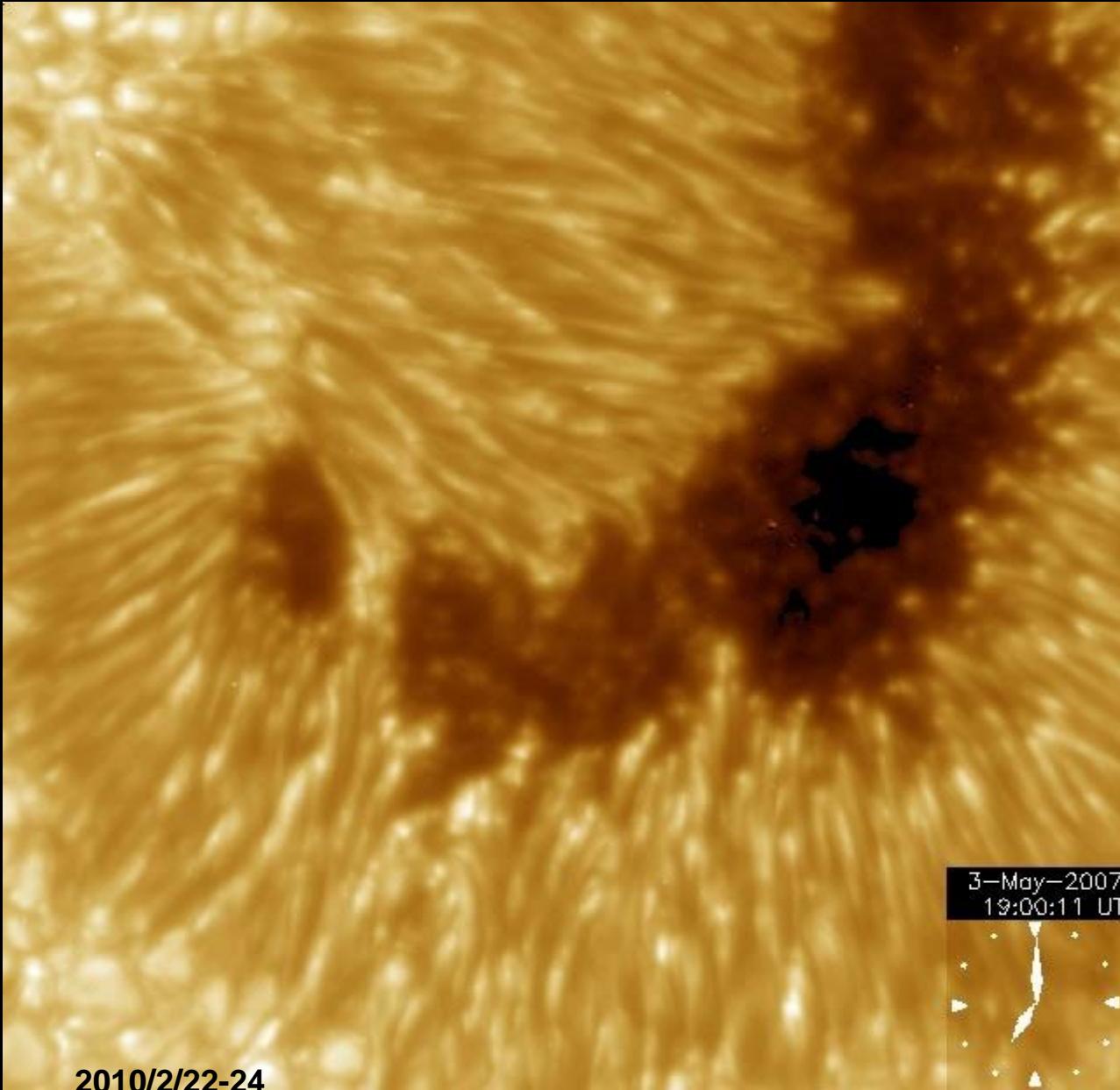
a

171,000 km



Emergence of magnetic field from inside the Sun

2010/2/22-24

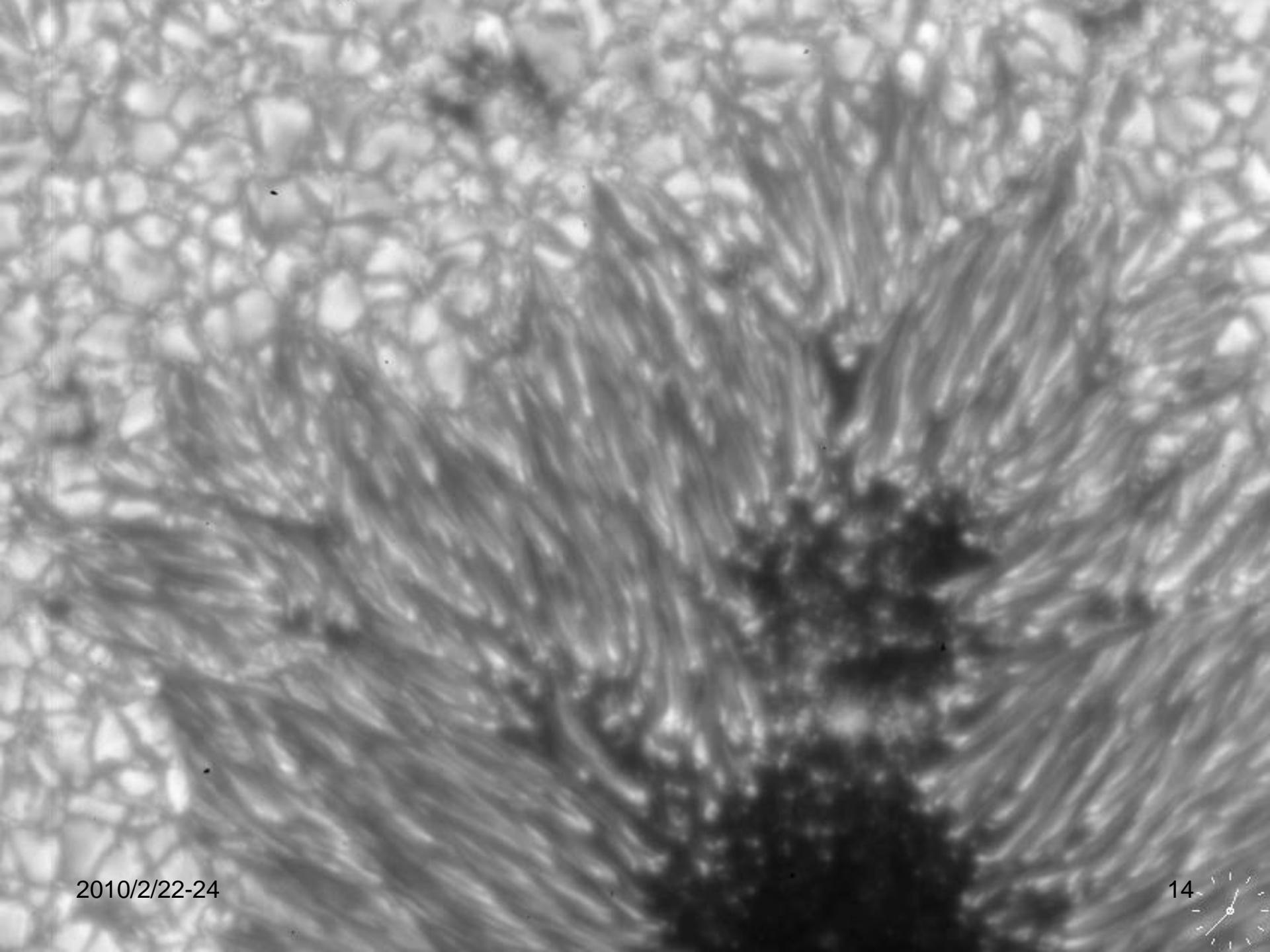


2010/2/22-24



2,000 km

*Disintegration of
sunspot due to attack
by convection motion*

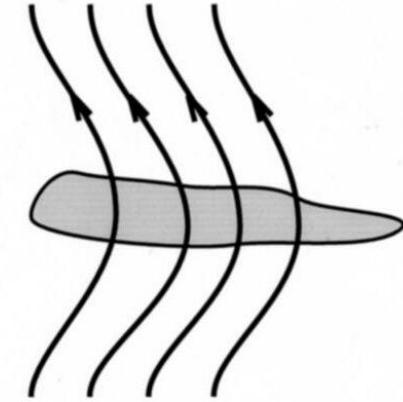
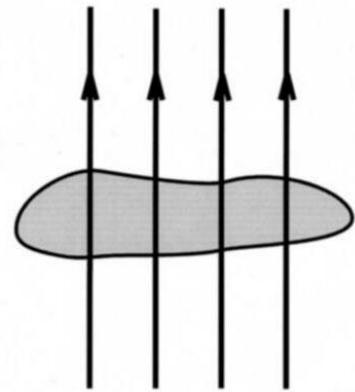


2010/2/22-24

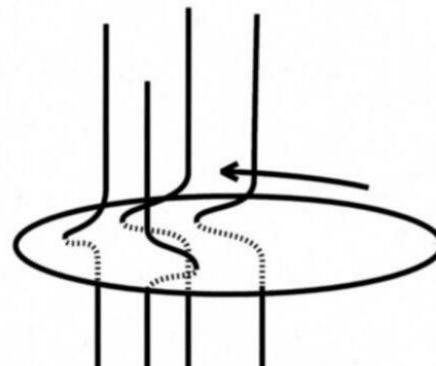
14

Magnetic fields *frozen* to plasma

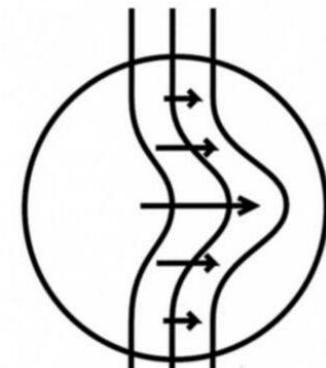
- Plasma cannot move across magnetic field.
- Magnetic fields moves with plasma and magnetic field lines are stretched (i.e. amplified).



Magnetic field



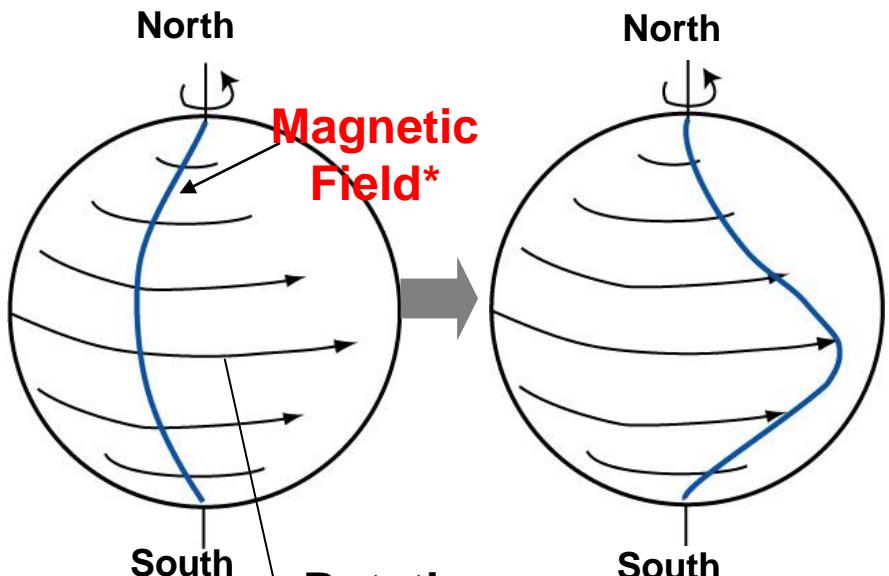
Galaxy



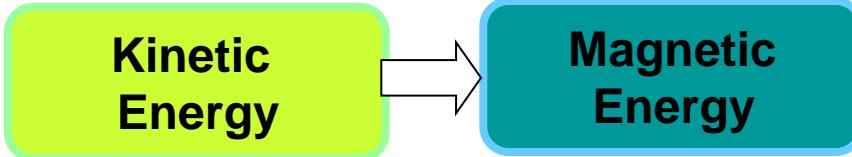
Differential rotation
of the Sun

Global dynamo generating sunspots

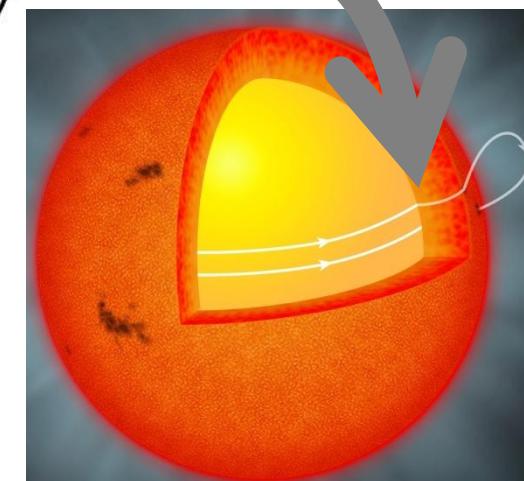
- Differential rotation stretches and amplifies magnetic field.



Rotation
velocity of
Sun



East-West directed magnetic field emerges to surface forming sunspots



* cosmic magnetic field is rubber band!

Too-strong Magnetic field in the Universe

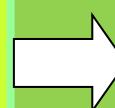
How does Universe create such strong fields?

- Early universe: 10^{-15} G?
- Galaxies and Clusters of Galaxy: 10^{-6} G
- ***Late type stars 10^3 G***
- ***Bottom of convection zone 10^5 G***
- Pulser 10^{12} G
- Magnetor 10^{15} G

Dynamo inside the Sun can amplify the magnetic fields

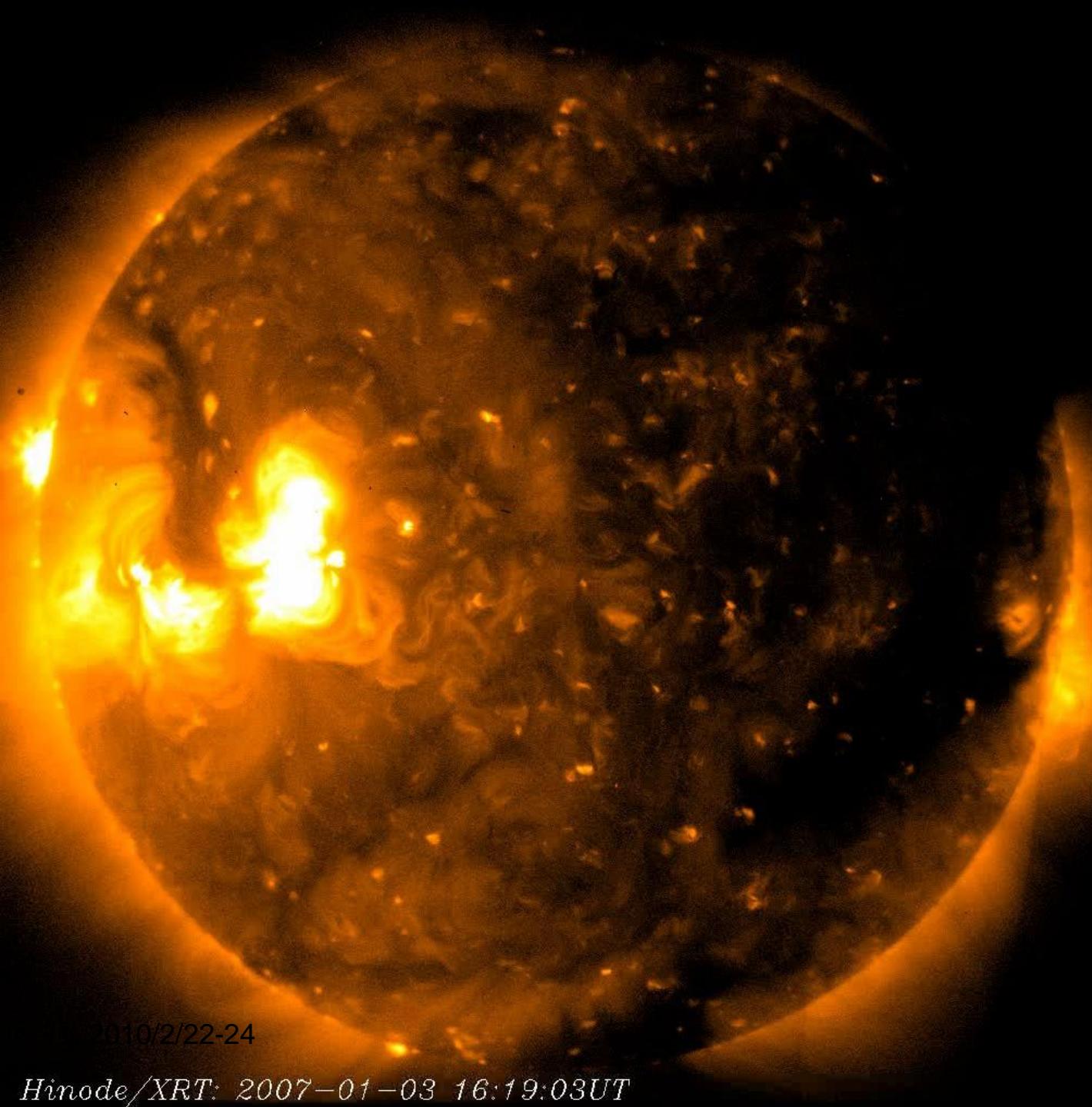
$$\frac{B_e^2}{8\pi} \approx \frac{1}{2} \rho v^2$$

Kinetic
Energy



Magnetic
Energy

And the magnetic energy is used to create the corona!

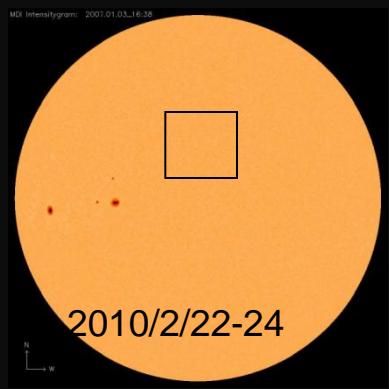


2010/2/22-24

Hinode/XRT: 2007-01-03 16:19:03UT

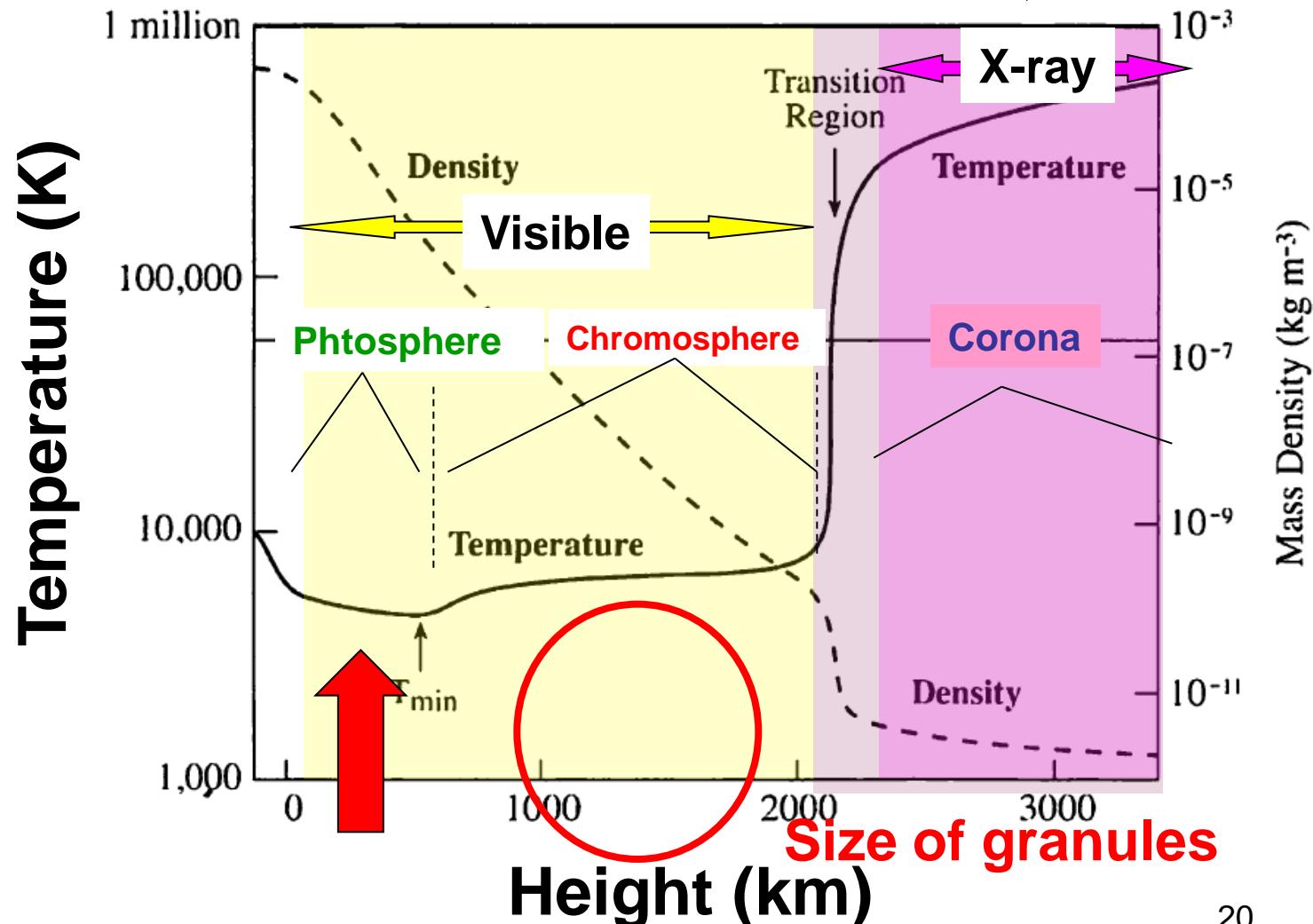
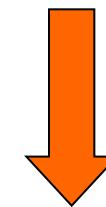
*2MK Solar Corona as
observed with Hinode
during solar minimum
2007 Oct. - 2009 Apr.*

*Zoom-up view of the
corona: Quiet Sun is
not quiet!*

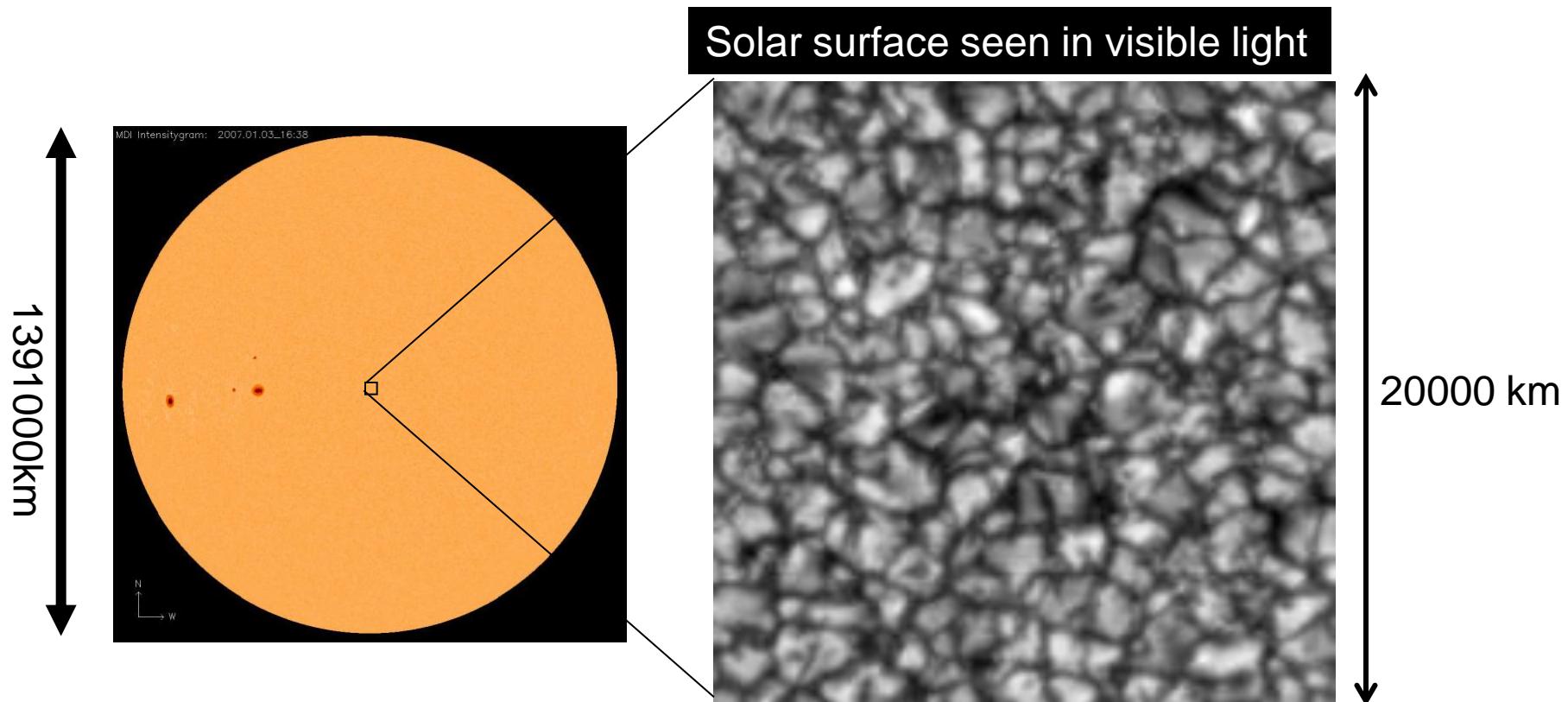


Where are we looking at?

Photosphere and corona



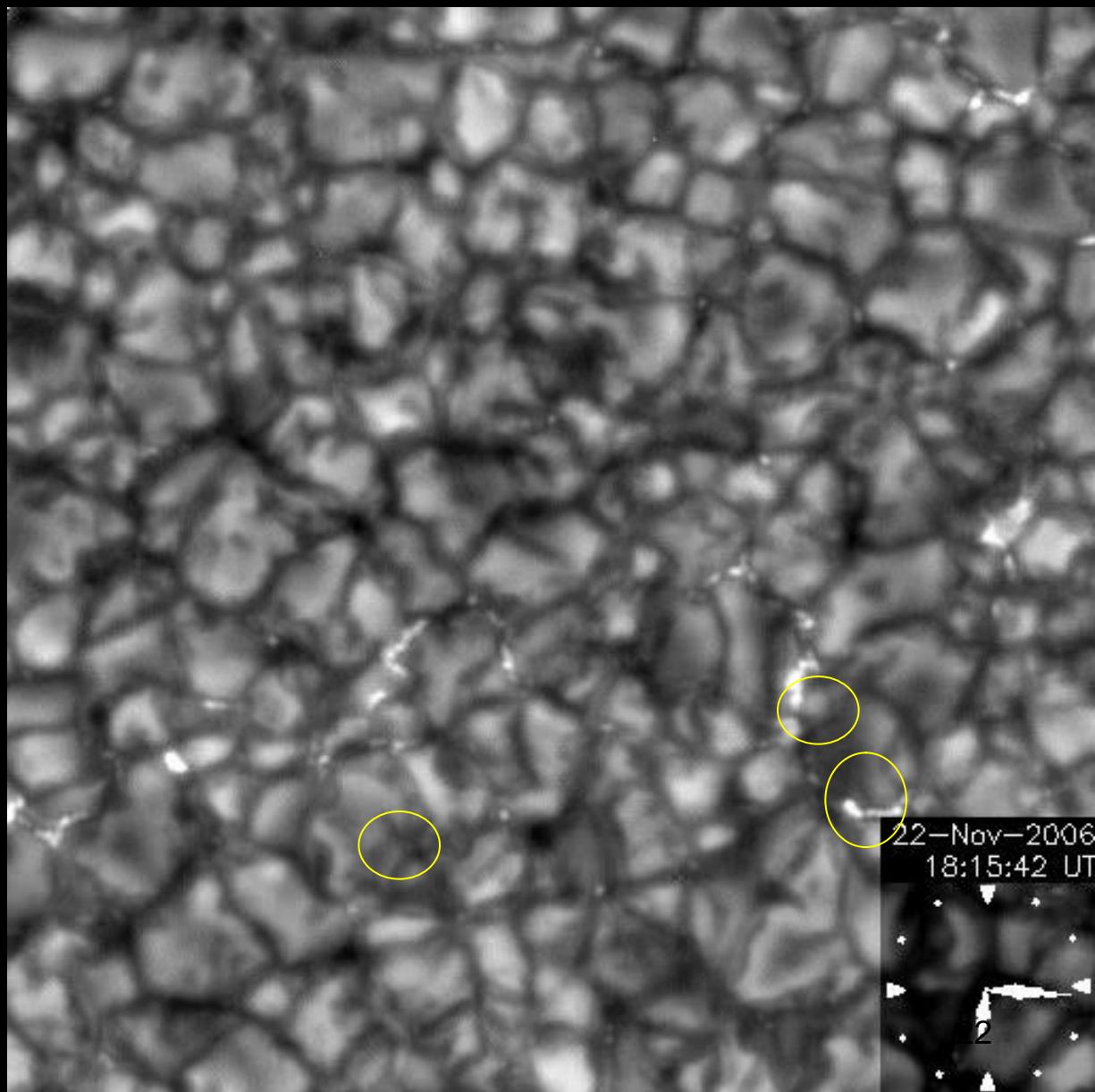
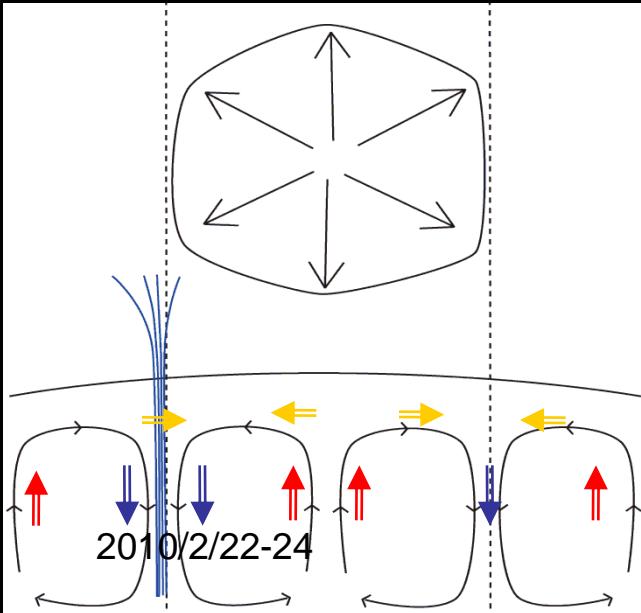
Hinode movies of Photosphere with Visible Light



2010/2/22-24

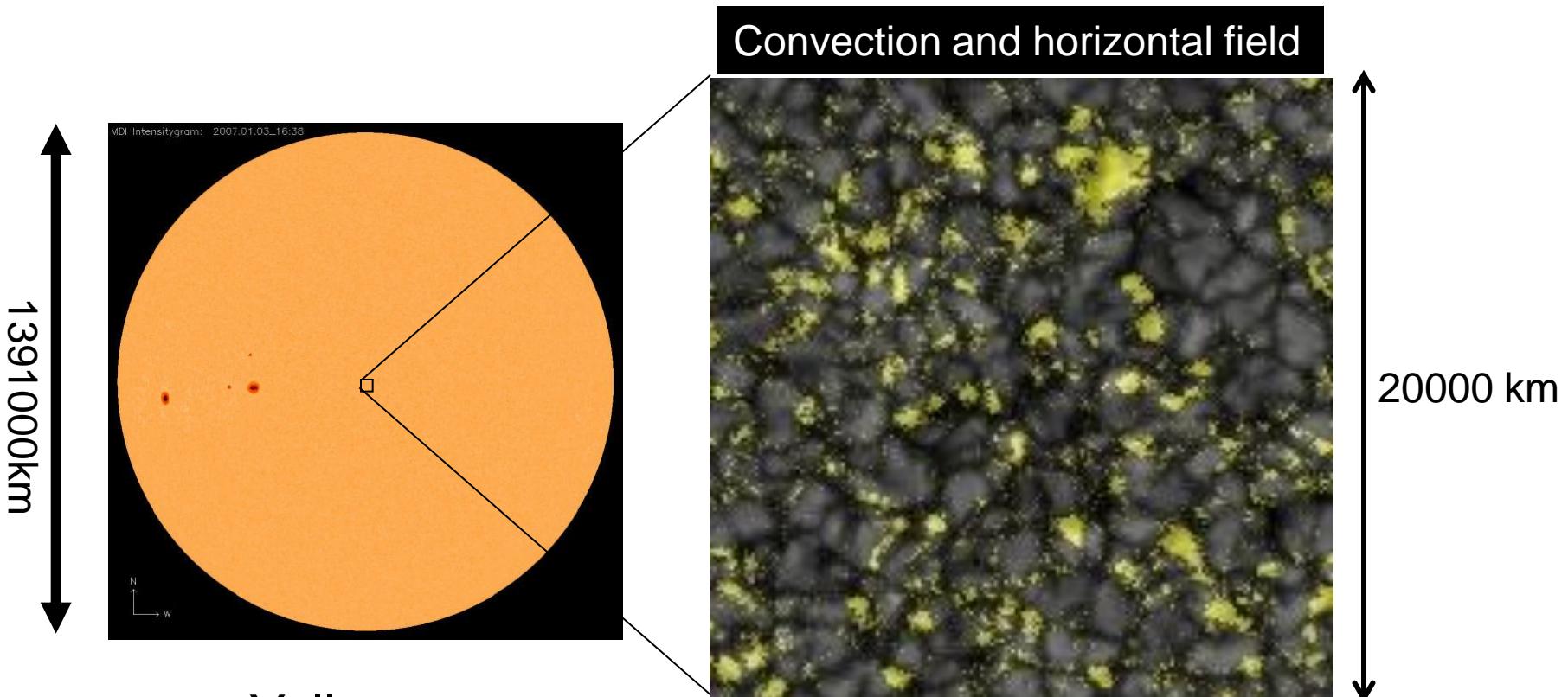
Paradigm: Magnetic Field is vertical to surface

- Strong kG magnetic fields
- Slender flux tubes seen in between convection cell



Hinode discovery of horizontal field

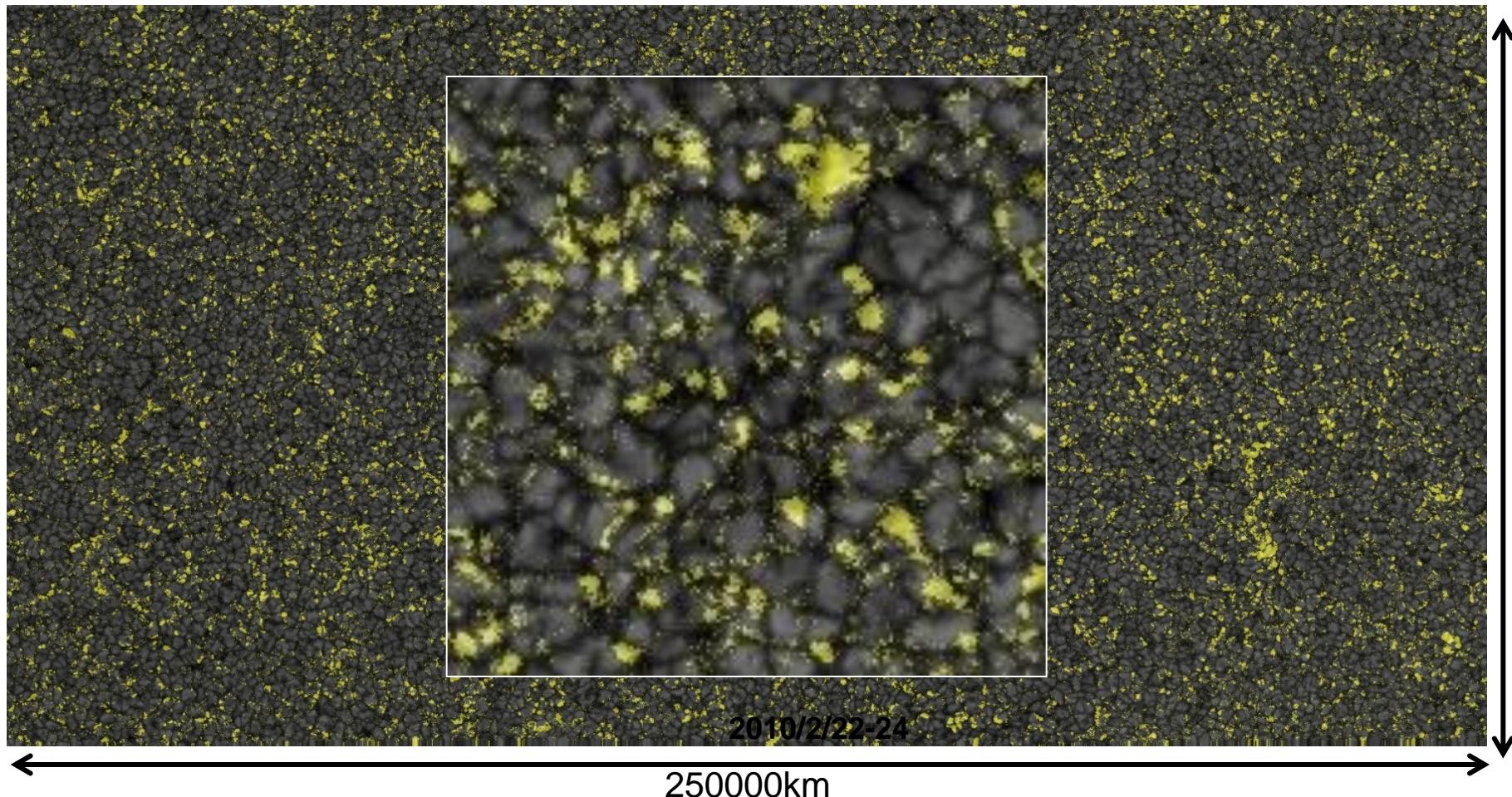
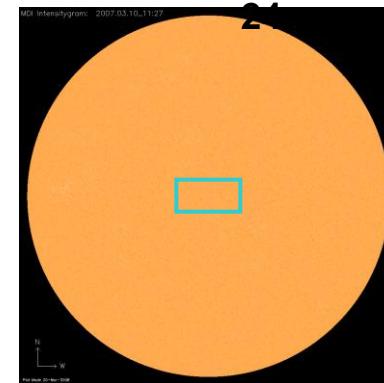
A new form of solar magnetic field



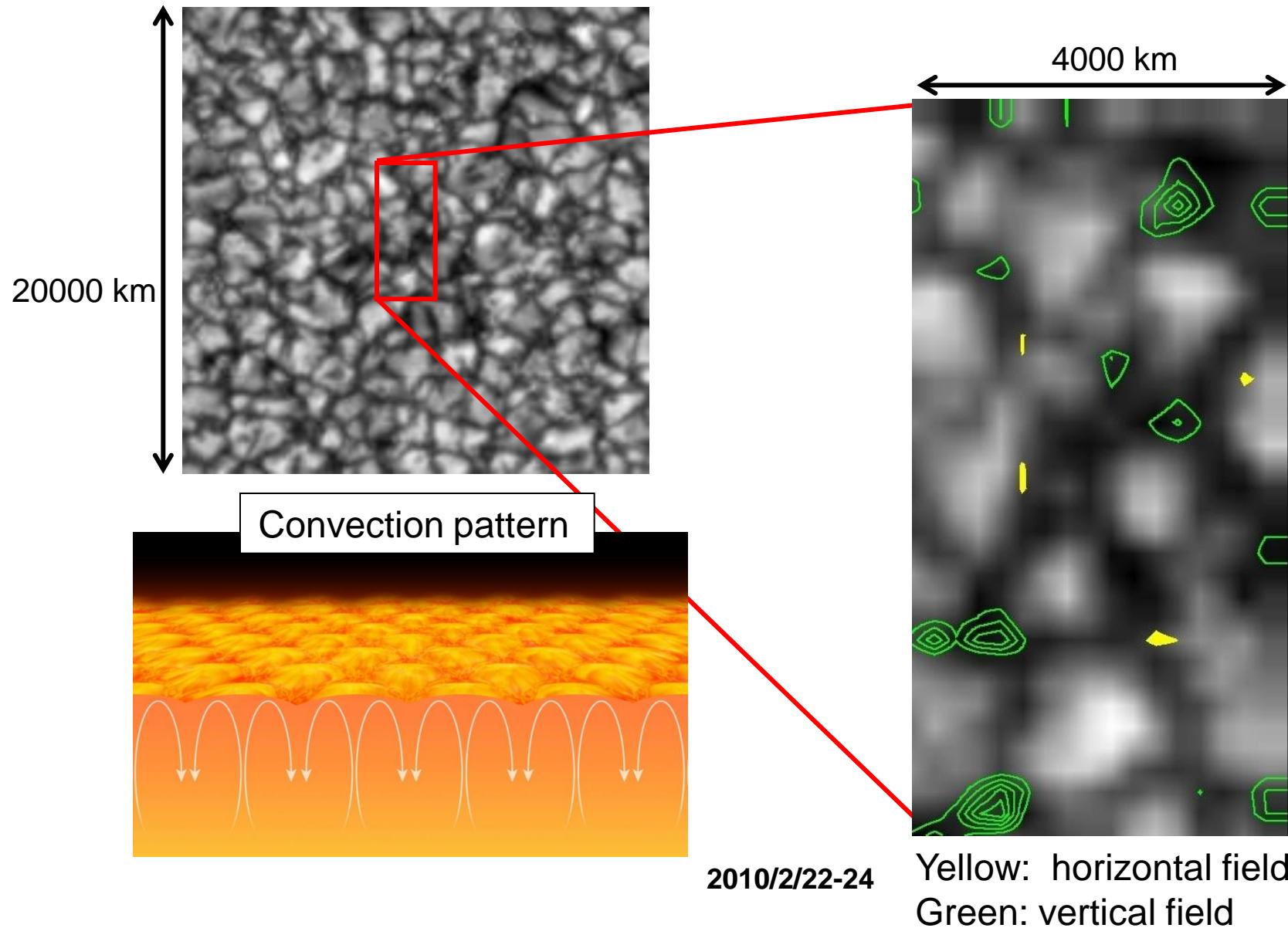
2010/2/22-24

Ubiquitous horizontal field

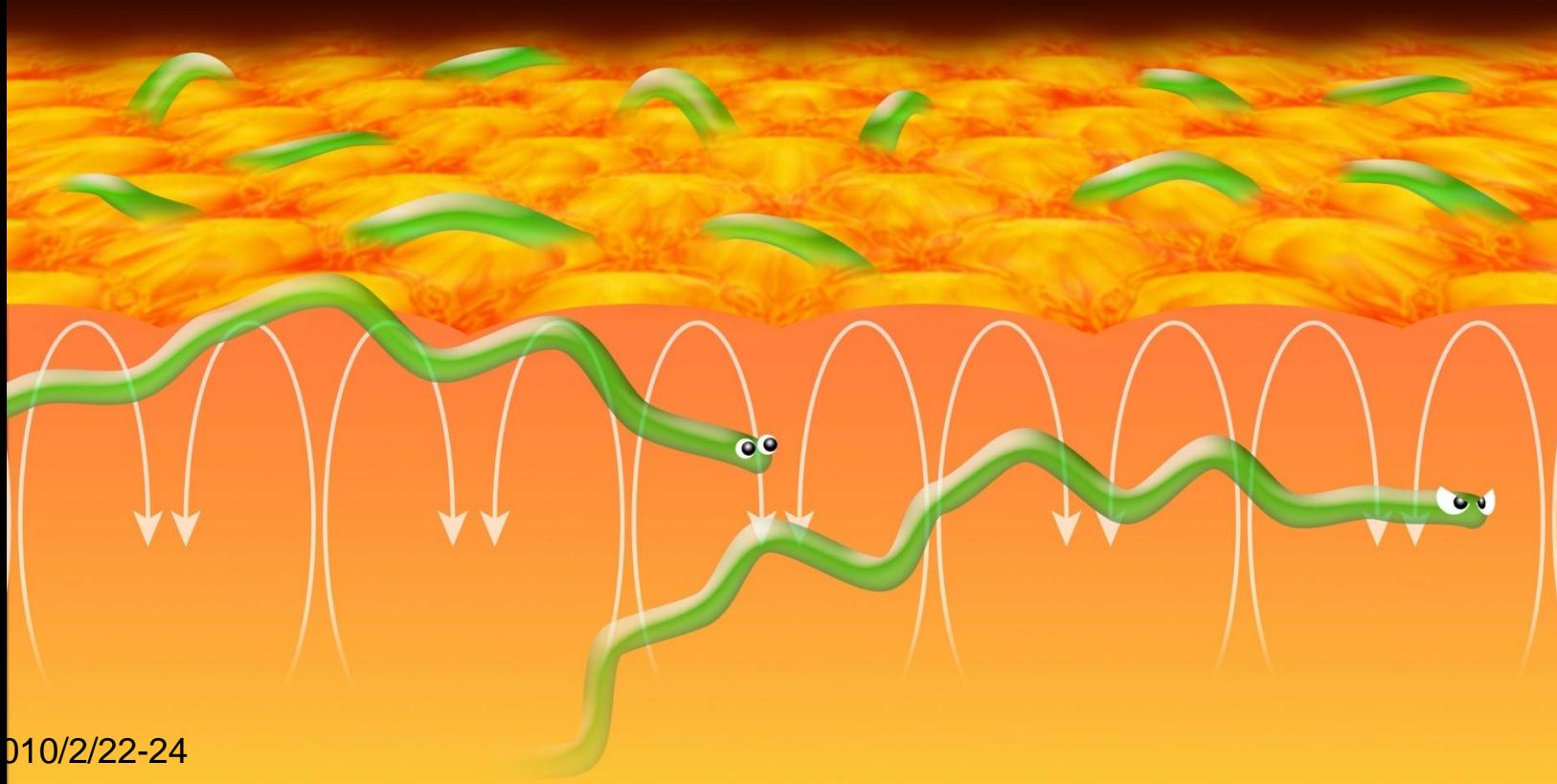
Wherever convection, horizontal fields exist



Hinode movies of *horizontal*²⁵ field



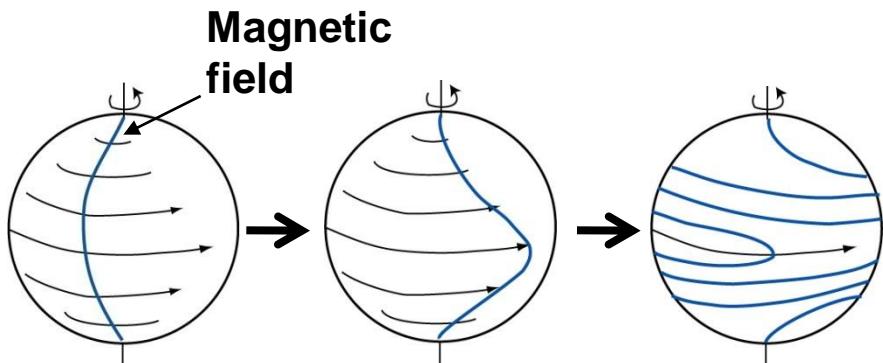
New magnetic creature in the Sun has energy much larger than sunspots and vertical fields



Discovery of New Dynamo Mechanism with Hinode²⁷

Sunspot

- Differential rotation of Sun amplifies magnetic field

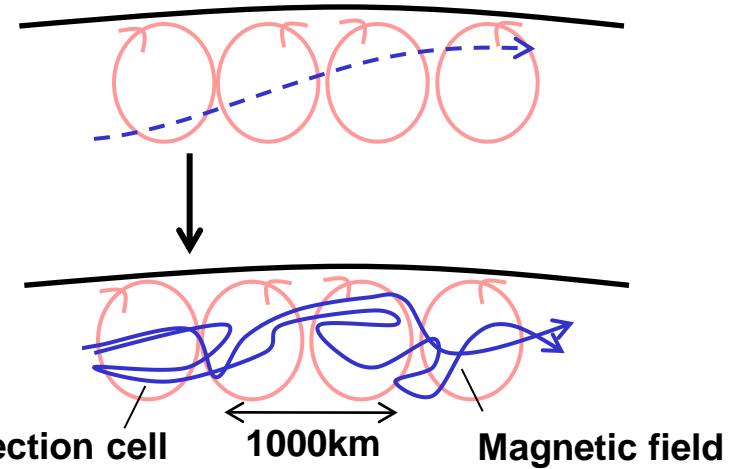


Rotation Energy

Magnetic Energy

Horizontal fields

- Convection motion of plasma amplifies magnetic field



Convection Energy

Magnetic Energy

Known mechanism

2010/2/22-24

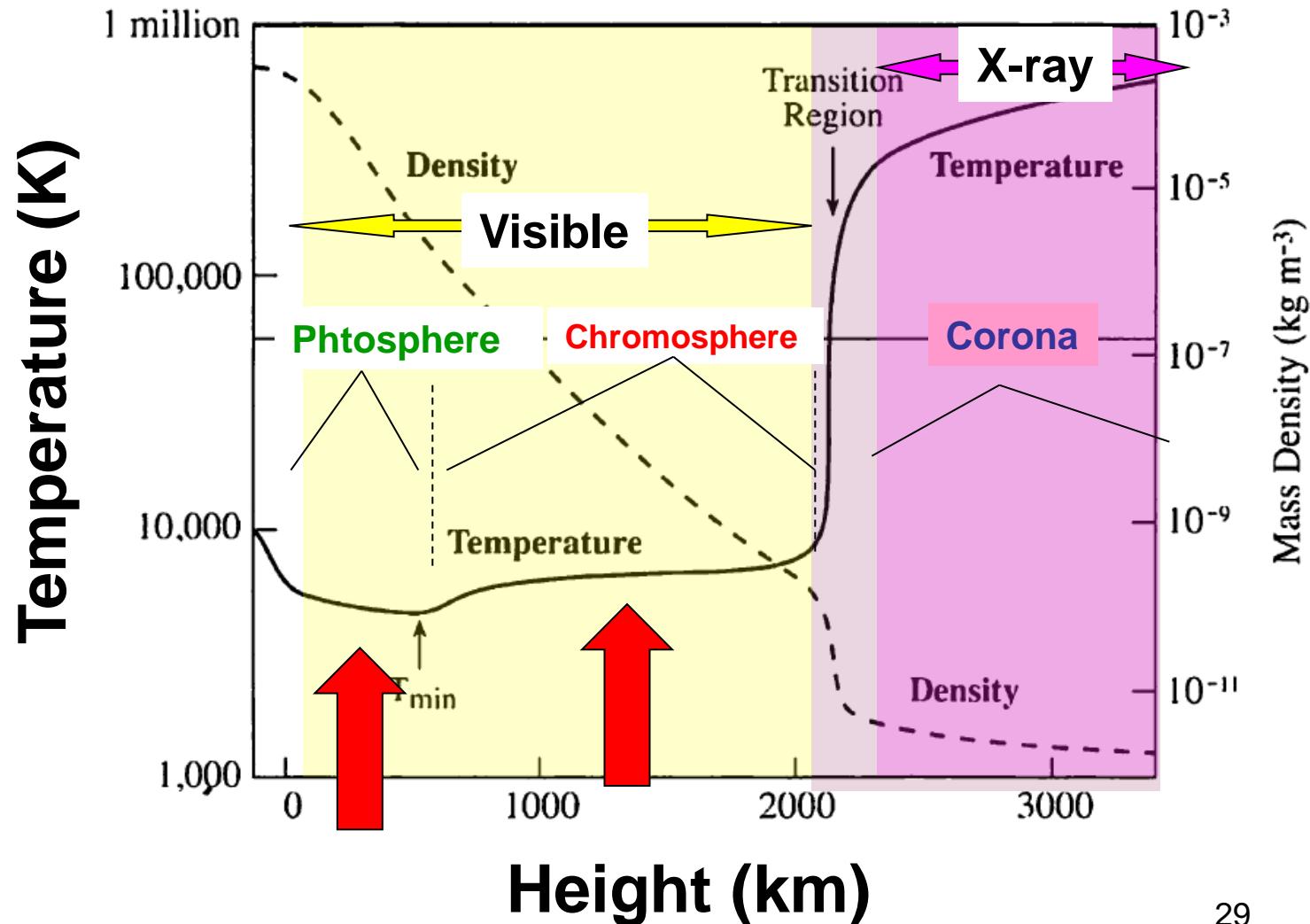
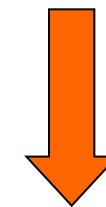
Newly discovered

初期太陽の活動性を²⁸ 担っているのは？

- ・ グローバルダイナモの作る黒点と活動領域か？
 - ・ 乱流局所ダイナモの作る水平磁場か？
- は自明でない。

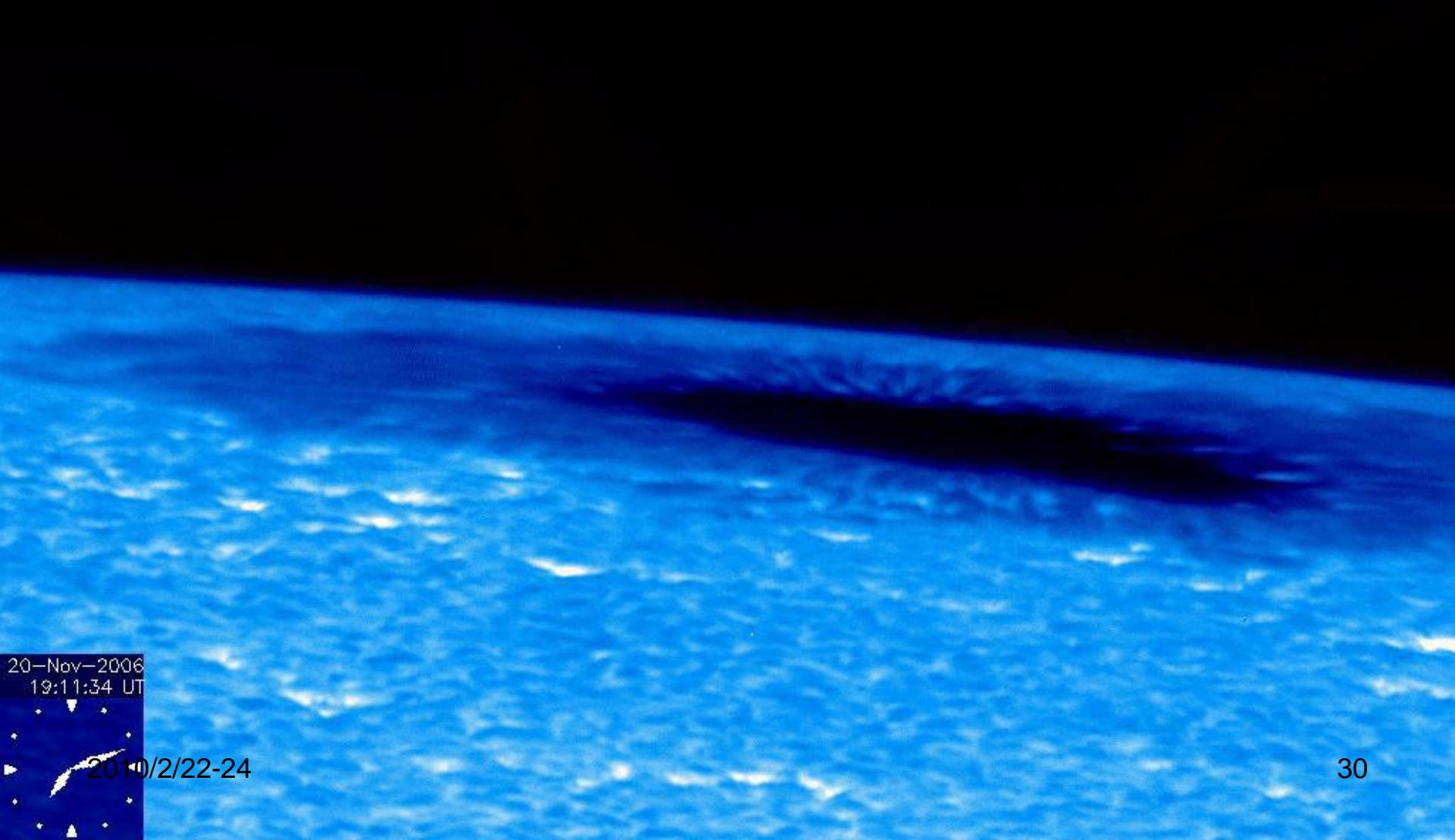
Where are we looking at?

Photosphere and corona



Chromosphere more dynamic than expected!

Chromospheric jets and fountain
driven by magnetic force



20-Nov-2006
19:11:34 UT

2010/2/22-24

What is going on in polar region ?

Source of fast solar wind

*Location of global poloidal fields
sink of meridional flow*



**High speed solar wind
observed with Ulysses
satellite**

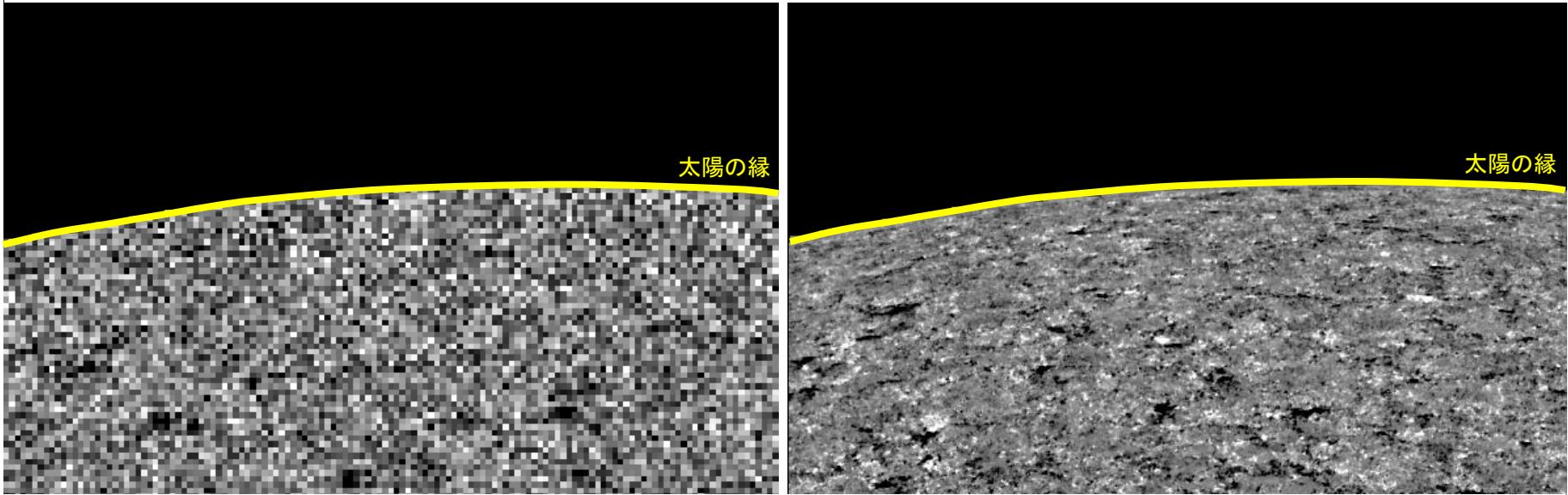
**Unexpected high coronal
activity in polar region
Hinode X-ray Telescope**



「ひので」と従来の観測装置による 北極域観測画像の比較

2007年9月7日 太陽の北極付近の磁場分布画像

白:N極 黒:S極



SOHO衛星 MDI
空間分解能 2秒角

「ひので」衛星 可視光・磁場望遠鏡
空間分解能 0.2秒角

「ひので」衛星搭載の可視光・磁場望遠鏡の
空間分解能がなければ、極域の構造は分解できない。

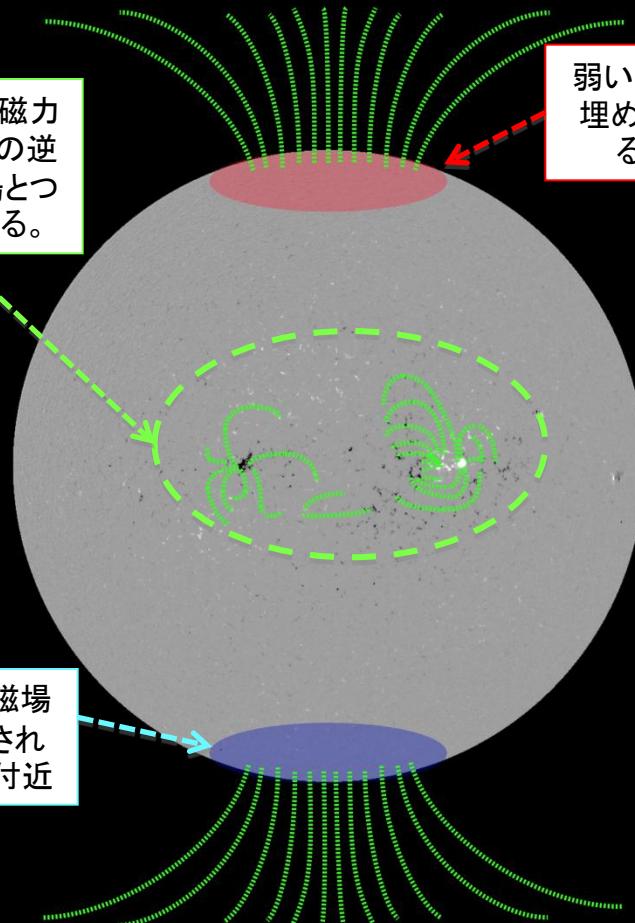
今回の発見以前の太陽磁場の描像とコロナ

(緑色の破線は、磁力線を示している。)

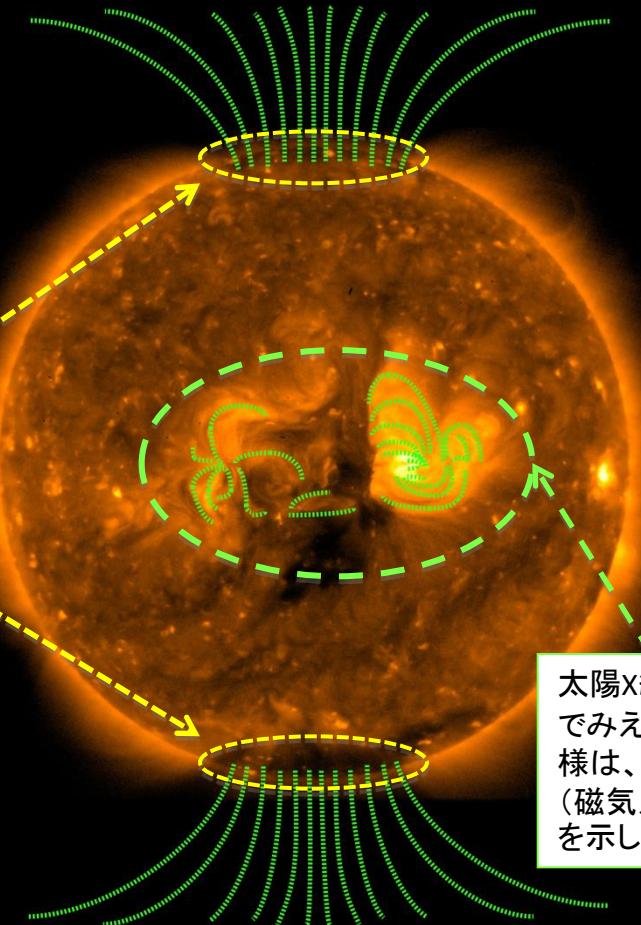
極域からの磁力線は、宇宙空間へ向かう。

黒点からの磁力線は、周囲の逆極性の磁場とつながっている。

弱いS極の磁場で埋め尽くされている北極付近



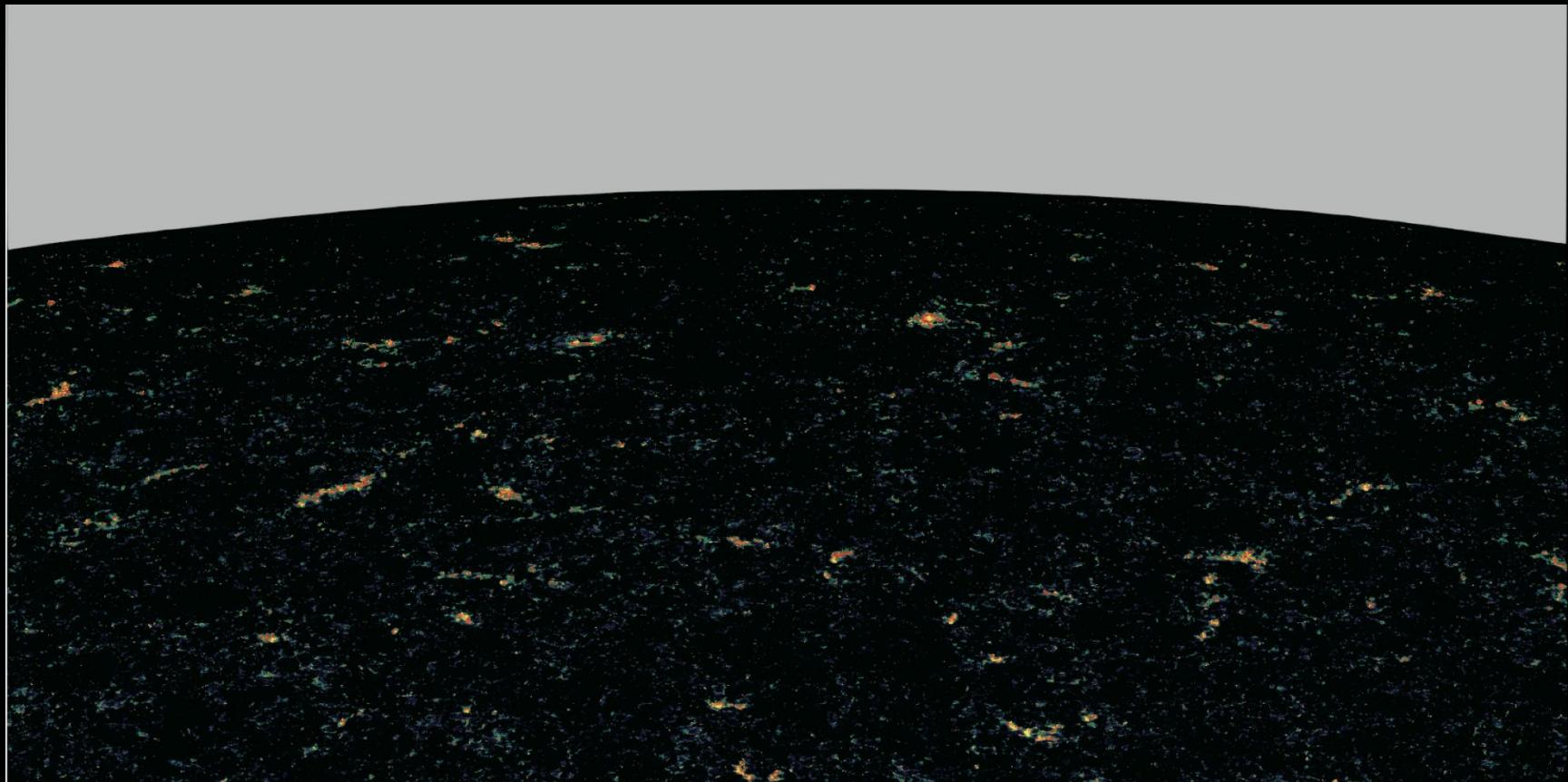
宇宙空間へ向かっている磁力線は、X線で暗い。



2010/2/22-24 太陽表面での磁場分布

(白:N極, 黒:S極)

「ひので」可視・光磁場望遠鏡で得られた 太陽の南極付近の磁場分布画像

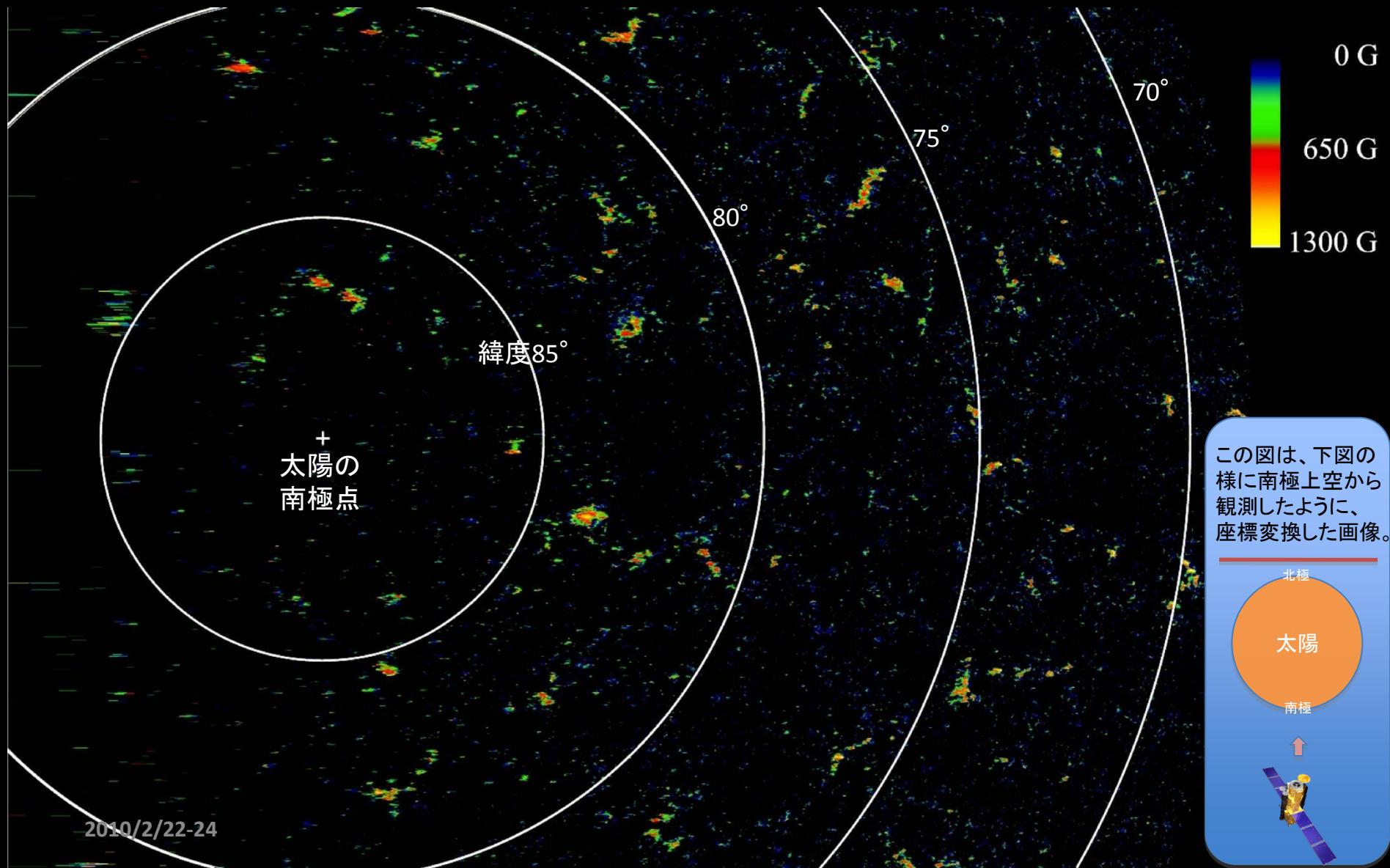


2007年9月25日の太陽南極の磁場強度分布画像

- 色が磁場の強度(黄/赤:磁場強い, 青/緑:磁場弱い)を示しており、強い斑点状の磁場が極域に点在している事がわかる。

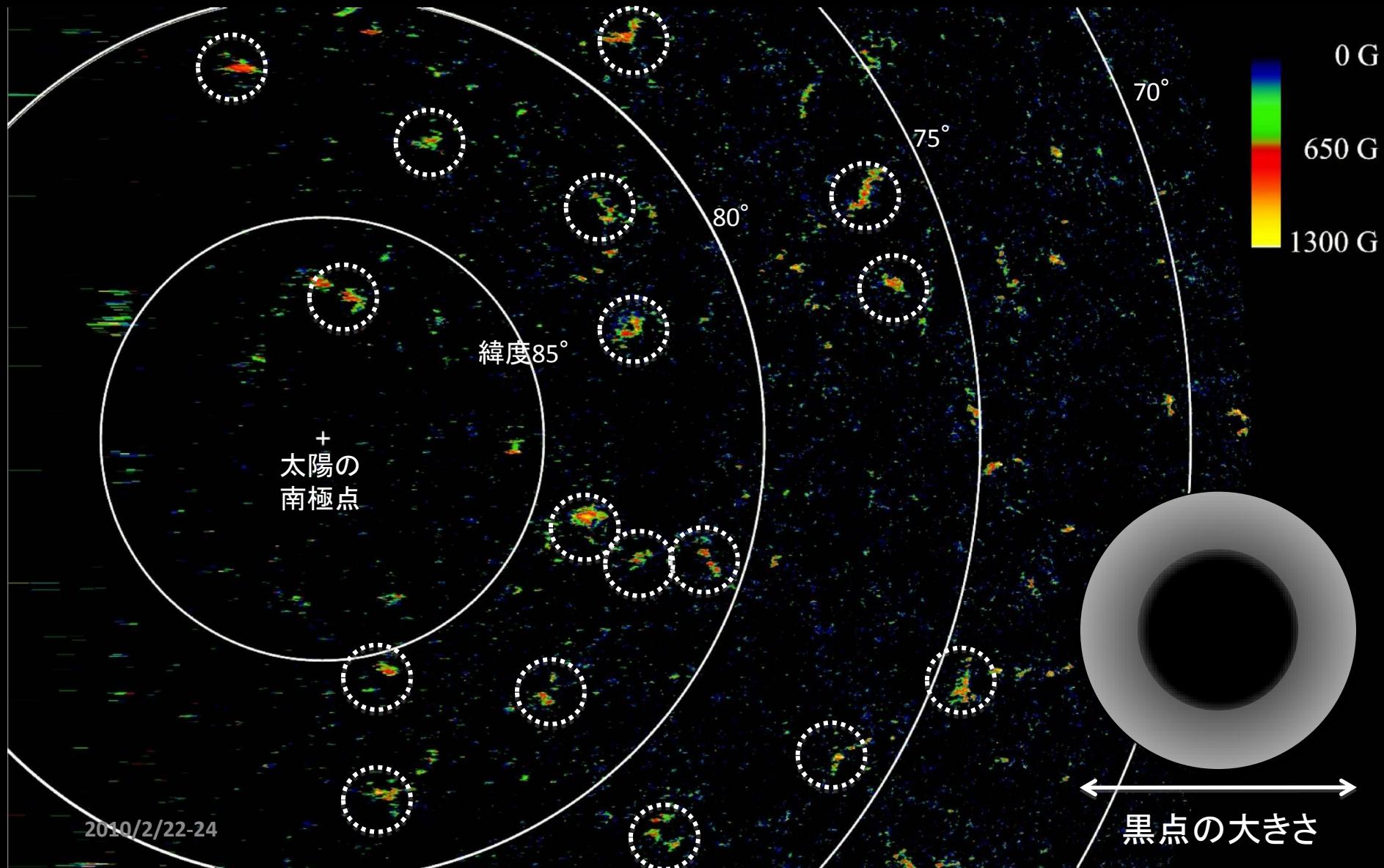
2010/2/22-24

南極上空から見た極域磁場



点在する極付近の強磁場斑点

(白い破線の円が、強磁場斑点を示している。)



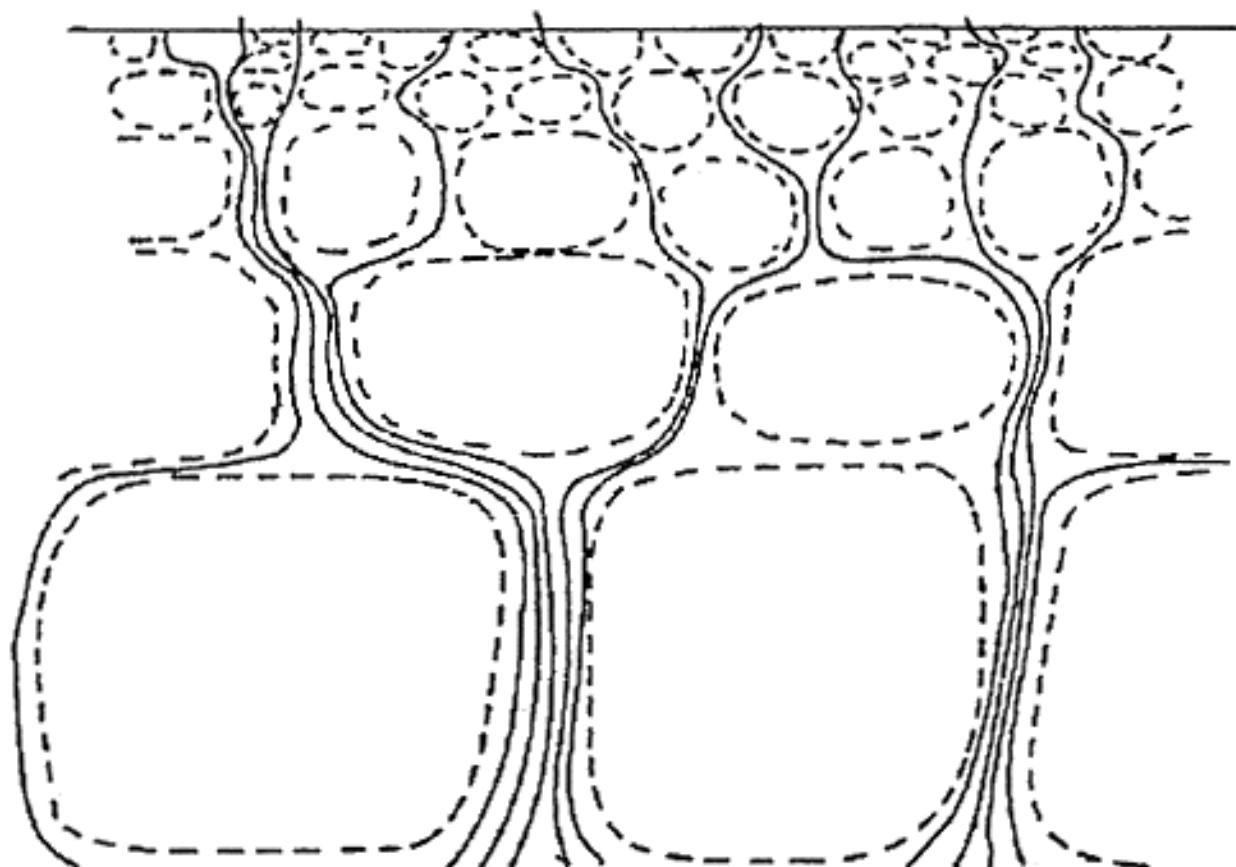
強磁場斑点の拡大図

黒点の様に丸くなく、
いびつな形をしている

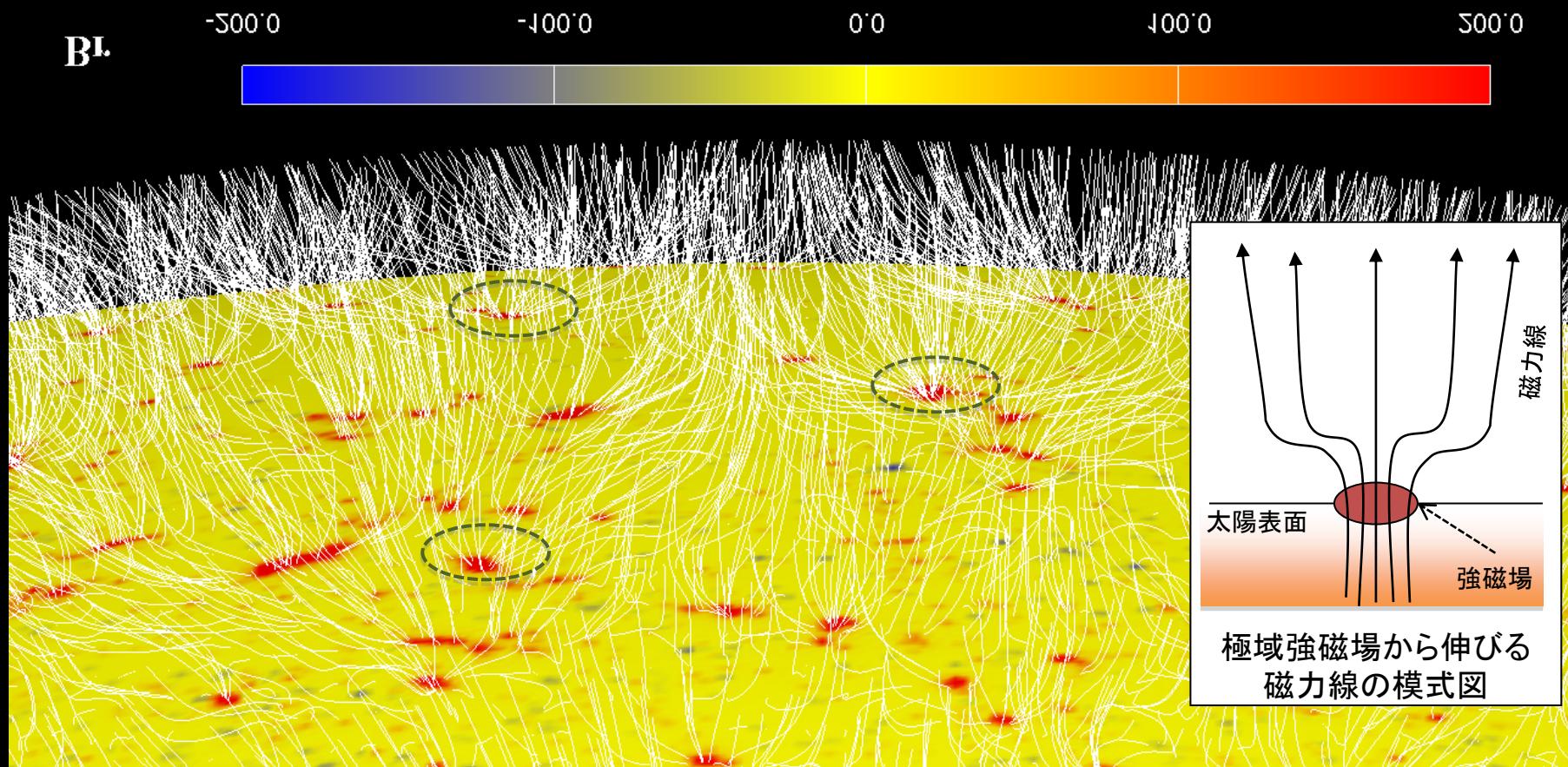
極域の斑点強磁場と黒点の特徴

	極域の強磁場斑点	黒点(活動領域)
発生領域	北極および南極付近	中緯度帯(緯度40° 以下)
磁場強度	1000ガウス程度	1000ガウス以上
大きさ	約4千km 黒点の10分の1以下	4万～6万km以上
磁場の極性	北極と南極によって極性が異なるが、同じ極域では、一方の極性しか現れない。	多くの場合、N極とS極の両方が一緒に現れる。
寿命	約10時間	数日～数ヶ月

磁場はフラックスチューブ



強磁場斑点から伸びるラッパ状の磁力線

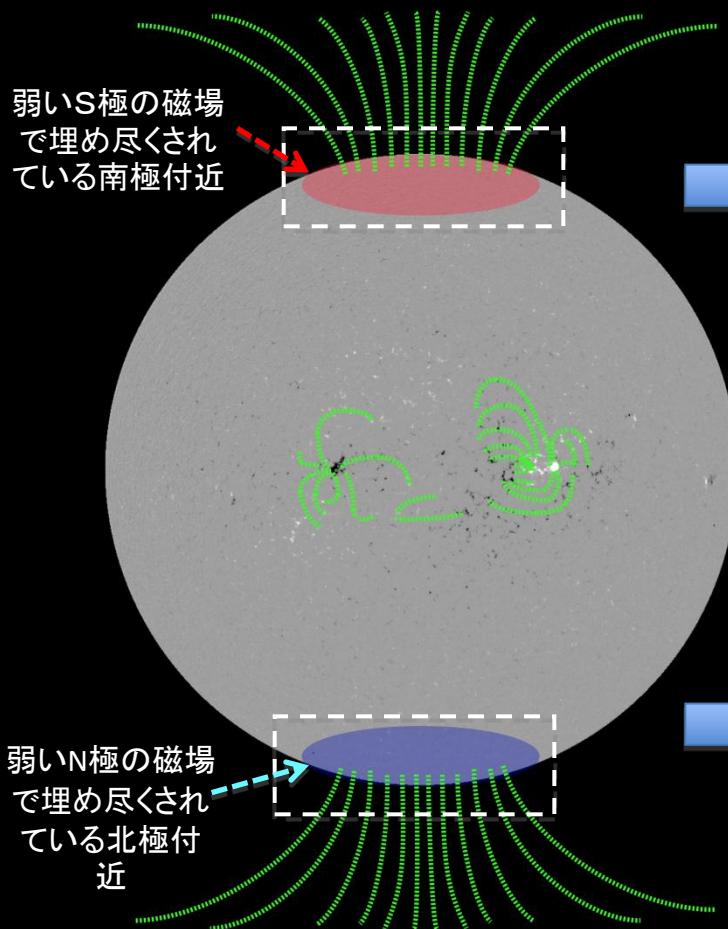


(色は、太陽表面の磁場強度を示し、白い線は磁力線を示している。緑の円は、一部のラッパ構造を示している)

- 強磁場斑点から伸びる磁力線は、ラッパの様に高度と共に広がっている。

今回の発見による太陽磁場像の変化

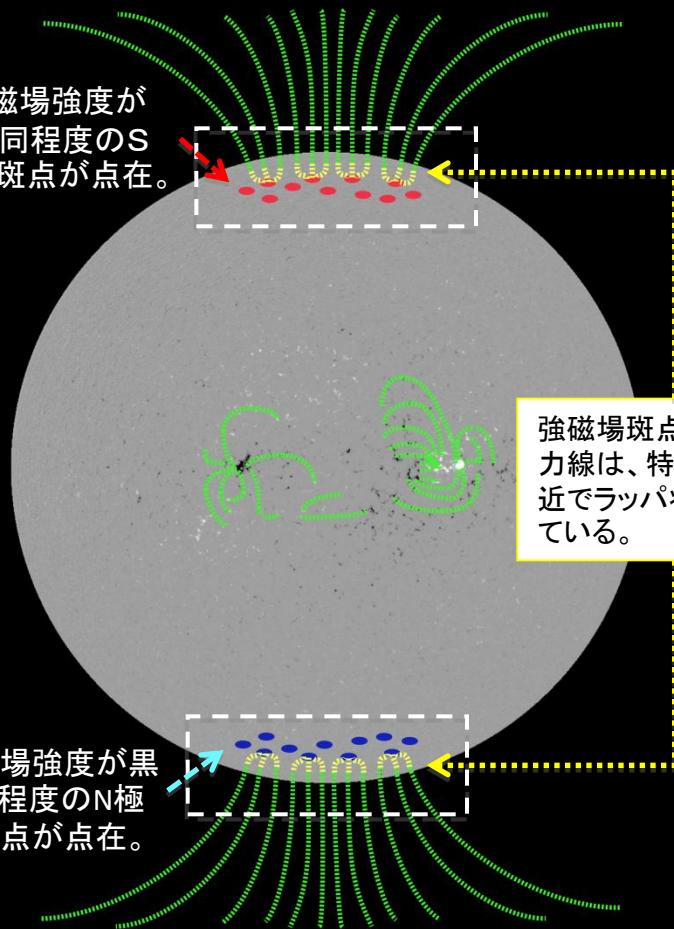
今回の発見以前



新たな太陽磁場の描像

今回の発見
による変化

小さく磁場強度が
黒点と同程度のS
極磁場斑点が点在。



太陽磁場の増幅に対する極域強磁場の意義

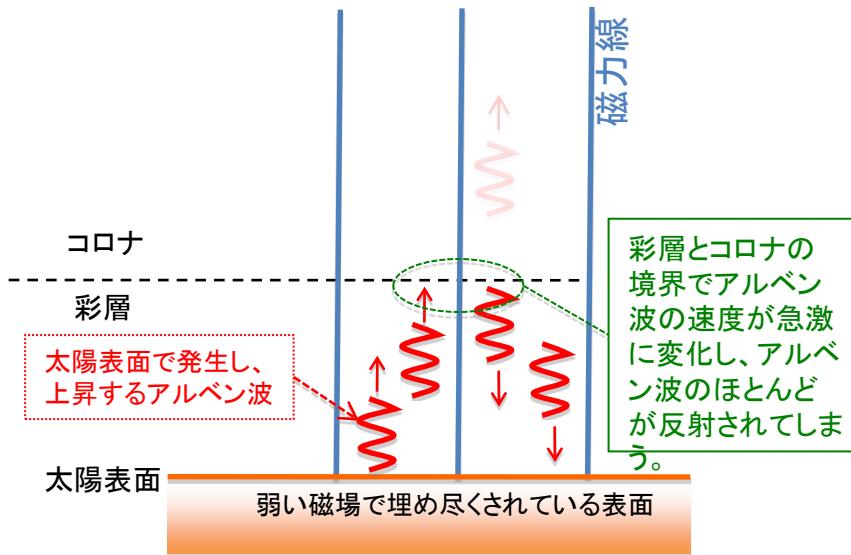
- ・「ひので」の観測以前
極域で観測される弱い磁場では、太陽内部で増幅されても、黒点を作る程度の磁場強度まで達しない。
- ・「ひので」による発見からの示唆
極域強磁場が次のサイクルの黒点を作る種磁場であれば、太陽内部で増幅されて、黒点が作れる程度まで磁場が増幅される。

今回の発見は、現在考えられている太陽内部で磁場増幅するメカニズムが成り立つ可能性を示している。

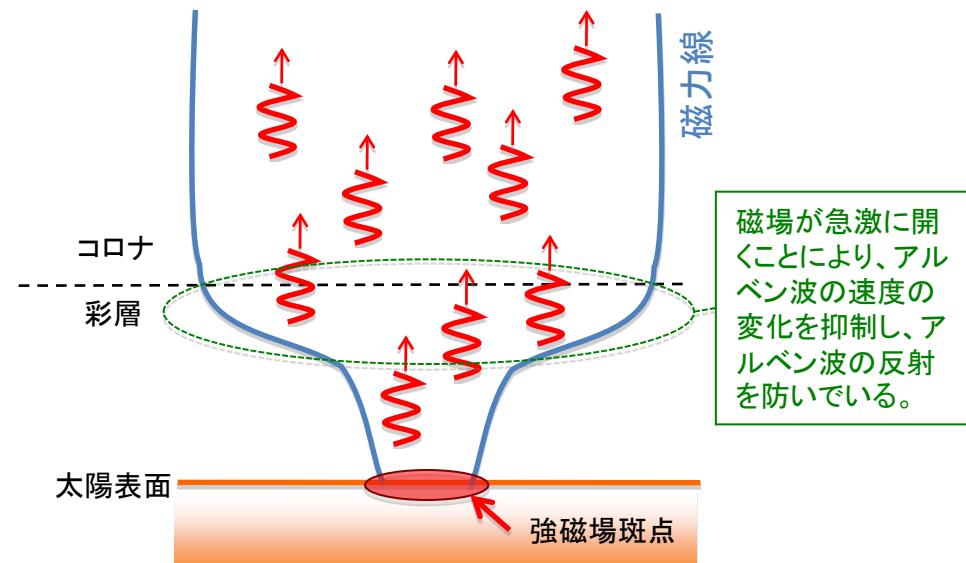
表面からコロナへアルベン波を通す強磁場斑点

- 高速太陽風は、アルベン波によって加速する説が有力であるが、太陽表面で発生したアルベン波がコロナに伝わらないという問題を抱えていた。

これまでの描像



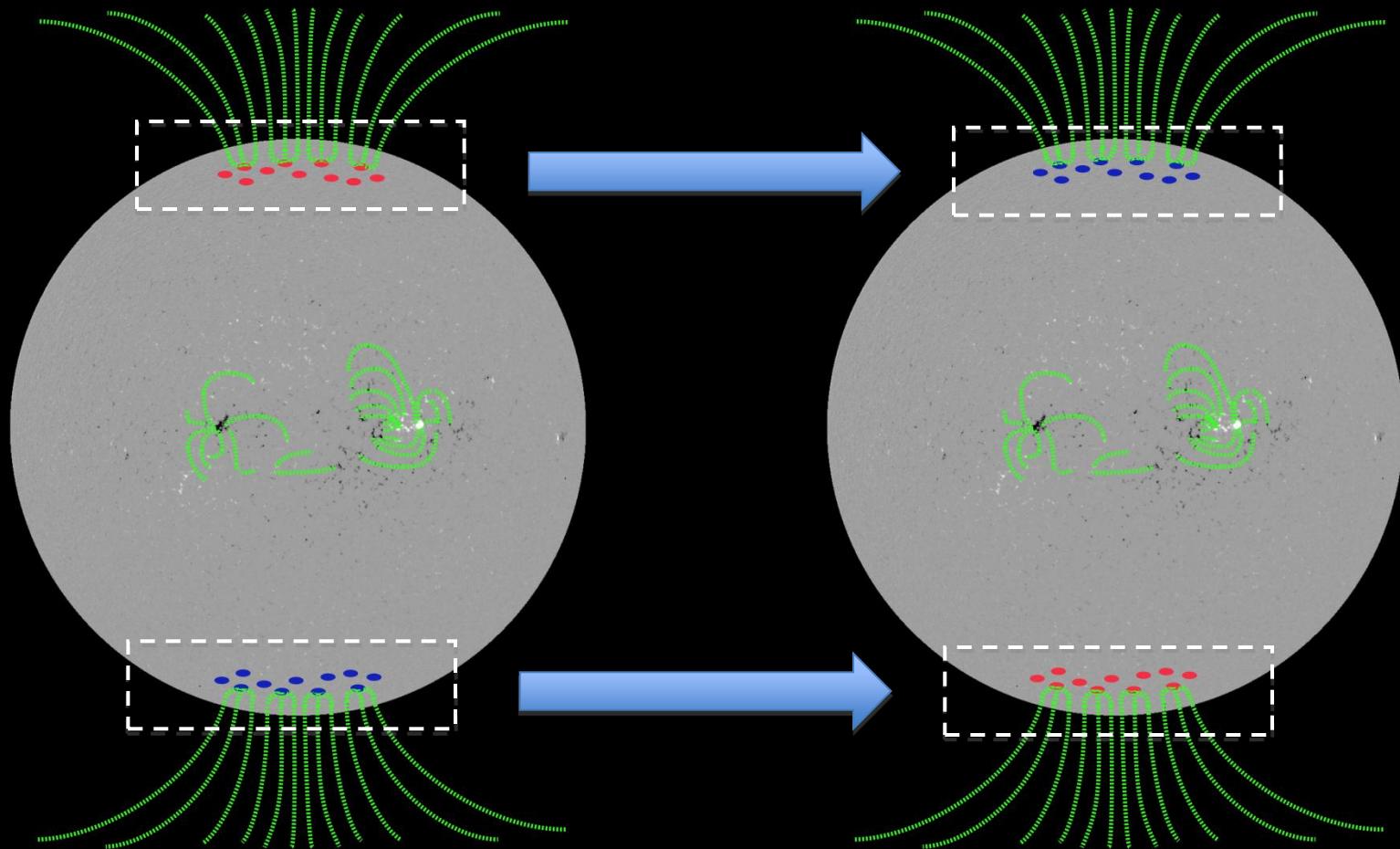
今回の発見による描像



- 強磁場斑点とそのラッパ状の磁場形状は、アルベン波がコロナと彩層の境界での反射を防ぎ、彩層からコロナへアルベン波を運ぶ、トンネルの役目を果たす。

「ひので」極域観測による今後の展開

- ・ 極域磁場は、数年後の極大期付近で反転する。

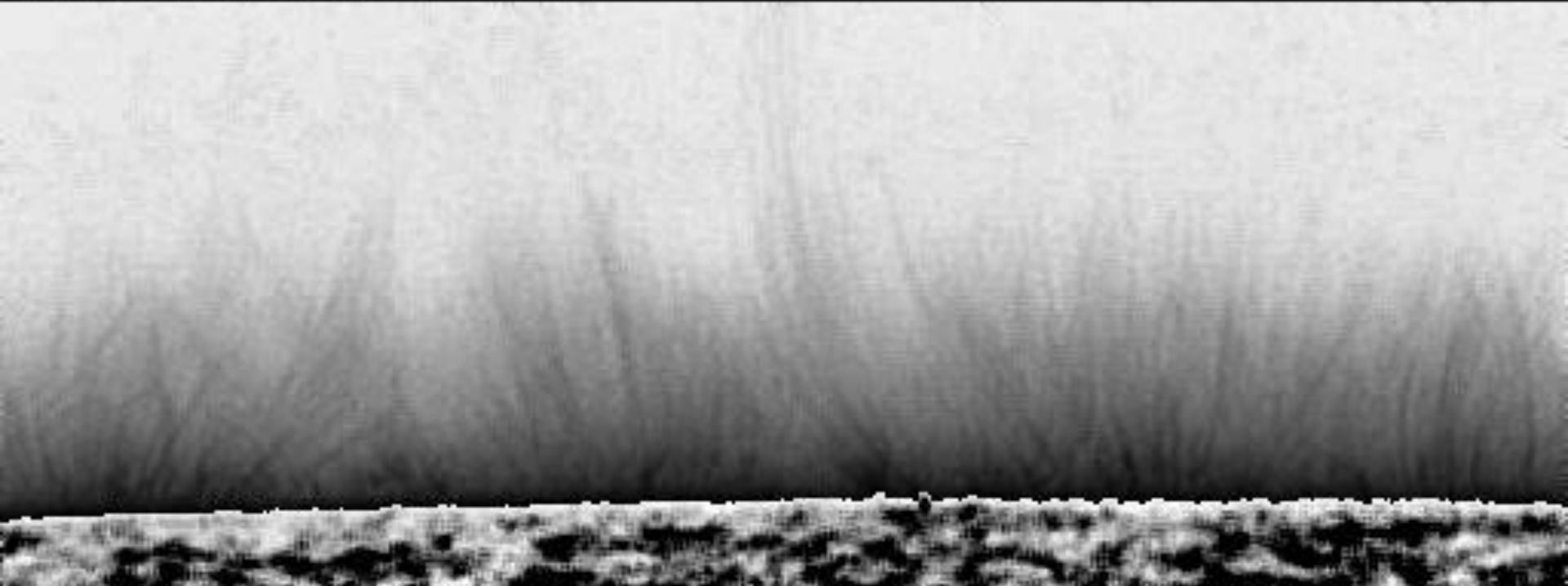


この反転時に極で何が起きているかを、「ひので」で観測し、太陽周期の解明を行っていきたい。

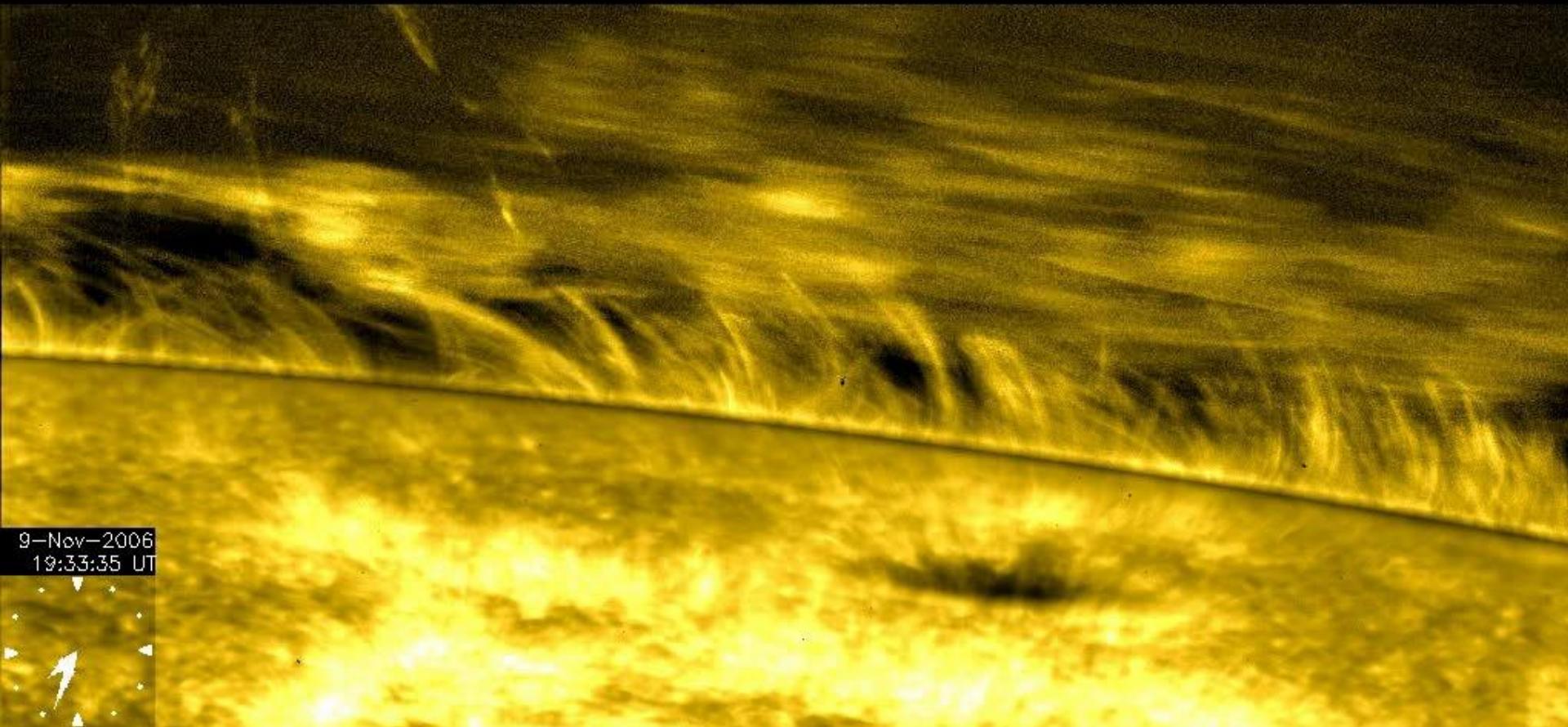
Polar Spicule

Narrow jets driven by magnetic field

2007-04-01T02:20:30.420



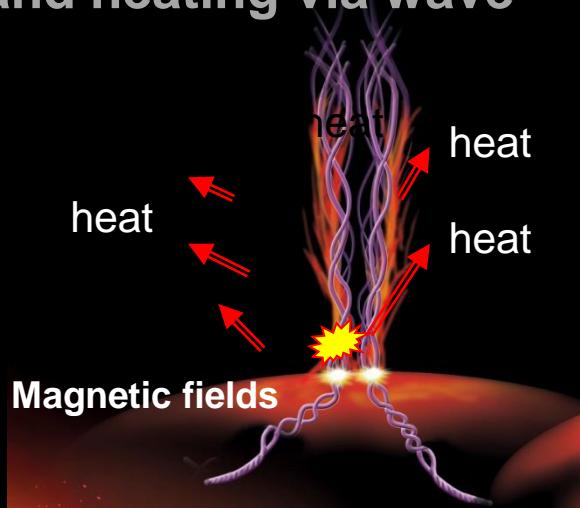
Spicules, coronal rains, and prominence



Waves along magnetic field line carry huge amount of energy potentially accelerating solar wind and heating corona

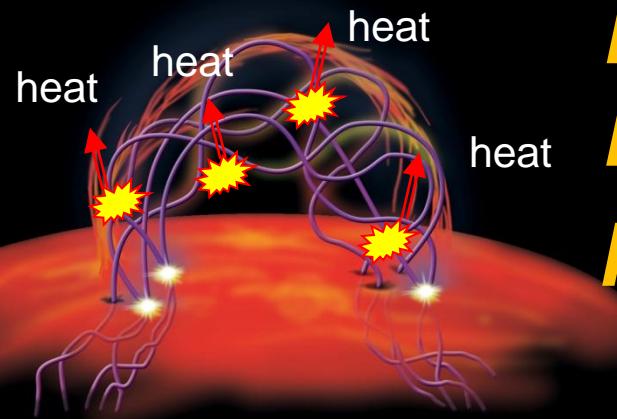


Energy transport
and heating via wave



2010/2/22-24

Annihilation of magnetic fields
called magnetic reconnection



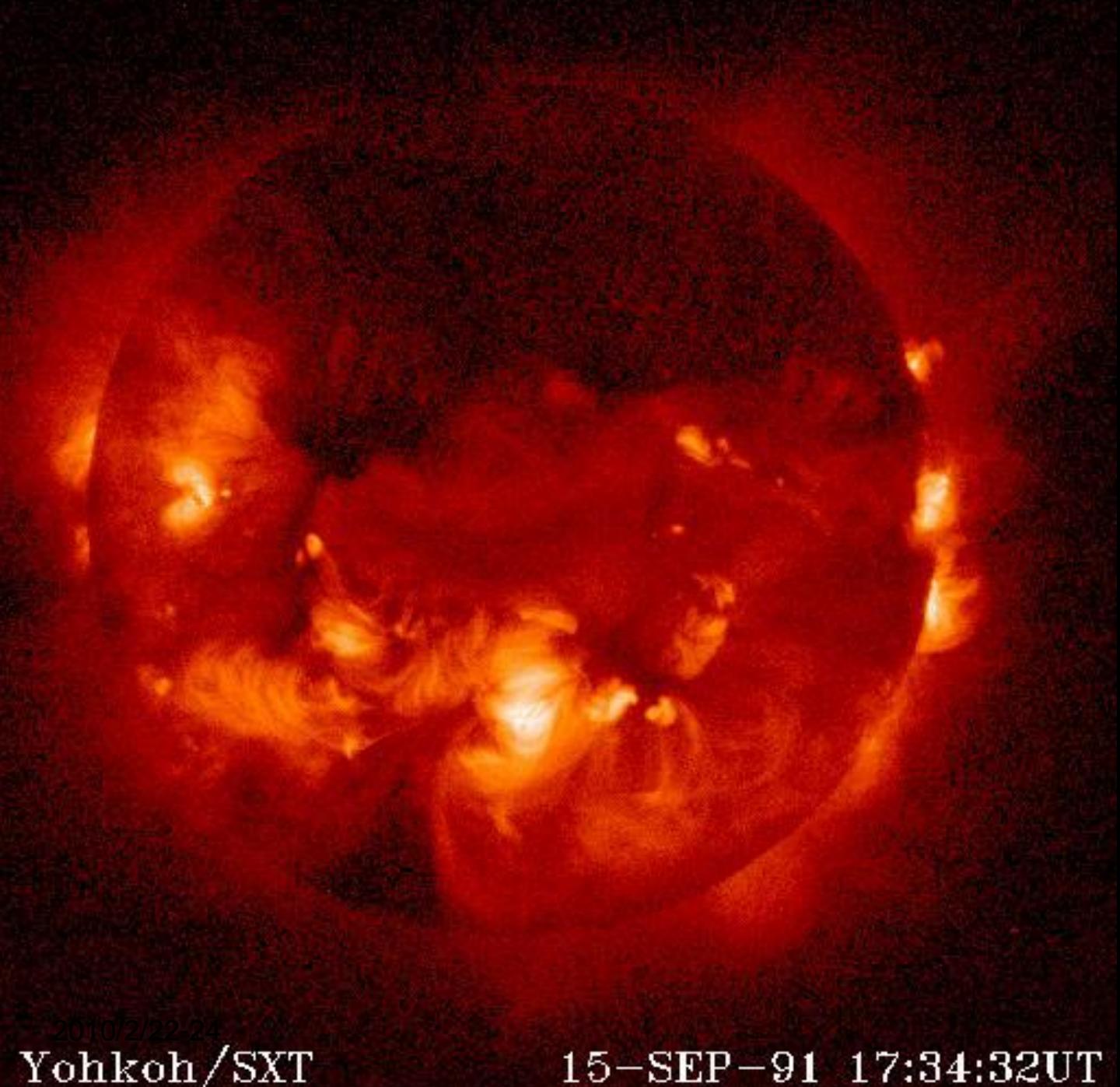
How is corona heated? Two possibilities

Enigmatic prominence

Prominence is a cool and heavy material in the corona supposed to be suspended by magnetic fields In the corona.

Call-H (ionized Calcium)



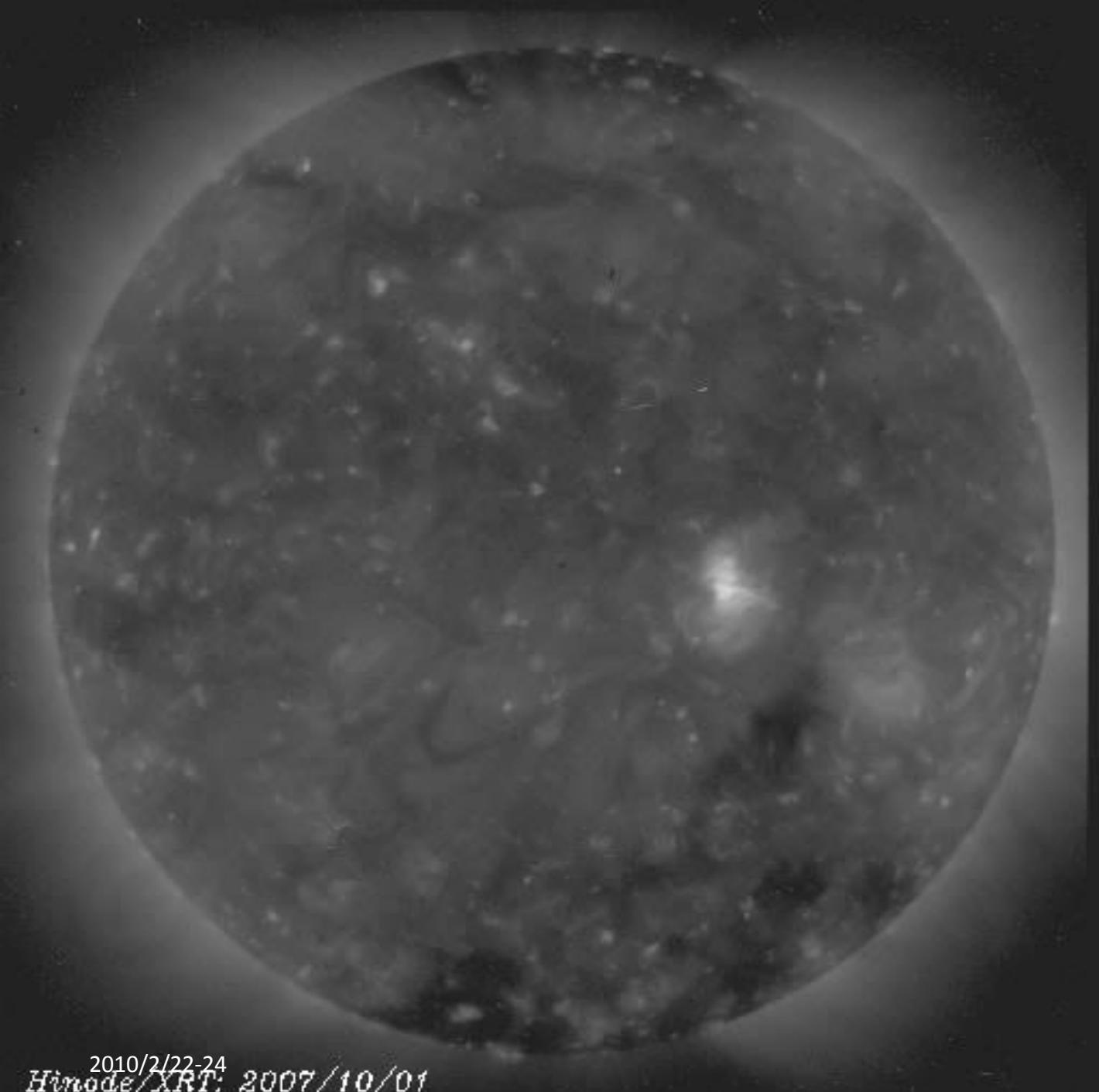


*10 years of X-ray Sun
from 1992 September to
2001 December*

2010/2/22-24

Yohkoh/SXT

15-SEP-91 17:34:32UT



2010/2/22-24
Hinode/XRT: 2007/10/01

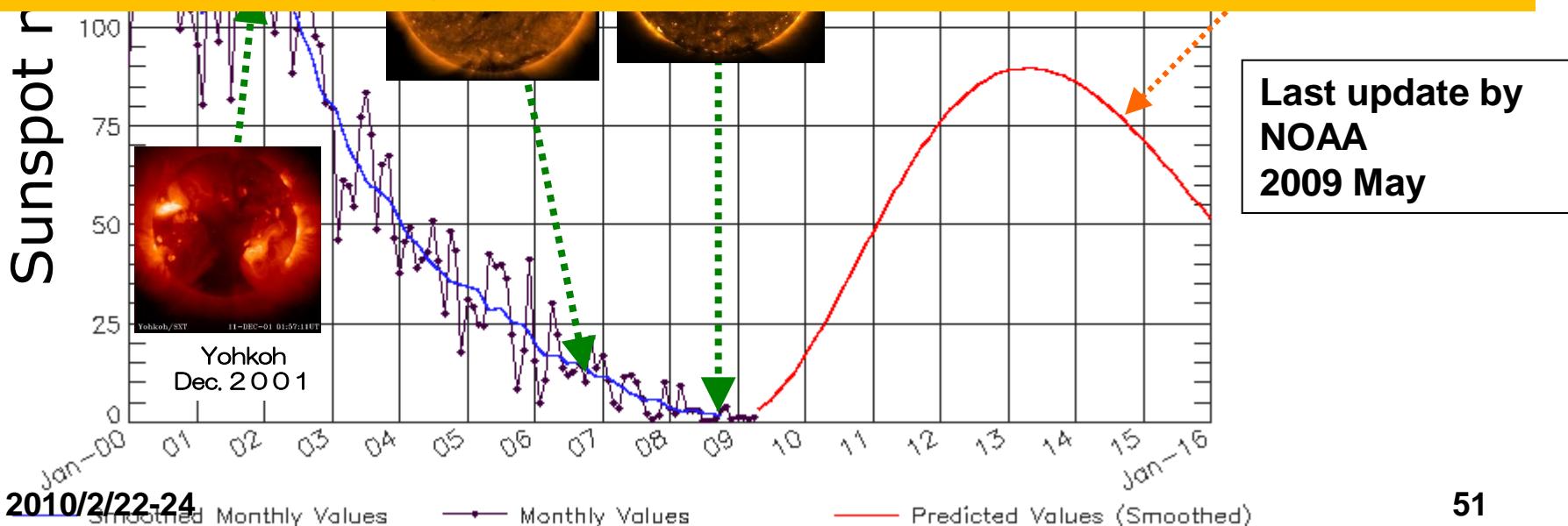
Extended solar minimum
Hinode X-ray corona
2007 Oct. – 2009 Apr.

NOAA predictions updated multiple times to cope with long solar minimum

Sunspot number and prediction by NOAA



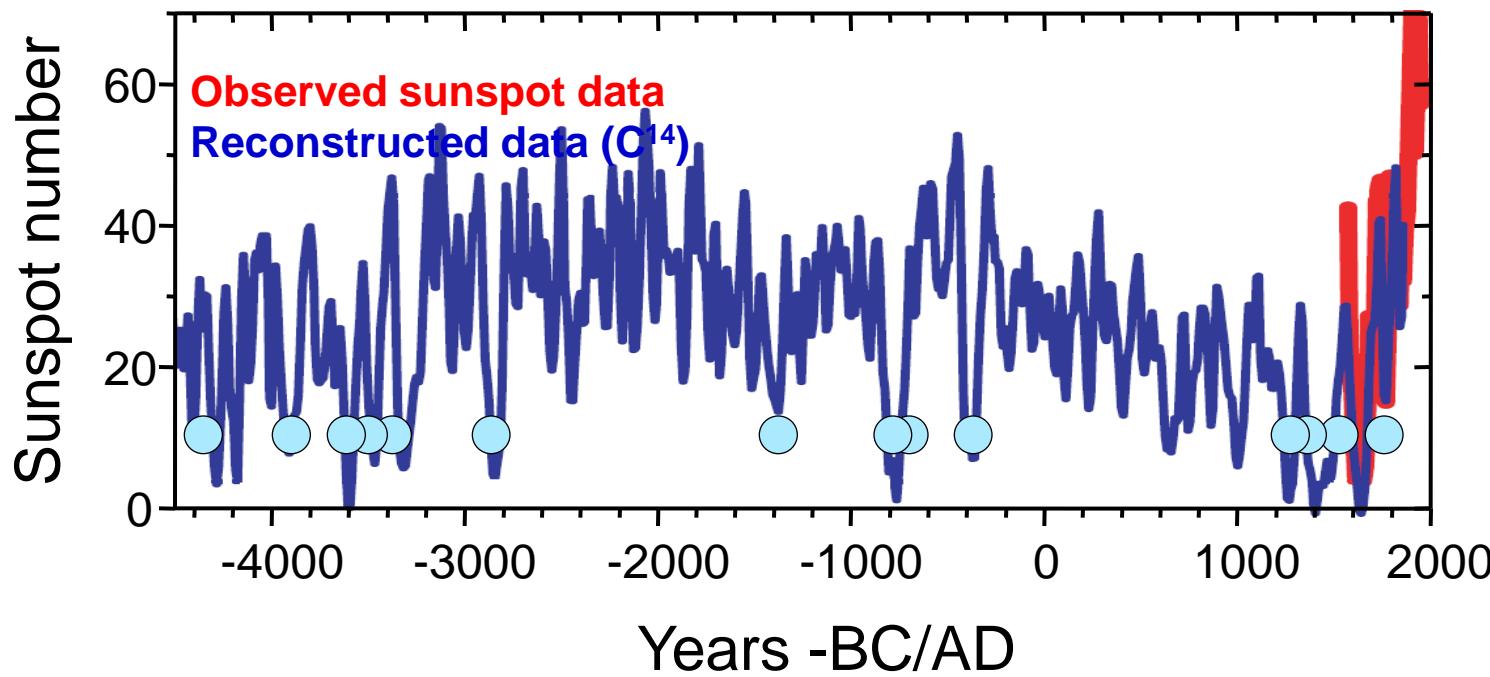
Next solar max was predicted to be October, 2011 by NOAA, and will be 2013-2014(?). The period is >12.5 year longer than nominal 11 year.



Summary of observations indicating unusual low solar activity

- ***Longer solar cycle*** (> 12 yr 6 month)
- Cumulative ***no-sunspot days*** is close to that of 100 years ago.
- New sunspots in northern high latitude appeared much earlier, while those in south appeared recently.
- ***Total solar luminosity may be lower*** as compared with those in the past two minimum.
- ***Polar magnetic flux is half*** of the previous value.
- ***Unusual solar wind*** distribution in heliosphere
- Lower solar wind pressure
- ***Highest cosmic ray*** flux in past 45 years

Cold spells vs. Grand solar minima



Sunspot number reconstruction (Usoskin et al., 2007) as well as known climate shifts in Europe to cold/wet conditions (Versteegh, 2005) for the last 6500 years:

14 cold spells – vs – 15 Grand minima → 12 coincide

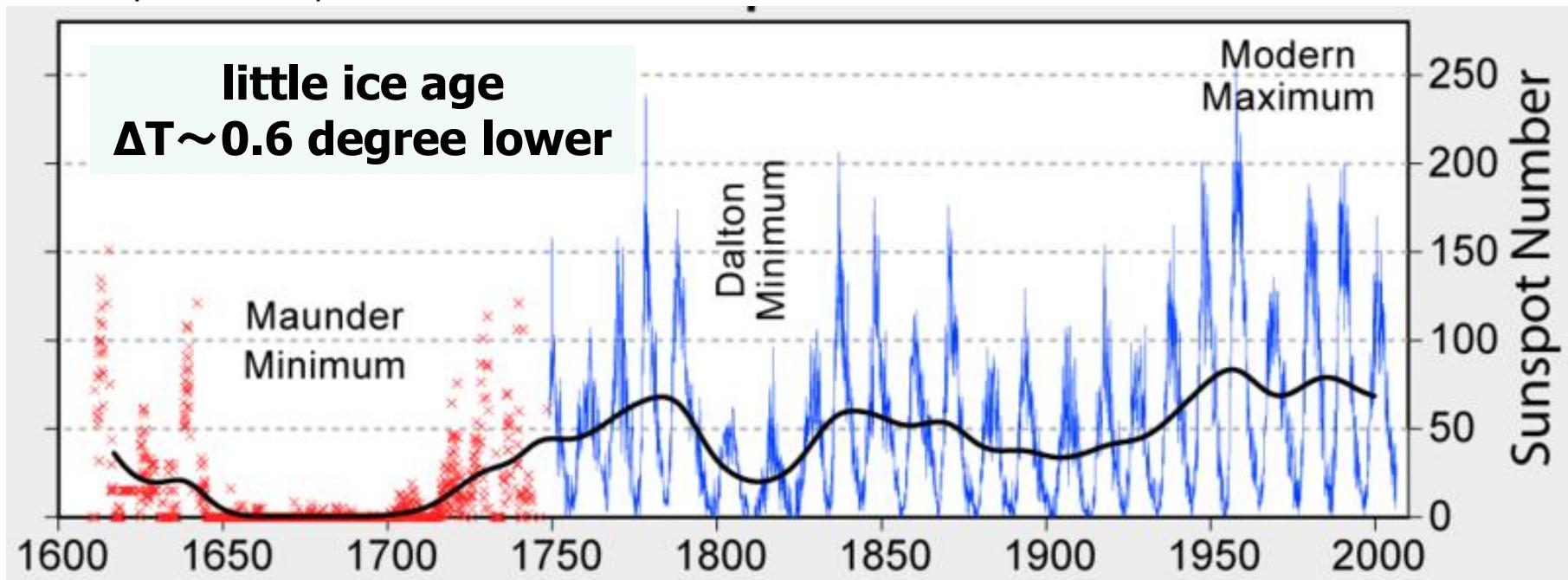


"Sports on a Frozen River"

by Aert van der Neer

Courtesy: The Metropolitan Museum of Art

Are we about to enter grand-solar minimum?



Combined data set suggest that we may have low activity comparable to the Dalton Minimum.

Influence to the Earth?



Influence to the Earth?

- The Sun has profound influence to our climate, life and civilization:
 - *Space weather: Short term effect of solar activities to human activities in space and on Earth*
 - *Space climate: effect of solar cycles to Earth climate*
 - *Faint young sun problem and origin of life on Earth*
- *Only through long-term observations and basic research from space and ground, we are able to predict the future activities of the Sun.*
- *Hinode continues to monitor critical polar regions.*

Contact

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参考文献

- Usoskin and Kovaltsov(2008), Comptes Rendus Geoscience, v. 340, iss. 7, p. 441-450.
- Usoskin et al.(2007), Astronomy and Astrophysics, Volume 471, Issue 1, August III 2007, pp.301-309