2016 March 2 Superflare workshop
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Can Superflares Occur on the Sun ?

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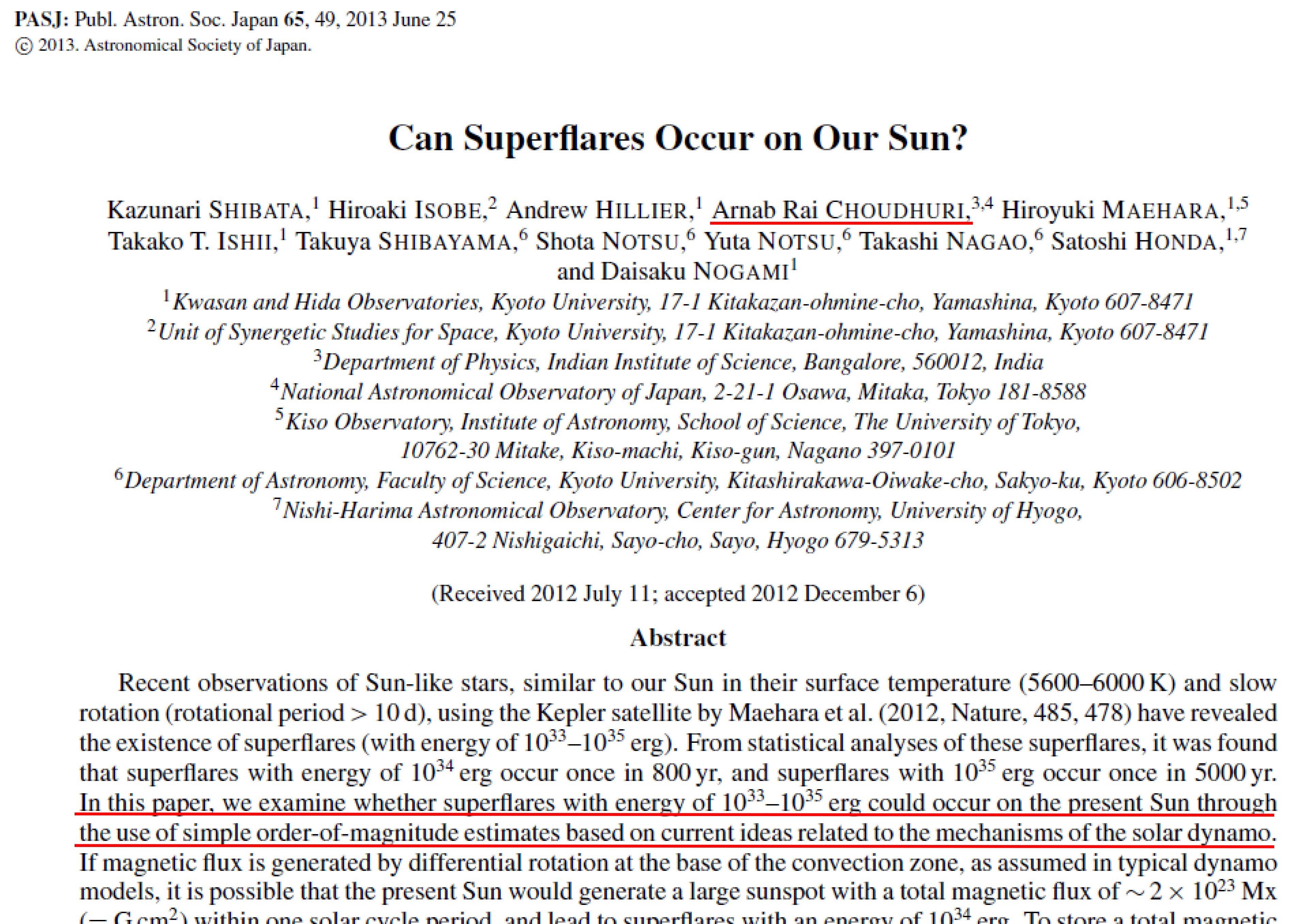

PASJ: Publ. Astron. Soc. Japan **65**, 49, 2013 June 25

Can Superflares Occur on Our Sun?

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(Received 2012 July 11; accepted 2012 December 6)

Abstract

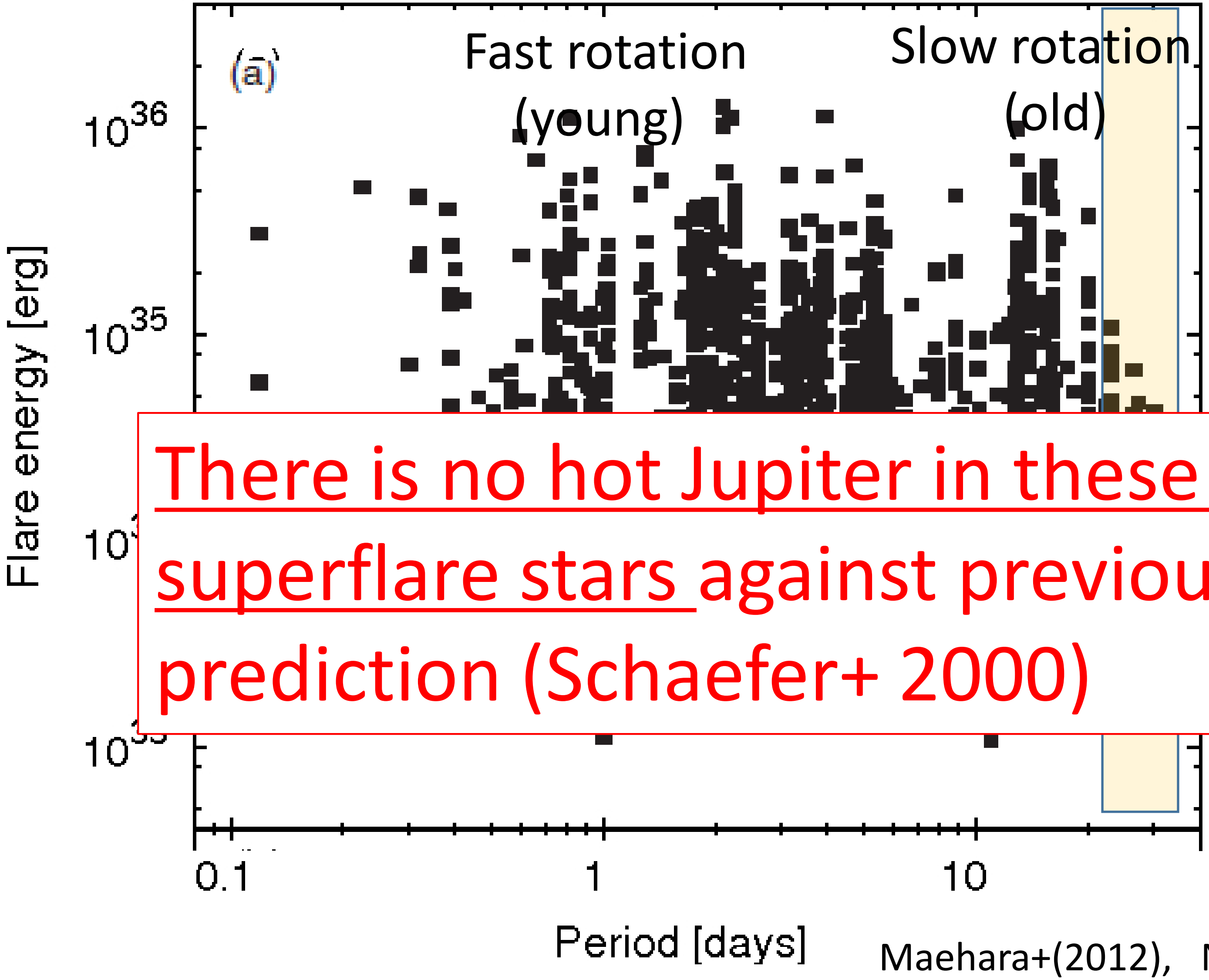
Recent observations of Sun-like stars, similar to our Sun in their surface temperature (5600–6000 K) and slow rotation (rotational period > 10 d), using the Kepler satellite by Maehara et al. (2012, Nature, 485, 478) have revealed the existence of superflares (with energy of 10^{33}–10^{35} erg). From statistical analyses of these superflares, it was found that superflares with energy of 10^{34} erg occur once in 800 yr, and superflares with 10^{35} erg occur once in 5000 yr. In this paper, we examine whether superflares with energy of 10^{33}–10^{35} erg could occur on the present Sun through the use of simple order-of-magnitude estimates based on current ideas related to the mechanisms of the solar dynamo. If magnetic flux is generated by differential rotation at the base of the convection zone, as assumed in typical dynamo models, it is possible that the present Sun would generate a large sunspot with a total magnetic flux of $\sim 2 \times 10^{23}$ Mx (= G cm^2) within one solar cycle period, and lead to superflares with an energy of 10^{34} erg. To store a total magnetic

Contents of Shibata et al. (2013) PASJ

1. Introduction
2. Big Sunspots are Necessary Condition for Superflares
3. Generation of Magnetic Flux at the Base of the Convection Zone
4. Storage of Magnetic Flux just below the Base of the Convection Zone (Tachocline)
5. Case of Rapidly Rotating Stars
6. Is it necessary to have a Hot Jupiter for the production of Superflares ?
7. Conclusion

Introduction

Flare energy vs rotational period



Fast rotation (young)

Slow rotation (old)

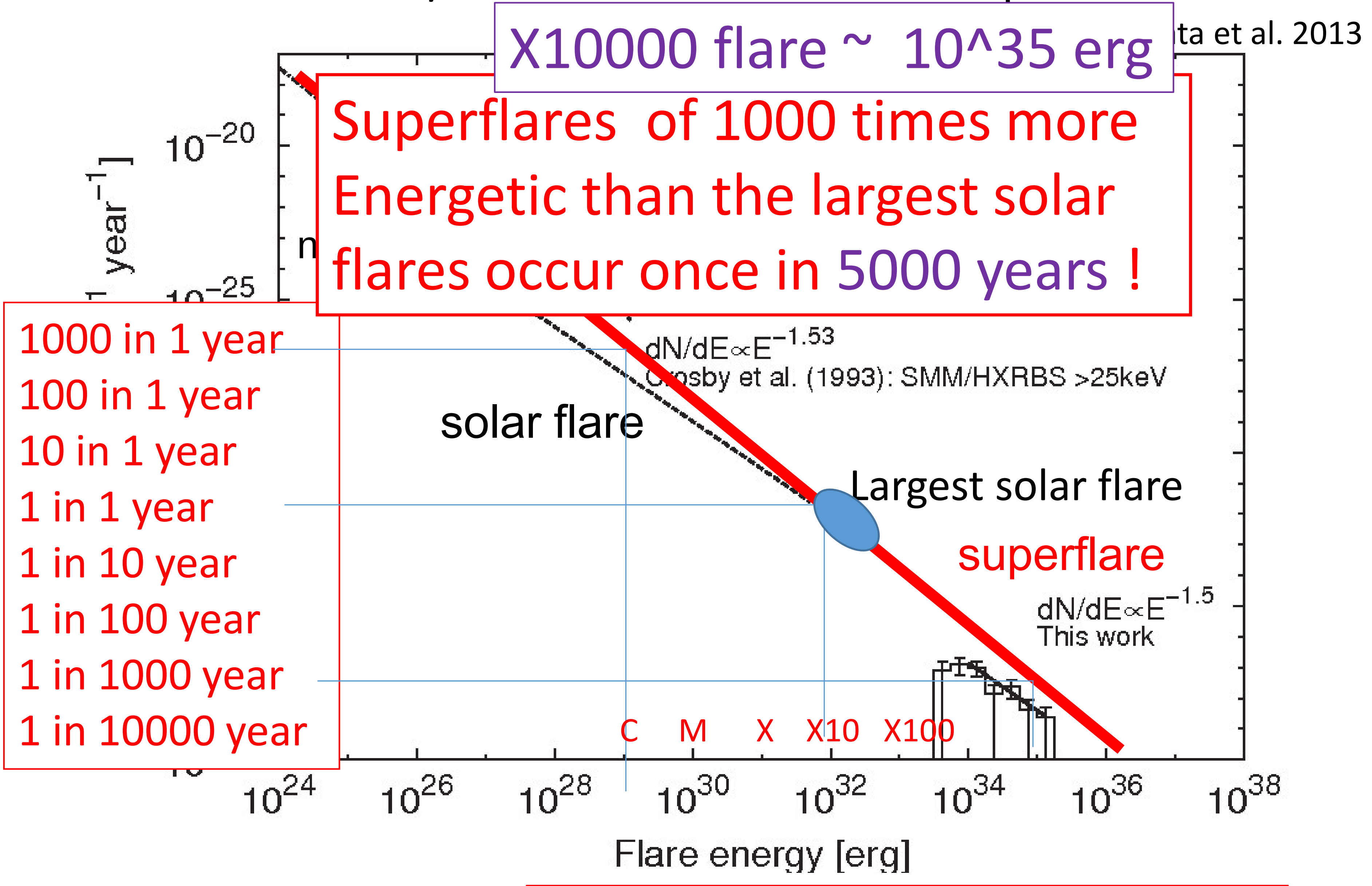
Stars with period longer than 20 days

olar rot
od ~ 25days

There is no hot Jupiter in these superflare stars against previous prediction (Schaefer+ 2000)

Maehara+(2012), Notsu+ (2013)

Comparison of statistics between solar flares/microflares and superflares



X10000 flare ~ 10^35 erg

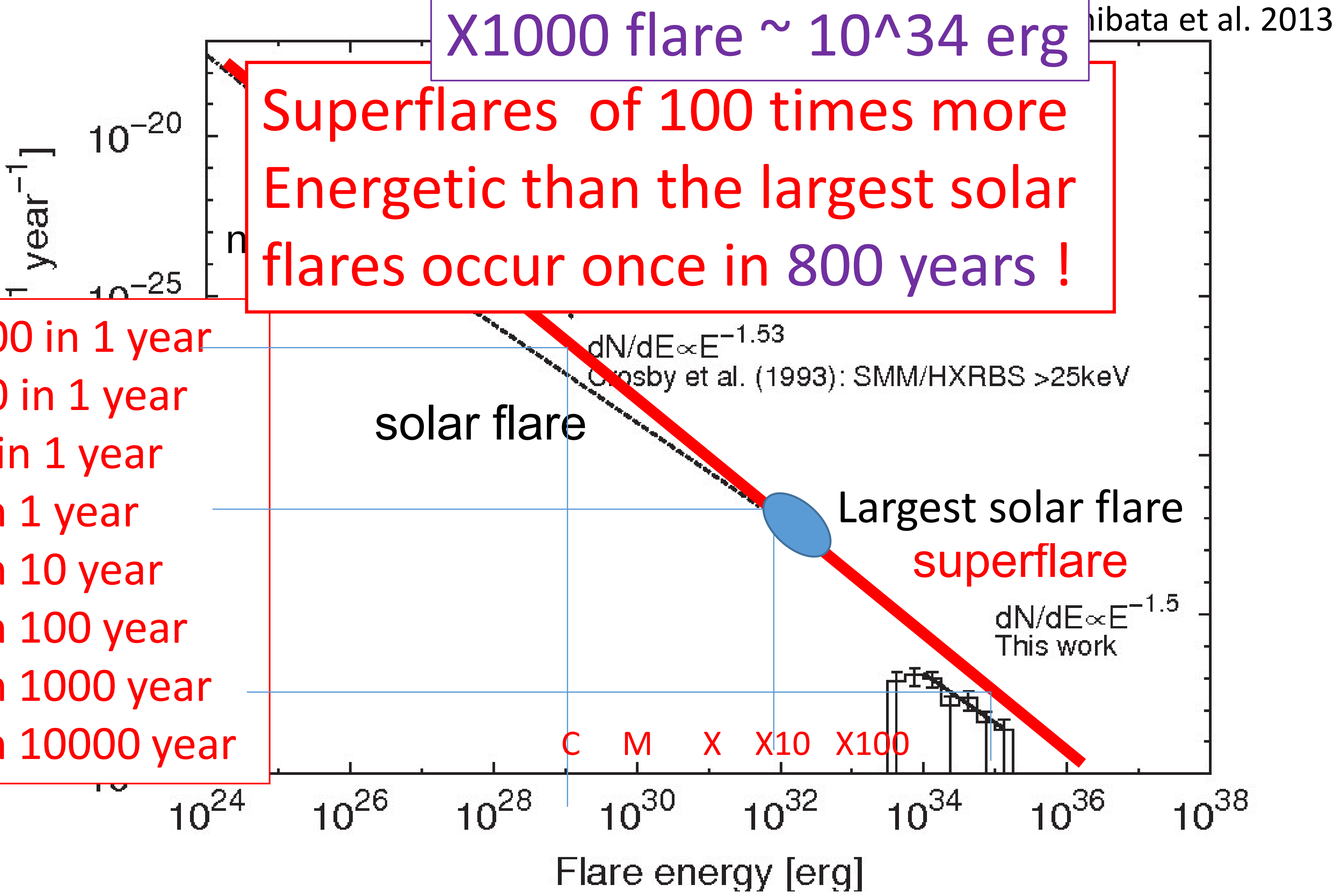
Superflares of 1000 times more Energetic than the largest solar flares occur once in 5000 years !

- 1000 in 1 year
- 100 in 1 year
- 10 in 1 year
- 1 in 1 year
- 1 in 10 year
- 1 in 100 year
- 1 in 1000 year
- 1 in 10000 year

Largest solar flare

superflare

Comparison of statistics between solar flares/microflares and superflares



ibata et al. 2013

X1000 flare ~ 10^34 erg

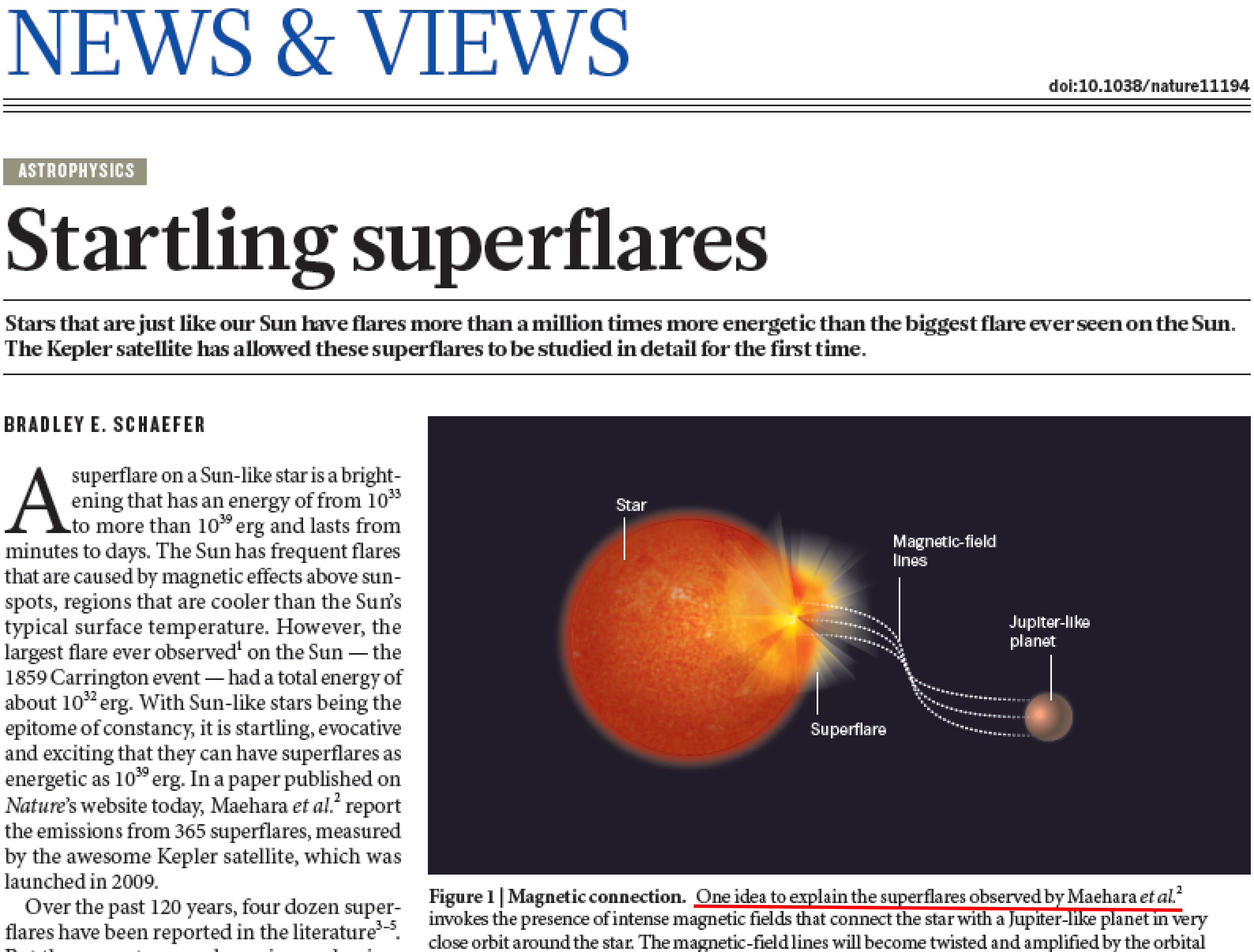
Superflares of 100 times more Energetic than the largest solar flares occur once in 800 years !

1000 in 1 year
100 in 1 year
10 in 1 year
1 in 1 year
1 in 10 year
1 in 100 year
1 in 1000 year
1 in 10000 year

Why we wrote Shibata et al.’s PASJ paper ?

- In a Referee report on Maehara et al. when we submitted the paper to Nature (Oct, 2011)
- Editor wrote
  “Referee 1 feels strongly -- as do we -- that any hype associated with solar superflares must be removed. Referee 1 argues cogently that there is compelling evidence that the Sun does not, nor has it for a rather long time, produce(d) a superflare -- that should be stated specifically in the text.”

Amazing article appear on Nature when Maehara et al. was published in May 2012 !



NEWS & VIEWS

doi:10.1038/nature11194

ASTROPHYSICS

Startling superflares

Stars that are just like our Sun have flares more than a million times more energetic than the biggest flare ever seen on the Sun. The Kepler satellite has allowed these superflares to be studied in detail for the first time.

BRADLEY E. SCHAEFER

A superflare on a Sun-like star is a brightening that has an energy of from 10^{33} to more than 10^{39} erg and lasts from minutes to days. The Sun has frequent flares that are caused by magnetic effects above sunspots, regions that are cooler than the Sun's typical surface temperature. However, the largest flare ever observed[1] on the Sun — the 1859 Carrington event — had a total energy of about 10^{32} erg. With Sun-like stars being the epitome of constancy, it is startling, evocative and exciting that they can have superflares as energetic as 10^{39} erg. In a paper published on *Nature*'s website today, Maehara *et al.*[2] report the emissions from 365 superflares, measured by the awesome Kepler satellite, which was launched in 2009.

Over the past 120 years, four dozen superflares have been reported in the literature[3–5].

Figure 1 | Magnetic connection. One idea to explain the superflares observed by Maehara *et al.*[2] invokes the presence of intense magnetic fields that connect the star with a Jupiter-like planet in very close orbit around the star. The magnetic-field lines will become twisted and amplified by the orbital

JAPAN TODAY
JAPAN NEWS AND DISCUSSION

Japan, U.S. disagree on possibility of solar apocalypse

By Jessica Ocheltree

→ NATIONAL MAY. 22, 2012 - 06:54AM JST (31) Recommend 34

TOKYO — If a superflare, which is an explosion up to millions or even a billion times more powerful than a typical solar flare, were to happen on our sun, it would release incredible amounts of electromagnetic energy that would likely fry the world's all-important electrical gri and send society spiraling into chaos. A large enough one could even burn up our protective ozone layer and turn all life on Earth extra-crispy.

So, what are the chances of that happening? Are we all doomed!? Well, depends on who you ask, apparently.

In a recent edition of Nature magazine, researchers from Japan and America went head to he on the likelihood of a superflare happening here in our solar system. According to a group of researchers at Kyoto University, it's a possibility. Meanwhile, astrophysicist at Louisiana State University responded in typical scientist fashion by saying it was theoretically improbable.

太陽スーパーフレア論争

地球から遠く離れた太陽に似た天体で観測される「スーパーフレア」と呼ばれる超巨大な爆発現象を巡り、17日の英科学誌ネイチャー（電子版）誌上で日米の研究者の学術論争が起きている。京都大グループが天体観測の結果から「私たちの太陽でも起きる可能性がある」と主張、これに米国の天文学者が「理論的にありえない」と反論している。

　スーパーフレアは、太陽表面で起きる爆発現象「太陽フレア」の最大1万倍にも達する。太陽で起きれば強烈な電磁波が地球を襲い、電子機器があふれる社会は壊滅状態に陥るという。

　京大付属天文台の柴田一成教授らは、米航空宇宙局（ＮＡＳＡ）の人工衛星が観測した太陽系外の天体16万個のデータを分析、太陽に似た10の天体で、14回のスーパーフレアが起きていたのを確認した。

京都大「可能性ある」　米学者「ありえない」

　スーパーフレアは、太陽に似た天体が、近くを回る地球の10倍ほどの巨大惑星の磁場の影響を受けて起きるとされる。太陽の近くには巨大惑星はないが、スーパーフレアを起こした10の天体の近くにも巨大惑星はなかった。この

もスーパーフ
性がある」と
論づけた。

　これに対し
唱える、米・
の研究者は、
天体の近くに
と起きえない
の間に地球
く、太陽では
反論。柴田教
発達していな
えないスーパ
きない」とし
示す科学的な
たい」という

スーパーフレアのイメージ図。右下にある白い塊がスーパーフレア（柴田京都大教授提供）

Evidence of superflare ?

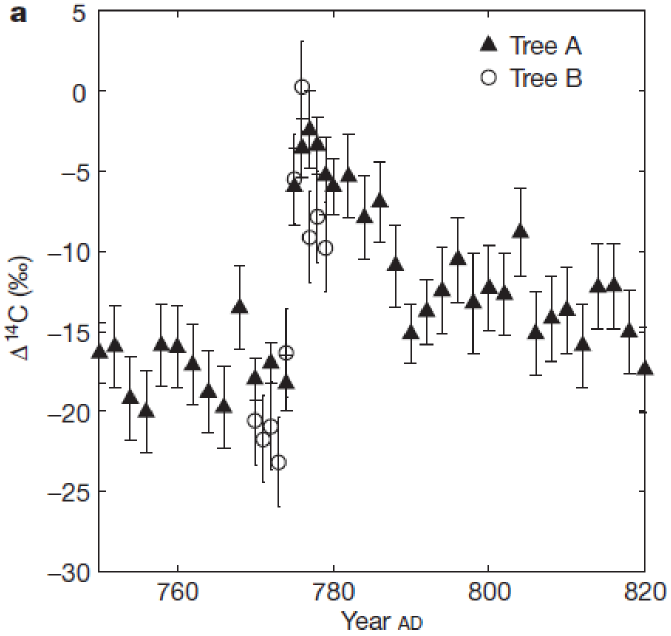
LETTER

doi:10.1038/nature11123

A signature of cosmic-ray increase in AD 774–775 from tree rings in Japan

Fusa Miyake[1], Kentaro Nagaya[1], Kimiaki Masuda[1] & Toshio Naka

Increases in ^{14}C concentrations in tree rings could be attributed to cosmic-ray events[1–7], as have increases in ^{10}Be and nitrate in ice cores[8,9]. The record of the past 3,000 years in the IntCal09 data set[10], which is a time series at 5-year intervals describing the ^{14}C content of trees over a period of approximately 10,000 years, shows three periods during which ^{14}C increased at a rate greater than 3‰ over 10 years. Two of these periods have been measured at high time resolution, but neither showed increases on a timescale of about 1 year (refs 11 and 12). Here we report ^{14}C measurements in annual rings of Japanese cedar trees from AD 750 to AD 820 (the



Corresponding to 10^34-10^35 erg superflare
If this is due to a solar flare

(Miyake et al. Nature ,
2012, June, 486, 240)

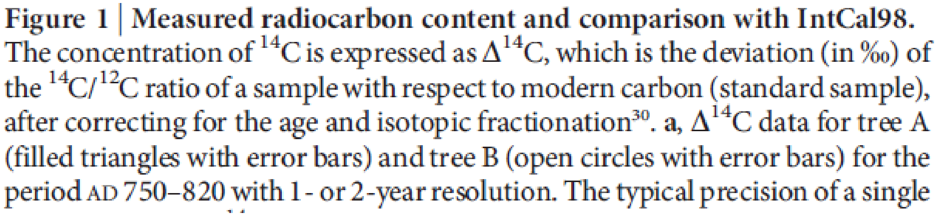
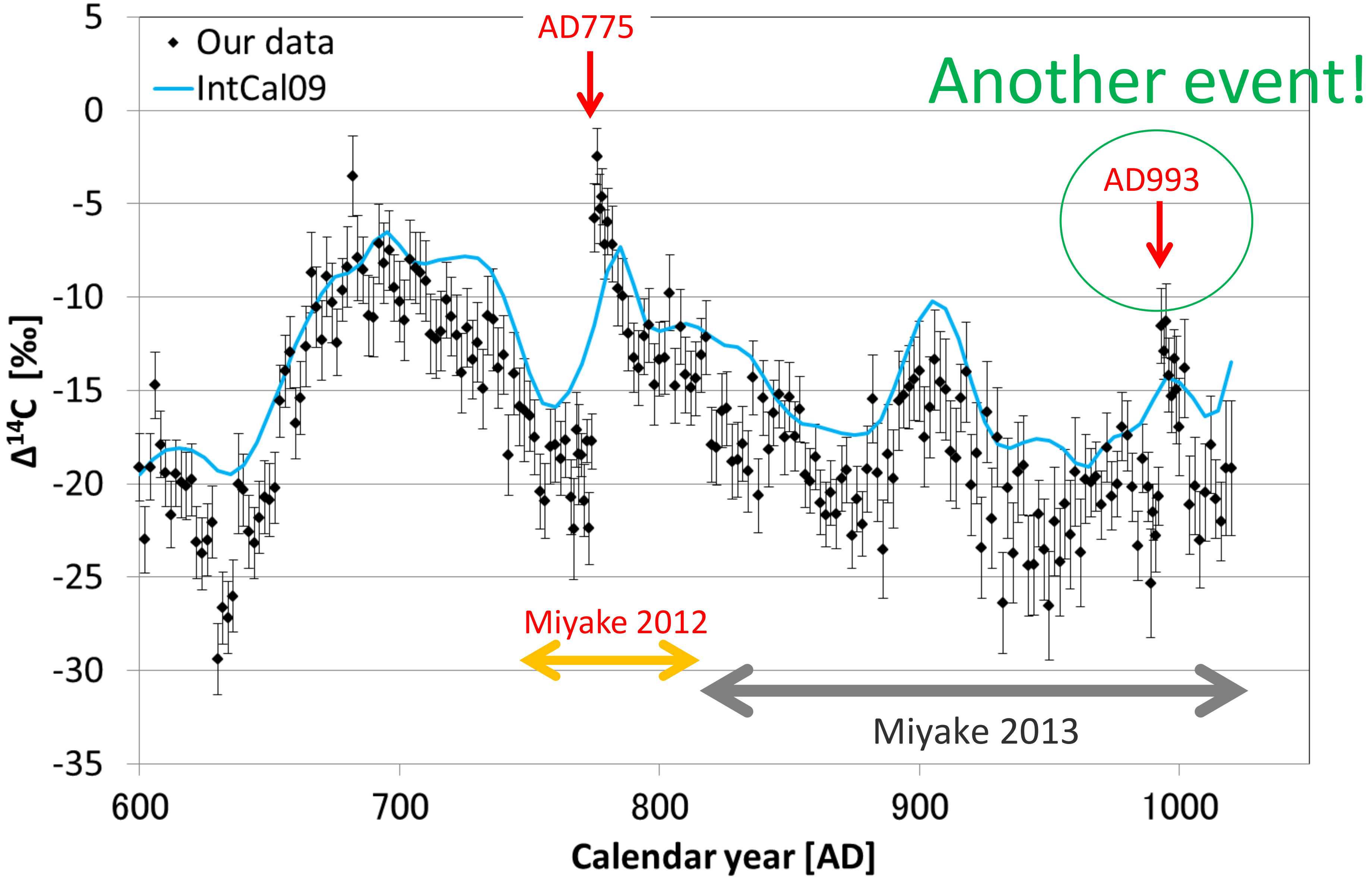


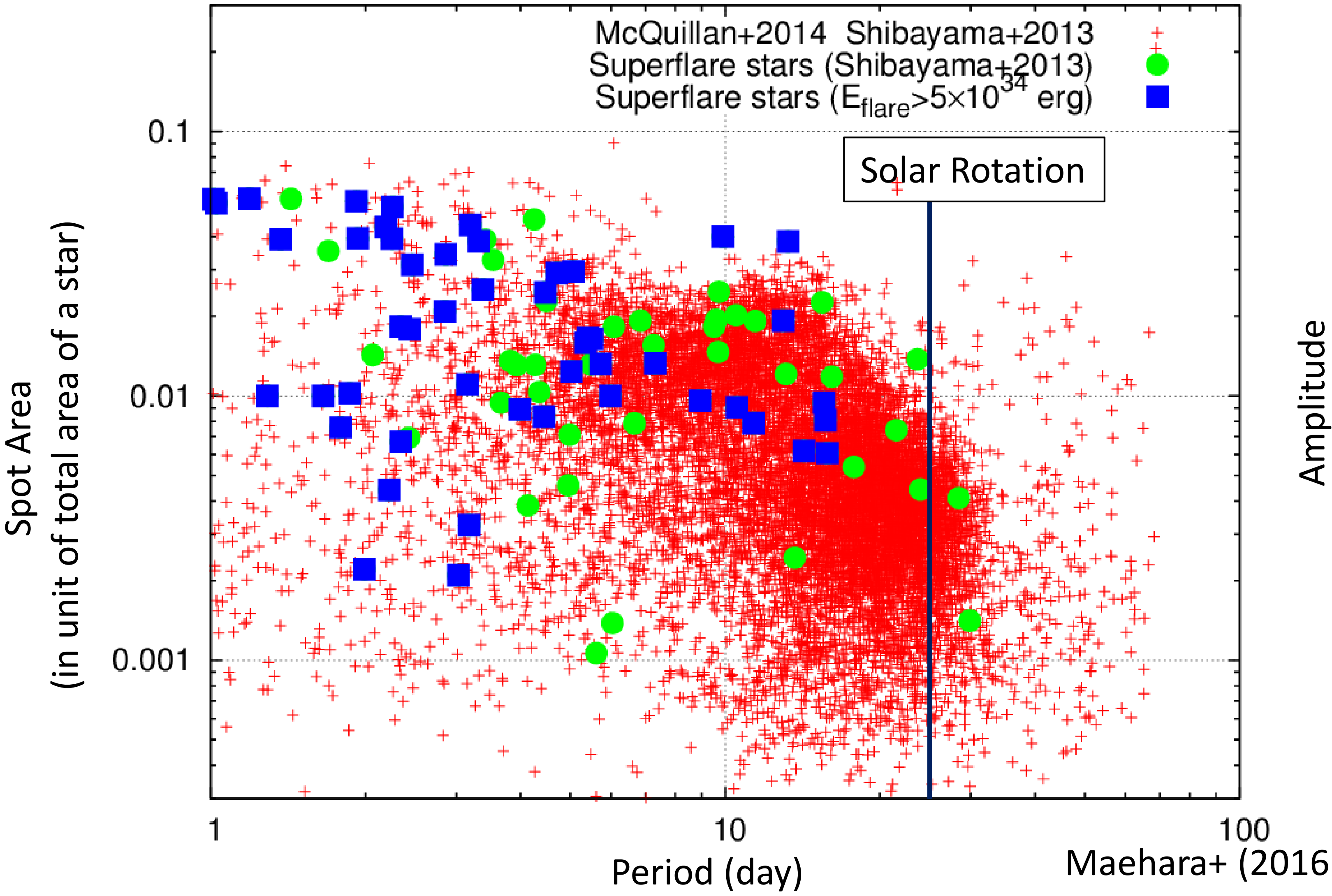
Figure 1 | Measured radiocarbon content and comparison with IntCal98. The concentration of ^{14}C is expressed as Δ^{14}C, which is the deviation (in ‰) of the ^{14}C/^{12}C ratio of a sample with respect to modern carbon (standard sample), after correcting for the age and isotopic fractionation[30]. **a**, Δ^{14}C data for tree A (filled triangles with error bars) and tree B (open circles with error bars) for the period AD 750–820 with 1- or 2-year resolution. The typical precision of a single

Another evidence ?

From Miyake et al. (2013)
Nature Communications 2783



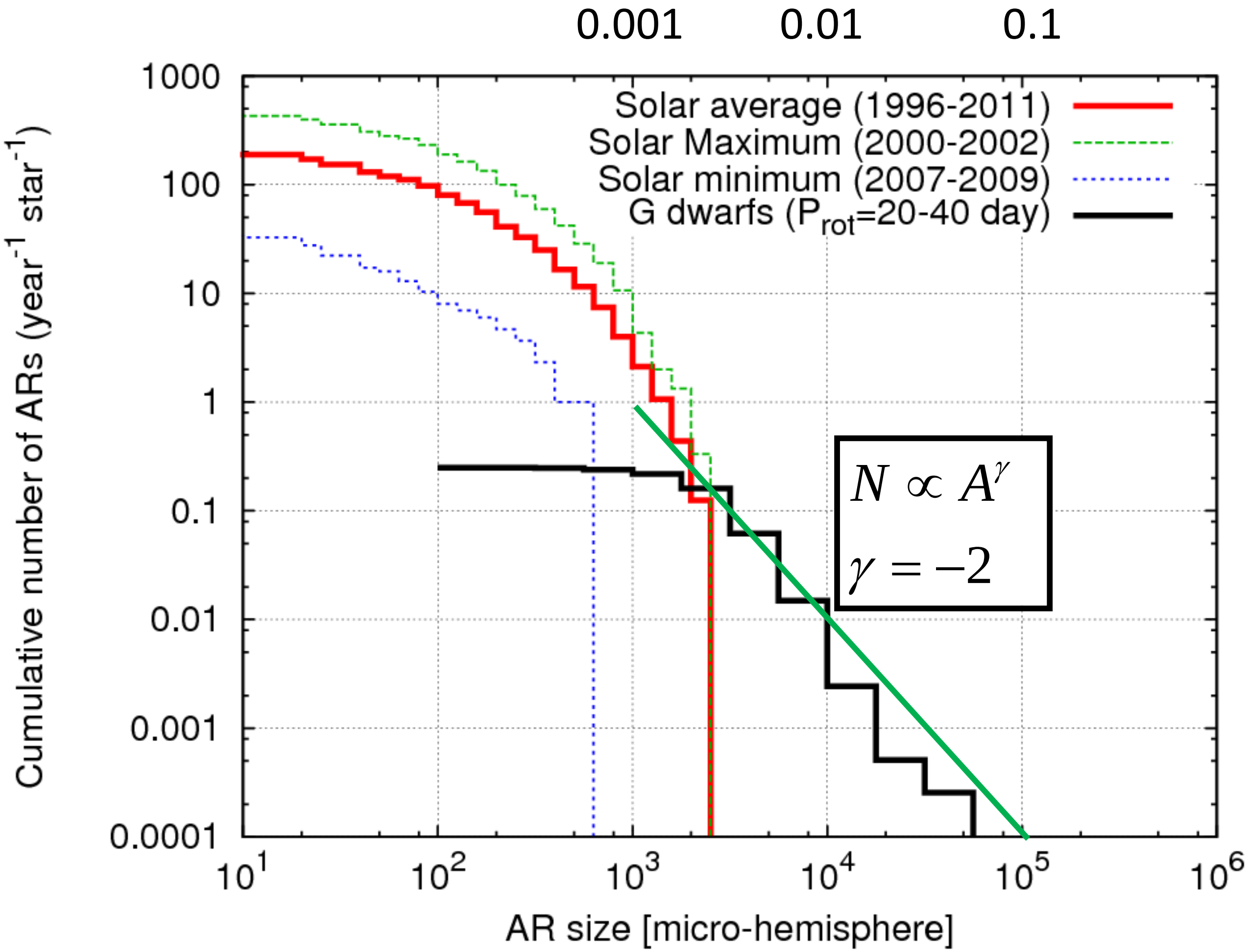
Many stars without superflares Show evidence of large spots !



Maehara+ (2016)

Statistics of Spot Area on the Sun and Sun-like Stars

Large spots exist in many Sun-like stars though frequency Is small



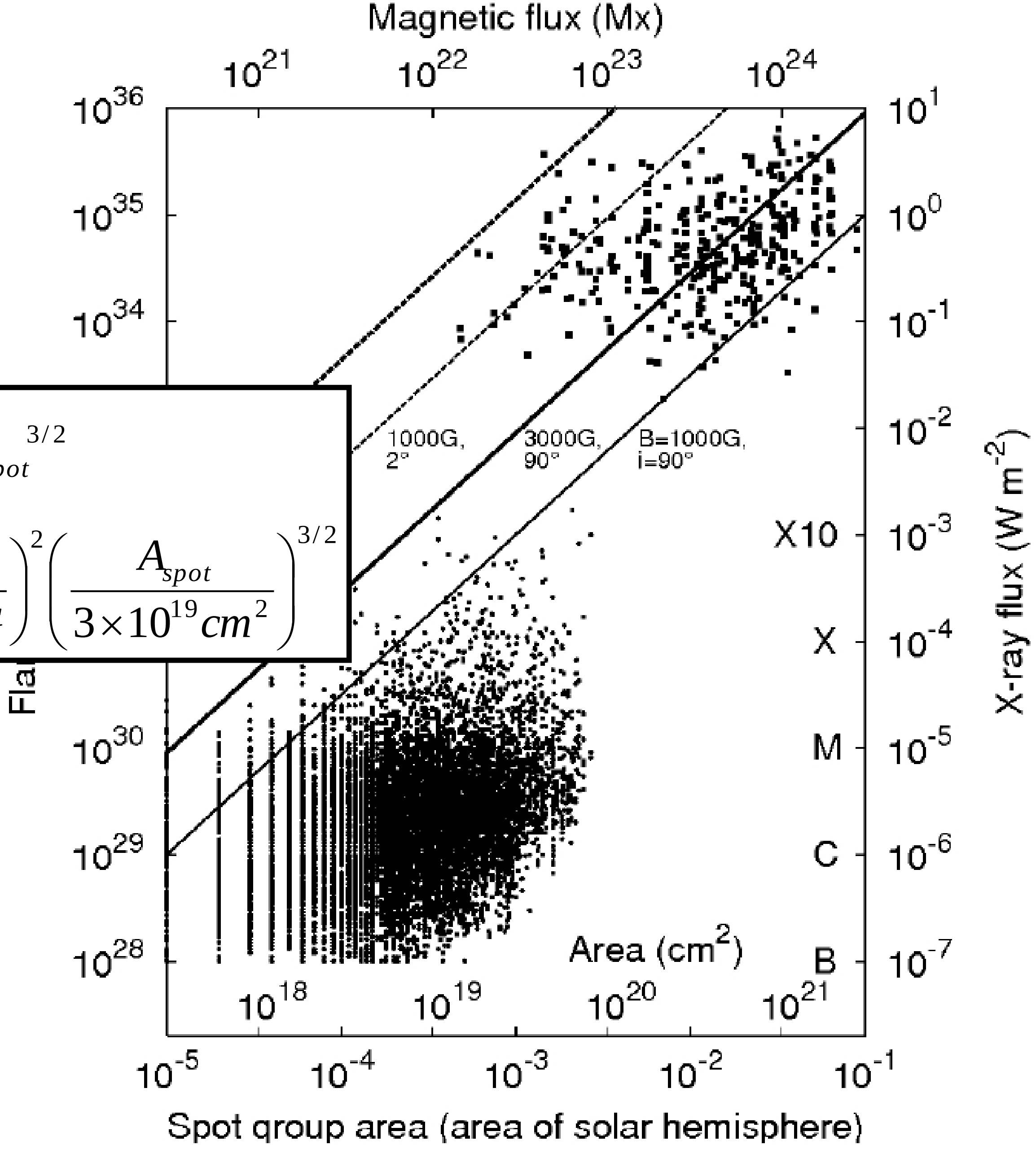
Courtesy of Ishii and Maehara+ (2015)

2. Large Sunspots are Necessary Condition for Superflares

Flare energy vs sunspot area (magnetic flux)

$$E_{flare} \approx fE_{mag} \approx f\,\frac{B^2L^3}{8\pi} \approx f\,\frac{B^2}{8\pi}A_{spot}{}^{3/2}$$

$$\approx 7\times10^{32}\ [erg]\left(\frac{f}{0.1}\right)\left(\frac{B}{10^3G}\right)^2\left(\frac{A_{spot}}{3\times10^{19}cm^2}\right)^{3/2}$$



Shibata et al. (2013)

Maehara et al. (2015)

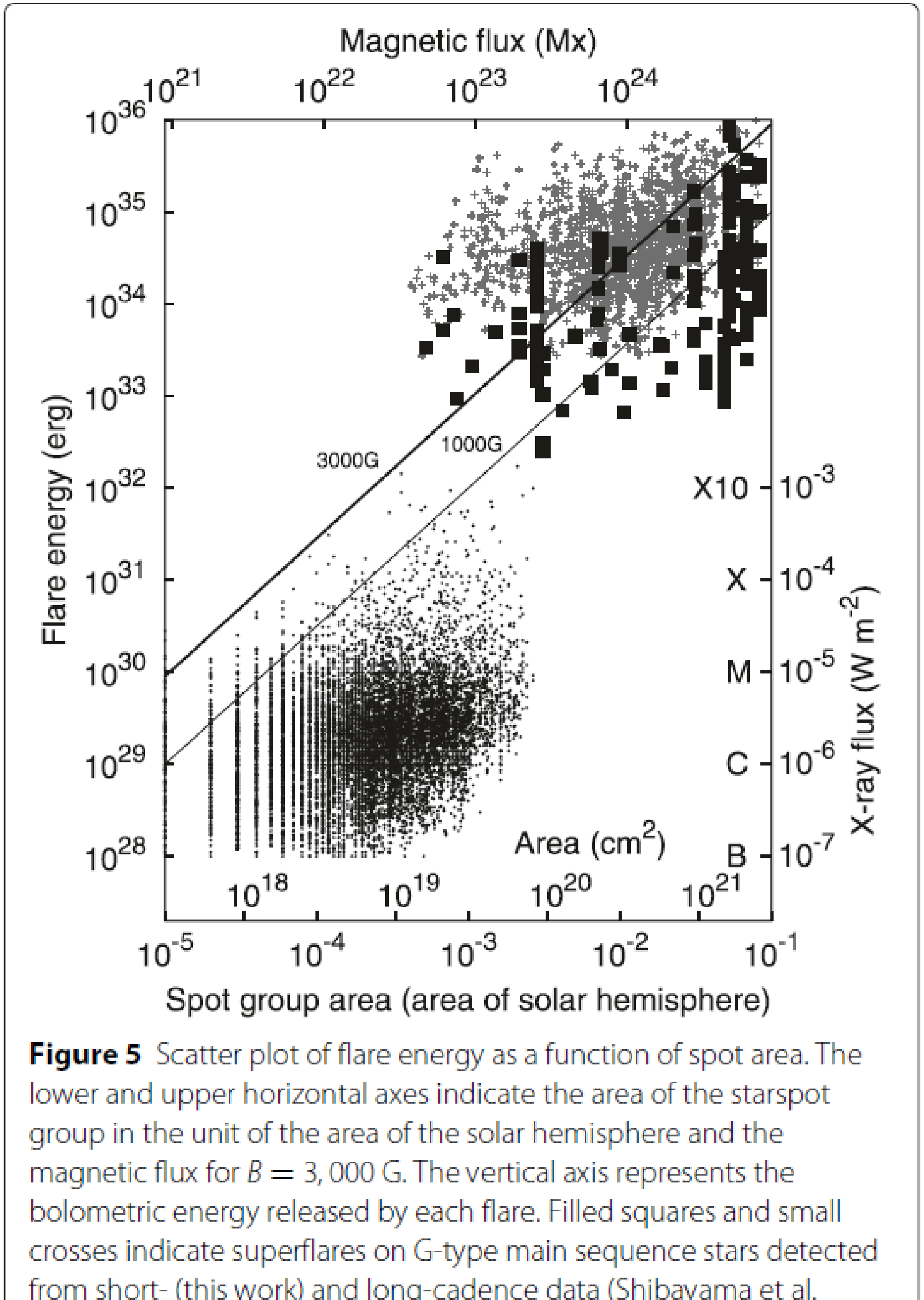


Figure 5 Scatter plot of flare energy as a function of spot area. The lower and upper horizontal axes indicate the area of the starspot group in the unit of the area of the solar hemisphere and the magnetic flux for $B = 3,000$ G. The vertical axis represents the bolometric energy released by each flare. Filled squares and small crosses indicate superflares on G-type main sequence stars detected from short- (this work) and long-cadence data (Shibayama et al.

Mechanism of superflare occurrence

Basic mechanism of superflare is the same as that of solar flares (i.e. reconnection) because
MHD (magneto-hydrodynamics) is scale free

Big starspot is necessary

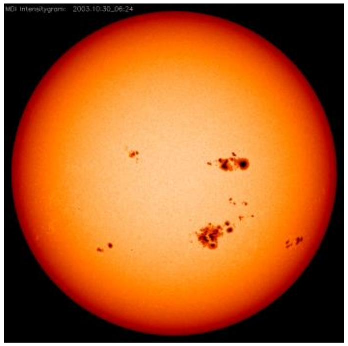
$$E_{flare} \approx fE_{mag} \approx f\frac{B^2L^3}{8\pi} \approx f\frac{B^2}{8\pi}A_{spot}^{3/2}$$

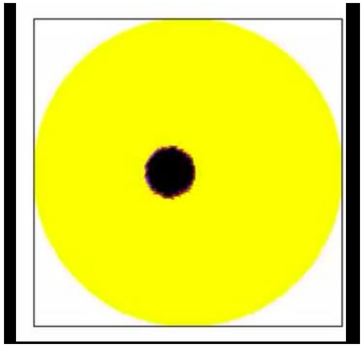
$$\approx 10^{32}\ [erg]\left(\frac{f}{0.1}\right)\left(\frac{B}{10^3G}\right)^2\left(\frac{L_{spot}}{0.04R_\Theta}\right)^3$$

$$If\ \ L_{spot} \approx 0.2-0.4\,R_\Theta\ \ ,$$

$$E_{flare} \approx 10^{34}-10^{35}\ erg$$

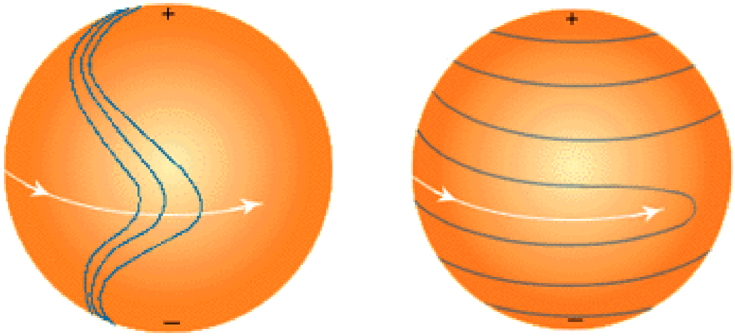
$$\Phi \approx BL_{spot}^{\ \ 2} \approx 10^{23}-10^{24}\ [Mx]$$





3. Generation of Magnetic Flux at the Base of the Convection Zone

How to make large star spot ?



Rotation is slow near poles

Rotation is fast near equator

$$\frac{\partial B_t}{\partial t} = rot\ (V \times B) \approx rot\ (r\Omega\ \times B)\ \approx \Delta\Omega\ B_p$$

$$V = r\Omega = \frac{2\pi r}{\tau_{rot}}$$

$$\tau_{rot} \approx 25 - 30\ days$$

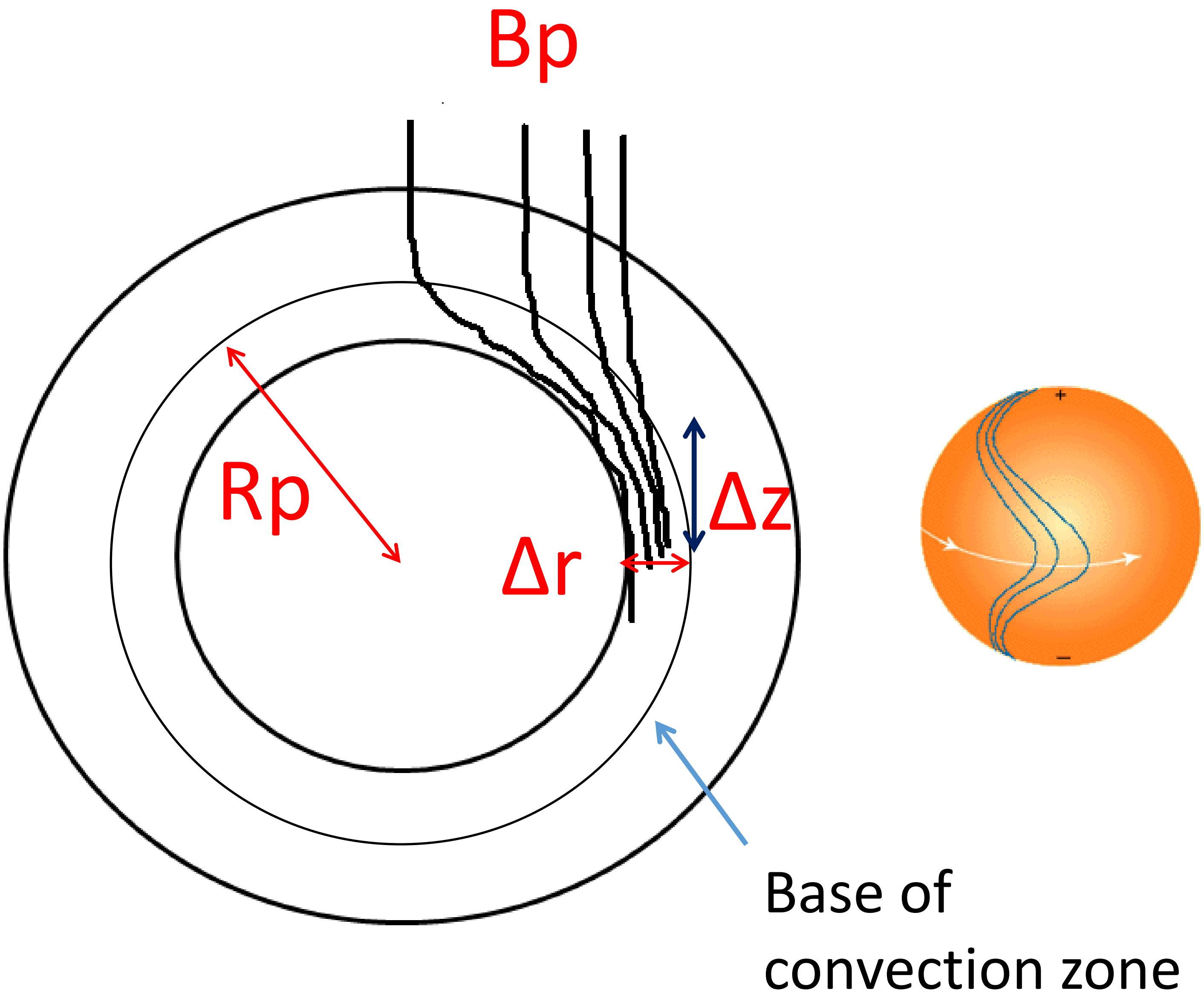
$$\Omega = \frac{2\pi}{\tau_{rot}} \approx (2.4 - 2.9) \times 10^{-6}\ Hz$$

$$\Omega = \frac{2\pi}{\tau_{rot}} = 2.8 \times 10^{-6}\ Hz\ (in\ our\ \ paper)$$

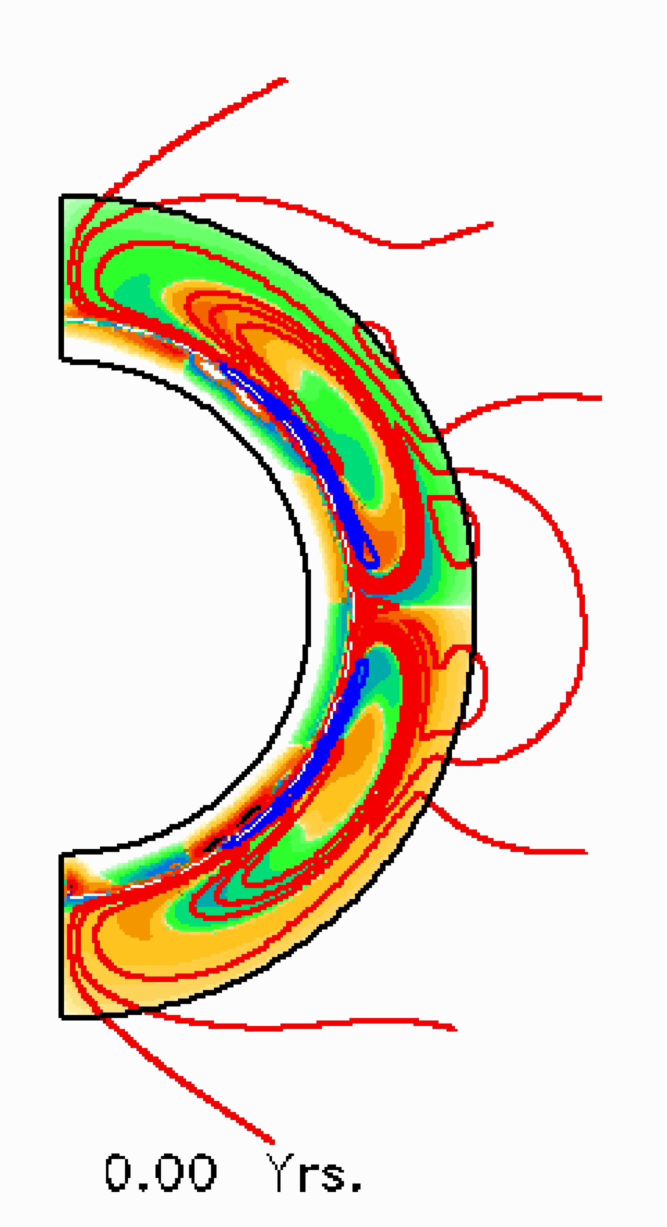
$$\Delta\Omega \approx \Delta z(d\Omega / dz)$$

$$\approx 0.2\Omega$$

$$\approx 5.6 \times 10^{-7}\ \ [Hz]$$

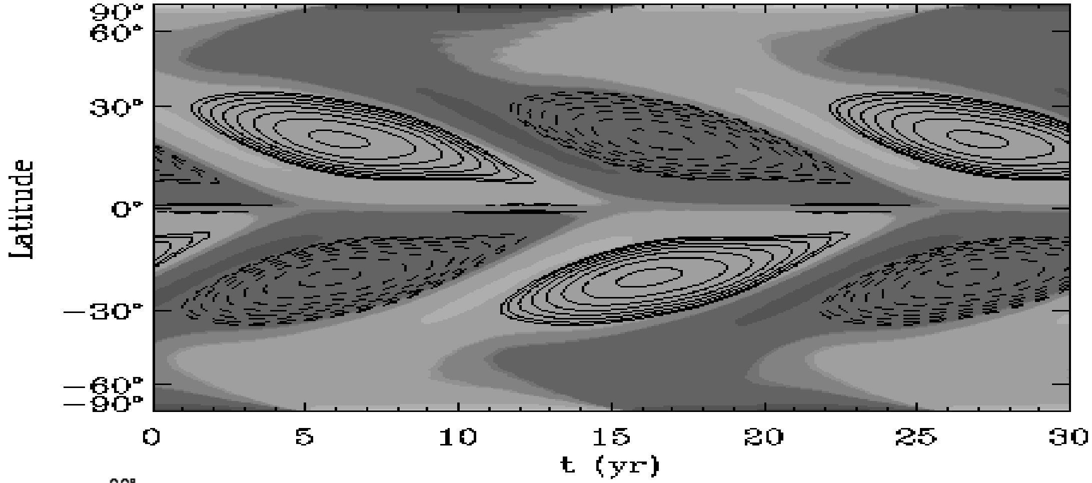

Bp
Rp
Δr
Δz
+
−
Base of convection zone

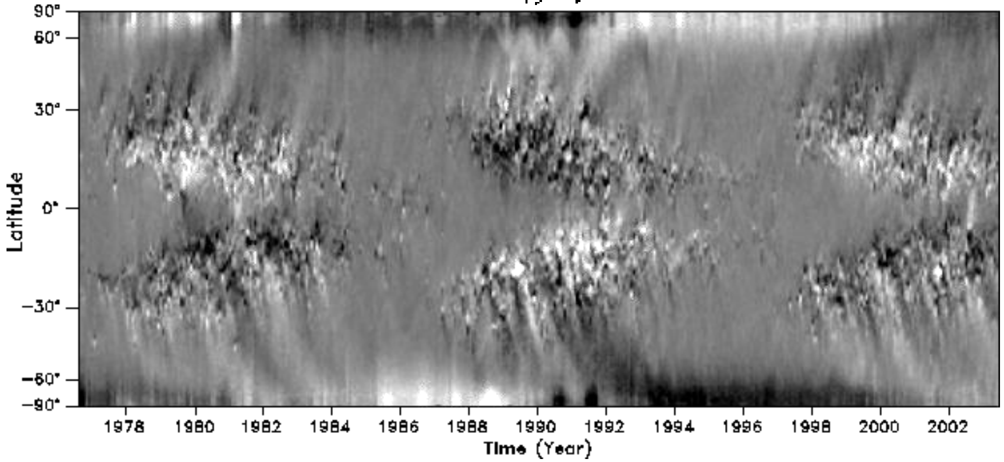
Flux Transport Model (Dikpati, Choudhuri, ,,)



Contours: toroidal fields at CZ base

Gray-shades: surface radial fields



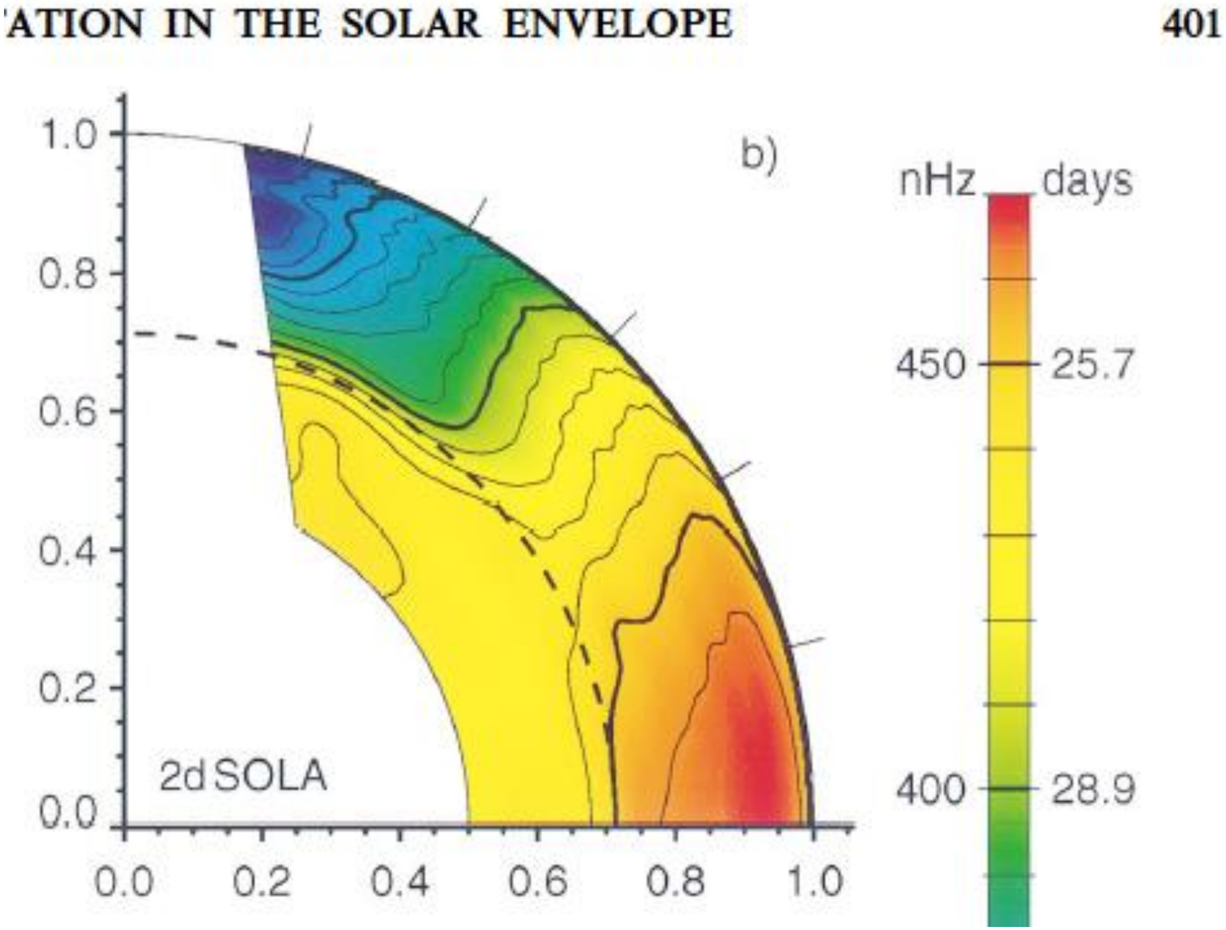


Observed NSO map of longitude-averaged photospheric fields

Dikpati, de Toma, Gilman, Arge & White, 2004, ApJ, 601, 1136

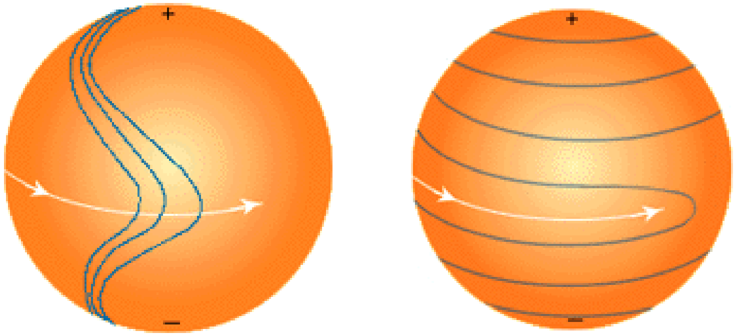
Solar differential rotation

(SOHO/MDI, Schou et al. 1998)



$\Omega/2\pi$

How to make large star spot ?



Rotation is slow near poles

Rotation is fast near equator

$$\frac{\partial B_t}{\partial t} = rot\ (V \times B) \approx rot\ (r\Omega \times B) \approx \Delta\Omega\ B_p$$

$$\frac{d\Phi_t}{dt} \approx \frac{\Delta\Omega}{2\pi}\Phi_p \approx \frac{\Delta\Omega}{2\pi} B_p 2\pi R_p \Delta r$$

$$t \approx 40 \left(\frac{\Phi_t}{10^{24}\, Mx}\right)\left(\frac{\Phi_p}{10^{22}\, Mx}\right)^{-1}\left(\frac{\Delta\Omega}{5.6\times10^{-7}\, Hz}\right)^{-1} years$$

$$\Delta\Omega \approx \Delta z (d\Omega / dz) \approx 5.6\times 10^{-7}\ [Hz]$$

Poloidal magnetic flux

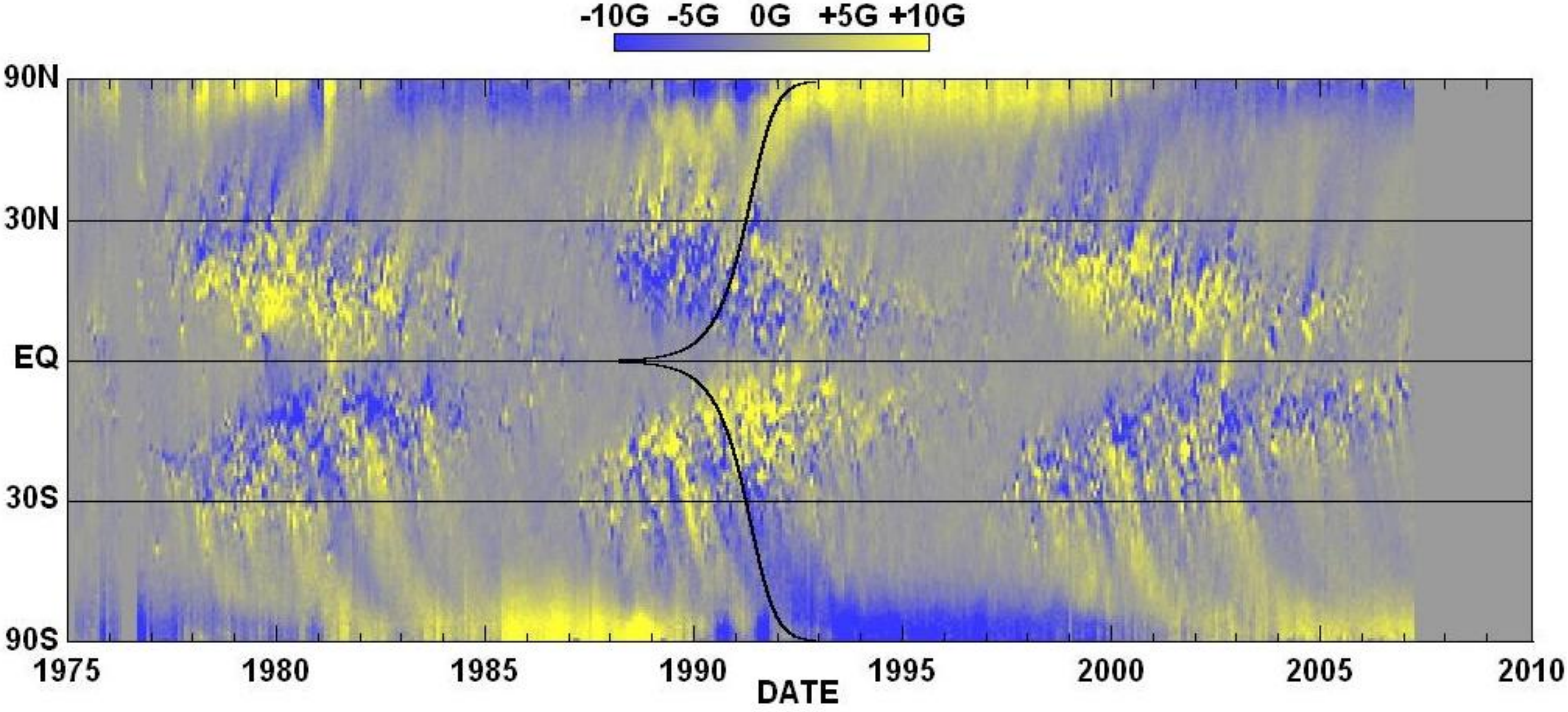
$$\Phi_p \approx B_{polarCH}\ \pi R_{polarCH}{}^2$$

$$\approx 10 \times 3 \times (0.3 R_\Theta)^2 \approx 1 \times 10^{22}\ Mx$$

$$B_{polarCH} \approx 10\ Gauss$$

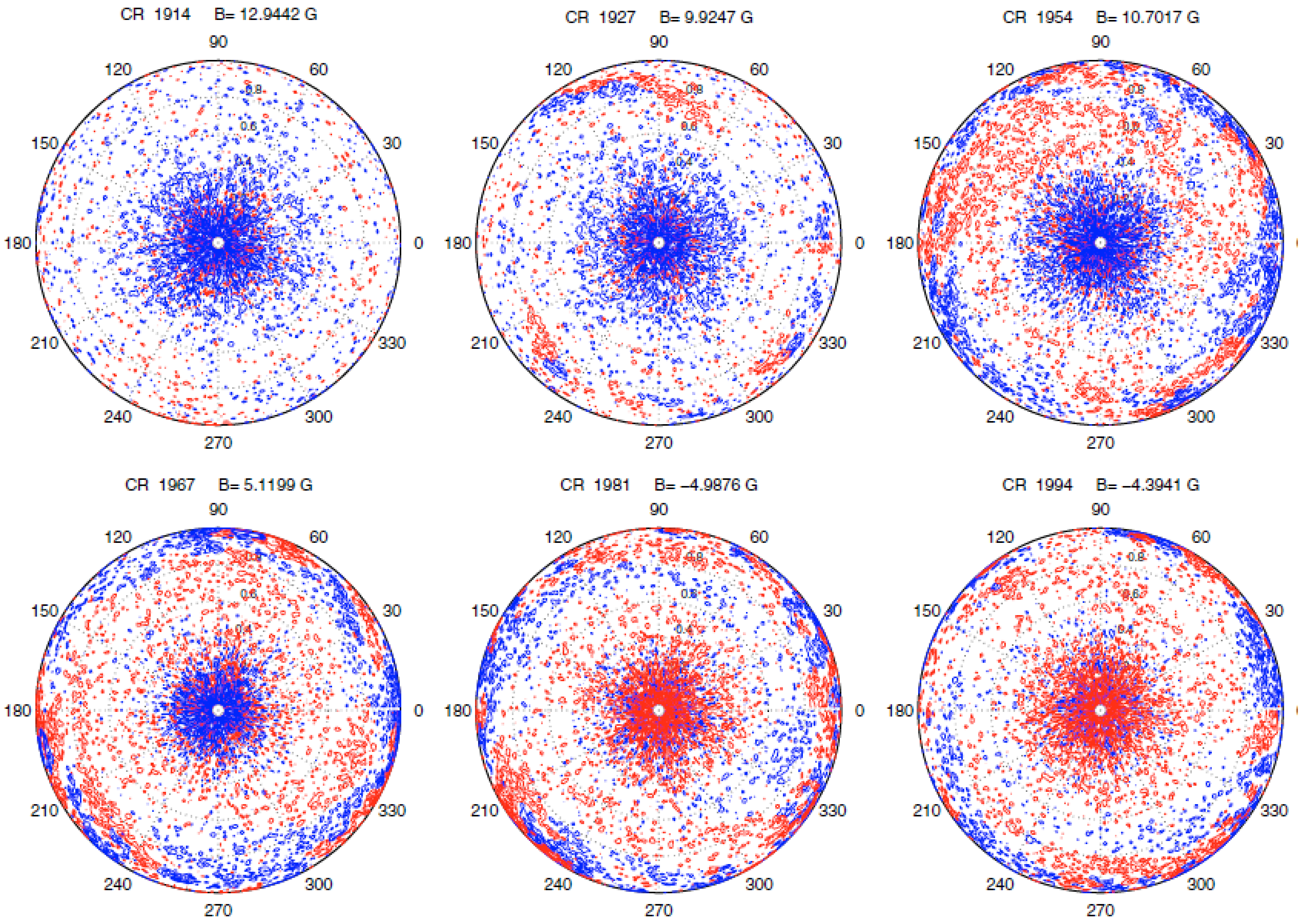
$$R_{polarCH} \approx 0.3 R_\Theta \approx 2 \times 10^{10}\ cm$$

Observations of solar magnetic field



NASA/MSFC/NSSTC/Hathaway 2007/05

Benevolenskaya A&A（2004）



Benevolenskaya A&A (2004)

1.5-2.5 x 10^22 Mx
In the polar region

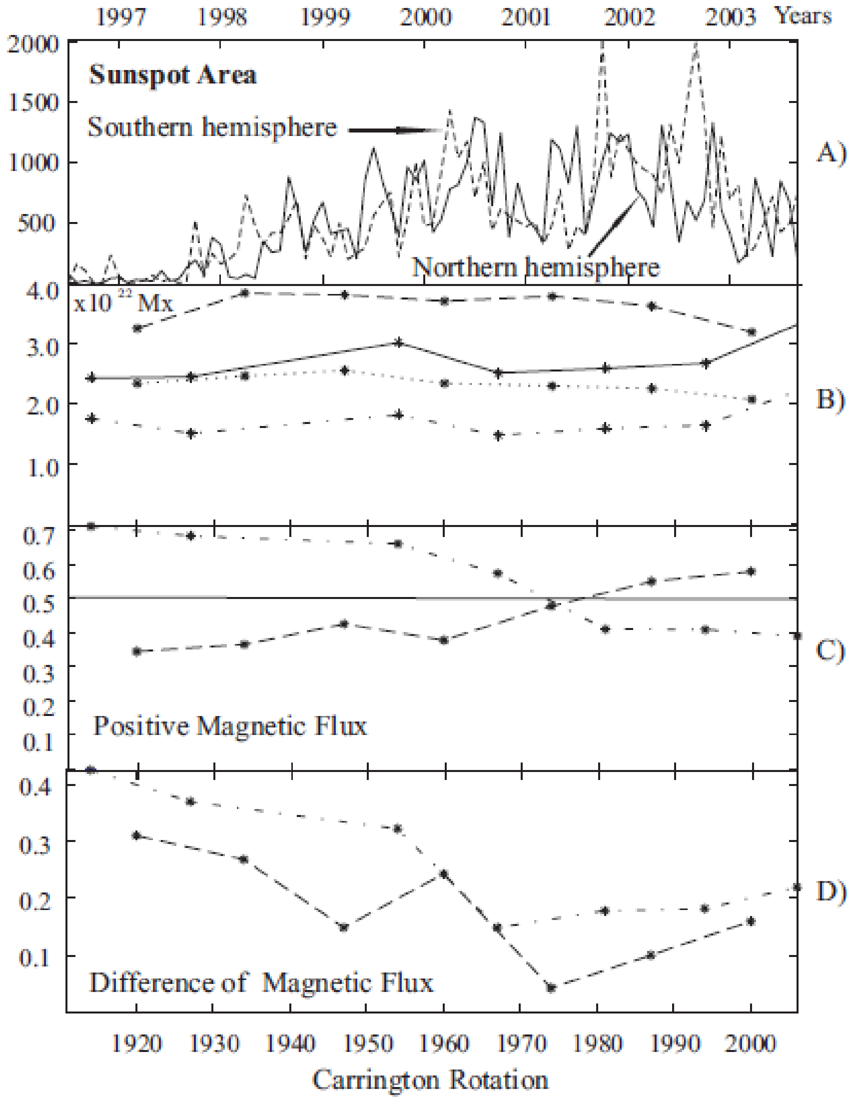


Fig. 3. Plots of: **A)** sunspot area in the Southern hemisphere (dash line) and in the Northern hemisphere (solid line); **B)** magnetic flux of the radial field component in the latitude zones from 78° to 88° in Northern (dash and dots line) and Southern hemispheres (dash line); C) the relative positive polarity parts of magnetic flux in Northern and

is estimated for different latitudinal zones. It is estimated that the total magnetic flux of the Northern polar zone, from 78° to 88°, is about 1.5–1.7 × 10^{22} Mx, and it is about 2.3–2.5 × 10^{22} Mx in the similar Southern polar zone. The new data reveal an

Necessary time to generate magnetic flux producing superflares

$$\frac{d\Phi_t}{dt} \approx \frac{\Delta\Omega}{2\pi}\Phi_p \approx \frac{\Delta\Omega}{2\pi}B_p 2\pi R_p \Delta r$$

$$t \approx 40\left(\frac{\Phi_t}{10^{24}\,Mx}\right)\left(\frac{\Phi_p}{10^{22}\,Mx}\right)^{-1}\left(\frac{\Delta\Omega}{5.6\times10^{-7}\,Hz}\right)^{-1} years$$

⇒The necessary time to generate magnetic flux of 10^{24} Mx that can produce superflares of 10^{35} erg are 40 years (<< 5000 years) (but > 11 years)

⇒ only 8 years (< 11 years) to generate $2\text{x}10^{23}$ Mx producing superflares of 10^{34} erg => easily occur !?

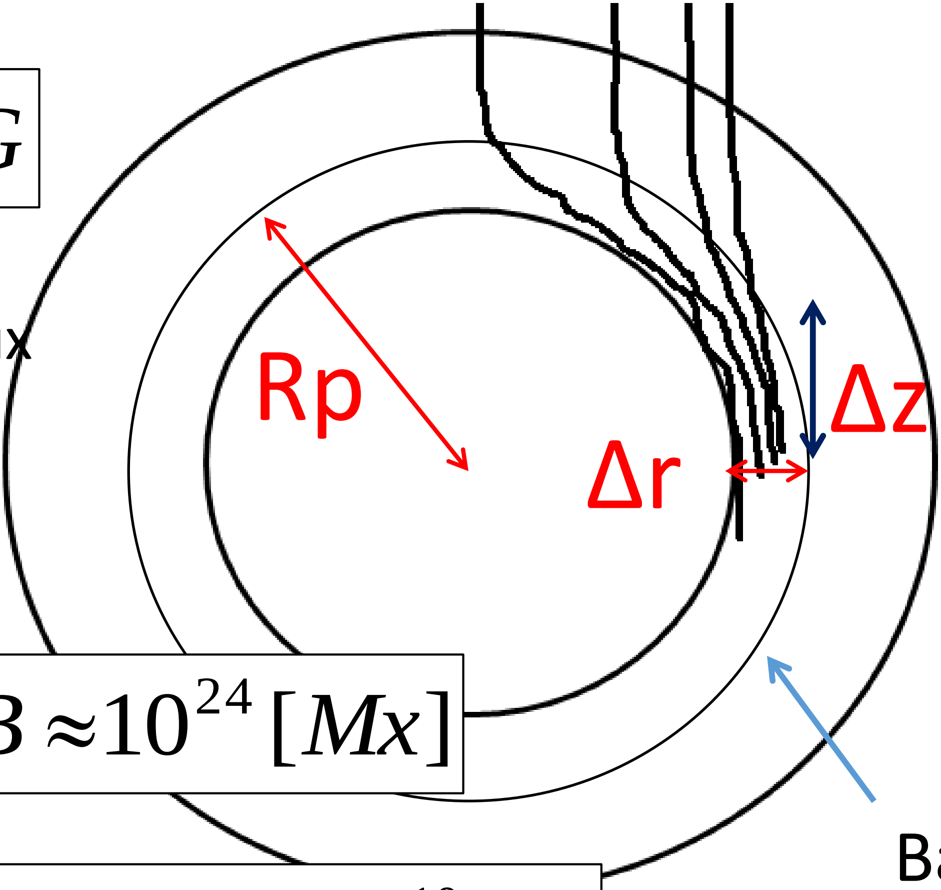
Is it possible to store such huge magnetic flux below the base of convection zone ?

=> big challenge to dynamo theorist !

4. Storage of Magnetic Flux just below the Base of the Convection Zone

How much magnetic flux can be stored in the overshoot layer ?

$$B \approx 10^5\,G$$

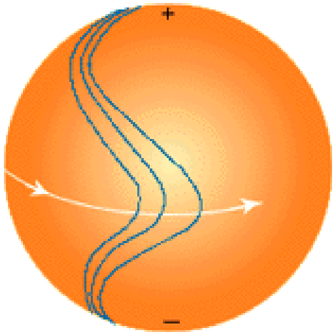


Magnetic flux stored in Overshoot Layer

$$\Phi \approx d\Delta z B \approx 10^{24}\,[Mx]$$

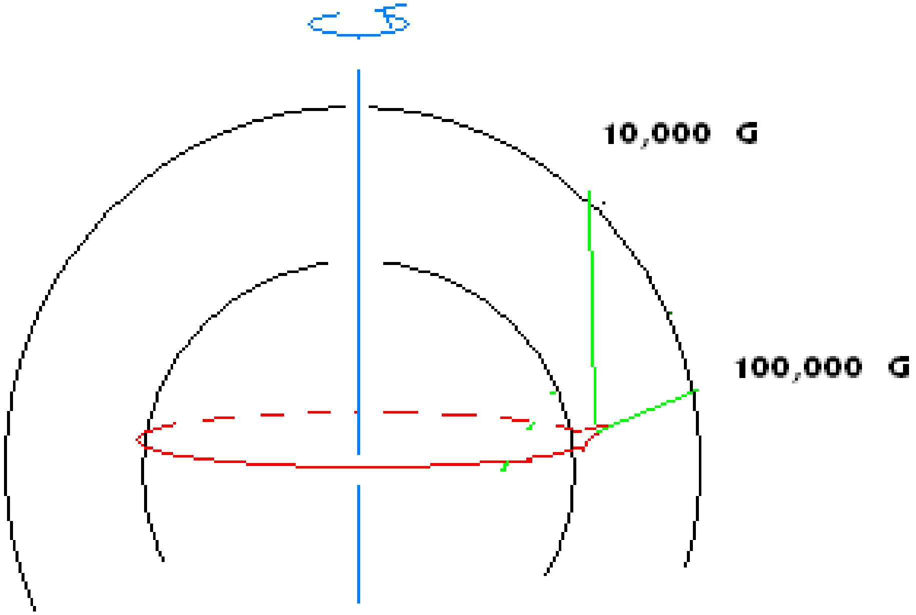
$$d \approx 10^9\ cm \qquad \Delta z \approx 10^{10}\,cm$$

Base of convection zone



3D dynamics of flux tubes in solar convection zone

(Choudhuri & Gilman 1987; Choudhuri 1989; D'Silva & Choudhuri 1993; Fan et al. 1993; Caligari et al. 1995)



Equipartition B at bottom is 10,000 G, but such fields are diverted by Coriolis force (Choudhuri & Gilman 1987)

Only 100,000 G fields can emerge at sunspot latitudes

From Choudhuri

Dynamo Energy Problem

Kinetic energy of Differential rotation

$$\boxed{E_{diff} \approx \frac{\pi}{2} R^2 d \rho_0 {v_0}^2 \quad \approx 4 \times 10^{37} \ [erg]}$$

$$R \quad \approx 0.7 \times R_\Theta \approx 5 \times 10^{10} [cm], \ d \approx 10^9 [cm],$$

$$\rho_0 \approx 0.1 [g\, cm^{-3}], \ v_0 \approx 10^4 [cm\, s^{-1}]$$

$$\Phi \approx d \Delta z B \approx 10^{24} [Mx]$$

Magnetic energy of stored magnetic Flux necessary for producing superflare

$$\boxed{E_{mag} \approx 2\pi R d \Delta z \frac{B^2}{8\pi} \approx \frac{R}{4} \Phi B \approx 1.3 \times 10^{39} [erg]}$$

How magnetic energy can be stored ?

One idea

Magnetic field intensification by Explosion of magnetic flux tube (Hotta et al. 2013)

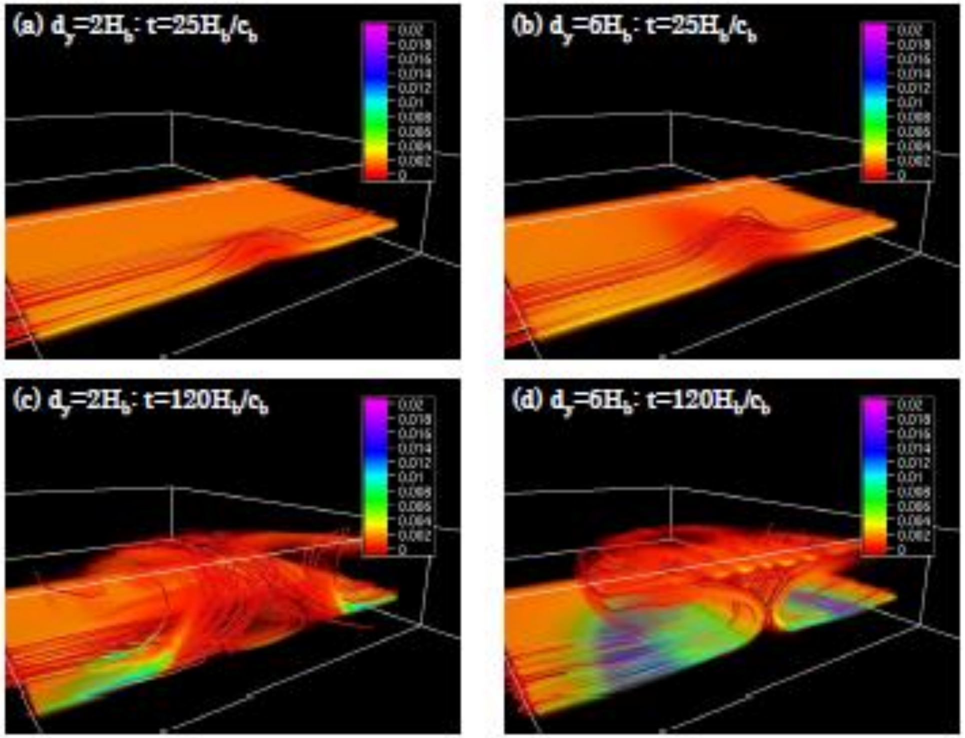


Fig. 1.— The volume-rendered magnetic energy and the magnetic field lines. The panels a and c (b and d) show the results with $d_y = 2H_b$ ($d_y = 6$b). For convenience of presentation, we show only the solution in the center region cut at $y = 0$. The color shows the magnetic energy normalized by the gas pressure at $z = 0$ (p_b). This visualization is created using the software of VAPOR (Clyne & Rast 2005; Clyne et al. 2007).

5. Case of Rapidly Rotating Stars

Flare frequency vs rotation speed

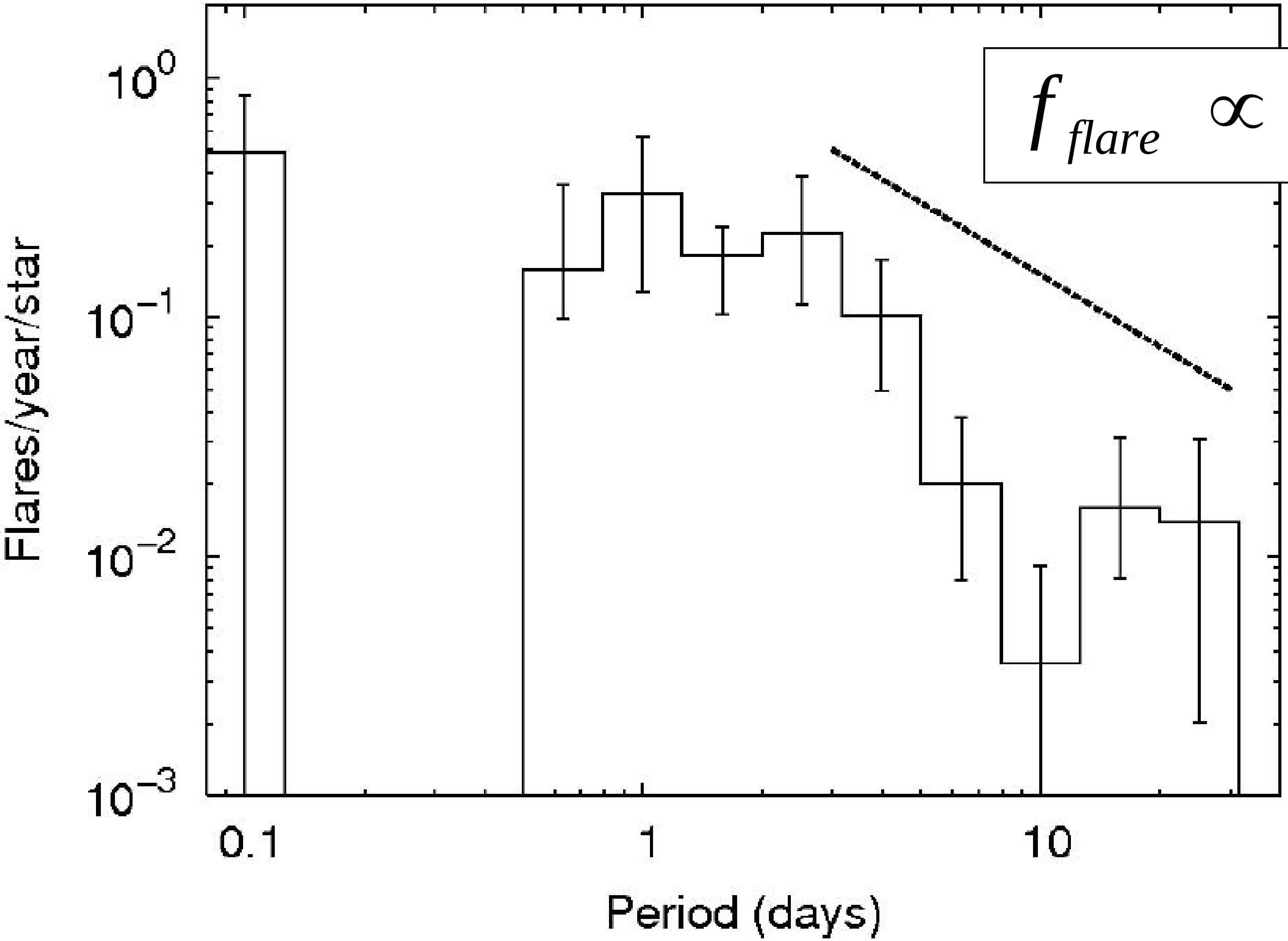
$$\boxed{\frac{d\Phi_t}{dt} \approx \frac{\Delta\Omega}{2\pi} B_p \; S}$$

- If $\boxed{\Delta\Omega \;\propto\; \Omega}$

$$\boxed{f_{dynamo} \approx \frac{d\Phi}{dt} \Big/ \Phi \propto \Omega} \Rightarrow \boxed{f_{flare} \;\propto\; \Omega}$$

If the flare frequency (f_{flare}) is correlated with magnetic flux generation rate, then we can relate the observed flare frequency with the rotation speed

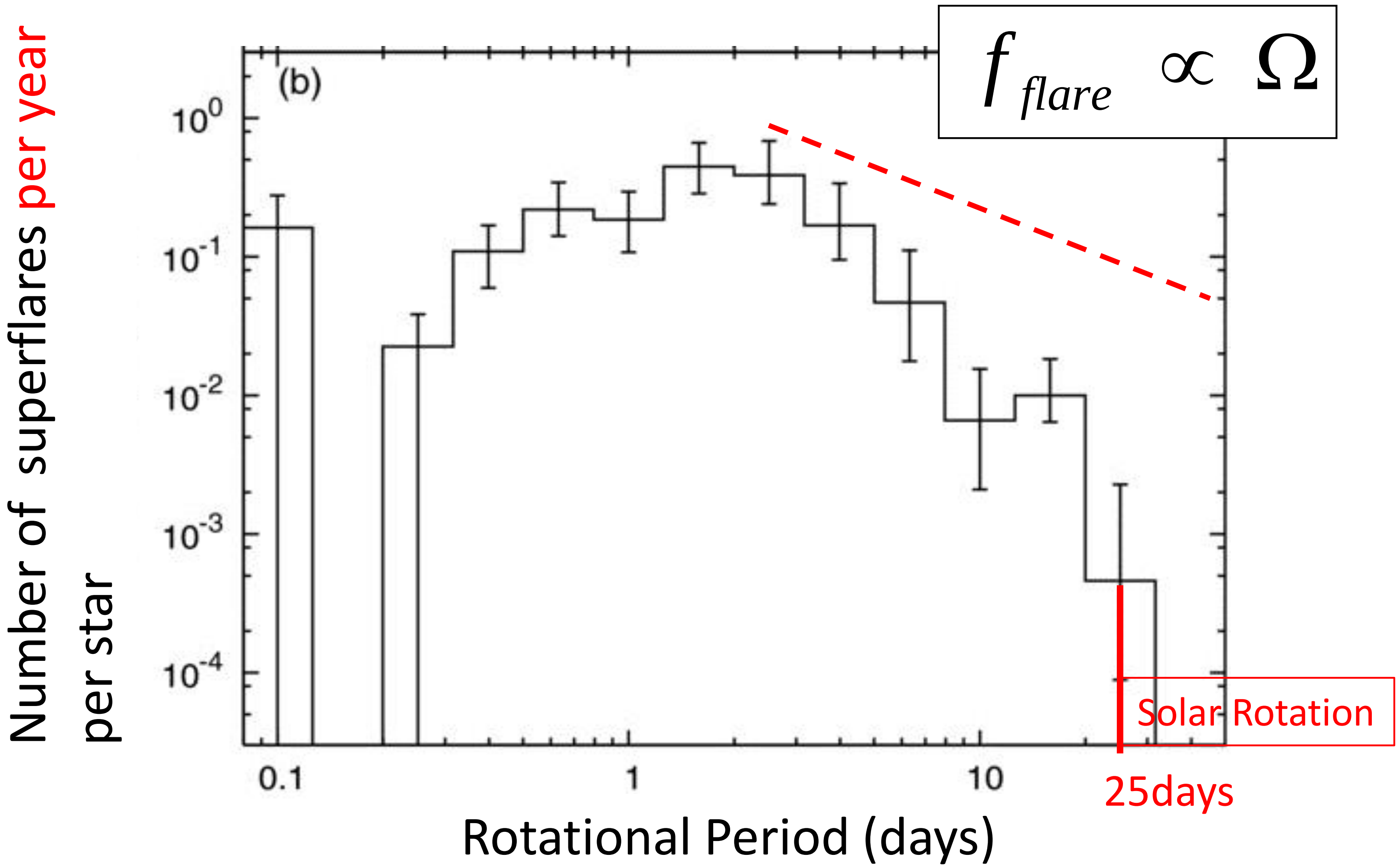
Observed superflare frequency vs rotation period (Maehara+ 2012)



$$f_{flare} \propto \Omega$$

Frequency of superflares

(New data: NotsuY+ 2013)



$$f_{flare} \propto \Omega$$

Activity-Rotation relationship (Guedel 2004 AApRev 12, 71)

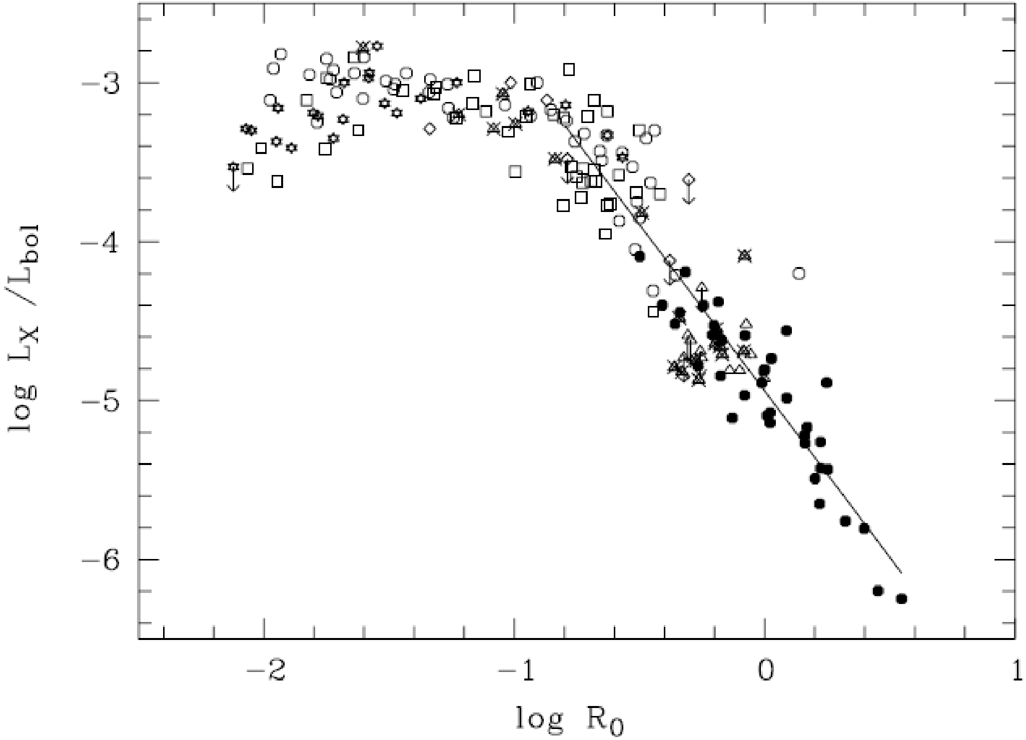


Fig. 4. Activity-rotation relationship compiled from several samples of open cluster stars. Key to the symbols: circles: Pleiades; squares: IC 2602 and IC 2391: stars: *α* Per; triangles: single Hyades stars; crossed triangles: Hyades binaries; diamonds: IC 4665; filled symbols: field stars (figure courtesy of S. Randich, after Randich et al. 2000, by the kind permission of the Astronomical Society of the Pacific)

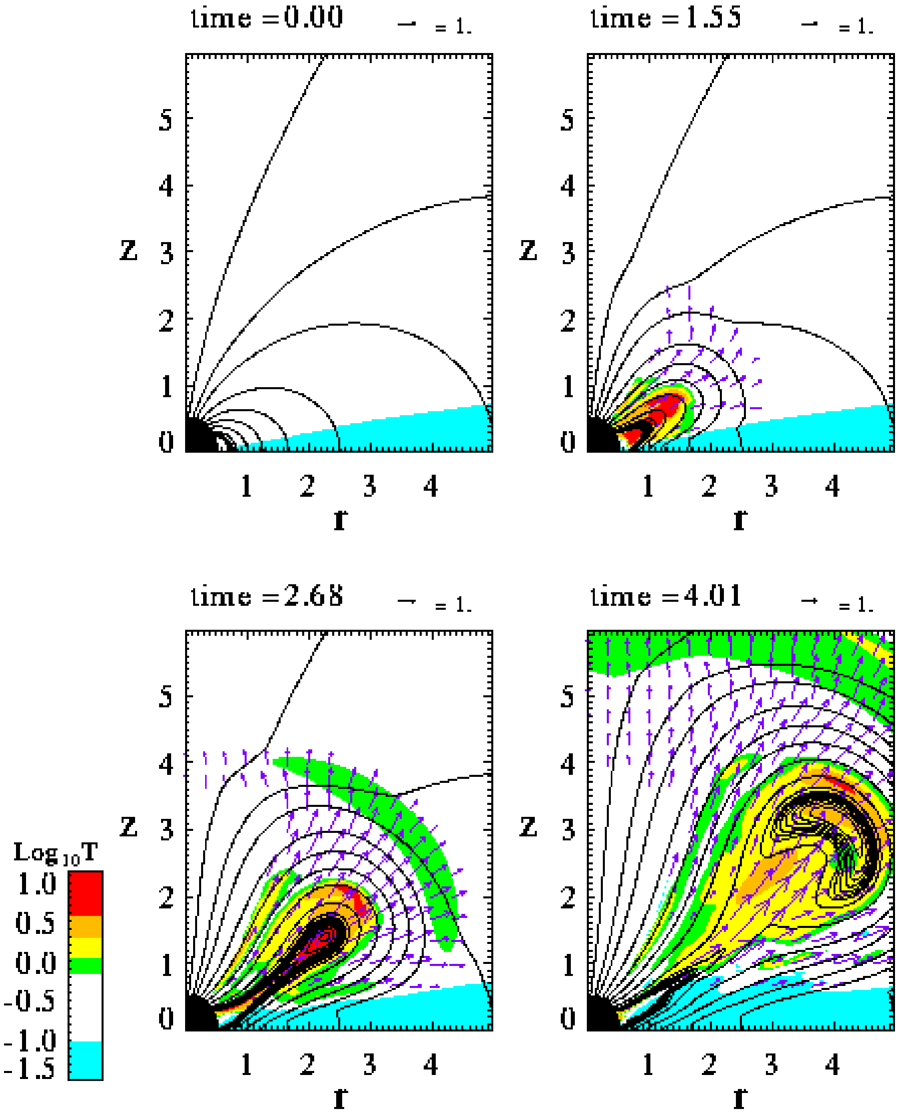
Ro = P/tau
(Rossby number)

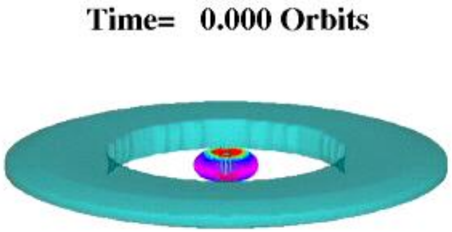
P= rotation period
Tau = convection turn over time

6. Is it necessary to have a Hot Jupiter for the production of Superflares ?

Effect of Magnetic Interaction

MHD reconnection model of protostellar flare (Hayashi, Shibata, Matsumoto 1996)





Effect of Tidal force

$$F_{tidal} \approx 2 \frac{GM_p}{d^2}\frac{R_*}{d}$$

$$\frac{\Delta g}{g} \approx \frac{F_{tidal}}{F_{gravity}} \approx 2\times\left(\frac{M_p}{M_*}\right)\left(\frac{R_*}{d}\right)^3 \approx 2\times 10^{-6}\left(\frac{M_p/M_*}{10^{-3}}\right)\left(\frac{R_*/d}{10^{-1}}\right)^3$$

$$\frac{F_{coriolis}}{F_{gravity}} \approx \frac{2V_{conv}\Omega}{GM_\Theta/R_\Theta^2} \approx 4\times 10^{-7}\left(\frac{V_{conv}}{10^3 cm/s}\right)\left(\frac{R_\Theta\Omega}{2km/s}\right)$$

Tidal force is more important than Coriolis force

summary

- If magnetic flux is generated by differential rotation at the base of the convection zone, it is possible that the present Sun would generate a large sunspot with a total magnetic flux of ~ 2 x 10^23 Mx (= G cm2) within one solar cycle period, and lead to superflares with an energy of 10^34 erg. To store a total magnetic flux of ~ 10^24 Mx necessary for generating 10^35 erg superflares, it would take ~ 40 yr.
- Hot Jupiters do not play any essential role in the generation of magnetic flux in the star itself, if we consider only the magnetic interaction between the star and the hot Jupiter.
- Our simple calculations, combined with Maehara et al.'s analysis of superflares on Sun-like stars, show that there is a possibility that superflares of 10^34 erg would occur once in 800 yr on our present Sun.

Thank you for your attention