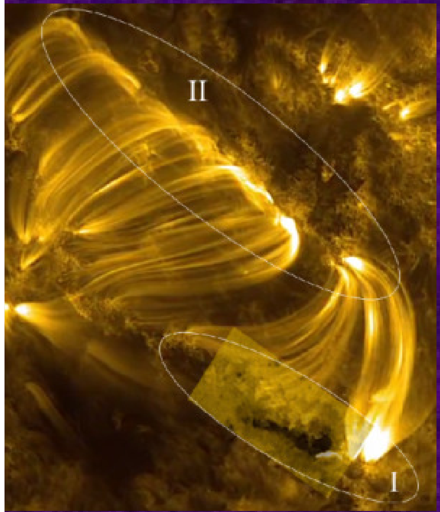

Can Superflares Occur on the Sun ?
A View from Dynamo Theory

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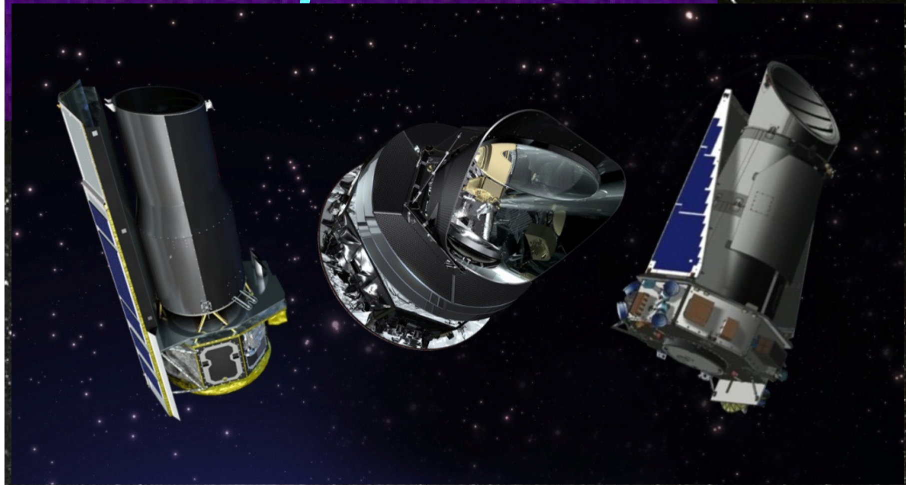
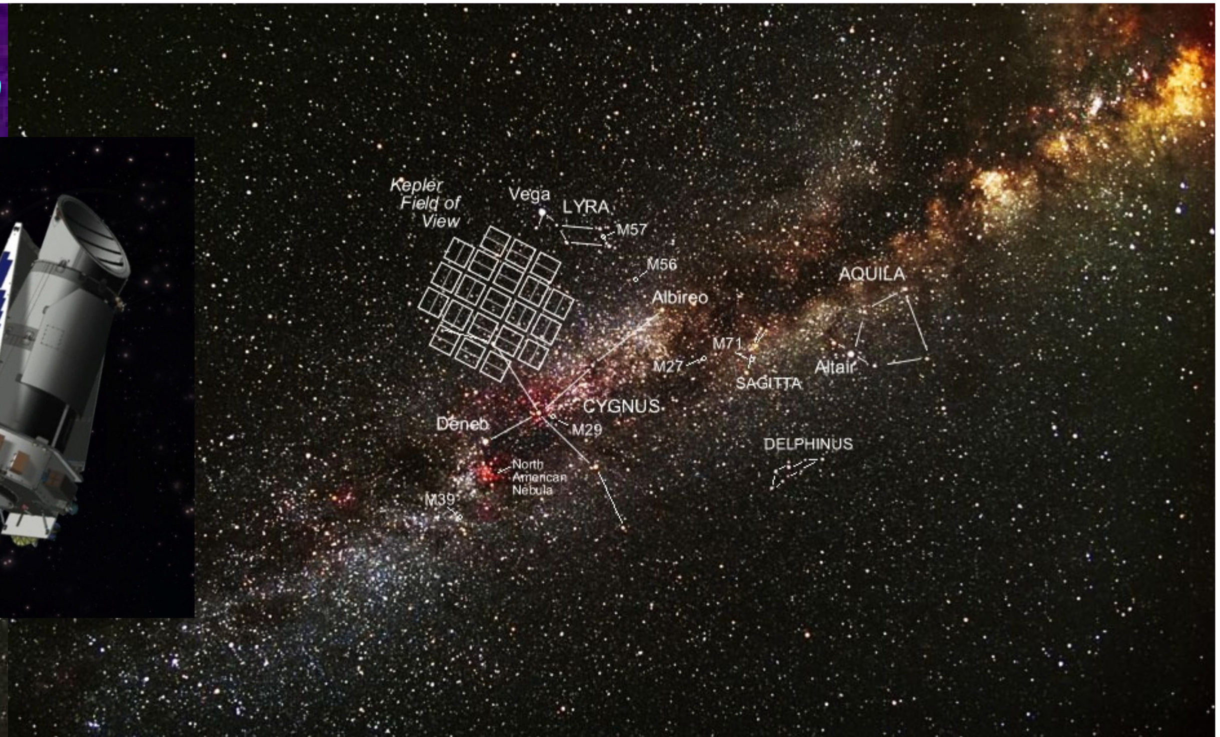
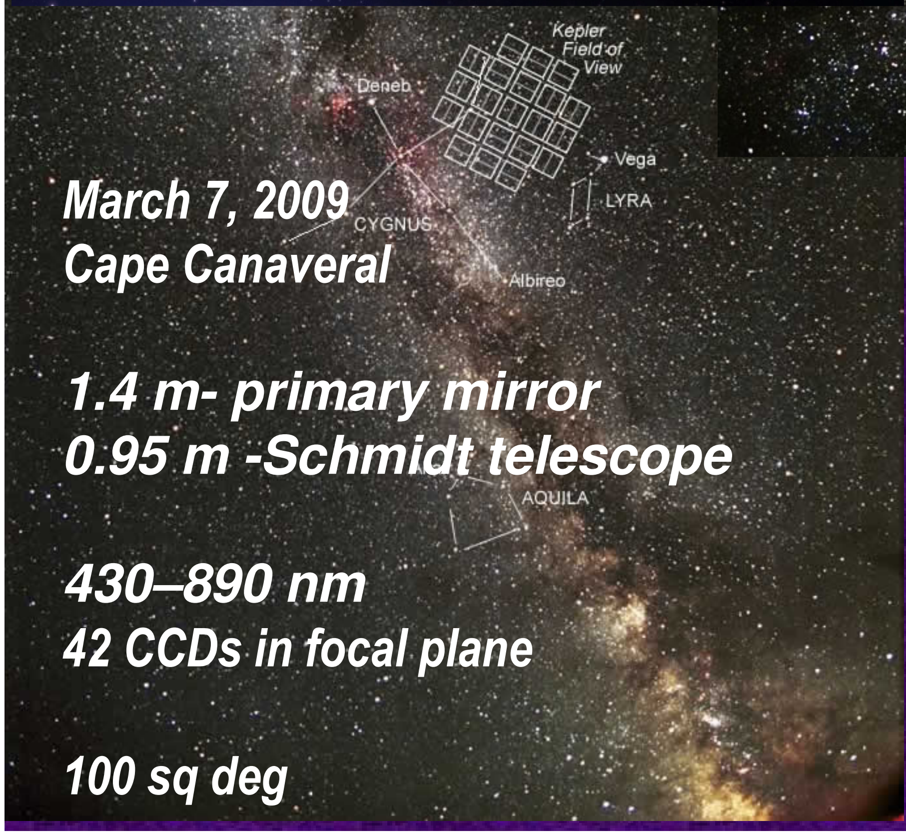
arXiv: 1710.00015 (Oct 2017) ;
Астрон. журн. 2018, Т.95 (1) С. 78

Bulgaria, June 2018

The Kepler mission





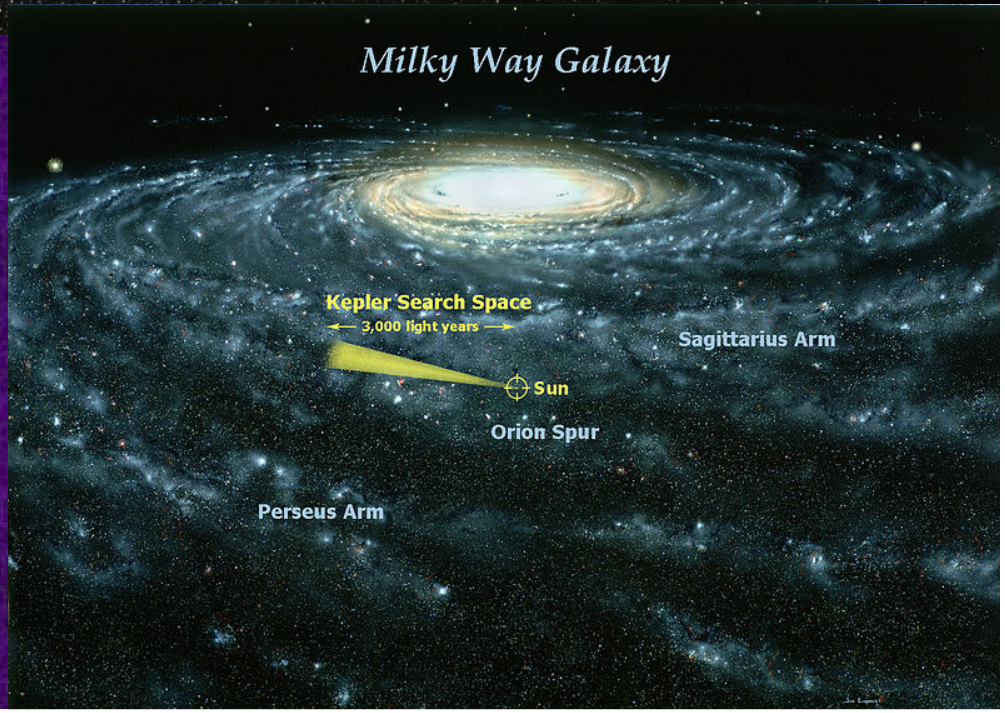


March 7, 2009
Cape Canaveral

1.4 m- primary mirror
0.95 m -Schmidt telescope

430–890 nm
42 CCDs in focal plane

100 sq deg

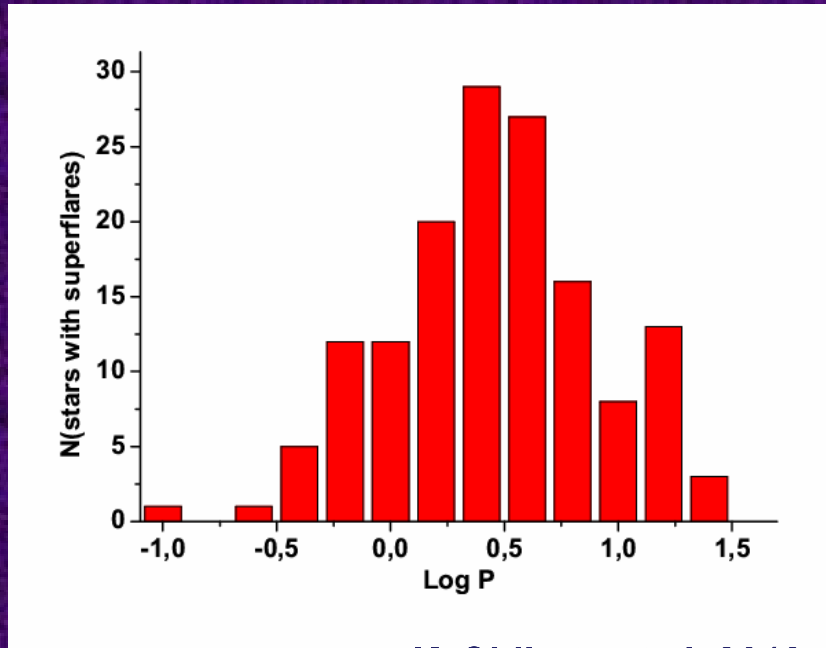


Flares on G stars from the Kepler observations

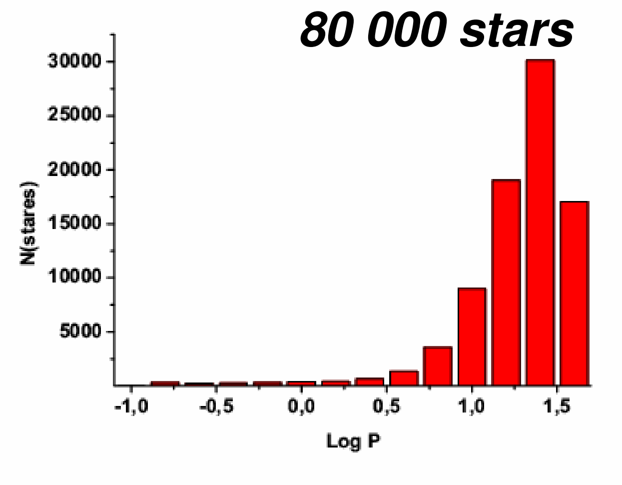
- April 2009 – May 2013
-
- 160 000 stars
- H. Maehara et al. (2012) , Nature

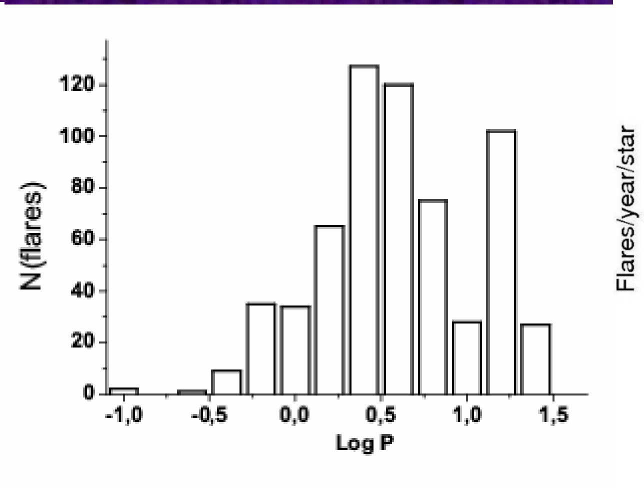
~1547 superflares (up to 5×10^{33} erg) on 279 G type dwarfs, including 44 superflares on the solar analogues during long-term monitoring

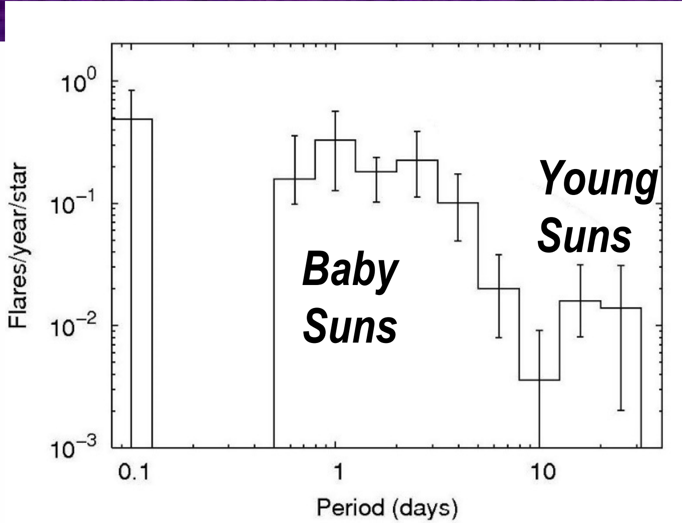
- or 57 superflares over 500 days



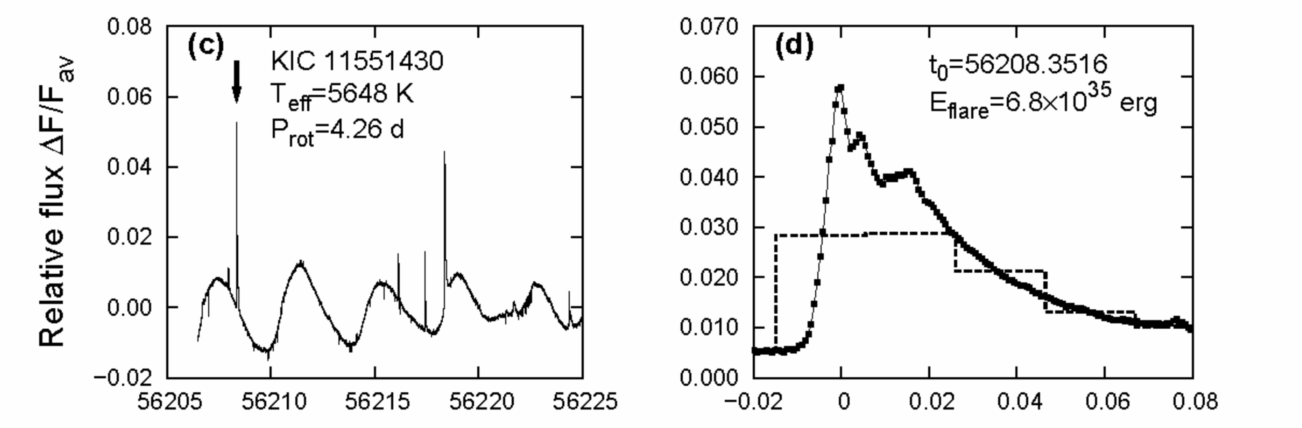
K. Shibata et al. 2013







Superflares on G stars discovered with the Kepler mission



Maehara et al. 2015 :
187 superflares on 23 solar-type G stars

The total flare energy $E = 10^{33} – 10^{36}$ erg

30 min - Long-Cadence data

1 min – Short-Cadence mode

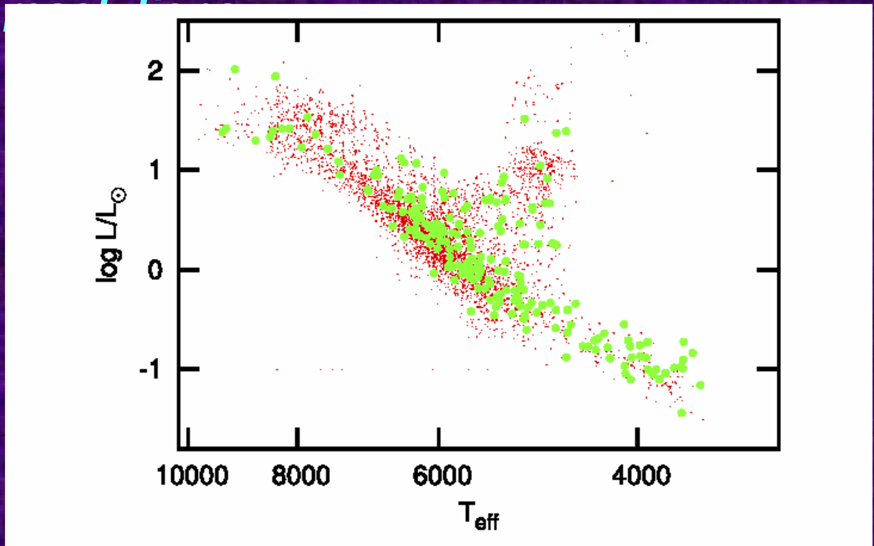


Figure 4. Theoretical H–R diagram for *Kepler* flare stars (large filled circles) observed in SC mode using stellar parameters in the KIC. The small dots are stars which were examined but no flares detected.

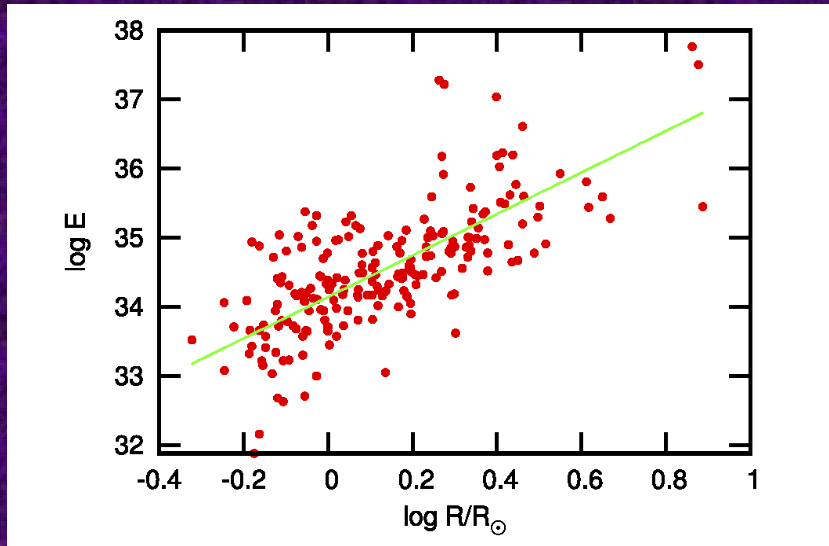
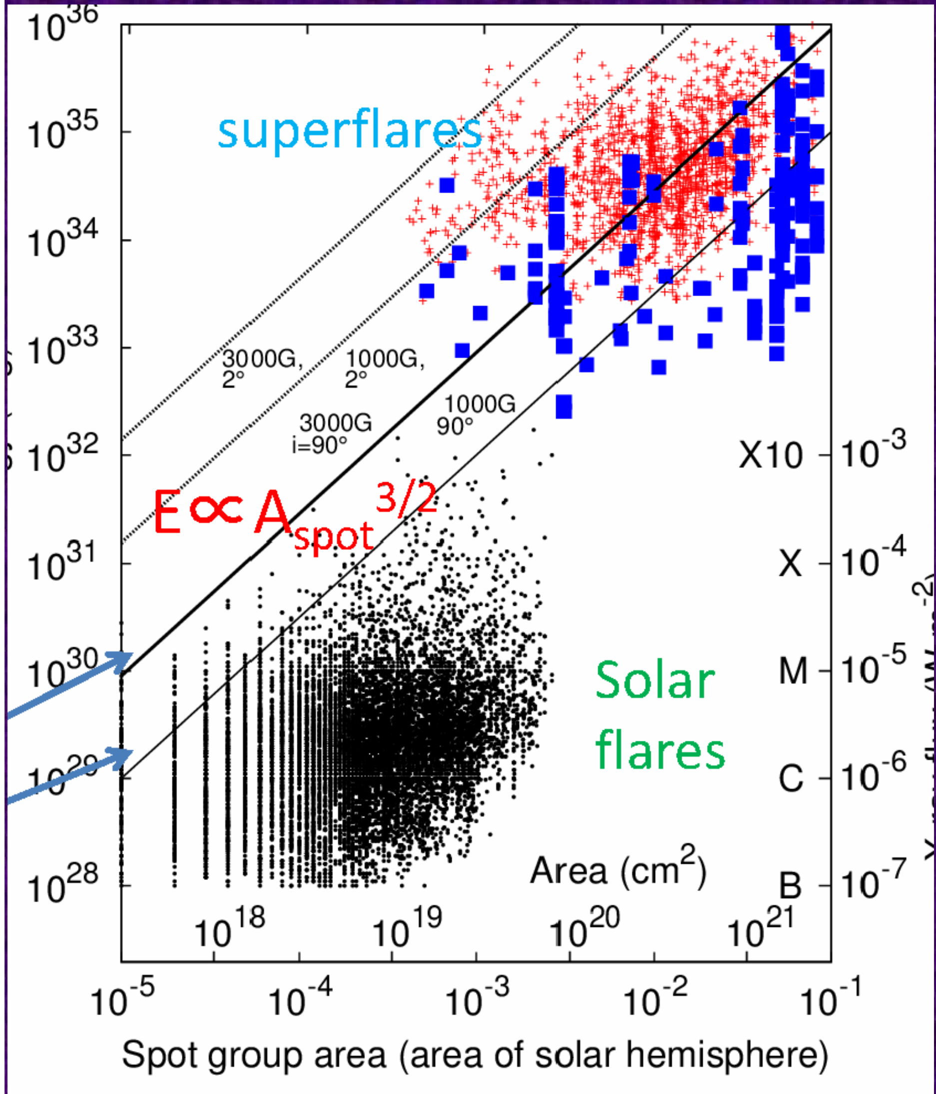


Figure 11. The median flare energy, (E, in erg) as a function of stellar radius, R. The straight line is $\log E = 3\log R/R_\odot + 34.14$, indicating that the flare energy is proportional to R^3.

Balona, 2015

Flare energy and relative spot group area on the Sun and other stars

E_tot, эрг   Wt/ m^2



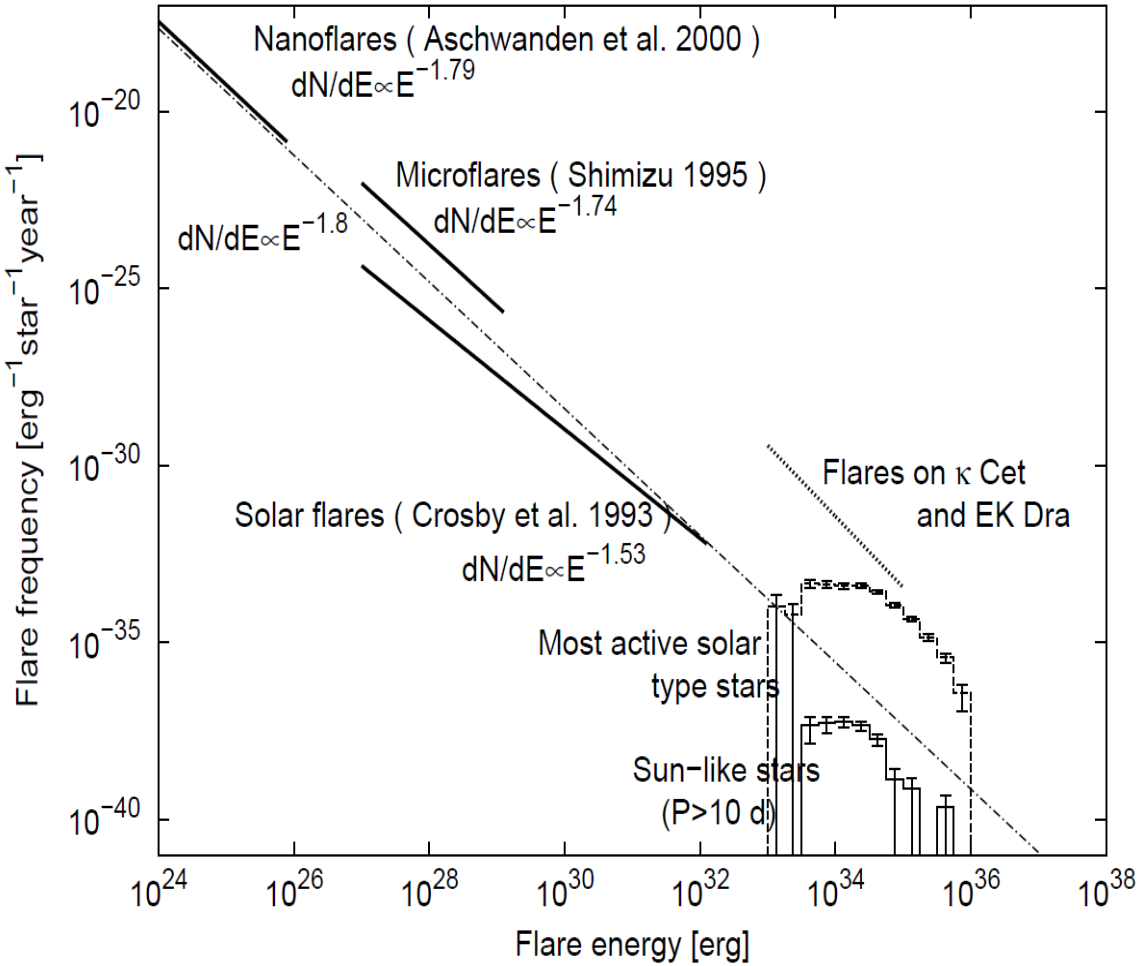
Filled-squares (blue) and small-crosses (red) indicate superflares on G-type main sequence stars detected from short - (Maehara, 2015) and long-cadence data (Shibayama et al. 2013) respectively.

The total flare energy E is a function of amplitude, mean magnetic field and inclination of rotation axis of a star to line of sight.

# Photosphere	P_rot	Relative Spot Area
Act Sun	25 d	0.3%
Young Sun	10 d	3%
BE Cet	8 d	3%
EK Dra	3 d	10–20%

Flare Occurrence Frequency on G stars

Shibayama et al. 2013



Flares with the total energy 10^{35} erg can occur on the Baby Sun (with P_rot < 3 day) about of one event per year

Stars -Toward a model of superflares

Comparison with the present day-Sun:

the averaged over the Carrington rotation the magnetic fields of the Sun as a stars at high activity level (for example, in 1980), |B_l| = 0.5 G.

The mean value of |B_l| for G-type stars is = 4.72 ± 0.53 G , i.e. approximately 5 G

(Marsden et al. 2013) – "Bcool collaboration".

THUS, the magnetic field of Young Sun is 10 times stronger than that in the present epoch and this is not due to large spottedness

Young Suns:

The maximal possible flare energy of G dwarfs with solar-type activity with an established cycle is close to 10^{34} erg.

The syndrom of large solar flares is an effective particle acceleration

Maehara et al. 2015 : 1547 single solar-like stars
with 5300 K < T_{eff} < 6300 K and 4.0 < log g< 4.8.
187 flares with the total energy from 2×10^{32} erg to 8×10^{35} erg
were registered in the only 23 such stars

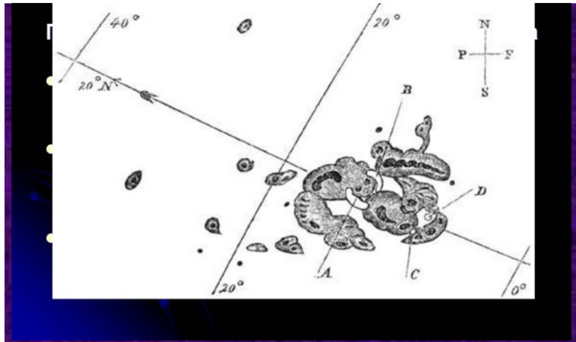
The mean flare occurrence frequences
for events with the total energy :

10^{33} erg – one event per 70 years,
10^{34} эрг occurs once in about 500 years
10^{35} эрг – once in about 4000 years

The average rate of appearance of an X100 class flare on a star
with P_rot = 25 days, like the Sun, is one event in 500-600 years

Note that only 0.2 to 0.3% of solar-type stars show superflares .

The origin of superflares on G-type stars of different ages
and their maximum energy are discussed in more details by
Katsova & Livshits Solar Phys. 2015 V. 290 P. 3663



- *On September 1–2, 1859, one of the largest recorded geomagnetic storms (as recorded by ground-based magnetometers) occurred. Auroras were seen around the world, those in the northern hemisphere as far south as the Caribbean; those over the Rocky Mountains in the USA were so bright that the glow woke gold miners, who began preparing breakfast because they thought it was morning. People in the northeastern United States could read a newspaper by the aurora's light. The aurora was visible as far from the poles as Monterrey and Tampico in Mexico, Queensland, Cuba, Hawaii, southern Japan and China, and even at lower latitudes very close to the equator, such as in Colombia.*
- *Estimates of the storm strength range from –800 nT to –1750 nT.*
- *Telegraph systems all over Europe and North America failed, in some cases giving telegraph operators electric shocks. Telegraph pylons threw sparks. Some telegraph operators could continue to send and receive messages despite having disconnected their power supplies.*
- ***Other extreme solar flares in the current epoch – February 1956,***
- ***August 1972, 1989, October 2003***

Other extreme solar events in the past:

Cosmogenic proxies:

C-14 (radiocarbon) - dendrochronology

Be-10 and Cl-36 - in polar ice cores

Because the half-life of C-14 is only 5730 yrs, this dating method is used only for dating things that lived within the last 50 000 yrs.

Low time resolution (annual at best)

The strongest event over the Holocene (the current interglacial period started about 11 000 yrs ago) :

774/775 AD (40 × the strongest SEP event of the instrumental era 23.Feb 1956)

993/994 AD (0.6 weaker than previous event)

Note that white-light flares can be not accompanied by a strong SEP event

Solar Energetic Particles can originate either from a solar-flare site or by shock waves associated with coronal mass ejections (CMEs). However, only about 1% of CMEs produce strong SEP events.

Radiocarbon Dating

- uses carbon-14
- carbon-14 is radioactive
- half-life is 5730 yrs
- Produced naturally from reaction between N-14 and cosmic rays
- Rate of production carbon-14 = rate of decay of carbon-14

Can superflares occur on the Sun?

*Very high-quality data on the total vector of the magnetic field in active regions and the large-scale magnetic field including the dipole field of the Sun as a star are available now. These observations make it possible to calculate **the free energy of the magnetic field in active regions** that can be released in flares. These estimates show that **even the largest active regions on the Sun are capable of producing non-stationary processes (flares and CME) with total energy not greater than 3 x10^{32} erg**. Such an upper limit for a given active region follows also from energy considerations, namely from the magnetic virial theorem (Livshits et al. 2015). There are modern spectro-polarimetric observations of the magnetic fields on active F, G, and K main-sequence stars which indicate that some fast rotating, young sun-like G stars possess magnetic fields around **5 G** (Marsden et al. 2014). Spots on these stars can cover up to **10% of a stellar surface**. These results, together with the magnetic virial theorem, imply that **the maximal possible energy of the strongest flare on these stars cannot exceed 10^{34} erg (**Katsova & Livshits 2015).*

Stronger events require for their explanation either another origin of flares or changes to the dynamo mechanism.

Dynamo is able to generate not only cycles, but also stationary configurations.

Numerical modelling experience shows that this realized in a case of anti-solar differential rotation. In this case the power of dynamo does not spend on reversal (change of the sign of the magnetic field), and its energy becomes significantly higher.

We confirm this point by calculations of numerical models of stellar dynamo with corresponding governing parameters.

Dynamo number $D = \Delta\Omega\ \alpha\ R^3 / \eta^2$

$D > 0$ for solar-type differential rotation with positive α (in the Northern hemisphere).

A reversal of the sign D switches the dynamo into a regime with much higher magnetic energy.

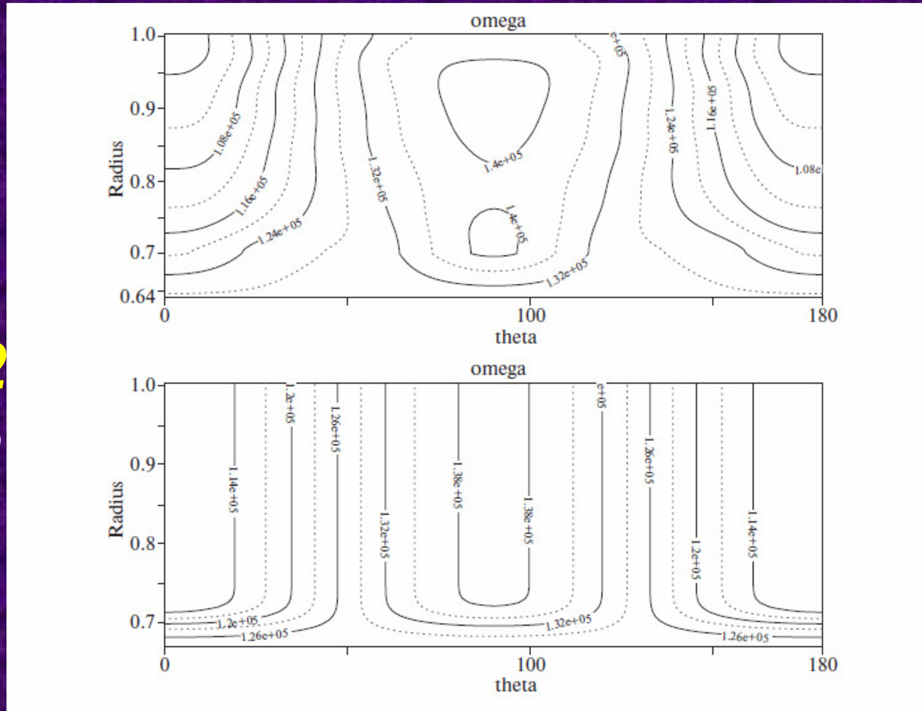


Рис. 1. Звездные кривые вращения: вверху — закон вращения по данным SOHO, внизу — закон вращения согласно [3

Stellar rotation curves: upper panel – SOHO-like, lpwer panel – Jouve et al . (2008) rotation curve

Magnetic field generation in the mean field theory is described as follows,

$$\frac{\partial \mathbf{B}}{\partial t} = \mathrm{rot}\left[\mathbf{V} \times \mathbf{B}\right] + \mathrm{rot}\alpha\mathbf{B} + \eta\Delta\mathbf{B},$$

where **V** is the mean rate of the differential rotation and **α** is a parameter of the mirror asymmetry (the rate of recovery of the toroidal magnetic field from the poloidal one due to cyclonic motions), **η** is the parameter of the turbulent diffusion

$D = \Delta\Omega\ \alpha\ R^3 / \eta^2$

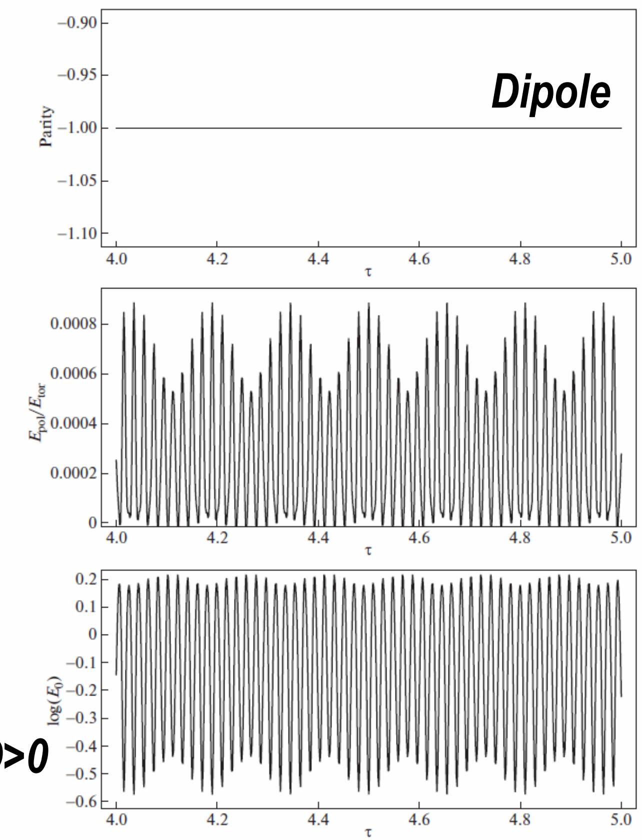


Рис. 2. Магнитное поле для закона вращения согласно [32], $D > 0$: временны́е ряды для четности (вверху), отношен магнитных энергий тороидального и полоидального компонентов (в центре) и полной энергии среднего магнитного по (внизу).

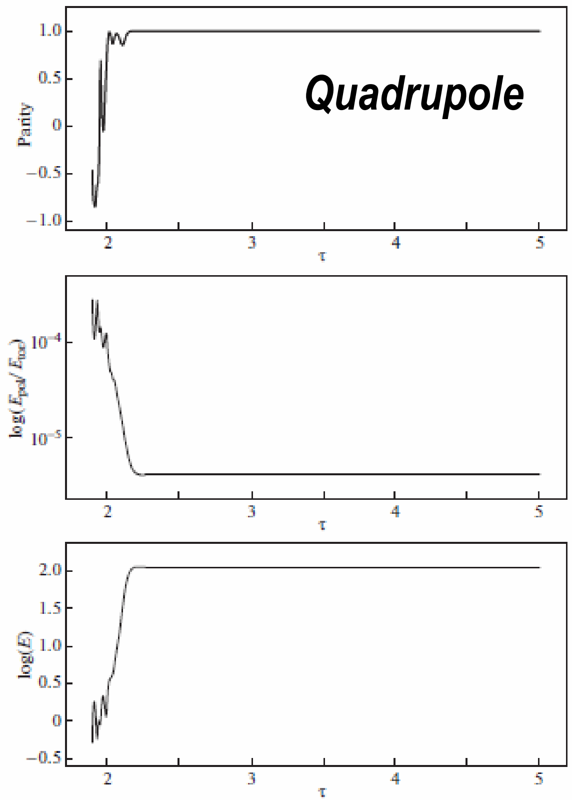


Fig. 3. Summary of the fields obtained using the rotation law [32], $D < 0$, time series for parity (top), ratio of magnetic energies of toroidal and poloidal magnetic fields (middle) and total energy of the mean magnetic field (bottom). The asymptotic ratio of E_{pol}/E_{tor} is approximately 4.1×10^{-6}.

Conclusions

Thus, the contemporary Sun

can not produce flares stronger than $3 \bullet 10^{32}$ erg.

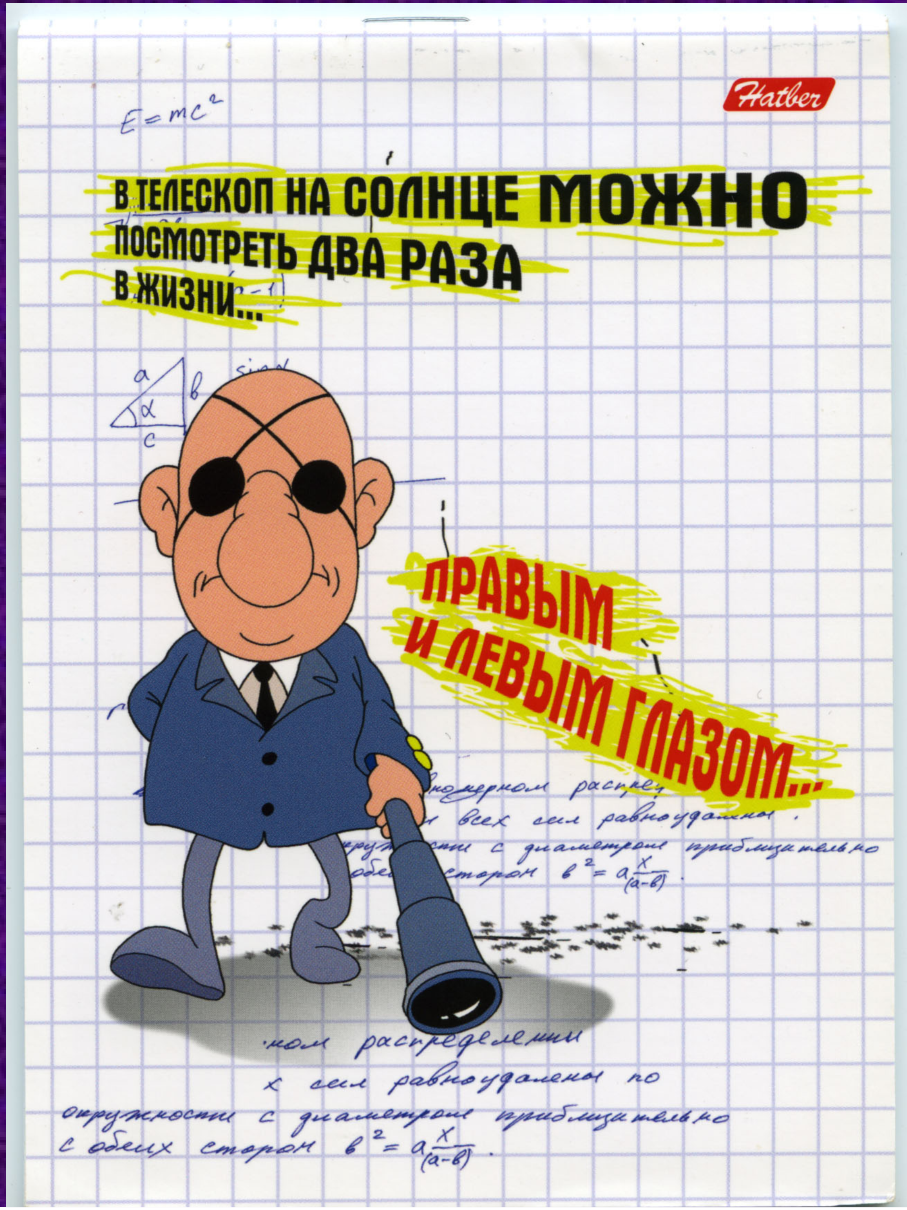
- The scenario proposed here allows us to understand how stellar dynamo can create the magnetic field whose energy exceeds significantly that of the Sun.

- The sign of dynamo sources of stars with superflares normally can be opposite to the solar case. A change of the sign of the dynamo number D can be due to anti-solar differential rotation or, possible, to anti-solar sign of the mirror-asymmetry of stellar convection (the sign of the parameter α as compared to the Sun).

- Hydrodynamics of stars with superflares can differ significantly from the solar case. These can be fast rotating young stars, subgiants and components of binary systems as well.

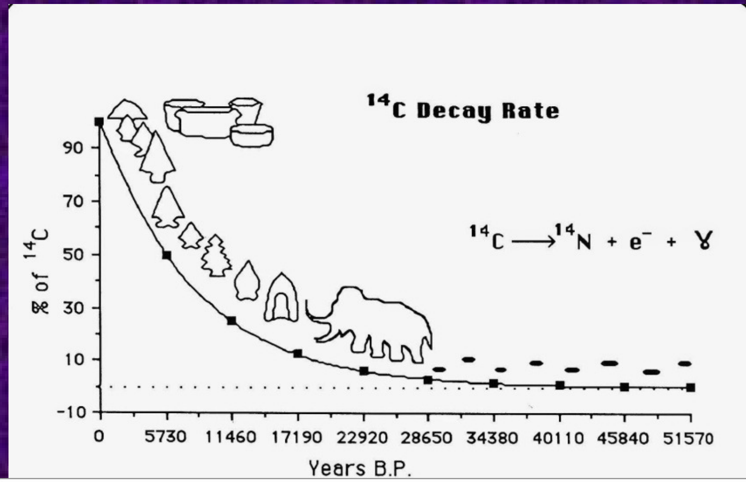
Be careful when working with the Sun!

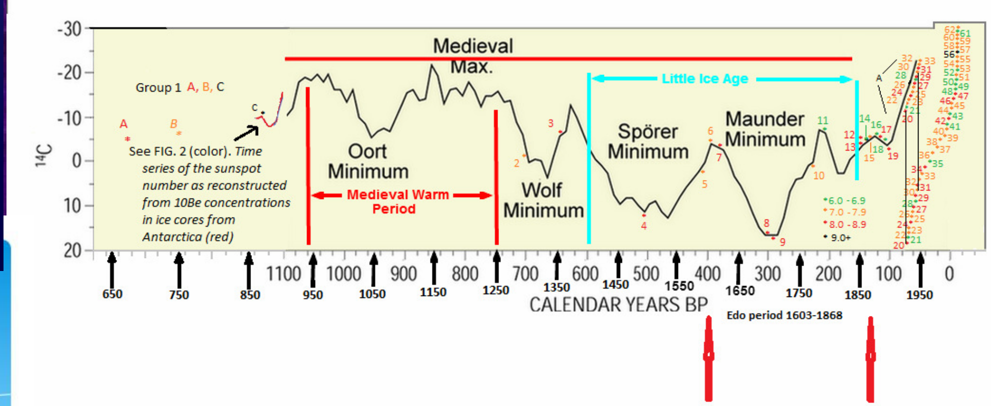
Спасибо за внимание !



4. Carbon-14 Method

- Carbon is found in three forms: Carbon-12, Carbon-13 and the **radioactive** form Carbon-14
- These carbons combine with **oxygen** to form the gas carbon dioxide, which is taken in by plants to perform **photosynthesis**
- As long as a plant is alive, new carbon dioxide with a constant carbon-14 to carbon-12 ratio is continually taken in
- Animals then eat the plants and contain the same ratio of carbon isotopes
- When a plant or animal dies, no new carbon is taken in.
- The amount of carbon-14 begins to **decrease** as the organism decays, and the ratio to carbon-12 to carbon-14 decreases.
- This decrease can be **measured** in a lab
- Because the half-life of carbon-14 is only **5,730 years**, this dating method is used mainly for dating things that lived within the last **50,000 years**





Half-Life and Radioisotope Dating (cont.)

Four different isotopes are commonly used for dating objects: carbon-14, uranium-238, rubidium-87, and potassium-40.

Carbon-14 dating is commonly used to measure the age of fossils.

To date objects that are more than 60,000 years old, carbon-14 dating cannot be used since