Stellar dynamo: new insights from the Kepler mission

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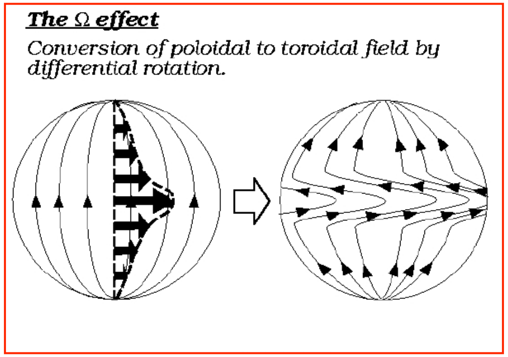
outline

- Review of MF-dynamo in stellar context
- Ground based data
- Dynamo in radiative zone
- The *Kepler* mission
- An explicit example: KIC 8429280

Stellar dynamo models

- Dynamo in convective zone (convective instability)
- Dynamo in the overshoot region – (buoyancy and/or Tayler instab.)
- Dynamo in radiative zone (quasi-interchange instability)
- Dynamo in compact objects (neutron-finger instability)

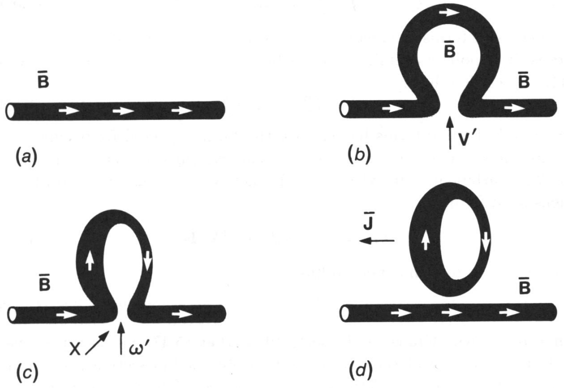
Ω-effect



The Ω effect

Conversion of poloidal to toroidal field by differential rotation.

α-effect



Mean-field dynamo in a nutshell

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{u} \times \vec{B} + \vec{\mathcal{E}} - \eta_{\mathrm{T}} \nabla \times \vec{B} \right)$$

$$\vec{\mathcal{E}} \equiv \langle \vec{u} \times \vec{b} \rangle = \alpha \vec{B} - \eta_{\mathrm{T}} \nabla \times \vec{B} + \cdots$$

$$\alpha = \frac{\tau}{3} \langle \vec{u} \cdot \nabla \times \vec{u} \rangle$$

Kinetic helicity – homogeneous turbulence

$$\alpha = \frac{\tau}{\rho} \langle \vec{b} \cdot \nabla \times \vec{b} \rangle$$

Magnetic cross-helicity

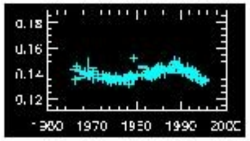
Magnetic activity in stars

- Late-type stars of solar type also exhibit magnetic activity

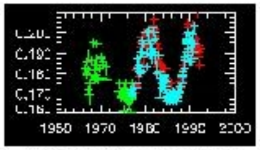
- Can be detected by Ca II HK emission profiles

- Mount Wilson survey shows a wide variety of behaviour

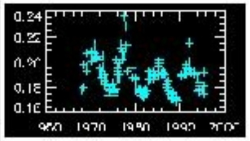
- Activity and modulation increases with rotation rate (decreases with Rossby no. Ro)



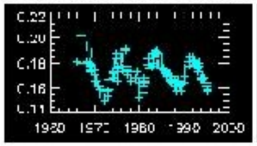
HD 136202 (F8IV-V) 23 yrs



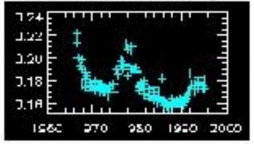
The Sun (G2V) 10.0 yrs



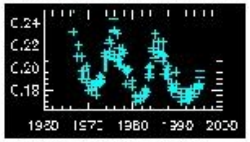
HD 103095 (G8VI) 7.3 yrs



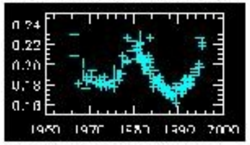
HD 81809 (K0V?) 8.2 yrs



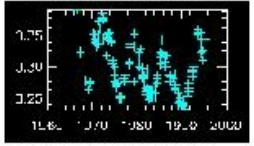
HD 3651 (K2V) 13.8 yrs



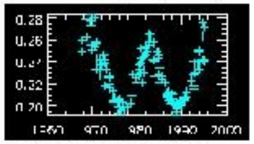
HD 10476 (K1V) 9.6 yrs



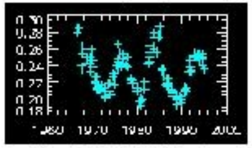
HD 166620 (K2V) 15.8 yrs



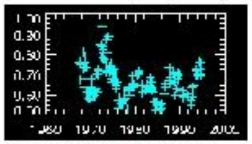
HD 160346 (K3V) 7.0 yrs



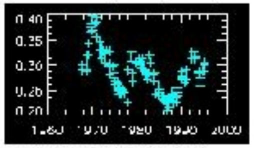
HD 16160 (K3V) 13.2 yrs



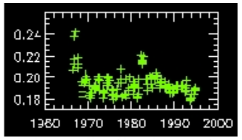
HD 4628 (K4V) 8.4 yrs



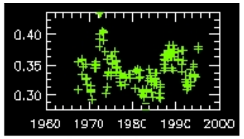
HD 201091 (K5V) 7.3 yrs



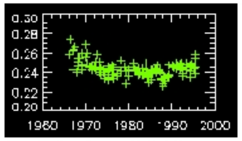
HD 32147 (K5V) 11.1 yrs



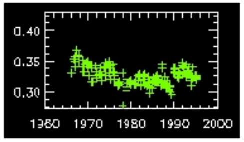
HD 190406 (G1V) 2.6 + 16.9 yrs



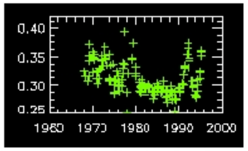
HD 149661 (K0V) 17.4 + 4.0 yrs



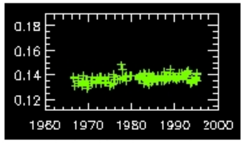
HD 114378 (F5V) Long



HD 39587 (G0V) Var

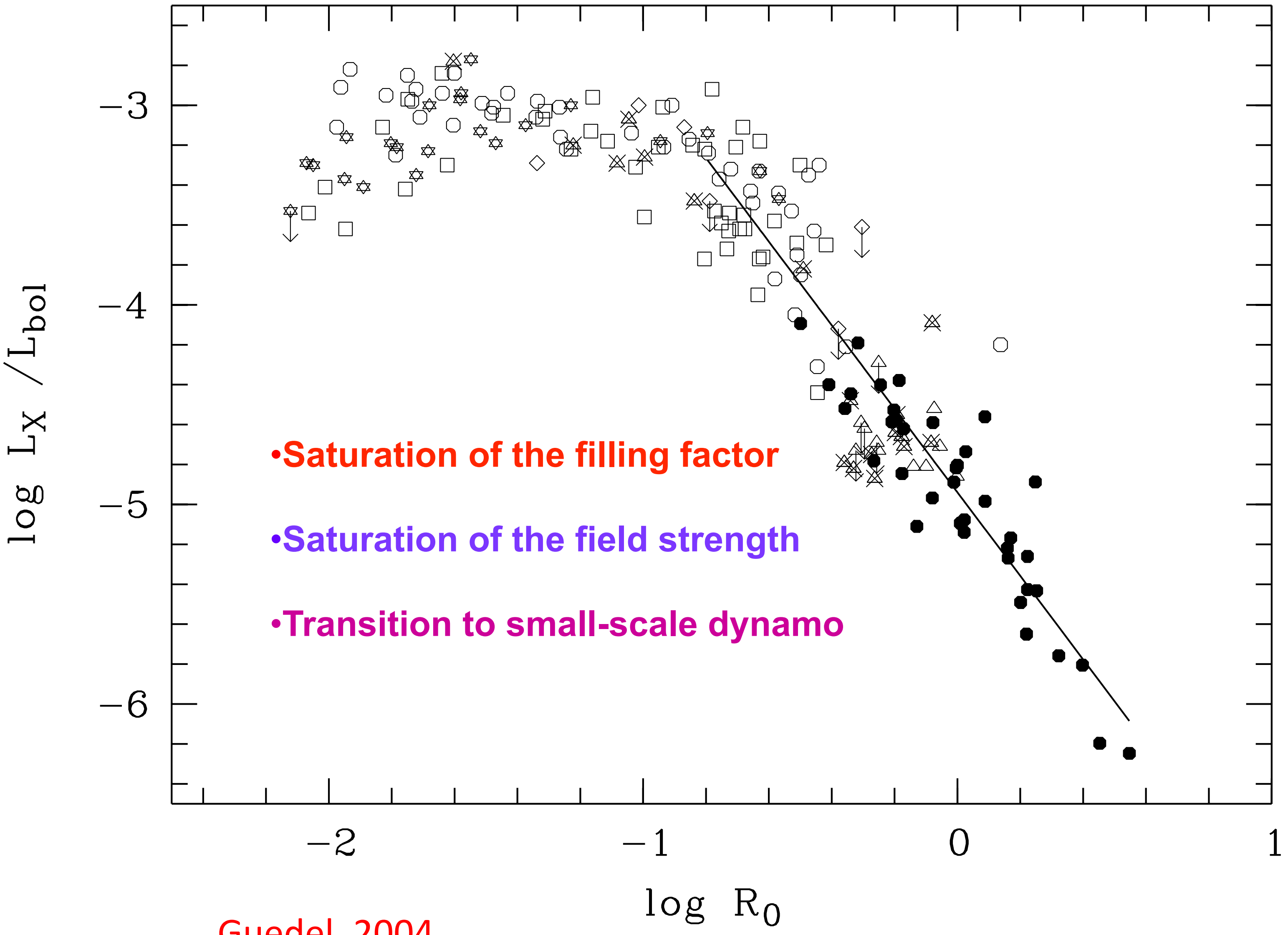


HD 101501 (G8V) Var



HD 9562 (G2V) Flat

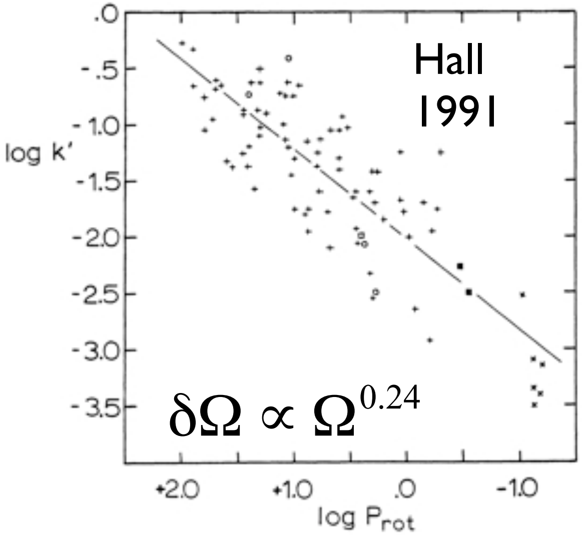
Activity-rotation relationship



- **Saturation of the filling factor**
- **Saturation of the field strength**
- **Transition to small-scale dynamo**

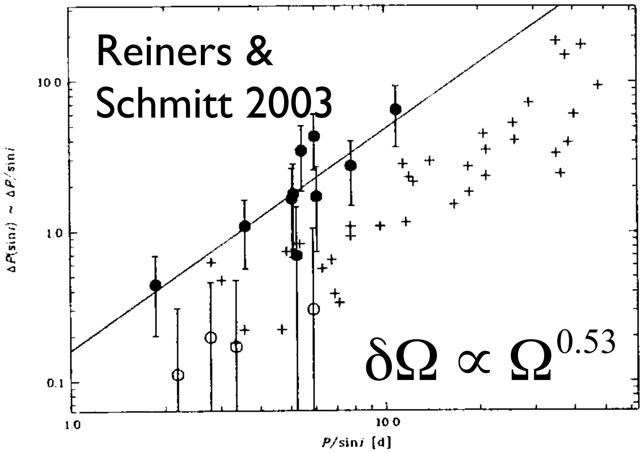
Guedel, 2004

Stellar differential rotation



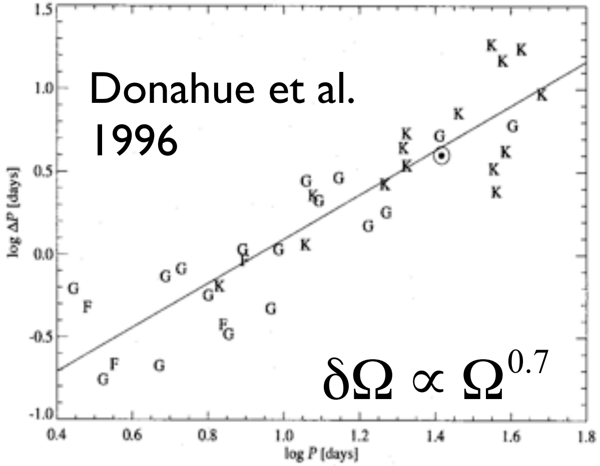
Hall 1991

$\delta\Omega \propto \Omega^{0.24}$



Reiners & Schmitt 2003

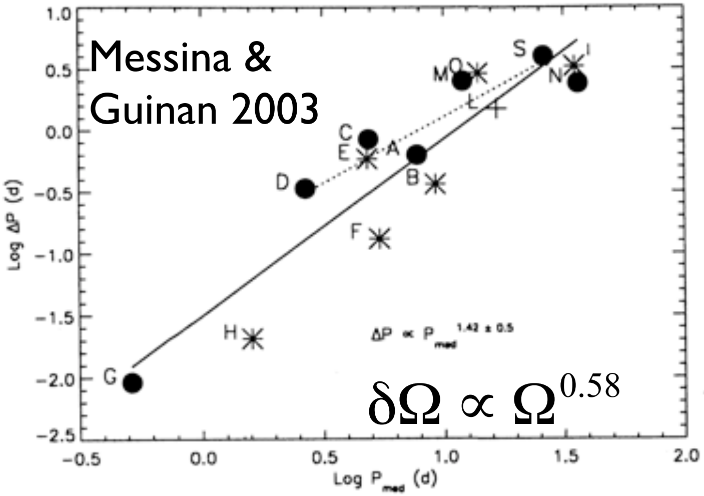
$\delta\Omega \propto \Omega^{0.53}$



Donahue et al. 1996

$\delta\Omega \propto \Omega^{0.7}$

FIG. 3.—Range of observed rotation periods vs. log $\langle P\rangle$. Least-squares fit of these data yields $\Delta P \propto \langle P\rangle^{1.3\pm0.1}$ (correlation coefficient $r = 0.90$).



Messina & Guinan 2003

$\delta\Omega \propto \Omega^{0.58}$

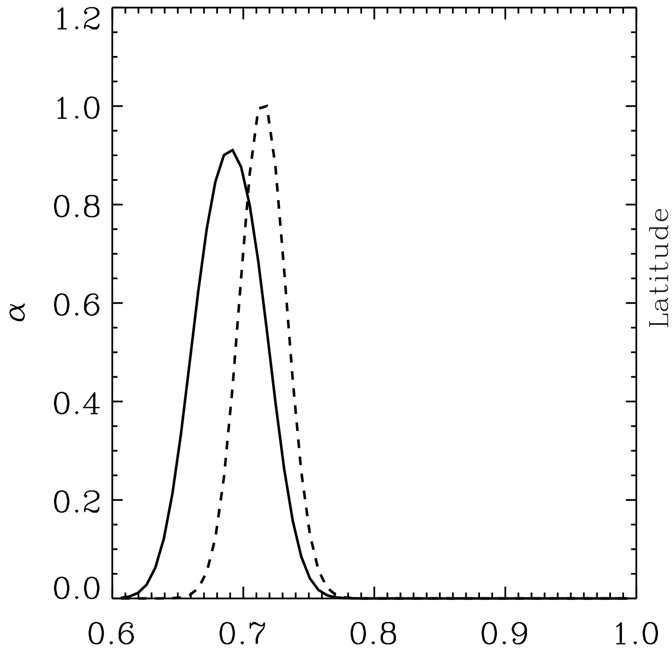
Dynamo in radiative zone

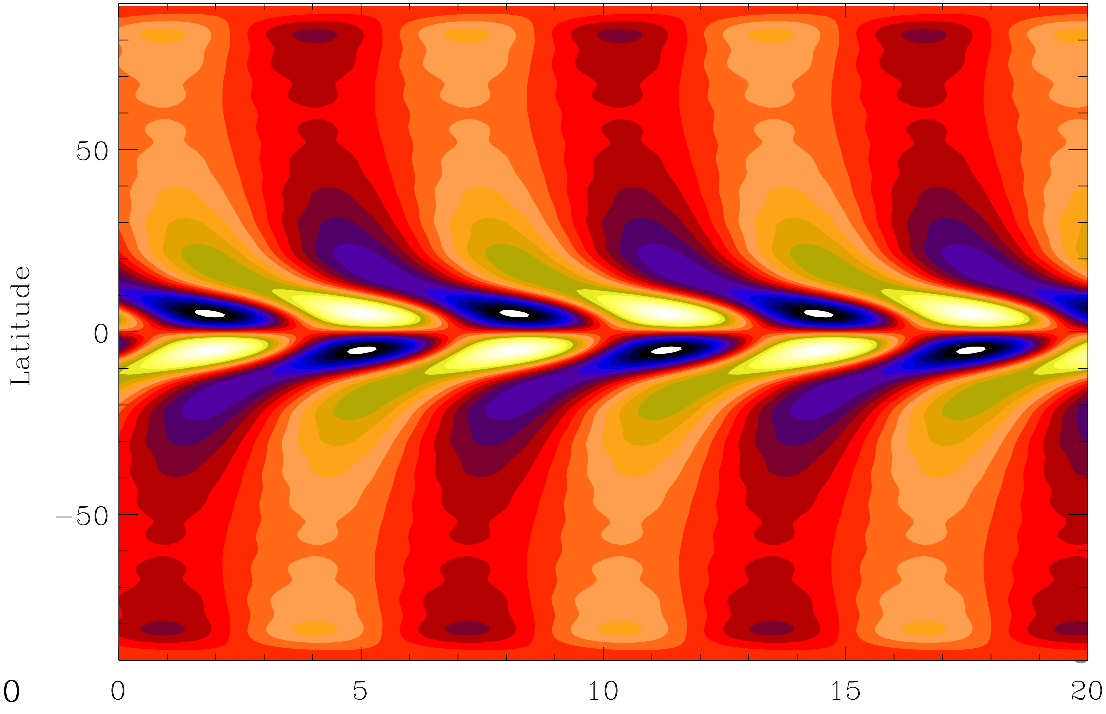
- Based on the Tayler instability: (Spruit 1999, Spruit 2000, Braithwaite 2006)

$$\alpha = \frac{\tau}{\rho}\langle \vec{b}\cdot\nabla\times\vec{b}\rangle$$

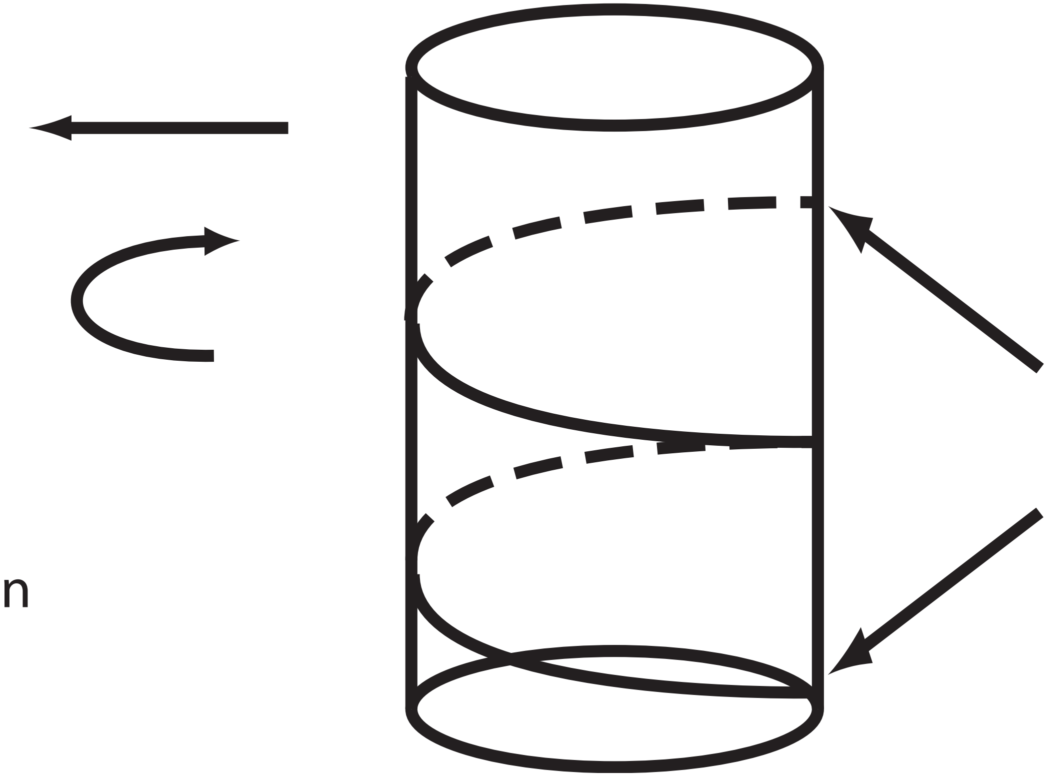
- The key question is how to close the dynamo loop (Mathis, Brun, Zahn, 2010)

- Or, how to produce a “magnetic” alpha-effect (see Ruediger, Kitchatinov, Elstner, arXiv-1107.2548)





Consider an idealized geometry: static MHD column model



pressure

+

curvature

=

pressure - driven
instability

Twist > a few
rotations

=

current - driven
instability

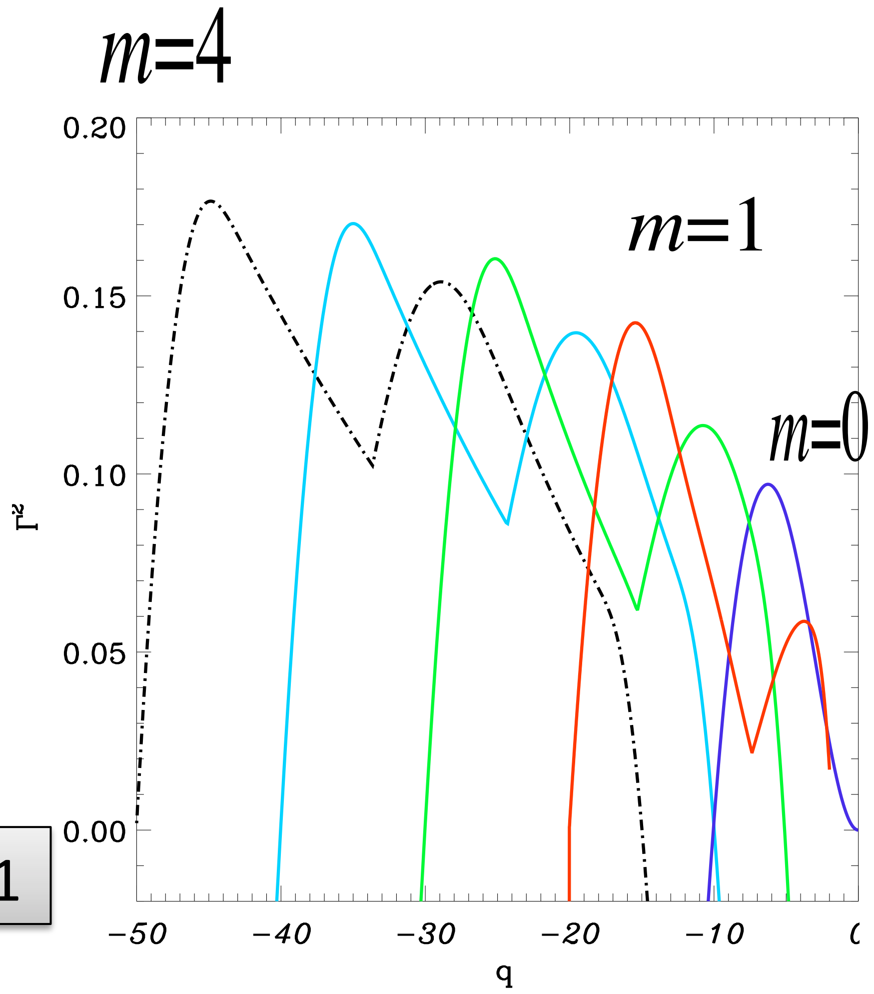
$$\omega_A = \frac{1}{\sqrt{4\pi\rho}}\left(k_z B_z + \frac{m}{s} B_\varphi\right) \approx 0$$

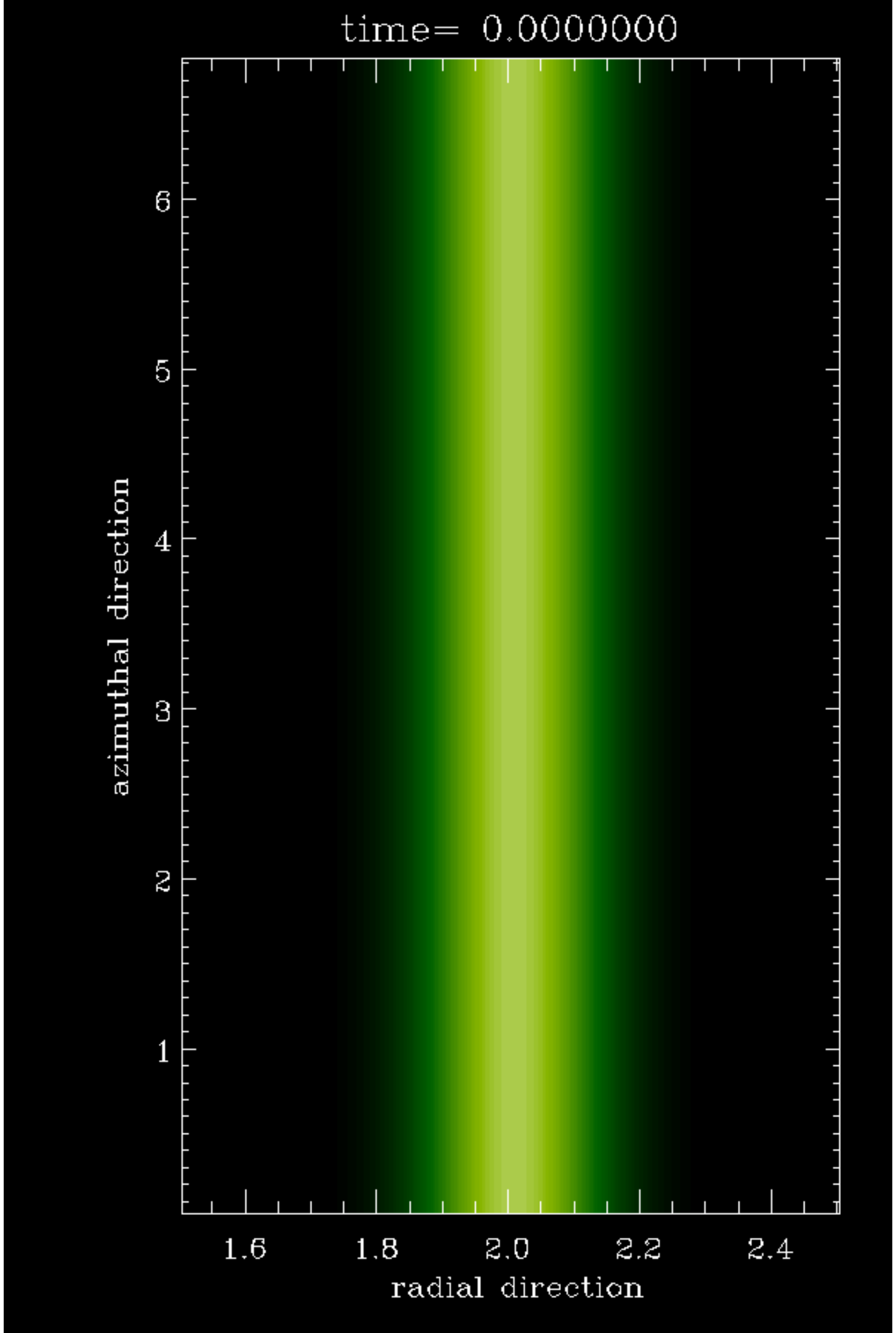
Quasi – interchange instability: Friedberg, 1970 – Goedbloed, 1971

$$\epsilon = \frac{B_z}{B_\varphi} = 0.1$$

- m ->- m and Bz->-Bz symmetry!
- m>1 in general if Bz is not zero!
- Does this trend saturate? Note the resonant character.

Bonanno and Urpin, A&A 2008,2011



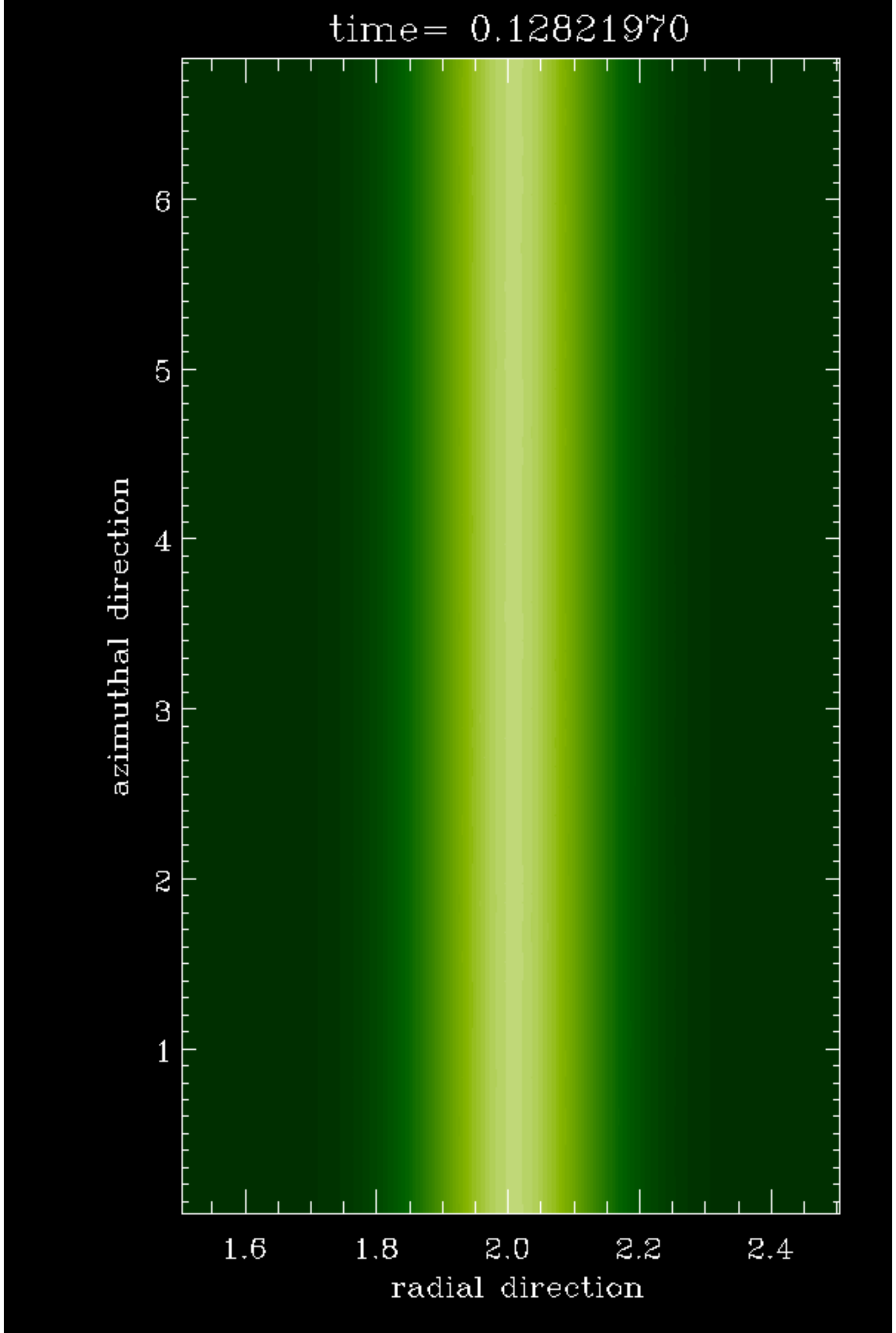


$$B_\phi = b_0 \, \frac{s}{s_0} \exp \frac{-(s-s_0)^2}{\sigma}$$

Balance this basic state with either gradient of pressure, or external force (gravitational potential).

$$\epsilon = 0$$

In this case a mode with m=1 dominates the non-linear evolution.

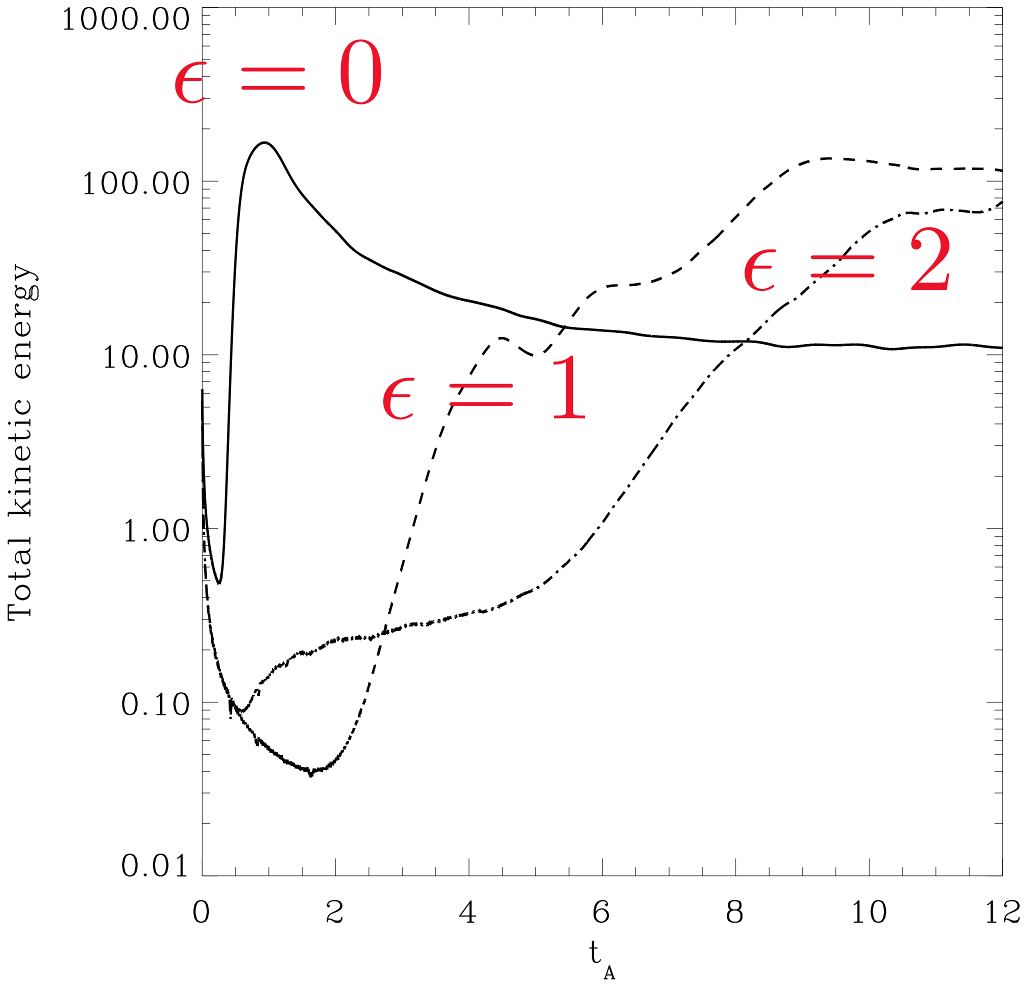


$$B_\phi = b_0 \, \frac{s}{s_0} \exp \frac{-(s-s_0)^2}{\sigma}$$

$$\epsilon = 2$$

In this case a mode with m=6 dominates the non-linear evolution. Similar selection occurs for the vertical wavenumber!

Kinetic energy evolution



$\epsilon = 2 \rightarrow m = 6$

$\epsilon = 1 \rightarrow m = 3$

$\epsilon = 0 \rightarrow m = 1$

Dynamo in PNS stars!

- **strong instabilities driven by lepton number gradients and temperature gradients**

$t \sim 40$ s　　　　$\Omega \cong 1000$ rad/sec

（This is ten times as fast as young pulsar accompanied with SNR（spin period ～10msec））

- **The features of pulsar suggested by observation**

Magnetic field of young pulsar　$B \cong 10^{12-13}\ G$

PNS are accompanied with magnetic fields

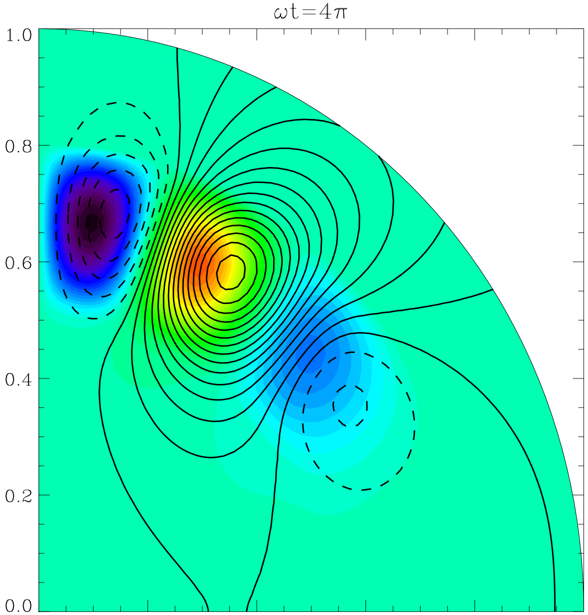
■ Possibility of dynamo action (Bonanno & Urpin 2005,2006)

■ Strong fields are generated with Bp/Bphi = O(1)

■ Possibility of explaining magnetars magnetic fields

■Now consistent with observations (Halpern and Gottlef, ApJ2010, PSR J1852+0040, *anti-magnetar*)

（Typical PNS - MF）



The *Kepler* Mission

1.4m primary mirror

Earth-trailing orbit

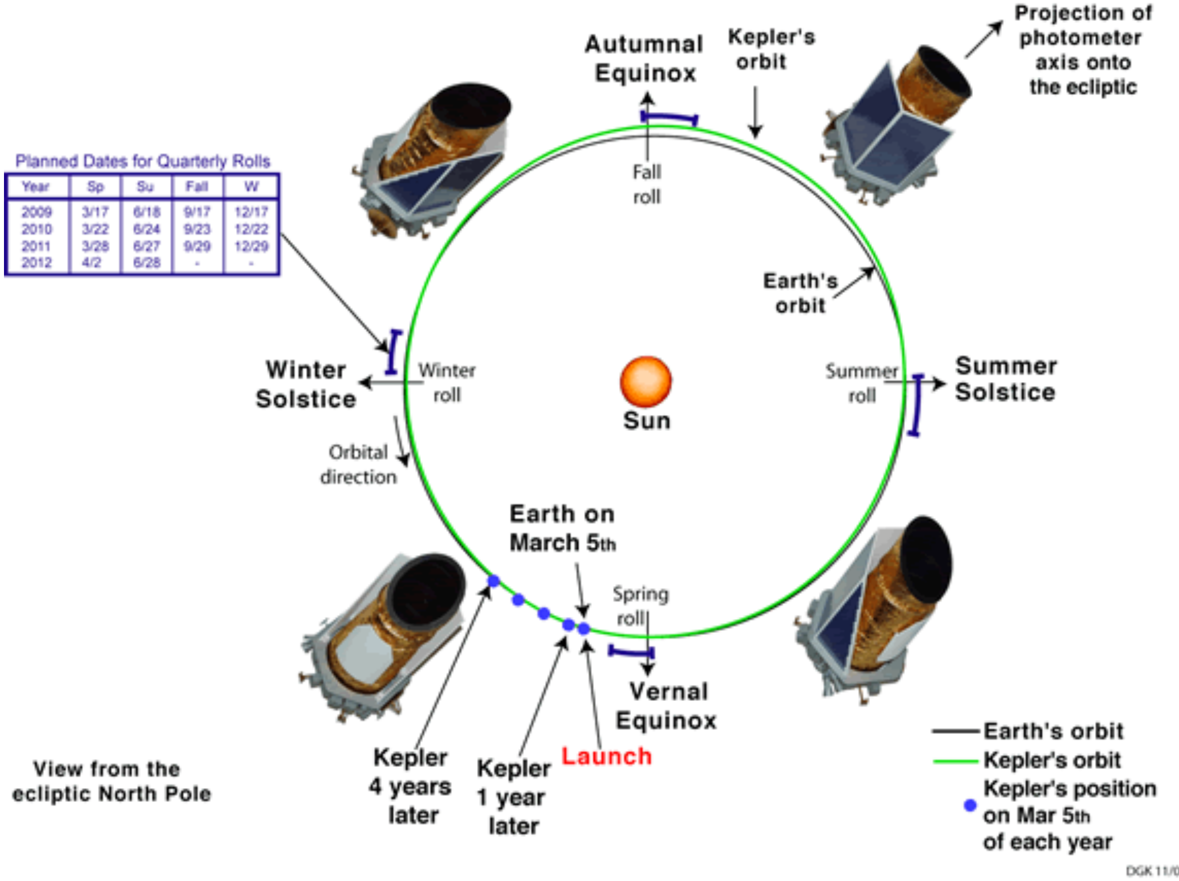
Mission lifetime of at least 3.5 years continuously viewing the same region of sky.

Vast (0.9 m across) broadband (4300-8900 Å) optical CCD array

105 square degrees of sky in Cygnus-Lyra region.

Long (30 min) and short (1 min) data cadence derived by summing 6 sec images.

Primary goal is detecting Earth-like planets through transit observations.

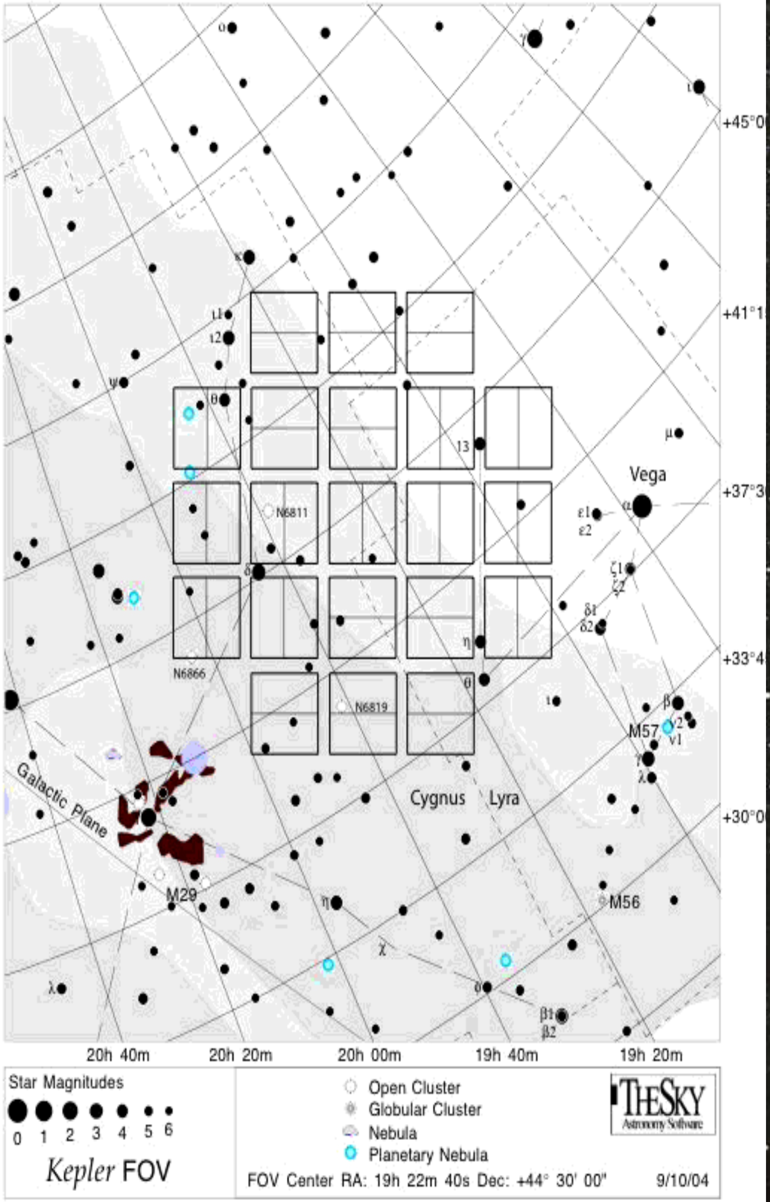


Planned Dates for Quarterly Rolls

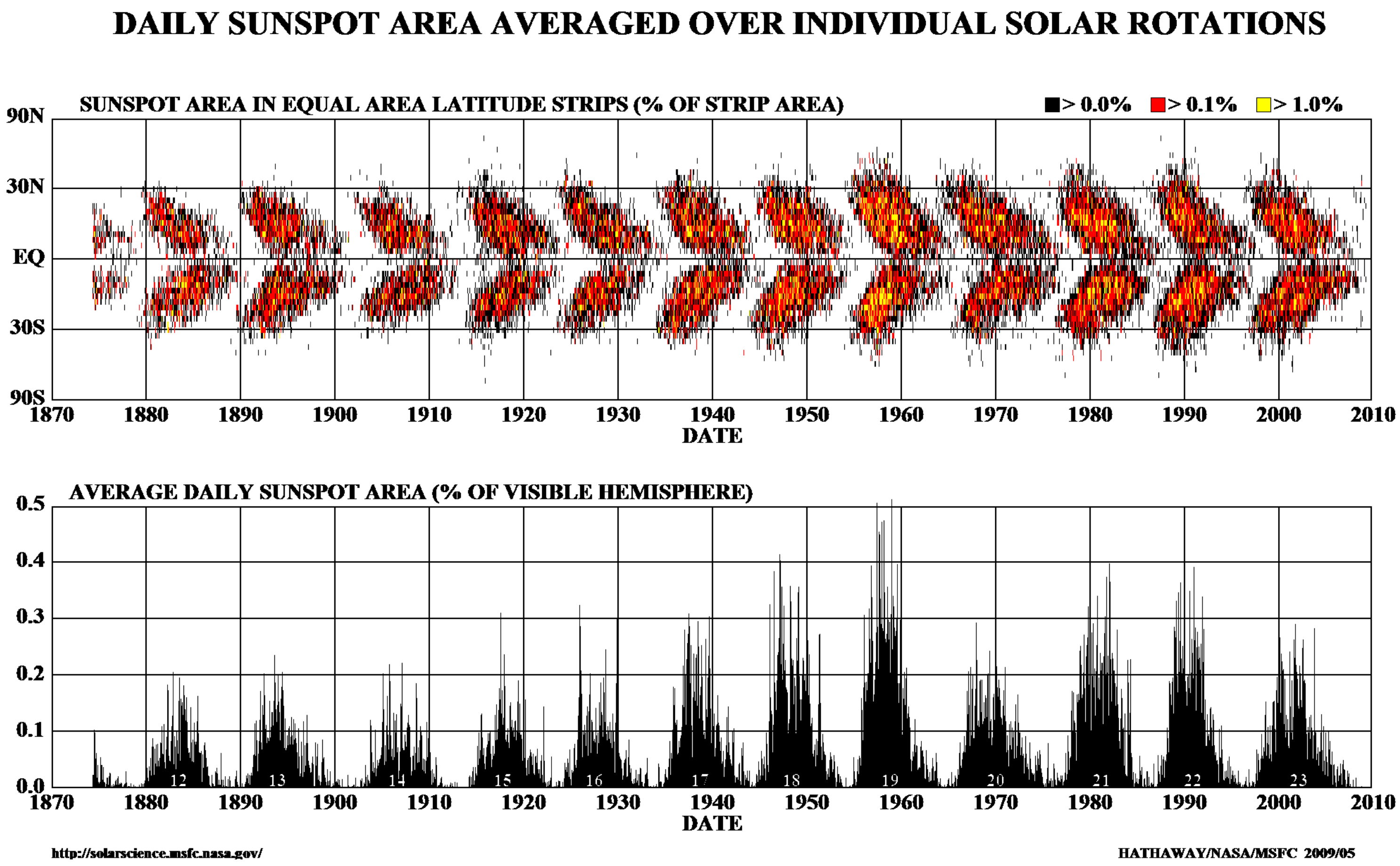
Year	Sp	Su	Fall	W
2009	3/17	6/18	9/17	12/17
2010	3/22	6/24	9/23	12/22
2011	3/28	6/27	9/29	12/29
2012	4/2	6/28	-	-

Source: NASA *Kepler* website

Kepler Field of View

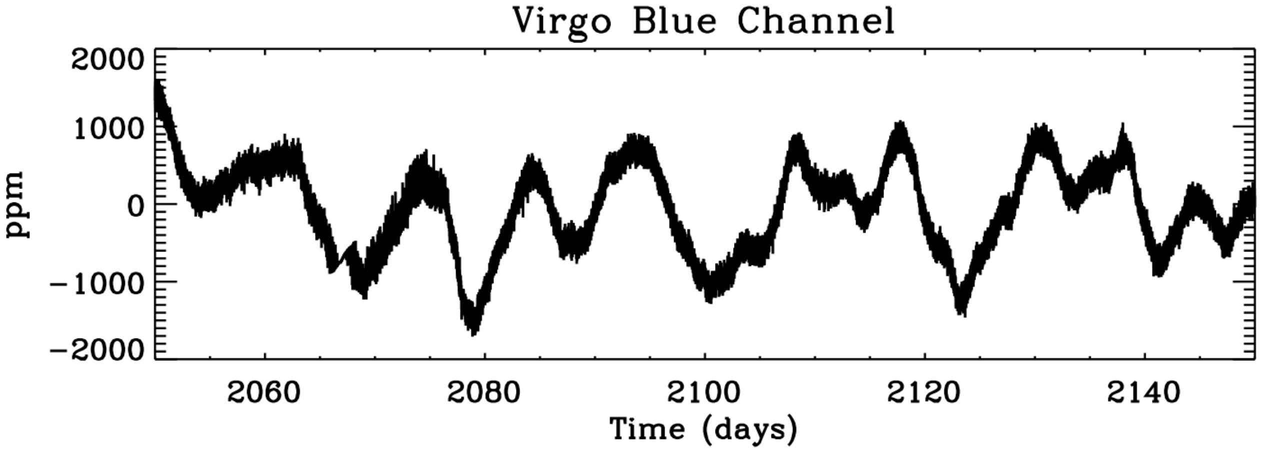


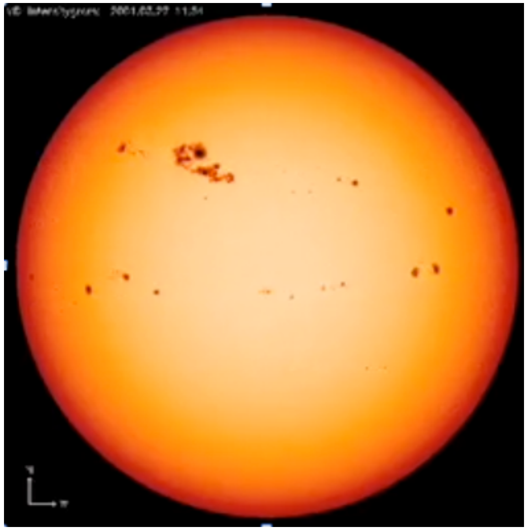
Solar butterfly diagram

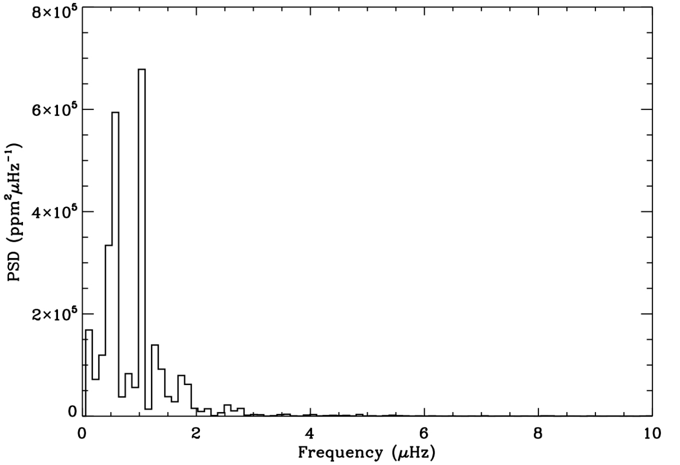


Sunspots appear in two bands on either side of the equator that drift toward the equator as the cycle progresses.

Can we retrieve this information in other stars from LC-data?

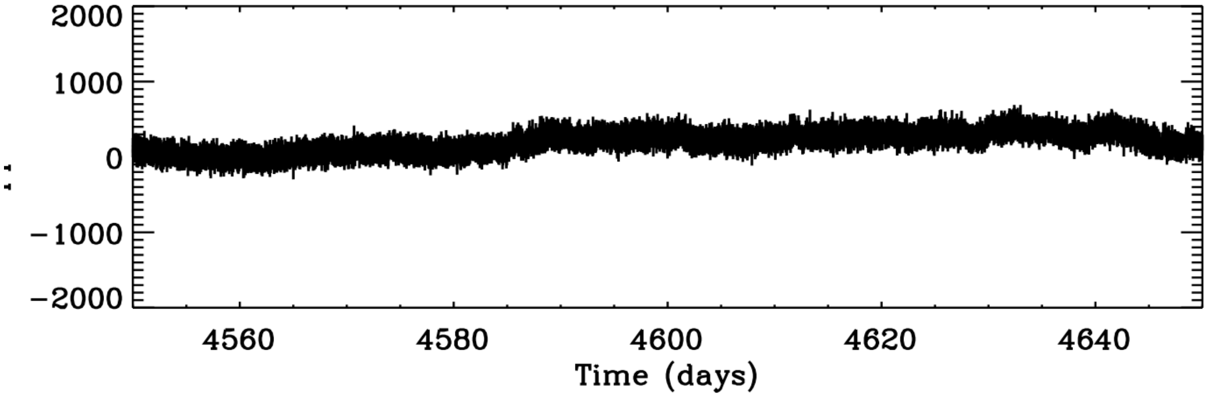


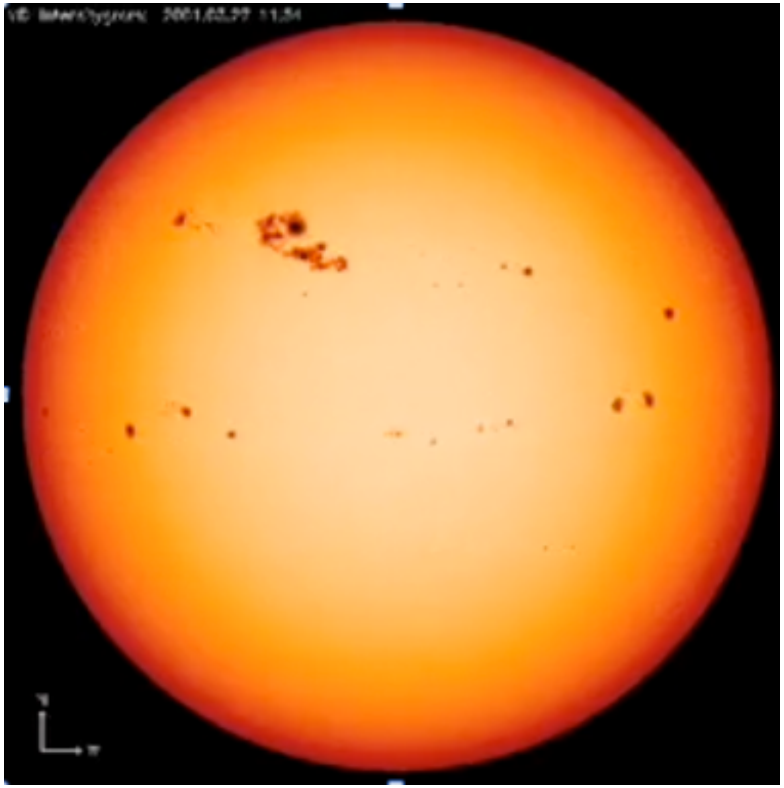




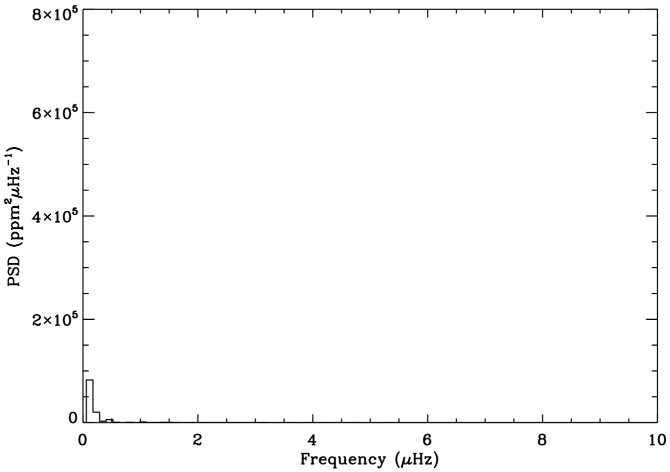
Solar Activity Maximum

Courtesy of R.A. Garcia, KASC PE11

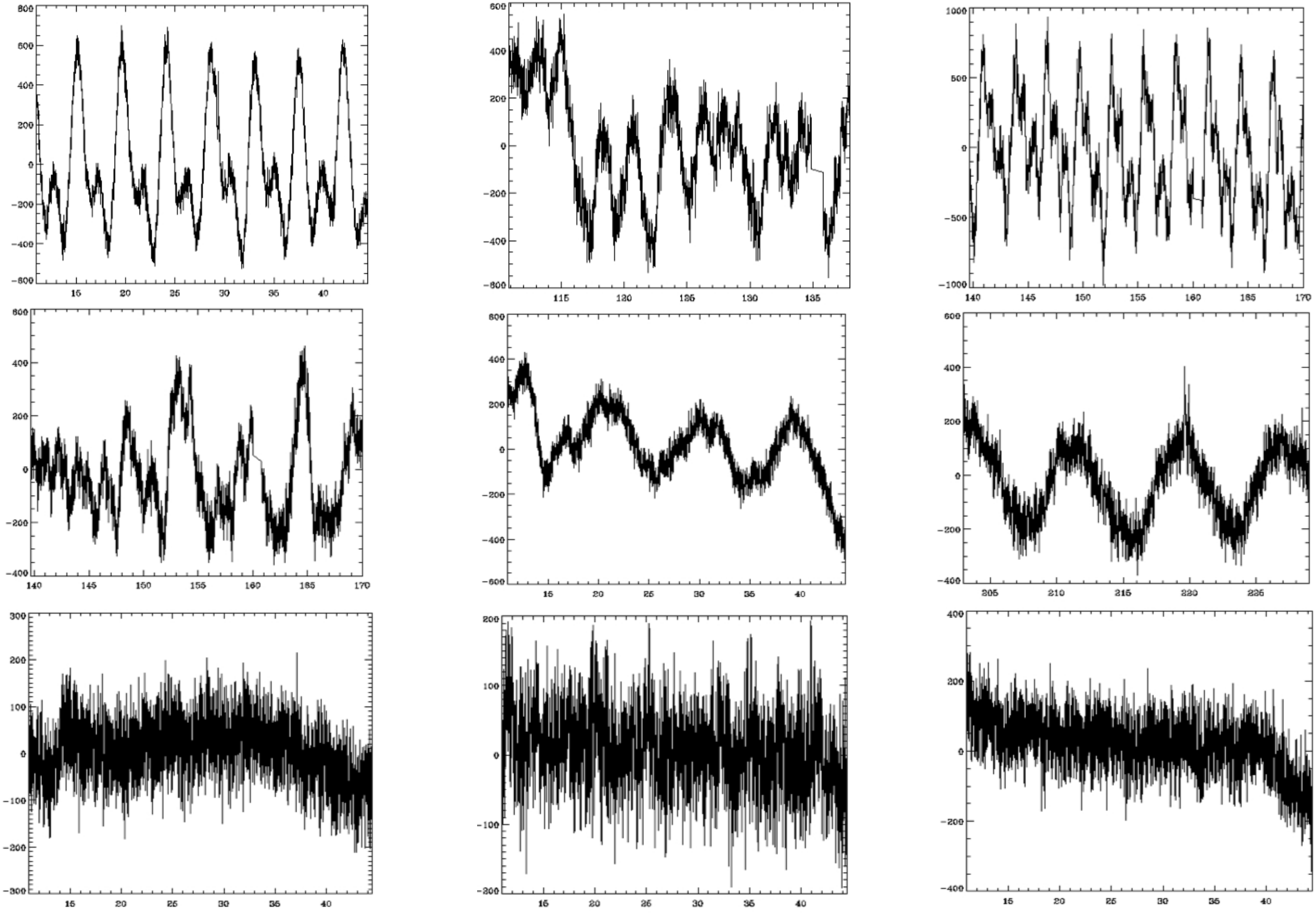




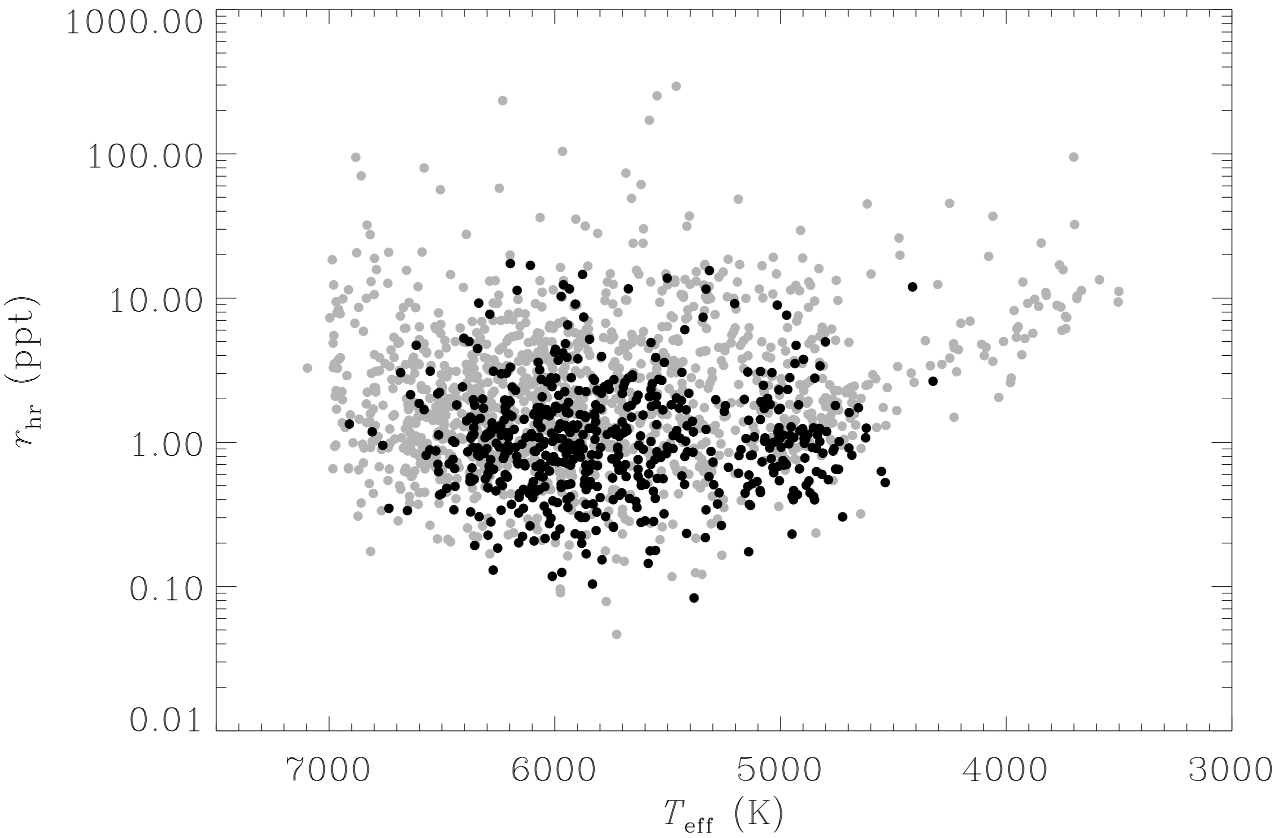
Solar Activity Minimum



Example of *Kepler* light curves (solar-like S)

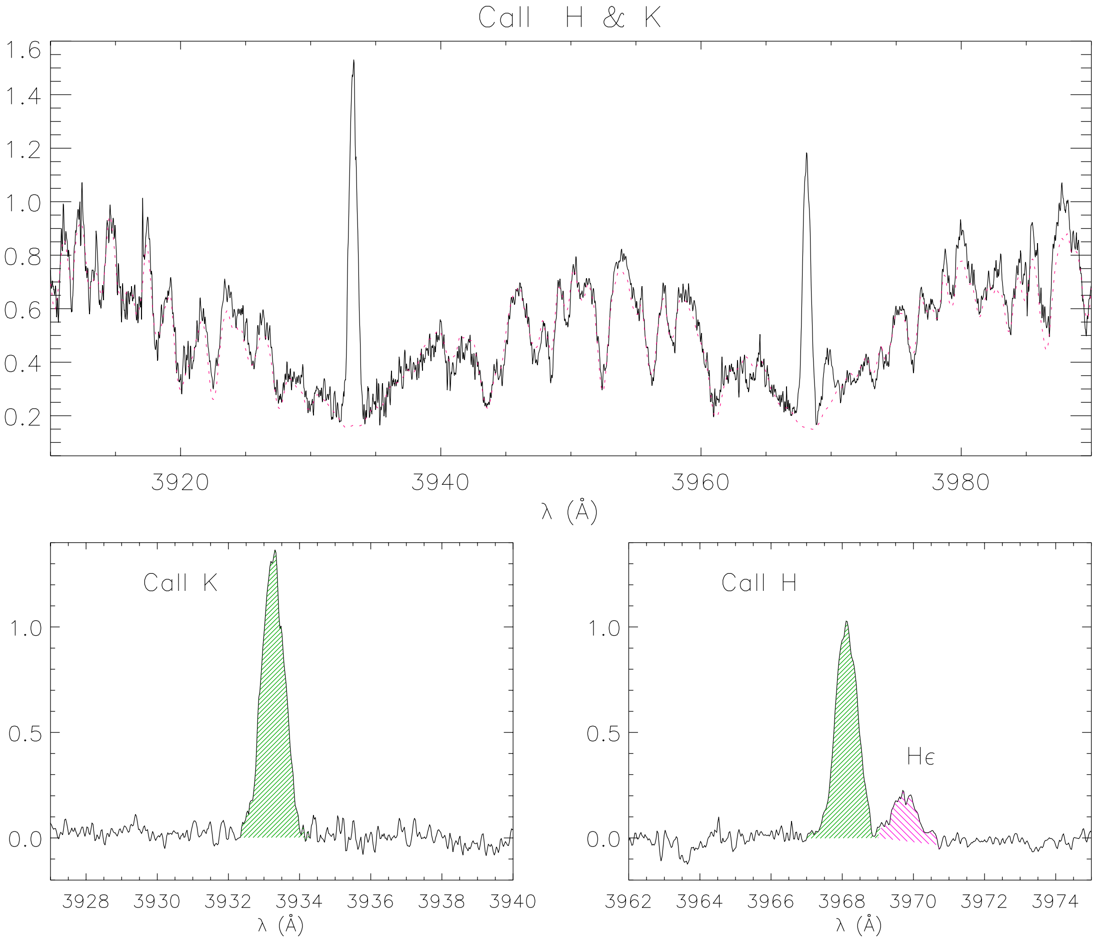


Magnetic field and pulsations: activity suppresses acoustic oscillations!



Chaplin, Bedding, Bonanno et al., ApJL, 2011

The case of KIC8428280



Stellar Parameters:

Spectral Type: K2V

Teff= 5055 K

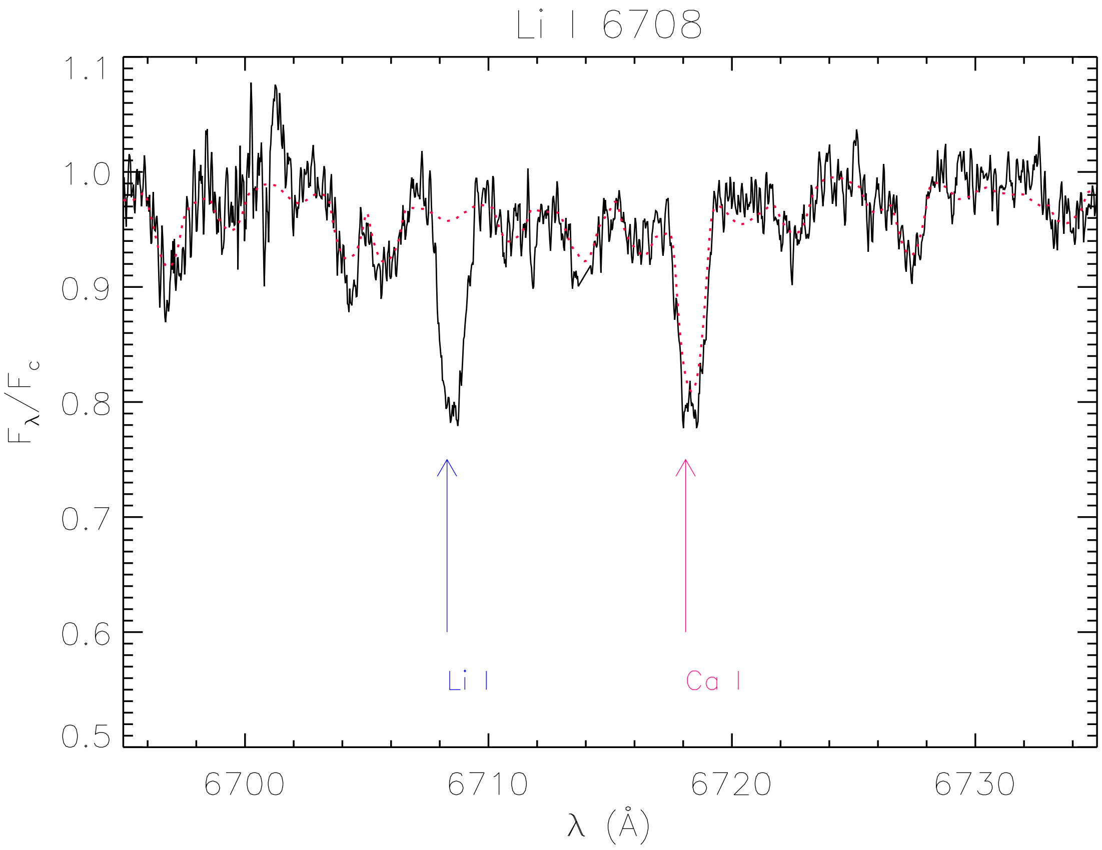
log g =4.41

Fe/H=-0.02

Vsini=38 km/s

Frasca, Froelich, Bonanno, Catanzaro, Biazzo, Molenda-Zackowicz, A&A 2011

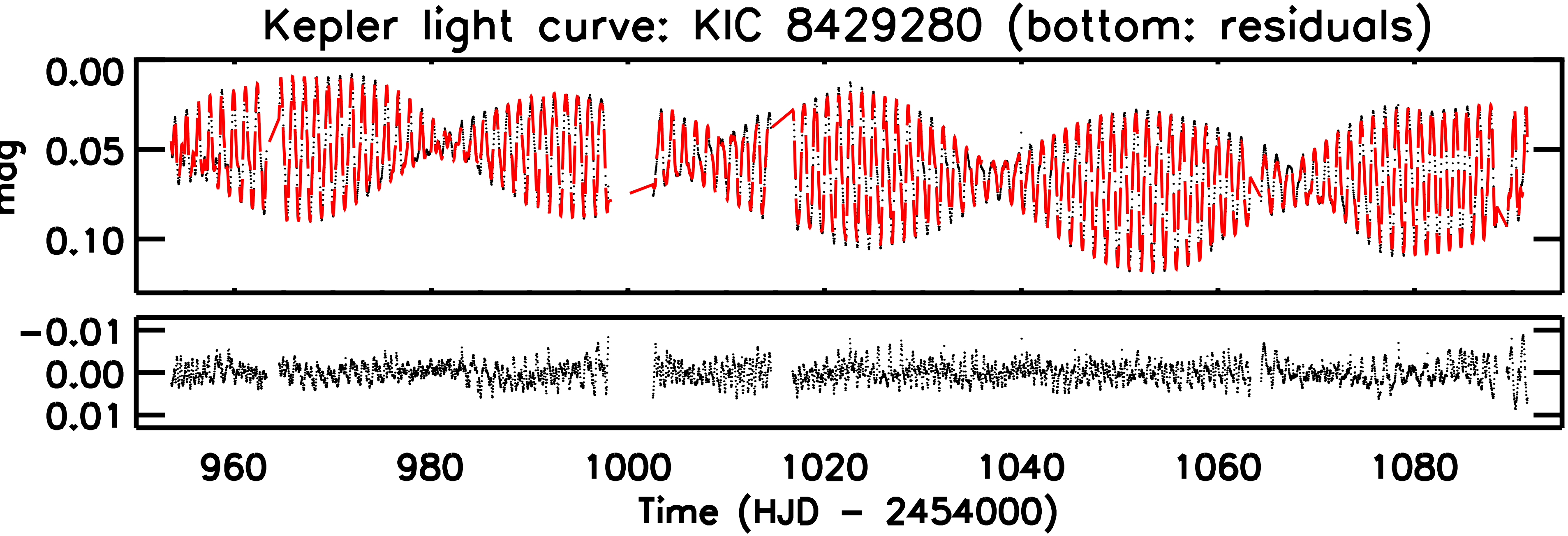
The case of KIC8428280



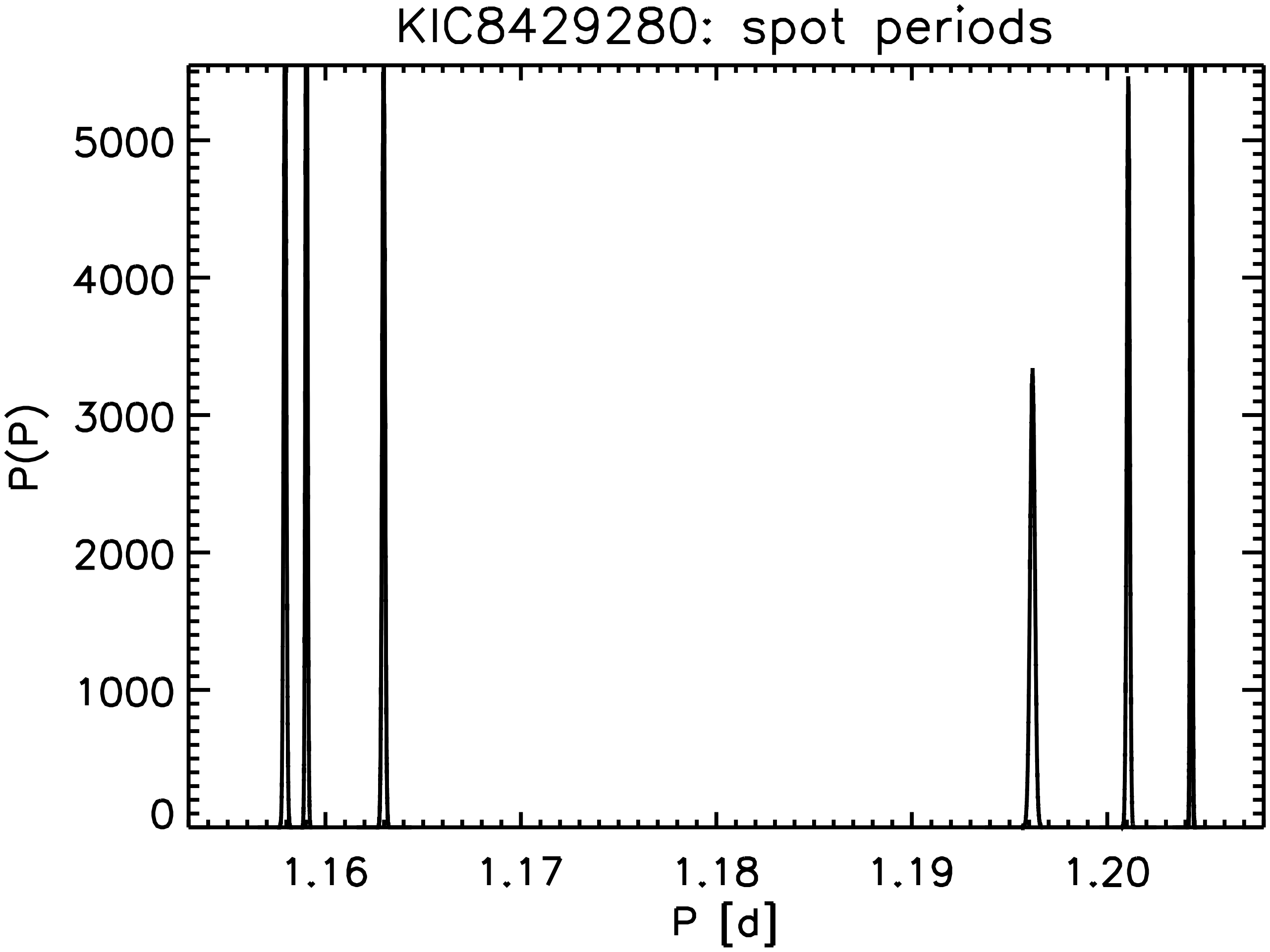
Stellar Parameters:

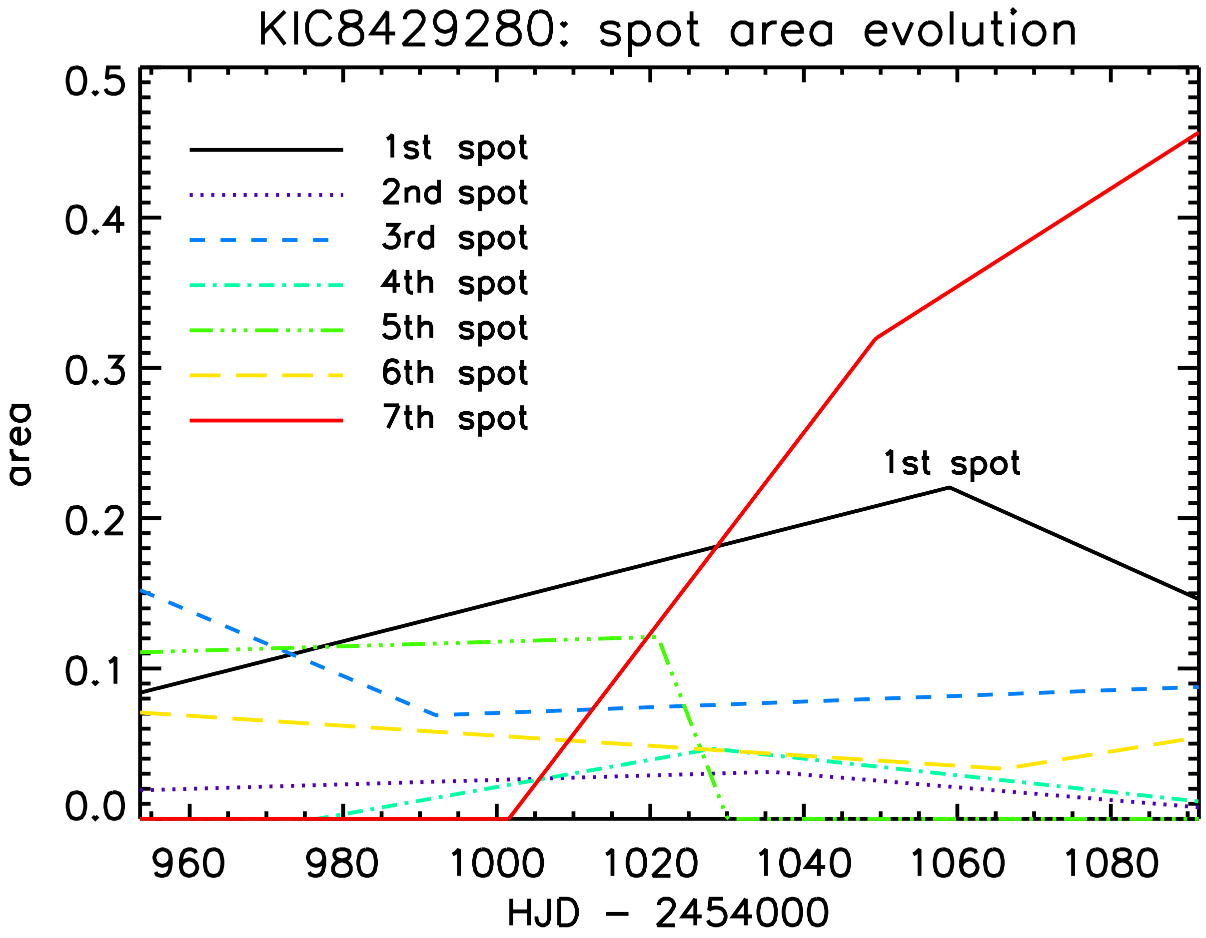
AGE: 50 Myrs,
Pleiads !

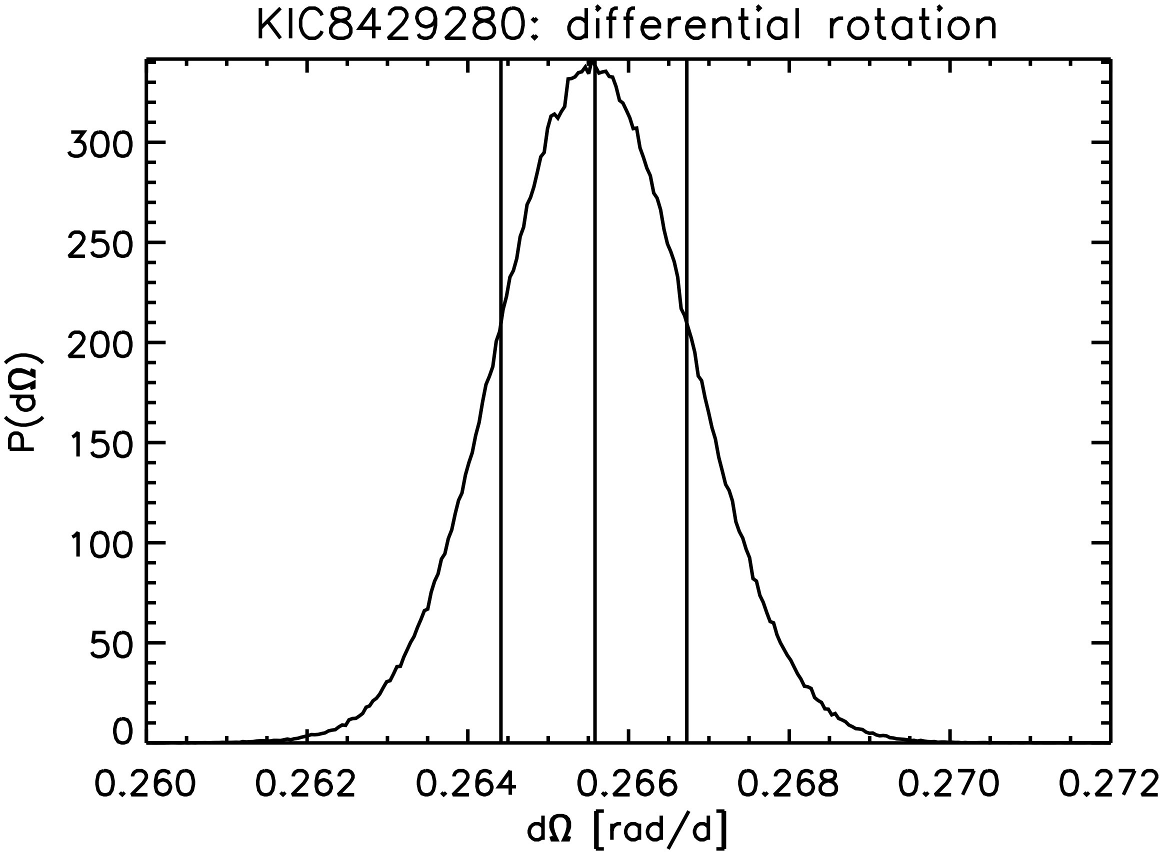
Frasca, Froelich, Bonanno, Catanzaro, Biazzo, Molenda-Zackowicz, A&A 2011



A Bayesian analysis of the 138days lightcurve in terms of circular spots revealed at least seven slowly evolving features. There are two possible darkspots solutions (if one dismisses a 3rd solution with very dark spots). The latitude dependence of angular velocity is prescribed by a sin^2 law. A quadratic limb-darkening law with fixed coefficients has been applied. Spot area evolution is parameterized by a simple ansatz: area goes linearly with time. The evolution model allows for one sudden change in the slope of the area vs time relation.


KIC8429280: spot periods
P(P)
5000
4000
3000
2000
1000
0
1.16
1.17
1.18
1.19
1.20
P [d]


KIC8429280: spot area evolution
area
0.5
0.4
0.3
0.2
0.1
0.0
960
980
1000
1020
1040
1060
1080
HJD − 2454000
1st spot
2nd spot
3rd spot
4th spot
5th spot
6th spot
7th spot
1st spot


KIC8429280: differential rotation
P(dΩ)
0
50
100
150
200
250
300
0.260
0.262
0.264
0.266
0.268
0.270
0.272
dΩ [rad/d]

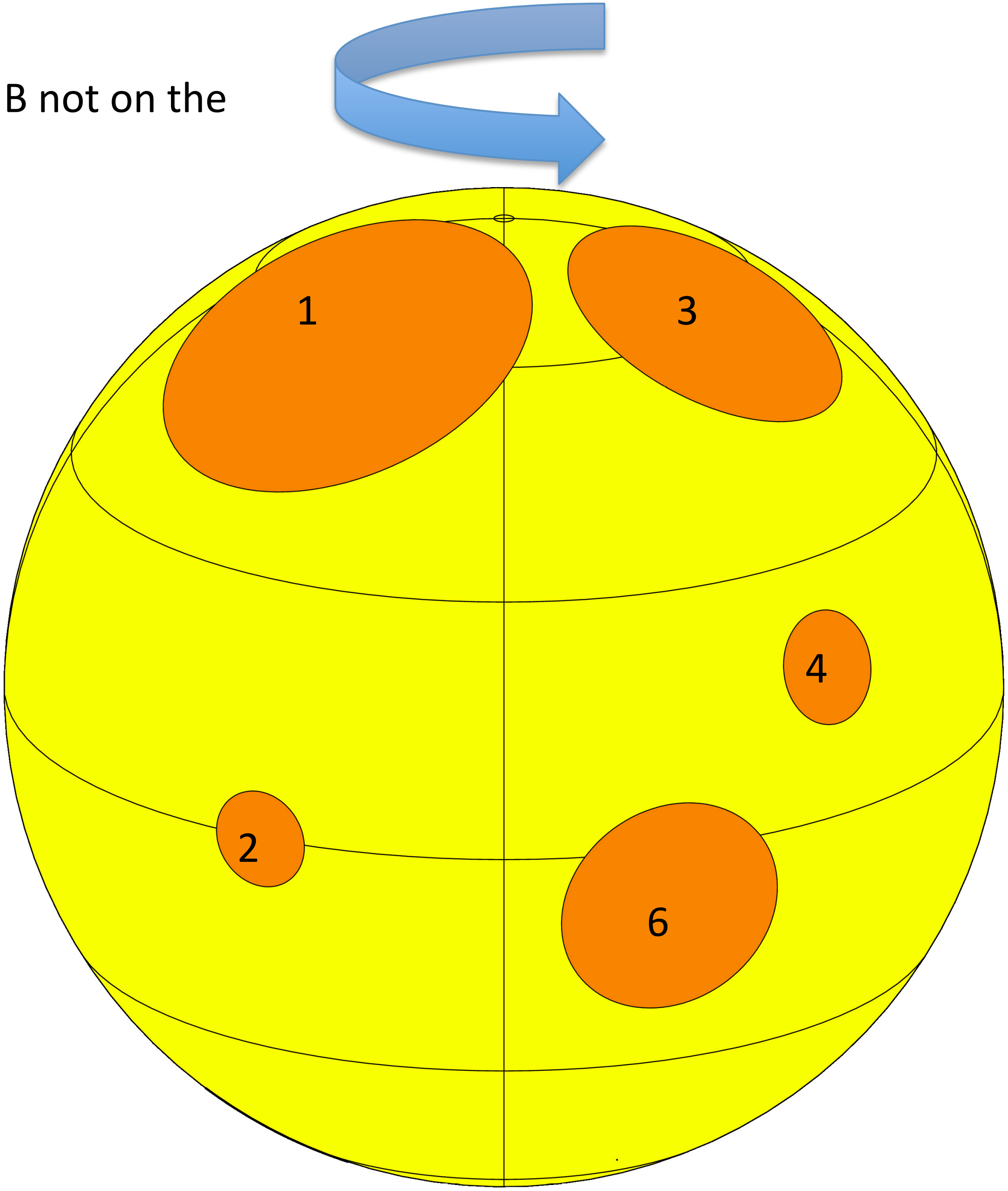
Posterior probability distributions for all parameters with mean and ±1σ credibility intervals.

In both solutions inclination (69.5 ± 0.4, 69.6 ± 0.4 deg) and spot contrast (0.57 ± 0.01, 0.60 ± 0.02) are comparable.

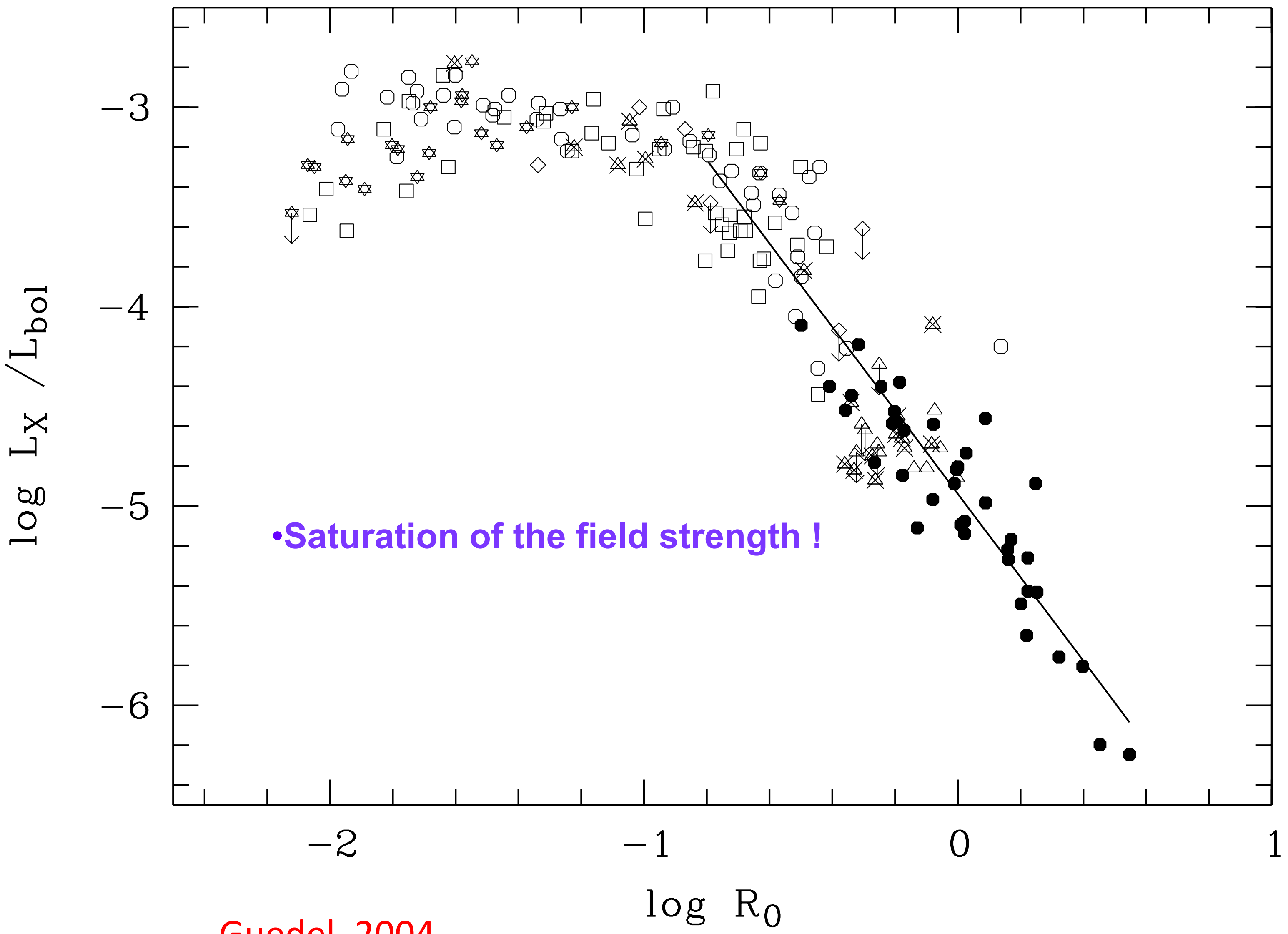
Two southern spots of the 1st solution changed the hemisphere in the 2nd solution.

For both solutions the solar-like differential rotation is surprisingly large: 0.2656 (+0.0012, 0.0011) and 0.2974 (+0.0032, 0.0016) rad/d, respectively.

The limit is on B not on the filling factor!



KIC8429280 lies in the saturated Ro



- **Saturation of the field strength !**

Guedel, 2004

Conclusions

- New *Kepler* data on fast rotating stars can explore the high Ro regime of dynamo action (small dynamo?) and obtain surface DR !!

- ESSENTIAL INGREDIENTS ARE GROUND-BASED OBSERVATIONS!

- Dynamo in radiative zone is a very exciting alternative to the standard dynamo based on kinetic-helicity alpha effect

- Much effort is still needed to understand ideal MHD

If dynamos do not work in such a simple case they will not work at all ! (A. Einstein)

Discussion

- Do we understand the triggering mechanism of MHD instabilities? (see also the talk of Shih-Ping Lai). How is turbulence related with basic MHD instability?

- Where is the location of the alpha effect? (CZ vs RZ dynamo)

- Do we expect answers from future/present missions or questions? (see SKA… remember the solar dynamo before and after helioseismology)?

- Role of reconnection on (small scale) dynamo?