



Simulations of dynamos in compressible flows

Lecture 3: Stellar dynamos

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Outline



- ⑥ Some observational facts(?)
 - △ Doppler imaging and results
 - △ Zeeman Dopple imaging and results
 - △ Surface differential rotation
 - △ Implications for dynamos

- ⑥ Directions to go for modellers...
 - △ ...when even reproducing the solar dynamo is difficult
 - △ Internal rotation laws for other stars unknown observationally
 - △ The quest for more realistic dynamical dynamo models
 - △ Avoiding the Taylor-Proudman balance for rapid rotators

Doppler imaging

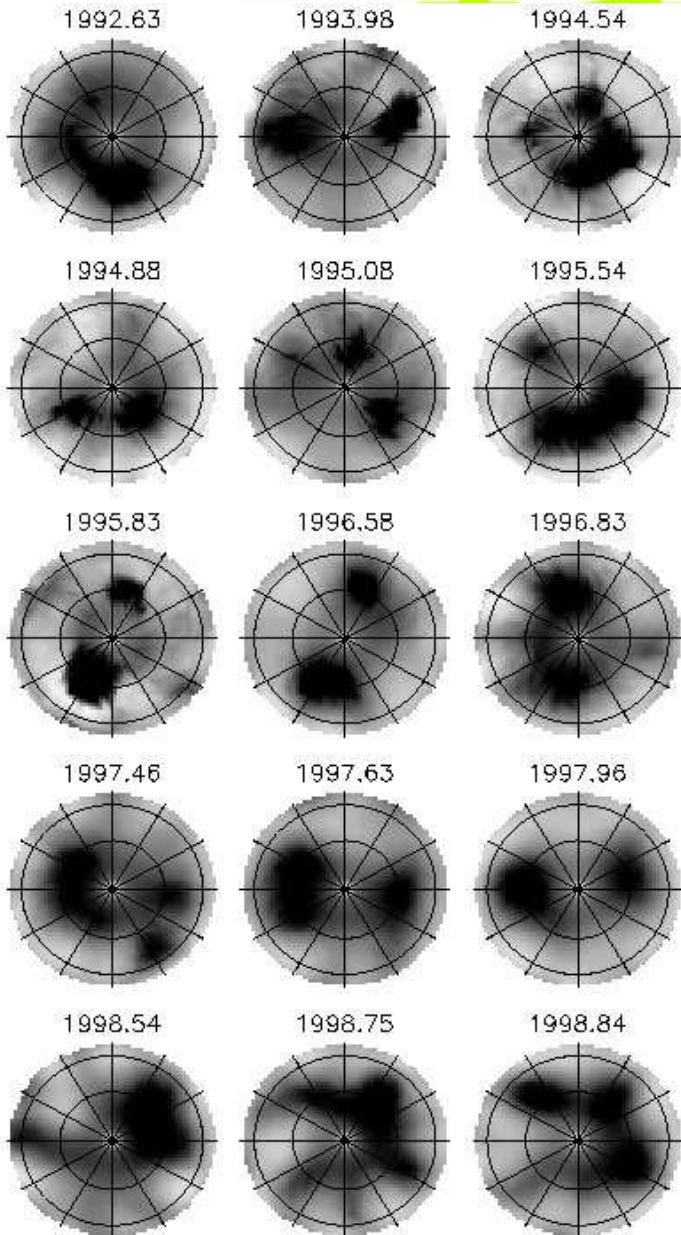
- ⑥ Cool spots or spot groups cause distortions in the absorption line profiles of stellar spectra (T sensitive lines)
 - △ High enough rotation rate
 - △ Suitable inclination (between 20-70 degrees)
- ⑥ The signature of a cool spot is a bump travelling from blue to red across the stellar spectral line [DI.gif by Oleg Kochukhov]
- ⑥ The longitude of the spot can be determined directly from the position of the corresponding distortion in the line profile.
- ⑥ The latitude can be inferred from the temporal behaviour of the distortion.
- ⑥ The reconstruction of the surface temperature map of a star is an ill-posed inverse problem, requiring the minimization of a discrepancy function between the synthetic spectral line profile and actual observation

Zeeman-Doppler imaging



- ⑥ Magnetic fields polarize the light emitted (or absorbed) in spectral lines formed in the stellar atmosphere (the Zeeman effect)
- ⑥ Spectropolarimetry
- ⑥ Circular polarisation i.e. the Stokes V signatures
 - △ sensitive to the line-of-sight component of the magnetic field
 - △ move across the line profile and change in amplitude depending on the field orientation inside the spot [DIV.gif] by OK
- ⑥ Linear polarisation i.e. the Stokes U and Q signatures
 - △ characterize the transverse magnetic field [DIVQU.gif] by OK

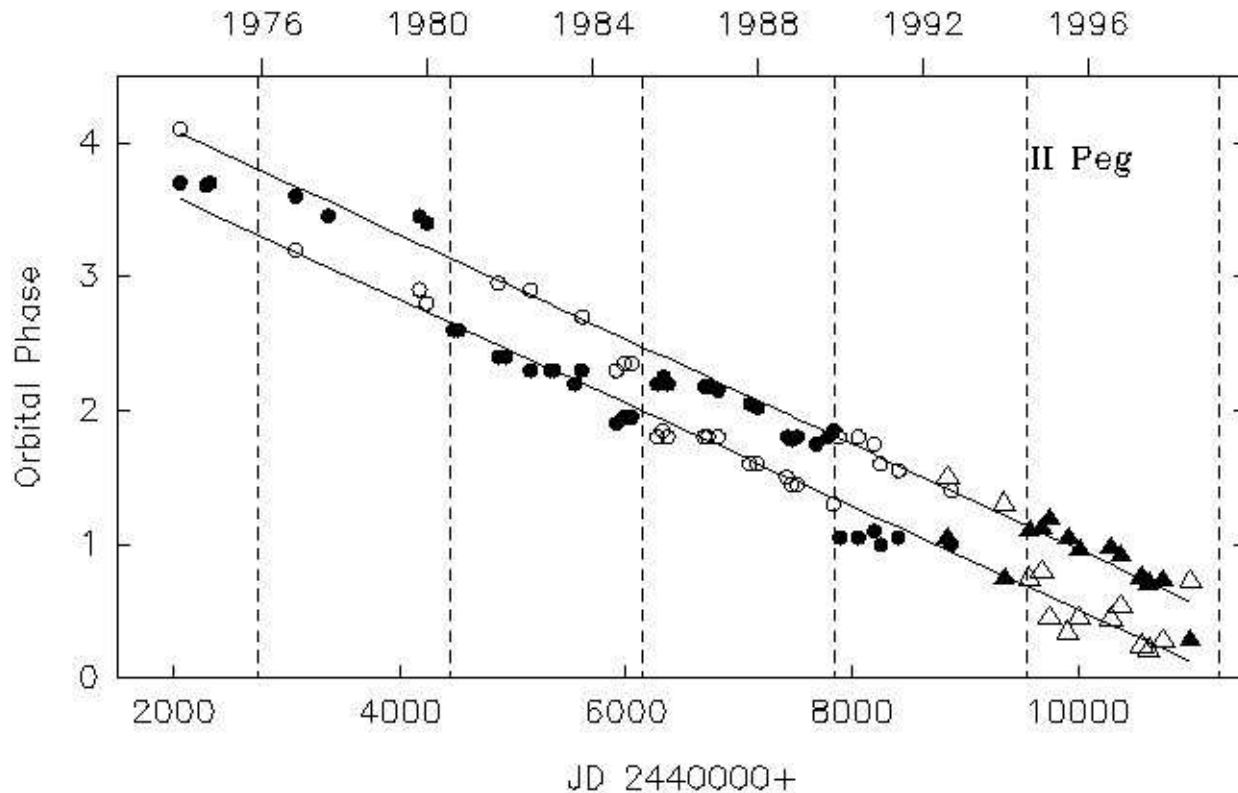
Results (1)



Some objects show strongly nonaxisymmetric spot structures, such as the RS CVn star II Peg, monitored spectroscopically over 18 years. The spots are large, and concentrated at high latitudes. From Tuominen et al. (2002).

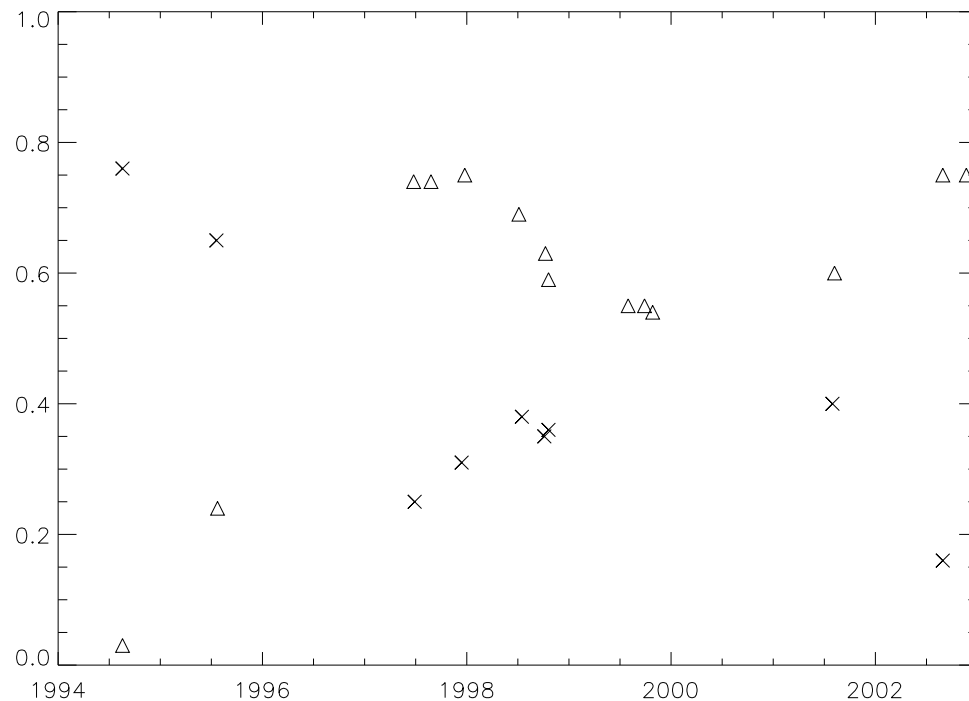
Results (2)

From Tuominen et al. (2002). The minima of the photometric light curves plotted as a function of the phase based on the orbital period for II Peg. The filled circles denote the stronger minimum, the open circles the weaker minimum. The triangles from 1992 onwards have been measured from the Doppler images. This cyclic activity has been termed as flip-flop due to the switch of activity from one side of the star to the other.



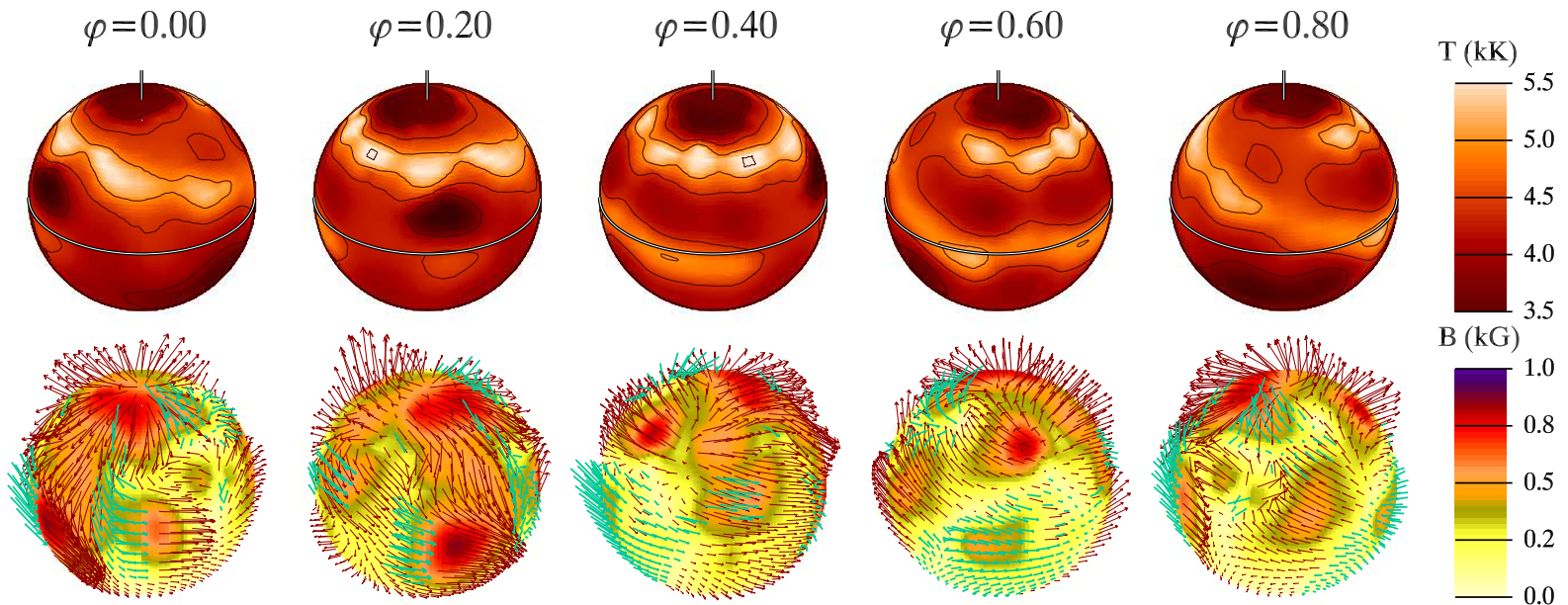
Results (3)

Reanalysis of the spectroscopic data for II Peg with a different inversion method (Lindborg et al. 2010, in preparation) and extending the dataset in time has revealed a more complicated picture. This is currently being checked against a longer timeseries of photometric observations (extending over 30 years).



Results (4)

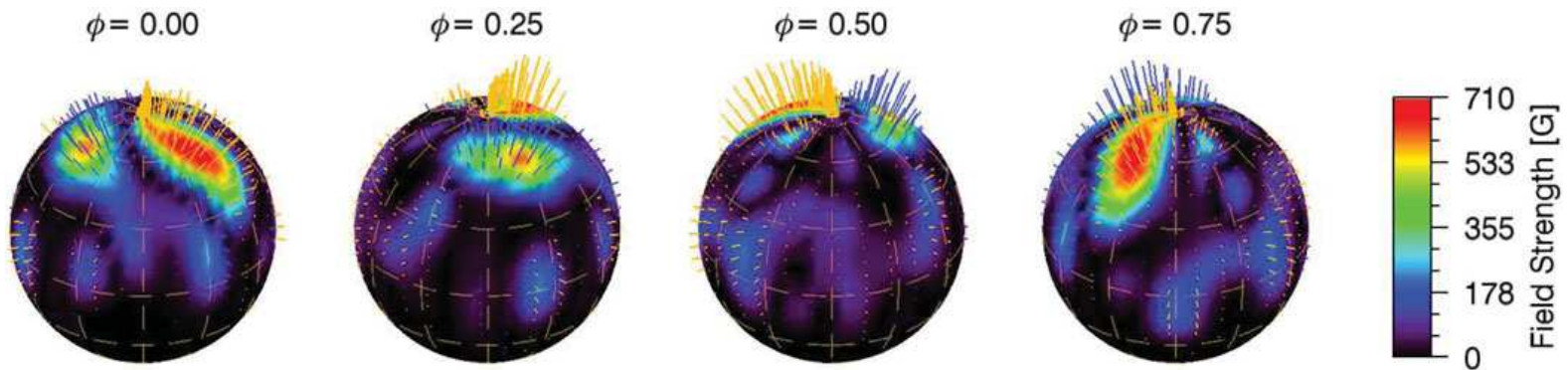
Surface temperature map (up) and magnetic field reconstruction (below) of II Peg for 2004 using the Zeeman-Doppler imaging method of Kochukhov and Piskunov. Temperature minima do not match the magnetic field maxima. The lines used for these inversions were not temperature sensitive, which might explain part of the puzzle. It might also be that the strong magnetic fields inhibit convection inside a strong spot so effectively, that only very few photons can escape from that region to create a Stokes signal. In that sense, the temperature map can be regarded as a more reliable indicator of strong magnetic fields.



Results (5)

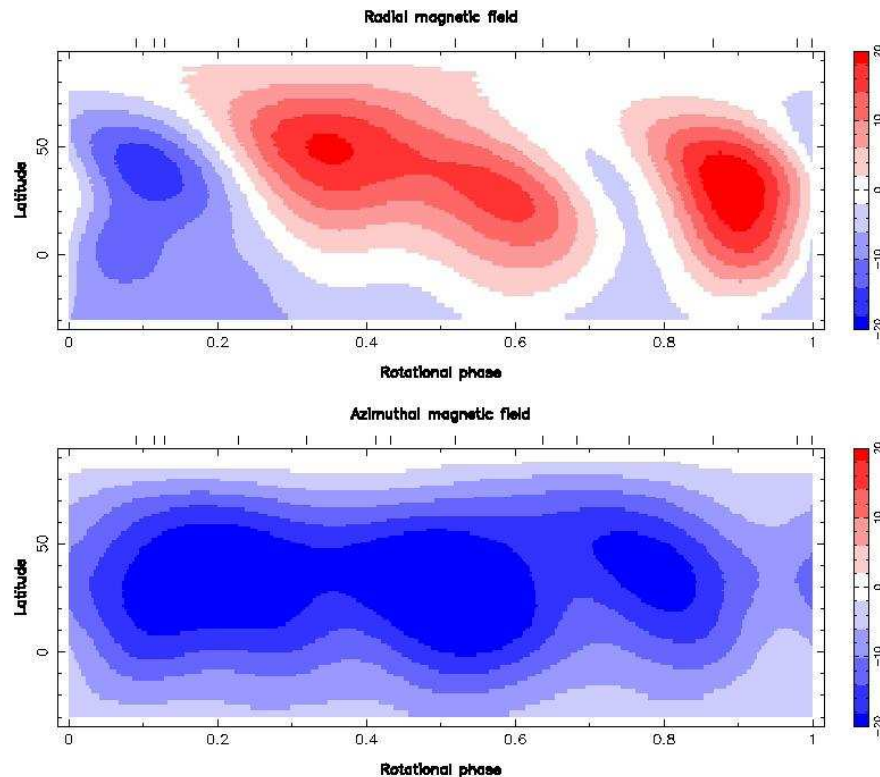


Somewhat clearer picture of the magnetic field configuration of II Peg was recently obtained by Carroll et al. (2009) using Multi-Line Principal Component Analysis. In this approach, the noise in the Stokes profiles is reduced by using several hundreds of lines instead of only a few, as by Kochukhov et al. It is evident that the active longitudes show radial magnetic field of different sign. To study the cycle (and possible flip-flops), a reliable independent determination of the period of the spot mechanism versus the orbital motion is needed.



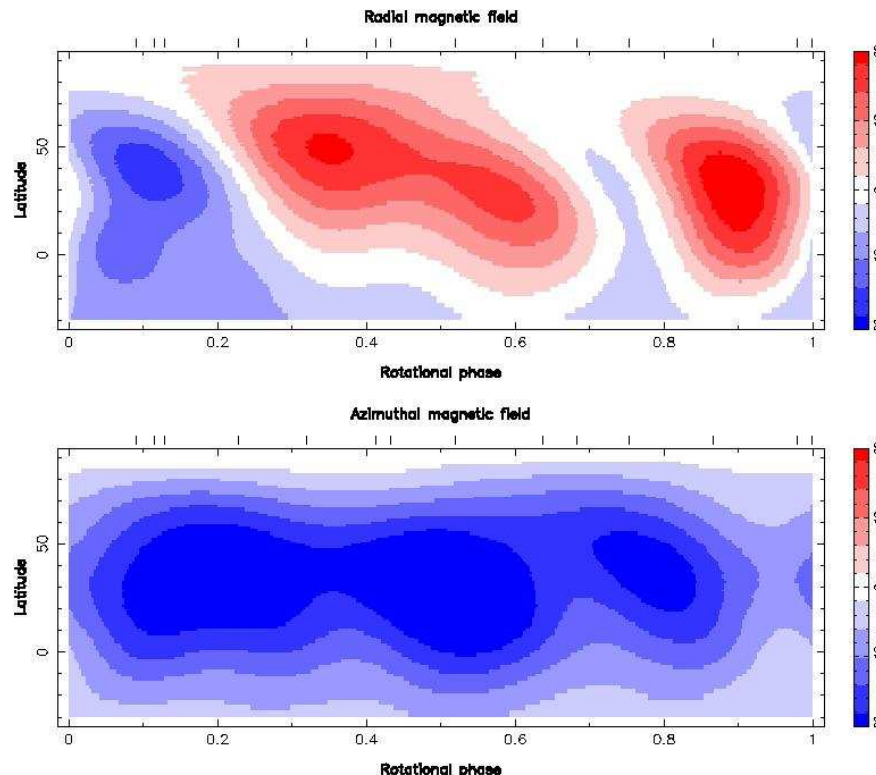
Results (6)

Some objects, such as HD190771, a dwarf star quite like the Sun, but rotating almost 3 times faster, have been reported to exhibit mostly axisymmetric magnetic structures. This object has been observed with NARVAL at Pic du Midi, and a Zeeman-Doppler inversion method of Donati et al. (using Stokes I and V) has been used (Petit et al. 2008). Their method uses the so-called LSD (Least Squares Deconvolution) method, in which the noise reduction of the Stokes profiles is done by calculating an average line profile of several hundreds of different lines.



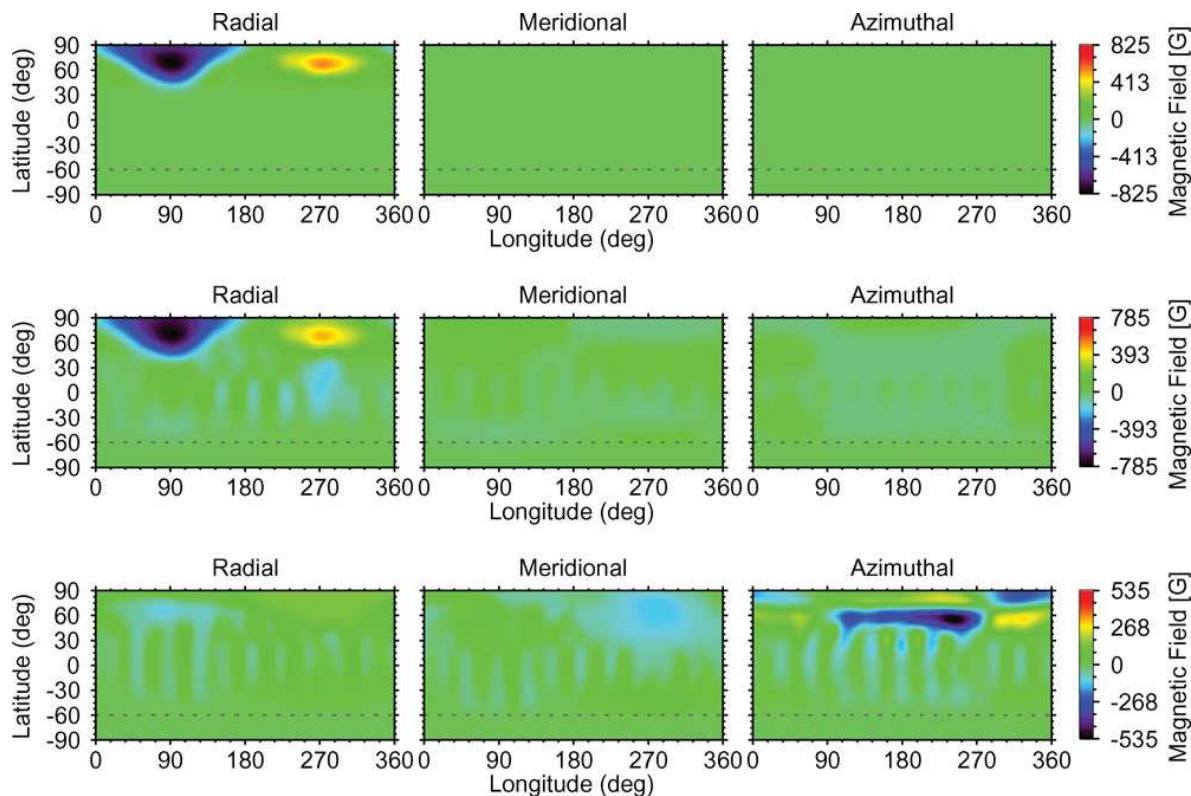
Results (7)

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Results (8)

Synthetic experiment by Carroll et al. (2009). Uppermost row: the artificially generated magnetic field configuration with two purely radial spots of opposite polarities. Middle row: a solution obtained from an inversion where both temperature and magnetic fields were inverted for. Lower row: a solution obtained from an inversion where only magnetic field was inverted for, and temperature kept fixed. Both solutions provide an equally good fit between the artificial observation and synthetic line profiles.



Differential rotation

Photometrically detected period variations (e.g. Hall 1991; Henry et al. 1995) indicate that relative differential rotation decreases as the rotation rate increases, so that

$$k = \frac{\Delta\Omega}{\Omega} = \Omega^{-n},$$

where the observationally determined $n \approx 0.8$. Therefore, the absolute differential rotation would slightly increase as function of rotation

$$\Delta\Omega = \Omega^{1-n} \approx \Omega^{0.2}.$$

This is in rough agreement with some mean-field models of global axisymmetric flow and heat transport (e.g. Kitchatinov & Rüdiger 1999), which indicate n values slightly larger than 1, implying slightly decreasing absolute differential rotation as function of rotation. The efficiency of dynamos is proportional to $\Delta\Omega$, so that the larger the shearing effect, the more efficient is the dynamo. Therefore it seems justified to assume that the contribution from differential rotation to dynamo amplification is more or less constant with growing rotation rate.

Turbulent quantities?

Dynamo number is a dimensionless quantity measuring the dynamo efficiency

$$D = \frac{\alpha \Delta \Omega R^3}{\eta_t^2},$$

where α describes the efficiency of induction effect of convective turbulence, R is the radius of the object, and η_t is the turbulent diffusivity. How do the turbulent quantities behave as function of rotation? Nothing is known observationally, some results from convection models exist (e.g. the series of papers by Käpylä et al. 2004-present). In short, these results indicate that α is growing and η_t is decreasing as function of Ω . This would imply that when rotation rate is increasing, the dynamo efficiency is increasing so that the α -effect is increasing while Ω -effect is roughly constant, i.e. the type of the dynamo would be changing from $\alpha\Omega$ to $\alpha^2\Omega$ type with increasing rotation.

Implications for dynamos?

- ⑥ Spectropolarimetry is a very important tool to further investigate the activity cycles
 - △ Polarity of the active longitudes; seems to be opposite on each hemisphere
 - △ Polarity changes or drifts?
 - △ Simultaneous observations with T-sensitive lines!
 - △ Systematic analysis and combination of spectroscopic, spectropolarimetric and photometric data!

- ⑥ Are there really two distinct classes of rapid rotators exhibiting
 - △ nonaxisymmetric cyclic spot activity
 - Consistent with the $\alpha^2\Omega$ -dynamo picture, although dynamo models including dynamics struggle to reproduce the rotation laws due to Taylor-Proudman balance

Implications for dynamos?

- ⑥ Are there really two distinct classes of rapid rotators exhibiting
 - △ axisymmetric (cyclic?) spot activity
 - Inconsistent with the picture of $\Delta\Omega$ being roughly constant as function of rotation
 - more $\Delta\Omega$ needed to keep the dynamo in the $\alpha\Omega$ and axisymmetric regime.
 - △ To fully answer this question, a benchmark would be needed for the Zeeman-Doppler imaging techniques.