Temporal Changes of p–Modes Properties Derived from Nearly 20 Years of Observations

SDO 16 Meeting — Burlington, VT

S.G. Korzennik

Harvard-Smithsonian Center for Astrophysics.

October 2016

Introduction

- 3 methodologies;
- 3 data sets;
- 20 years of observations:

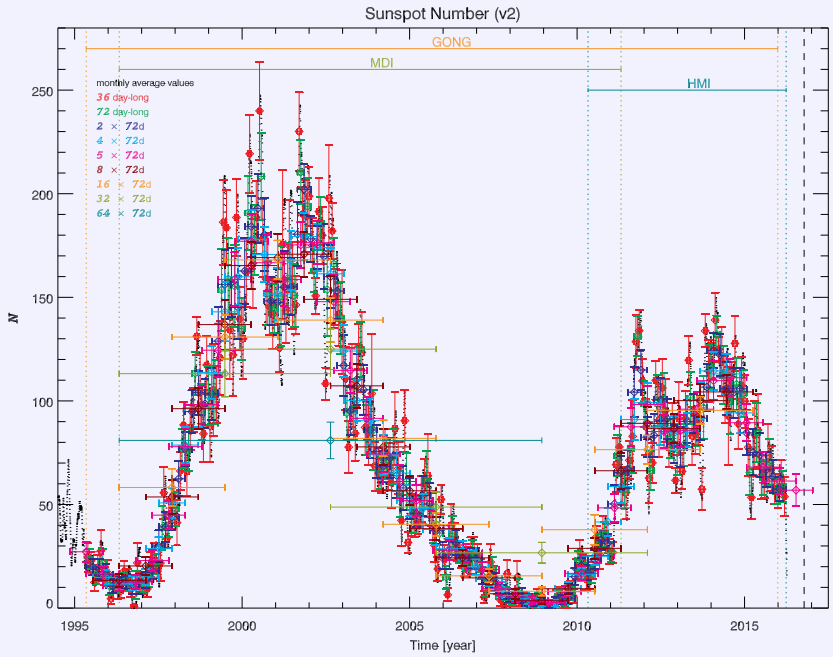
	NSO		SU		CfA	
	sym.	asym.	sym.	asym.	sym.	asym.
GONG	$\surd$	$\star$	$\times$	$\times$	$\surd$	$\surd$
MDI	$\times$	$\times$	$\surd$	$\surd$	$\surd$	$\surd$
HMI	$\times$	$\times$	$\surd$	$\surd$	$\surd$	$\surd$

$\star$: preliminary results, tables not available.

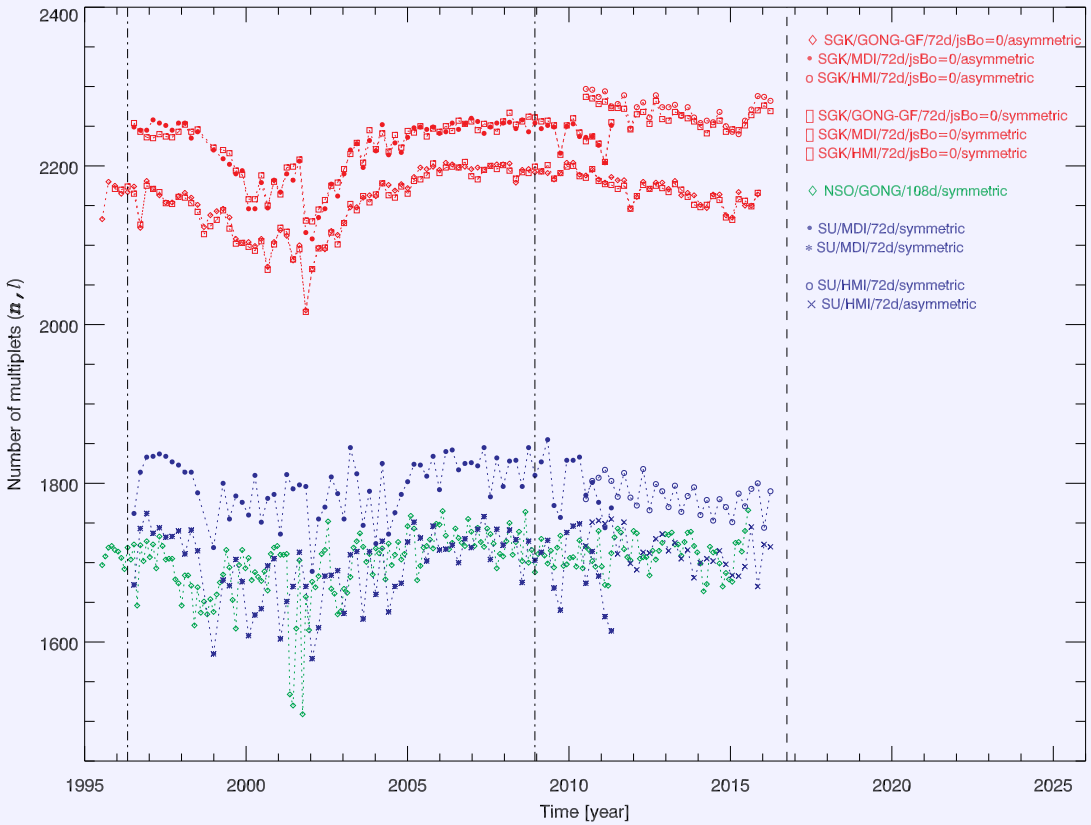
Fitting Methods, Data Sets & Activity

Fitting methods:

- NSO: $\{\nu_{n,l,m}\}$
  "whack-a-mole"
  each m independently
  no leakage matrix information
  symmetric profile only ($\star$)
- SU: $\{\nu_{n,l}, c_i^{n,l}\}$
  $\nu_{n,l,m} = \nu_{n,l} + \Sigma_i c_i^{n,l}(m) P_m^l(i)$
  all m simultaneously
  leakage matrix
  symmetric & asymmetric profile
- SGK: $\{\nu_{n,l,m}\}$
  all m simultaneously
  leakage matrix
  sanity check
  asymmetric (& symmetric) profile

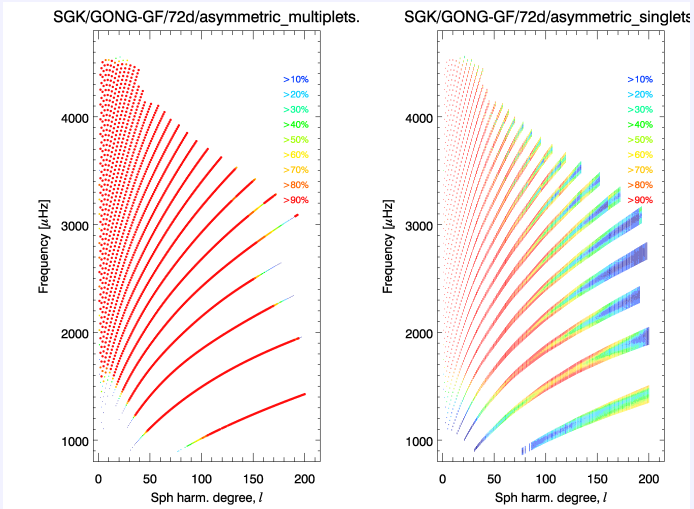


Fitted Modes – Multiplets

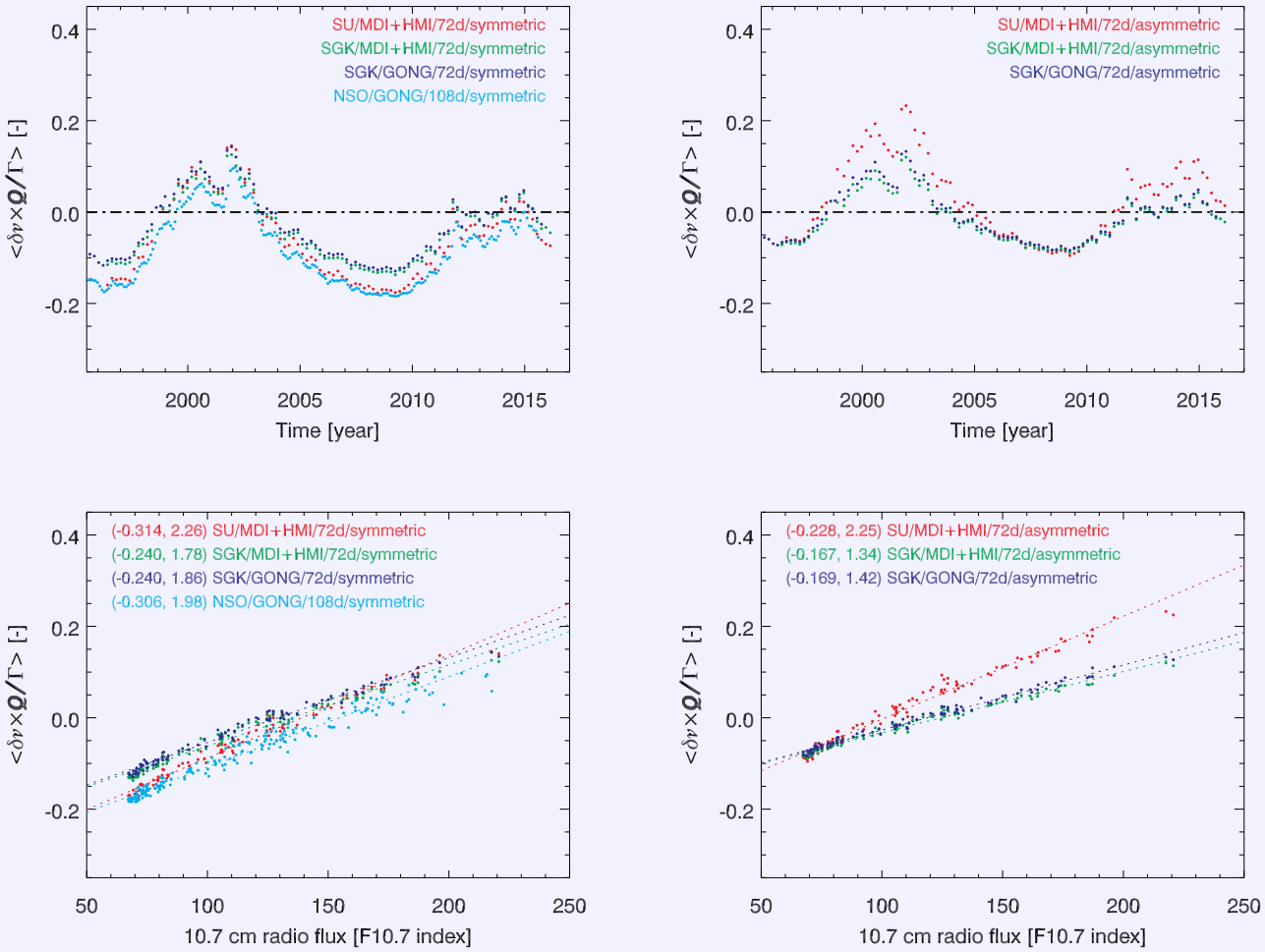


- Number of fitted multiplets, $\{\nu_{n,l}\}$, different fitting methods.

Mode Attrition



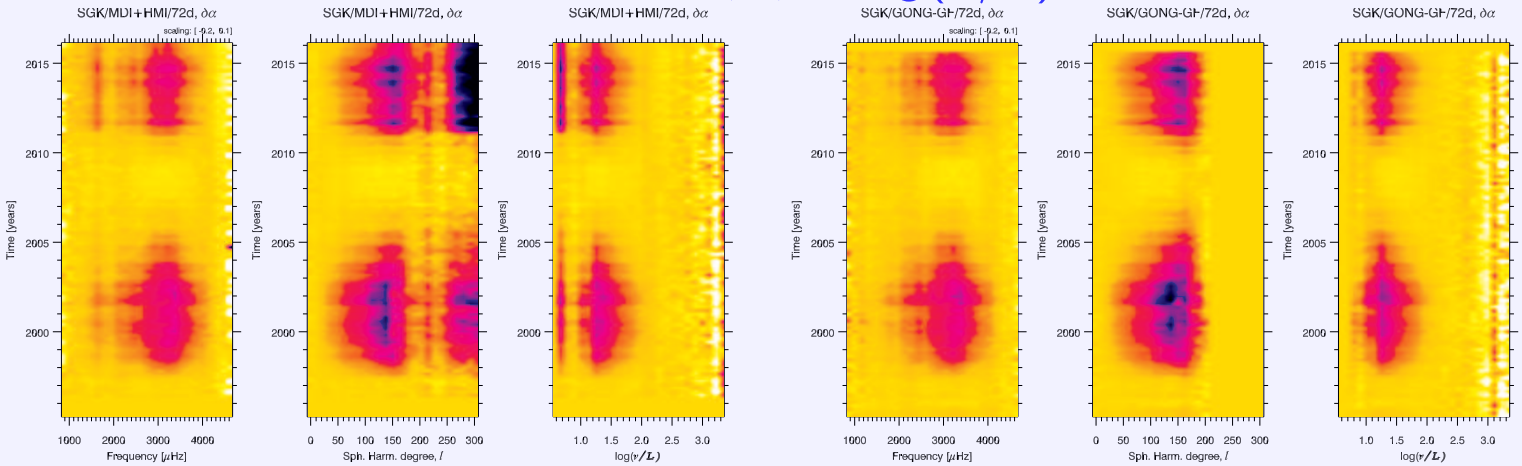
Scaled Frequency Changes wrt Time



- $< \delta\nu \times Q/\Gamma >$ vs time and vs F10.7

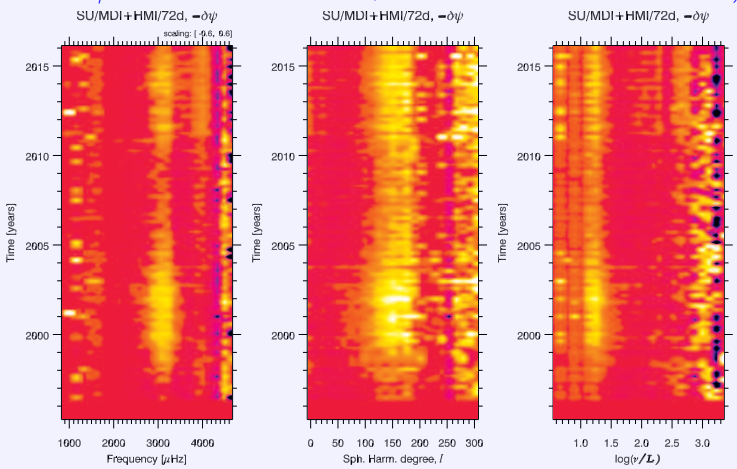
Changes in Asymmetry, α

- $< \delta\alpha >$ vs time, binned over $\nu, \ell,$ or $\log(\nu/L)$



SGK/MDI+HMI/72d SGK/GONG-GF/72d

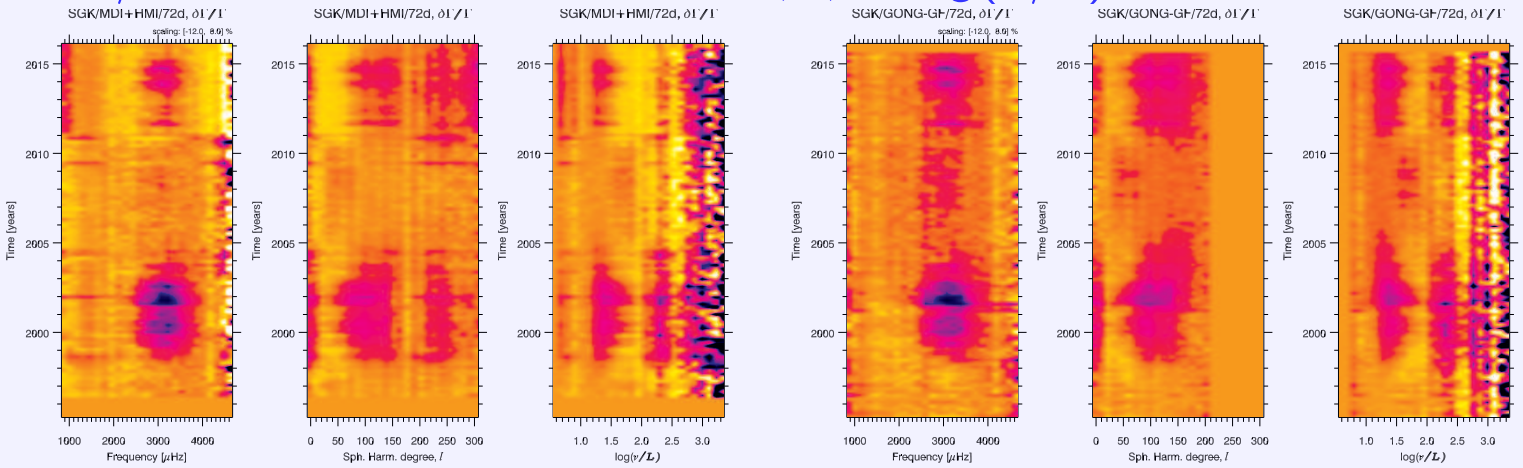
- $< \delta\psi >$ vs time, binned over $\nu, \ell,$ or $\log(\nu/L)$



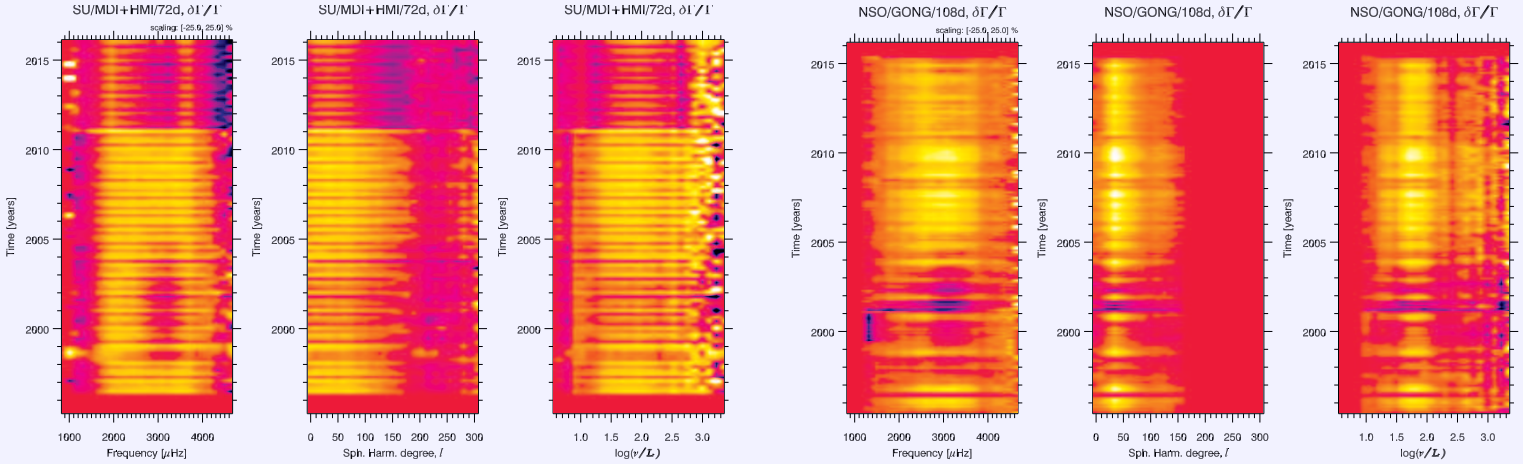
SU/MDI+HMI/72d

Changes in FWHM, Γ

- $< \delta\Gamma/\Gamma >$ vs time, binned over $\nu, \ell,$ or $\log(\nu/L)$



SGK/MDI+HMI/72d SGK/GONG-GF/72d



SU/MDI+HMI/72d NSO/GONG/108d

Rotation Inversion – Introduction

- Inverse problem

$$\frac{\Delta\nu_{n,\ell}}{2\,m} = \int K_{\Omega}^{n,\ell}(r,\theta)\,\Omega(r,\theta)\,dr\,\sin(\theta)d\theta$$

- Full 2D inversions, $\Delta\nu_{n,\ell} = \nu_{n,\ell,m} - \nu_{n,\ell,-m}$
- Two methods:
  - Cholesky factorization
  - Regularized least squares
    $\Rightarrow \bar{\Omega}(r_k,\theta_k)$
- Optimized model grid $\{r_k,\theta_k\}$
- Estimates of averaging kernels
- See Eff-Darwich & Pérez-Hernández (1997)

Rotation Inversion – Introduction

- Averaging kernels

$$\bar{\Omega}(r_k, \theta_k) = \int A_k(r, \theta)\ \Omega(r, \theta)\ dr\ \sin(\theta) d\theta$$

- Center of gravity:

$$\begin{aligned} r_{cog} &= \frac{1}{X_A} \int r\ A_k(r, \theta)\ dr\ \sin(\theta) d\theta \\ \cos(\theta)_{cog} &= \frac{1}{X_A} \int cos(\theta)\ A_k(r, \theta)\ dr\ \sin(\theta) d\theta \end{aligned}$$

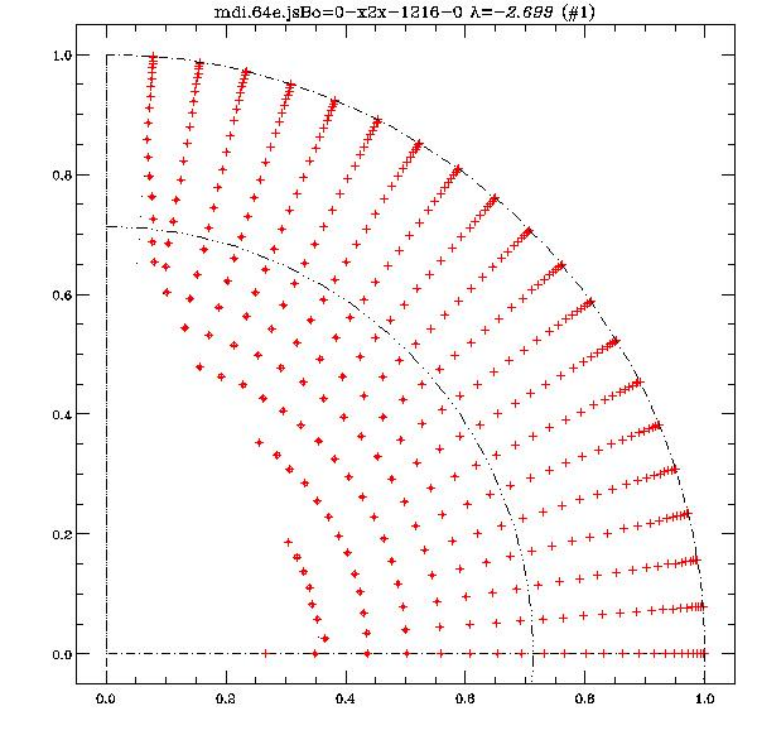
- Width:

$$\begin{aligned} w^2_{cog} &= \frac{1}{2\ Y_A} \int d^2_{cog} |A_k(r, \theta)|\ dr\ \sin(\theta) d\theta \\ d^2_{cog} &= (r - r_{cog})^2 + (\cos(\theta) - \cos(\theta)_{cog})^2 \end{aligned}$$

where

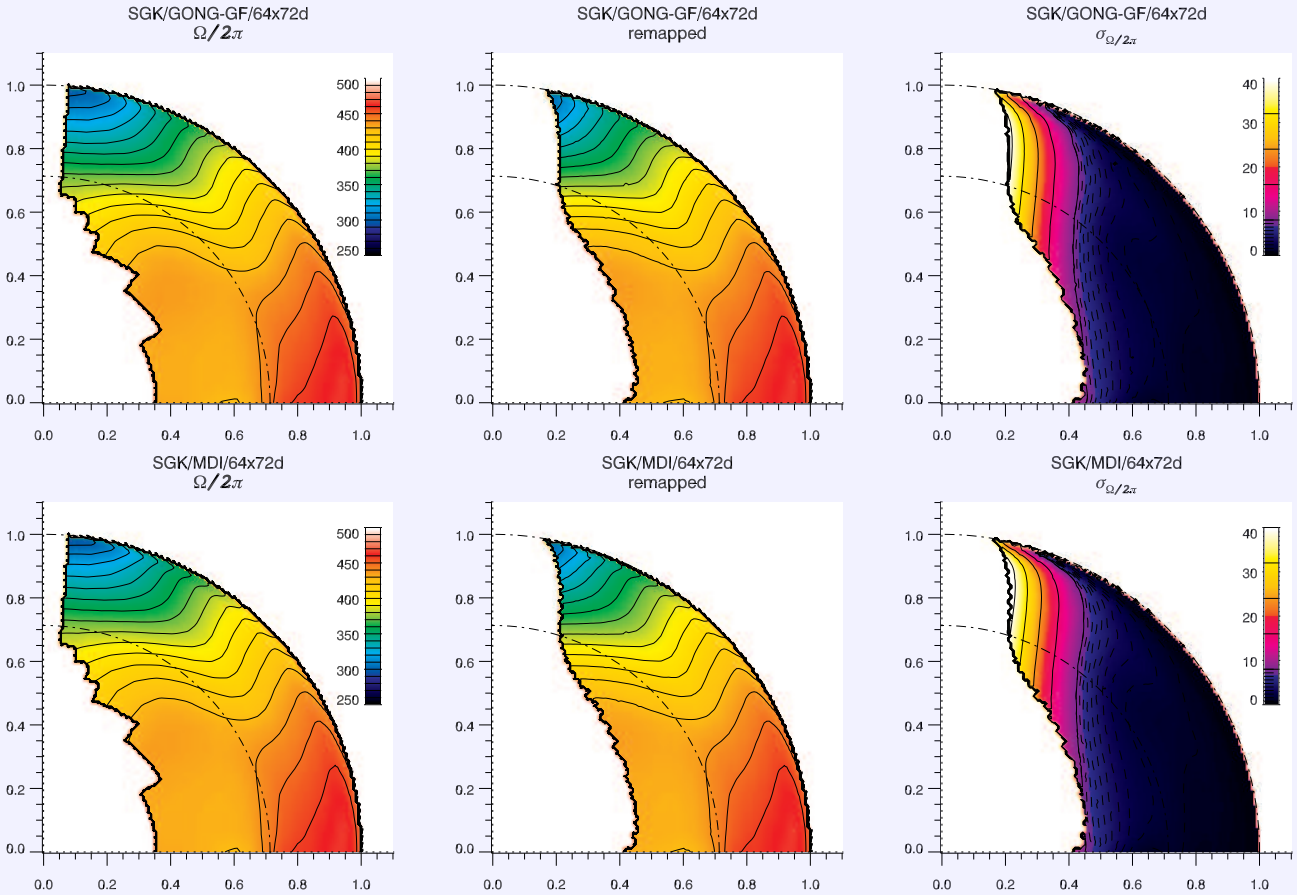
$$\begin{aligned} X_A &= \int A_k(r, \theta)\ dr\ \sin(\theta) d\theta \\ Y_A &= \int |A_k(r, \theta)|\ dr\ \sin(\theta) d\theta \end{aligned}$$

Rotation Inversion – Averaging kernels



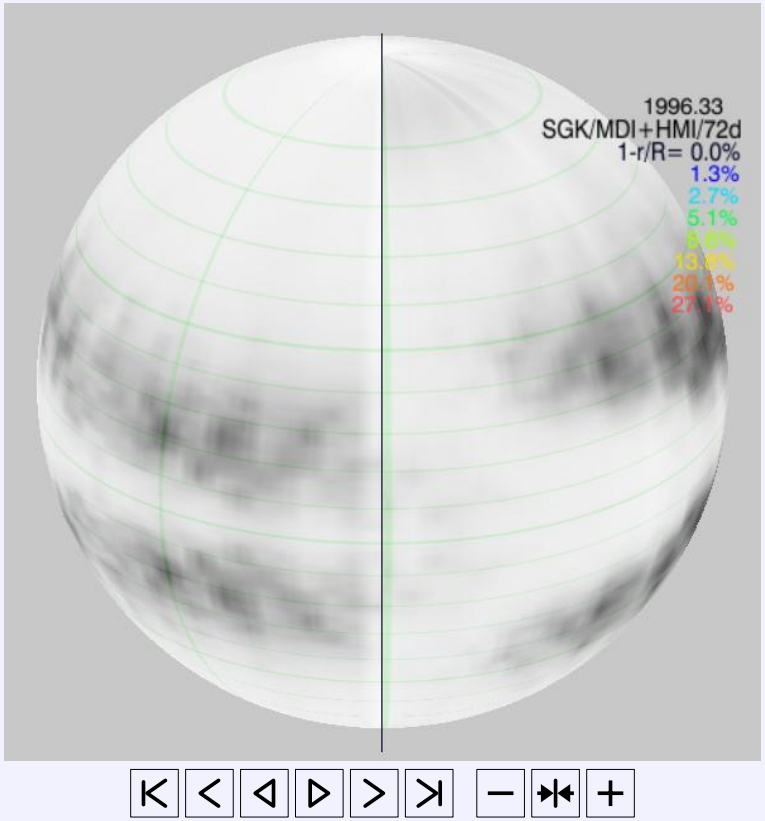
- Averaging kernels COG and width, as a function of smoothing
- SGK/MDI/64×72d – Cycle 23

Rotation Inversion – Mean Profile



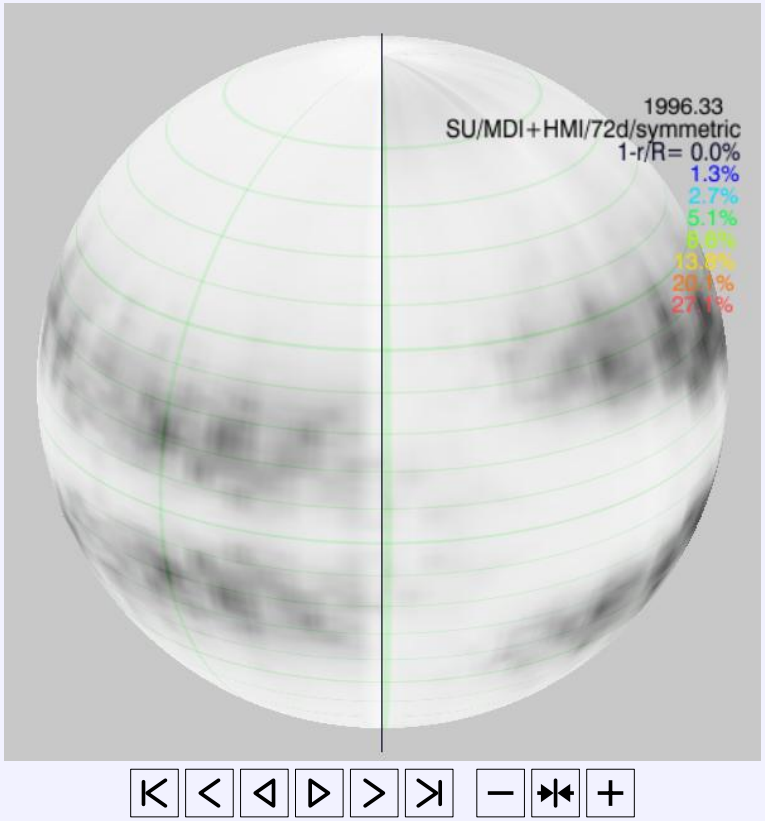
- Mean rotation profile for Cycle 23.

Propagation Diagrams: SGK/MDI+HMI/72d



- "Deformation" by $\delta\Omega(r,\theta) = \Omega(r,\theta) - <\Omega(r,\theta)>_{\text{Cycle 23}}$
- SGK/MDI+HMI/72d

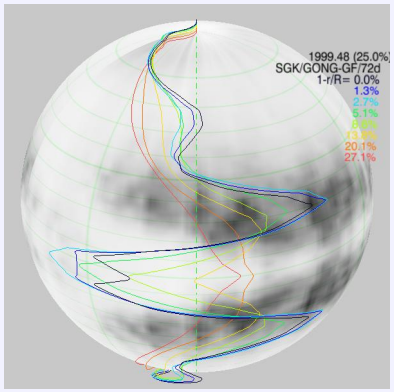
Propagation Diagrams: SU/MDI+HMI/72d/symmetric

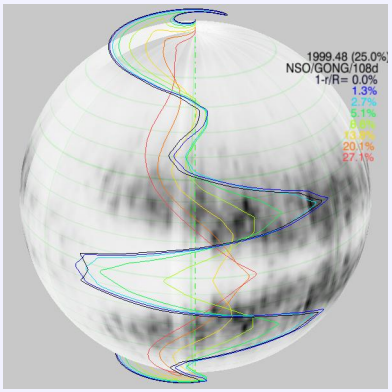


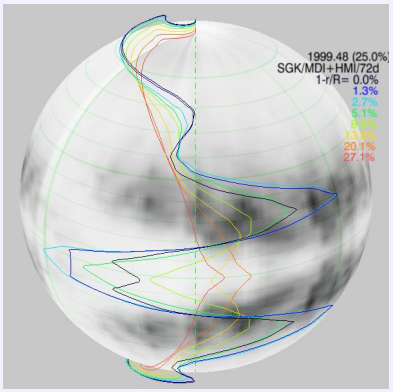
- "Deformation" by $\delta\Omega(r,\theta)$
- SU/MDI+HMI/72d/symmetric

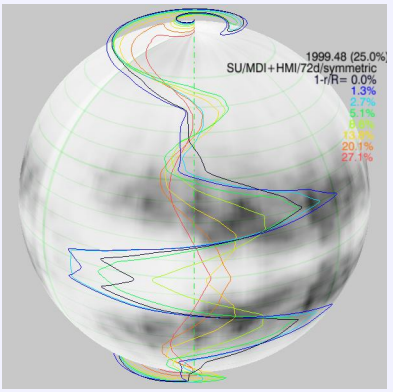
Propagation Diagrams: Comparisons - I

- 1999.48 (25% Cycle 23)

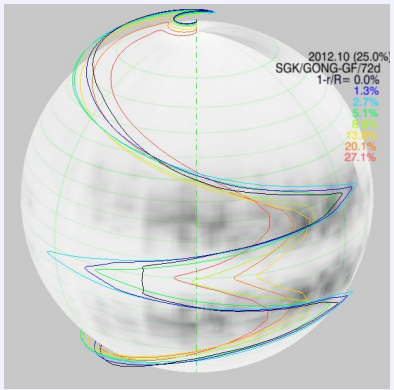


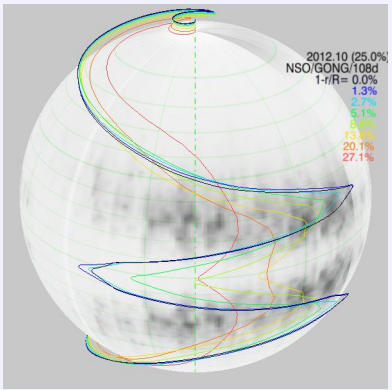


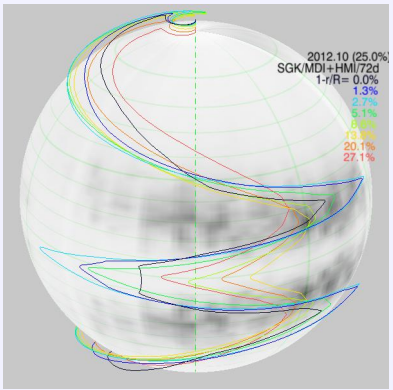


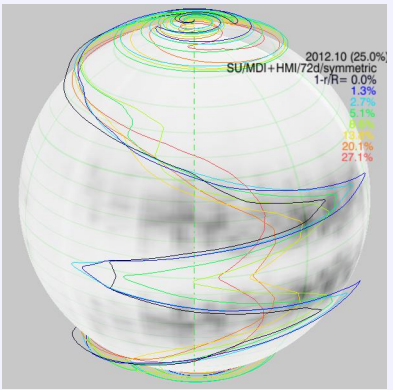


- 2012.10 (25% Cycle 24)







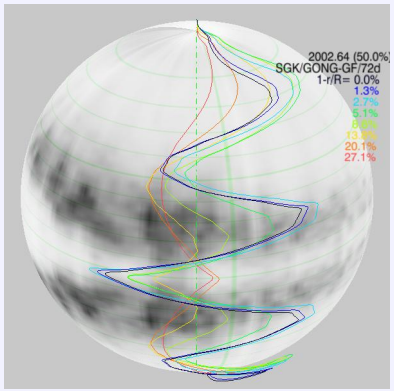


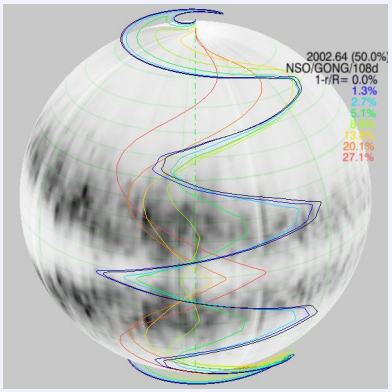
SGK/GONG/72d NSO/GONG/108d SGK/MDI+HMI/72d SU/MDI+HMI/72d

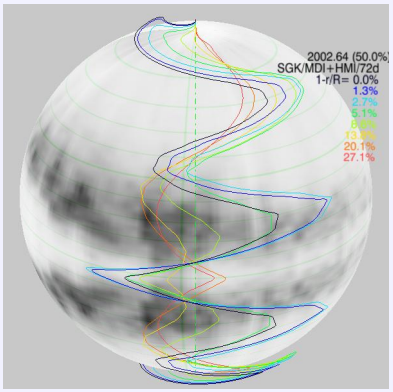
lines at $1 - r/R_\odot = 0, 1.3, 2.7, 5.1, 8, 13, 20, 27\%$

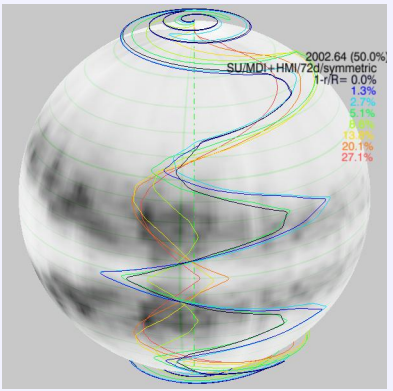
Propagation Diagrams: Comparisons - II

- 2002.64 (50% Cycle 23)

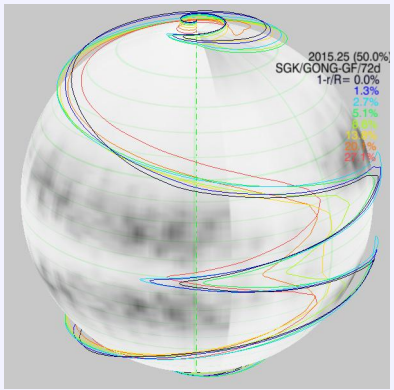


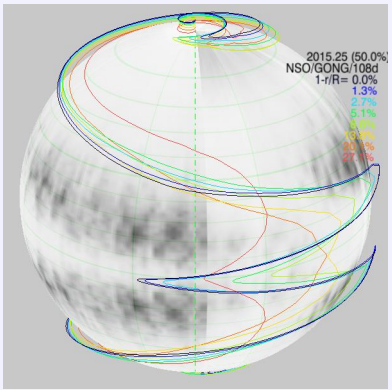


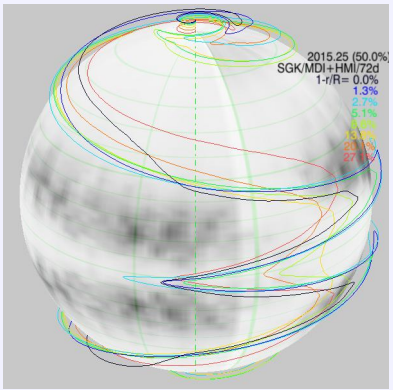


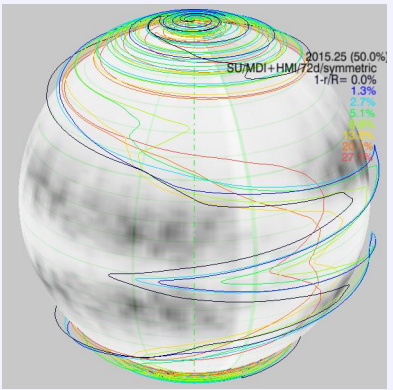


- 2015.25 (50% Cycle 24)









SGK/GONG/72d NSO/GONG/108d SGK/MDI+HMI/72d SU/MDI+HMI/72d

lines at $1 - r/R_{\odot} = 0, 1.3, 2.7, 5.1, 8, 13, 20, 27\%$

Conclusions

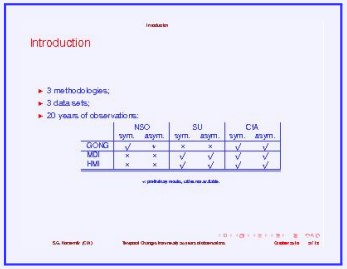
- Changes in frequencies, asymmetry & line-width:
  - changes are consistent w/ activity level, not between methods;
  - residual offsets between methods;
  - different mode attrition pattern;
  - assymetric fit: reduced $\delta\nu$ sensitivity w/ F10.7, and
  - clear variation of $\delta\alpha$ & $\delta\Gamma/\Gamma$;
  - short period oscillation in SU's & NSO's $\delta\Gamma/\Gamma$.

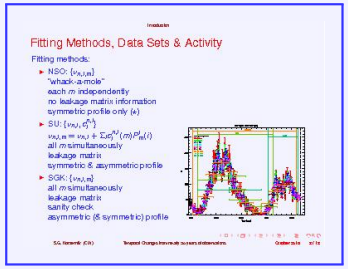
- Rotation Inversions:
  - remapping at COG:
    shows inference limit close to the rotation axis;
  - $\delta\Omega$ for Cycle 24 is different from Cycle 23:
    weaker $B_{\rm surf} \Longleftrightarrow$ stronger $\delta\Omega$;
  - different inferences in the deeper layers;
  - un-physical twist at high latitudes (esp. for some cases)

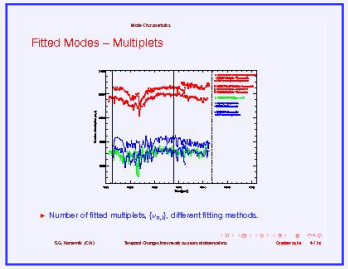
Updated tables available at

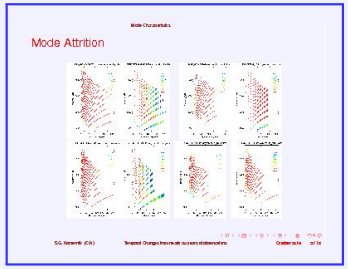
`https://www.cfa.harvard.edu/~sylvain/research/tables/MediumL/`

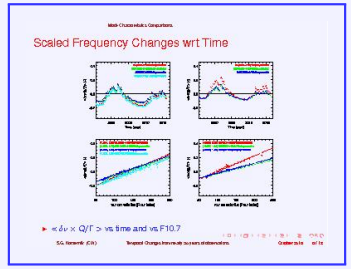
The End

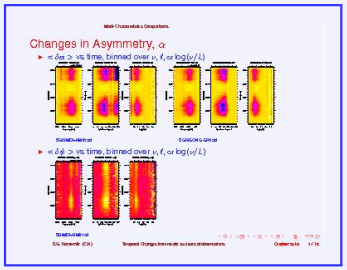

Introduction
Introduction
3 methodologies;
3 data sets;
20 years of observations;
NSO sym. asym.
SU sym. asym.
CfA sym. asym.
GONG √ × × √ √
MDI × × √ √ √ √
HMI × × √ √ √ √
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18

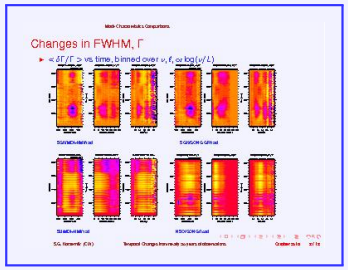

Introduction
Fitting Methods, Data Sets & Activity
Fitting methods:
NSO: $\{\nu_{n,l,m}\}$
"whack-a-mole"
each m independently
no leakage matrix information
symmetric profile only (a)
SU: $\{\nu_{n,l}, a_j^{n,l}\}$
$\nu_{n,l,m} = \nu_{n,l} + \Sigma a_j^{n,l}(m) P_m^j(i)$
all m simultaneously
leakage matrix
symmetric & asymmetric profile
SGK: $\{\nu_{n,l,m}\}$
all m simultaneously
leakage matrix
sanity check:
asymmetric (& symmetric) profile
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18

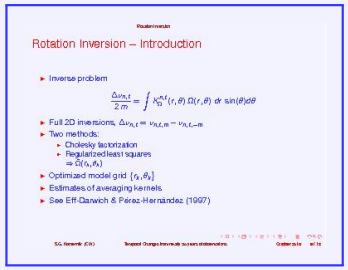

Mode Characteristics
Fitted Modes – Multiplets
Number of fitted multiplets, $\{\nu_{n,l}\}$, different fitting methods.
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18

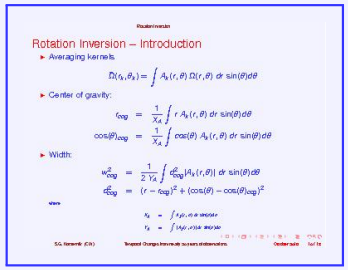

Mode Characteristics
Mode Attrition
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18

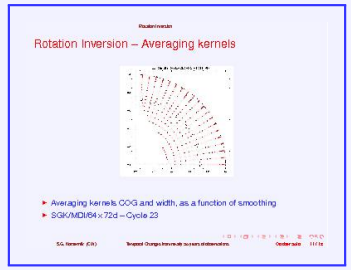

Mode Characteristics Comparisons
Scaled Frequency Changes wrt Time
$\propto \delta\nu \times Q/\Gamma >$ vs time and vs F10.7
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18

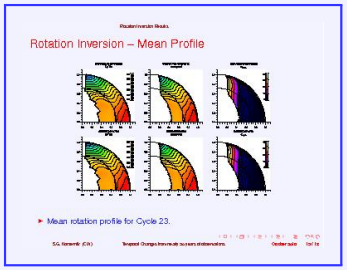

Mode Characteristics Comparisons
Changes in Asymmetry, α
$\propto \delta\alpha >$ vs time, binned over $\nu, l, \alpha \log(\omega/L)$
$\propto \delta\frac{a}{\nu} >$ vs time, binned over $\nu, l, \alpha \log(\omega/L)$
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18

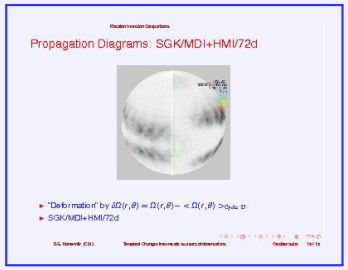

Mode Characteristics Comparisons
Changes in FWHM, Γ
$\propto \delta\Gamma/\Gamma >$ vs time, binned over $\nu, l, \alpha \log(\omega/L)$
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18

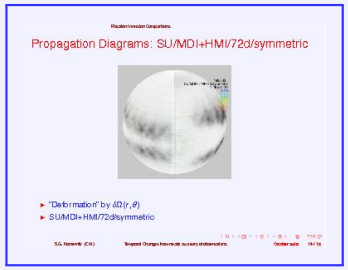

Rotation Inversion
Rotation Inversion – Introduction
Inverse problem
$\frac{\Delta\nu_{n,l}}{2m} = \int K_{\Omega}^{n,l}(r,\theta)\,\Omega(r,\theta)\,dr\,\sin(\theta)d\theta$
Full 2D inversions, $\Delta\nu_{n,l,t} = \nu_{n,l,m} - \nu_{n,l,-m}$
Two methods:
Cholesky factorization
Regularized least squares
$\Rightarrow \bar{\Omega}(r_0,\theta_0)$
Optimized model grid $\{r_0,\theta_0\}$
Estimates of averaging kernels.
See Eff-Darwich & Pérez-Hernández (1997)
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18

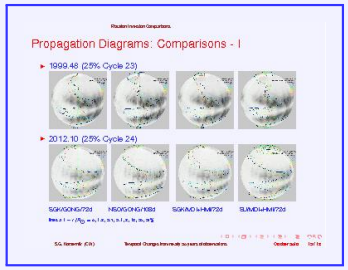

Rotation Inversion
Rotation Inversion – Introduction
Averaging kernels
$\bar{\Omega}(r_0,\theta_0) = \int A_{\theta}(r,\theta)\,\Omega(r,\theta)\,dr\,\sin(\theta)d\theta$
Center of gravity:
$r_{cog} = \frac{1}{\chi_A}\int r\,A_{\theta}(r,\theta)\,dr\,\sin(\theta)d\theta$
$\cos(\theta)_{cog} = \frac{1}{\chi_A}\int \cos(\theta)\,A_{\theta}(r,\theta)\,dr\,\sin(\theta)d\theta$
Width:
$w^2_{cog} = \frac{1}{2\,\chi_A}\int d^2_{cog}|A_{\theta}(r,\theta)|\,dr\,\sin(\theta)d\theta$
$d^2_{cog} = (r-r_{cog})^2 + (\cos(\theta)-\cos(\theta)_{cog})^2$
where
$\chi_A = \int r\,\rho\,dr\,d\theta$ area
$r_0 = \int r\,\rho\,dr\,d\theta$ moment
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18


Rotation Inversion
Rotation Inversion – Averaging kernels
Averaging kernels COG and width, as a function of smoothing
SGK/MDI/64×72d – Cycle 23
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18

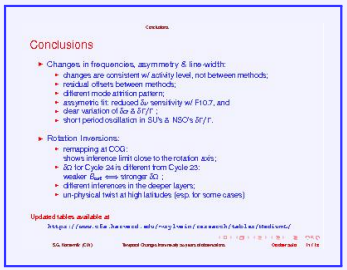

Rotation Inversion Results
Rotation Inversion – Mean Profile
Mean rotation profile for Cycle 23.
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18


Rotation Inversion Comparisons
Propagation Diagrams: SGK/MDI+HMI/72d
"Deformation" by $\delta\Omega(r,\theta) = \Omega(r,\theta) - \langle\Omega(r,\theta)\rangle_{\text{Cycle 23}}$
SGK/MDI+HMI/72d
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18


Rotation Inversion Comparisons
Propagation Diagrams: SU/MDI+HMI/72d/symmetric
"Deformation" by $\delta\Omega(r,\theta)$
SU/MDI+HMI/72d/symmetric
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18


Rotation Inversion Comparisons
Propagation Diagrams: Comparisons - I
1999.48 (25% Cycle 23)
2012.10 (25% Cycle 24)
SGK/GONG/72d
NSO/GONG/108d
SGK/MDI+HMI/72d
SU/MDI+HMI/72d
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18


Rotation Inversion Comparisons
Propagation Diagrams: Comparisons - II
2002.64 (50% Cycle 23)
2015.25 (50% Cycle 24)
SGK/GONG/72d
NSO/GONG/108d
SGK/MDI+HMI/72d
SU/MDI+HMI/72d
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18


Conclusions
Changes in frequencies, asymmetry & line-width:
changes are consistent w/ activity level, not between methods;
residual offsets between methods;
different mode attrition pattern;
assymetric fit reduced $\delta\alpha$ sensitivity w/ F10.7, and
clear variation of $\delta\alpha$ & $\delta\Gamma/\Gamma$;
short period oscillation in SU's & NSO's $\delta\Gamma/\Gamma$.
Rotation Inversions:
remapping at COG:
shows inference limit close to the rotation axis;
$\delta\Omega$ for Cycle 24 is different from Cycle 23:
weaker δ_{NS} even stronger $\delta\Omega$;
different inferences in the deeper layers;
un-physical twist at high latitudes (esp. for some cases)
Updated tables available at
S.G. Korzennik (CfA)
Temporal Changes from nearly 20 years of observations
October 2016
18 / 18