Monitoring stellar optical centroid variations due to magnetic activity for astrometric detection of exoplanets:

Lessons from the Gravity Probe B mission

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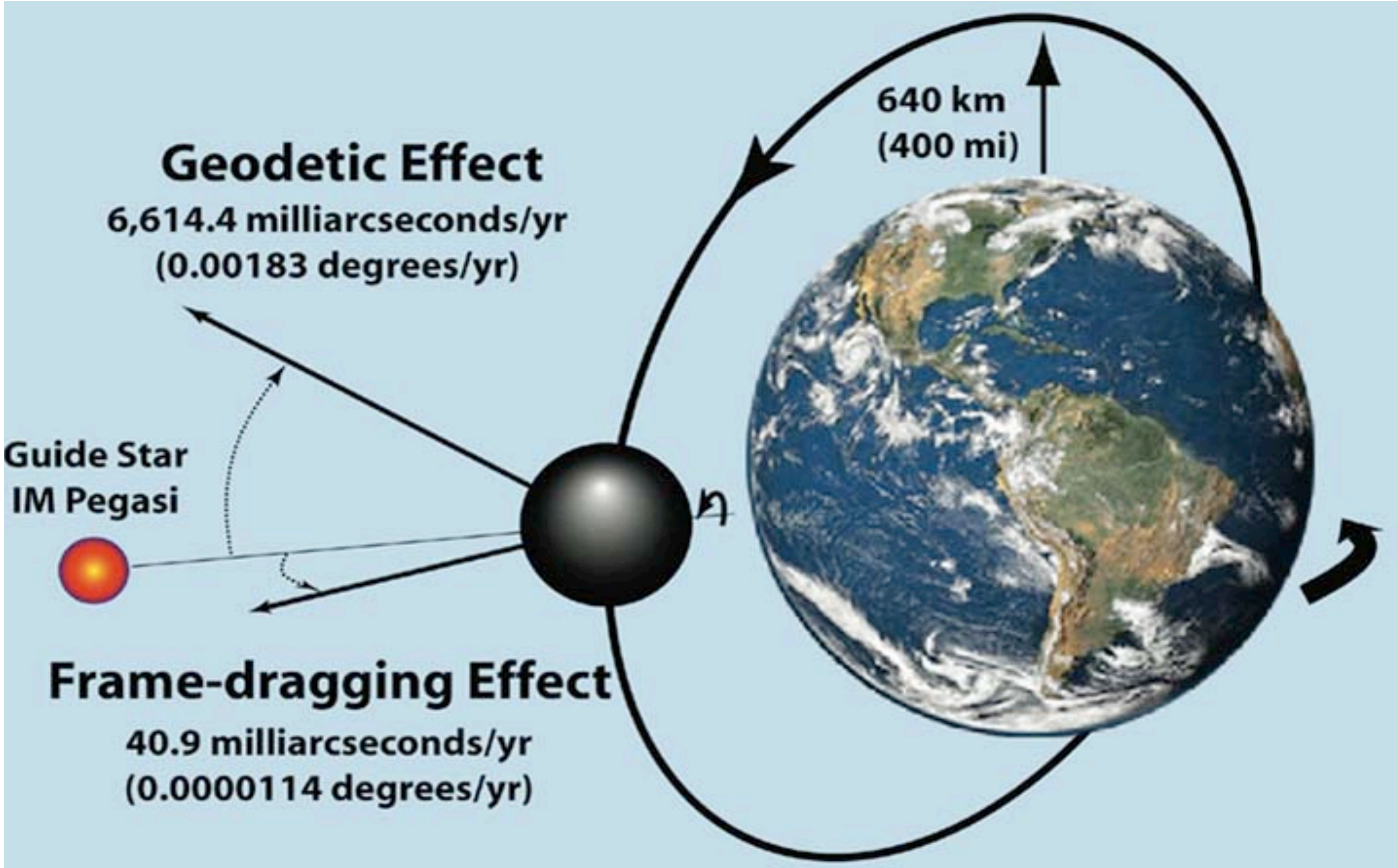
TOLIMAN Mission, Rome, 2018

Gravity Probe B (GPB) Misison

- NASA/Stanford mission to test predictions of GR (F. Everitt)



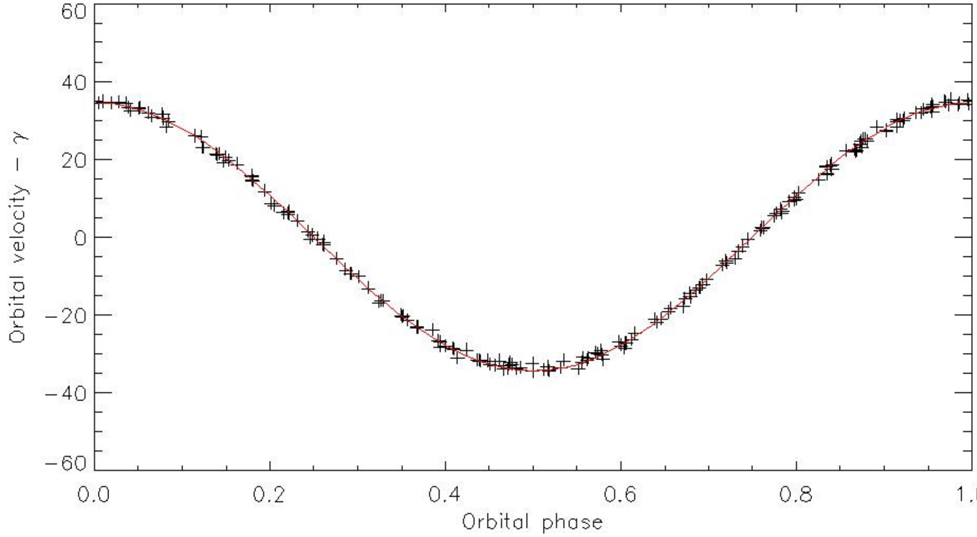
- Uses gyroscopes in a polar orbit (Sep 2004 – Sep 2005)
- Motion of gyroscopes relative to the guide star = IM Peg

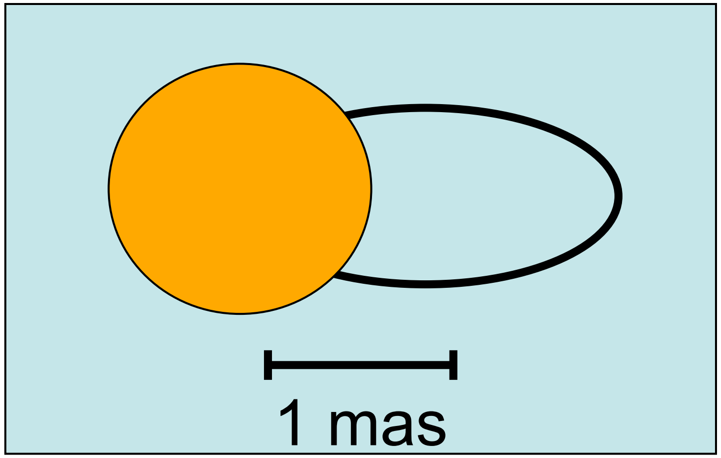
GPB guide star IM Pegasi

- **Bright in optical & radio**
  - nearby giant (optical)
  - magnetically active (radio)
  - ? RS CVn-type binary
- **Near a reference quasar**
  - Astrometric reference
- **Convenient for tracking**

? IM Pegasi: K2 III + ?

Berdyugina et al. (1999)





- Geodetic effect:

required accuracy ~0.7 mas (~R_{star}).

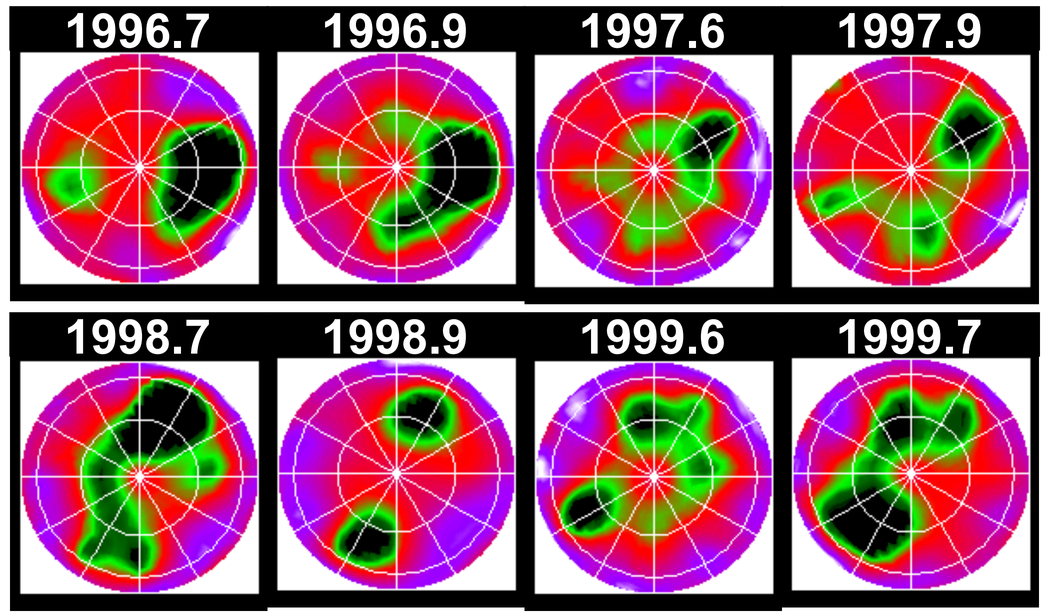
- Frame-dragging (Lense-Thirring):

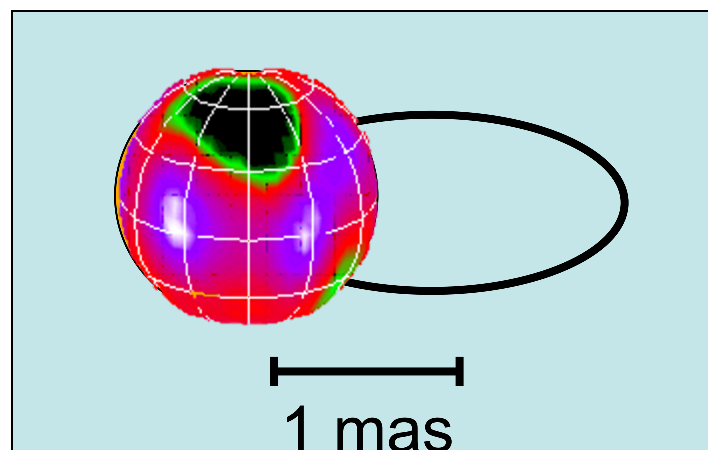
required accuracy ~0.4 mas (~½R_{star}).

Starspots on IM Peg

- **Spectroscopy**
  - Radial velocities (orbit)
  - Starspot Doppler Imaging
  - Molecules -> Teff, Tspot
- **Spectro-polarimetry**
  - Magnetic field Imaging
- **Photometry**
  - Activity, light curve invers.
- **Polarimetry**
  - Starspot limb polarization
- **Radio VLBI**
  - Astrometry (orbit)
- **Optical centroid shifts**

Berdyugina et al. (2000)

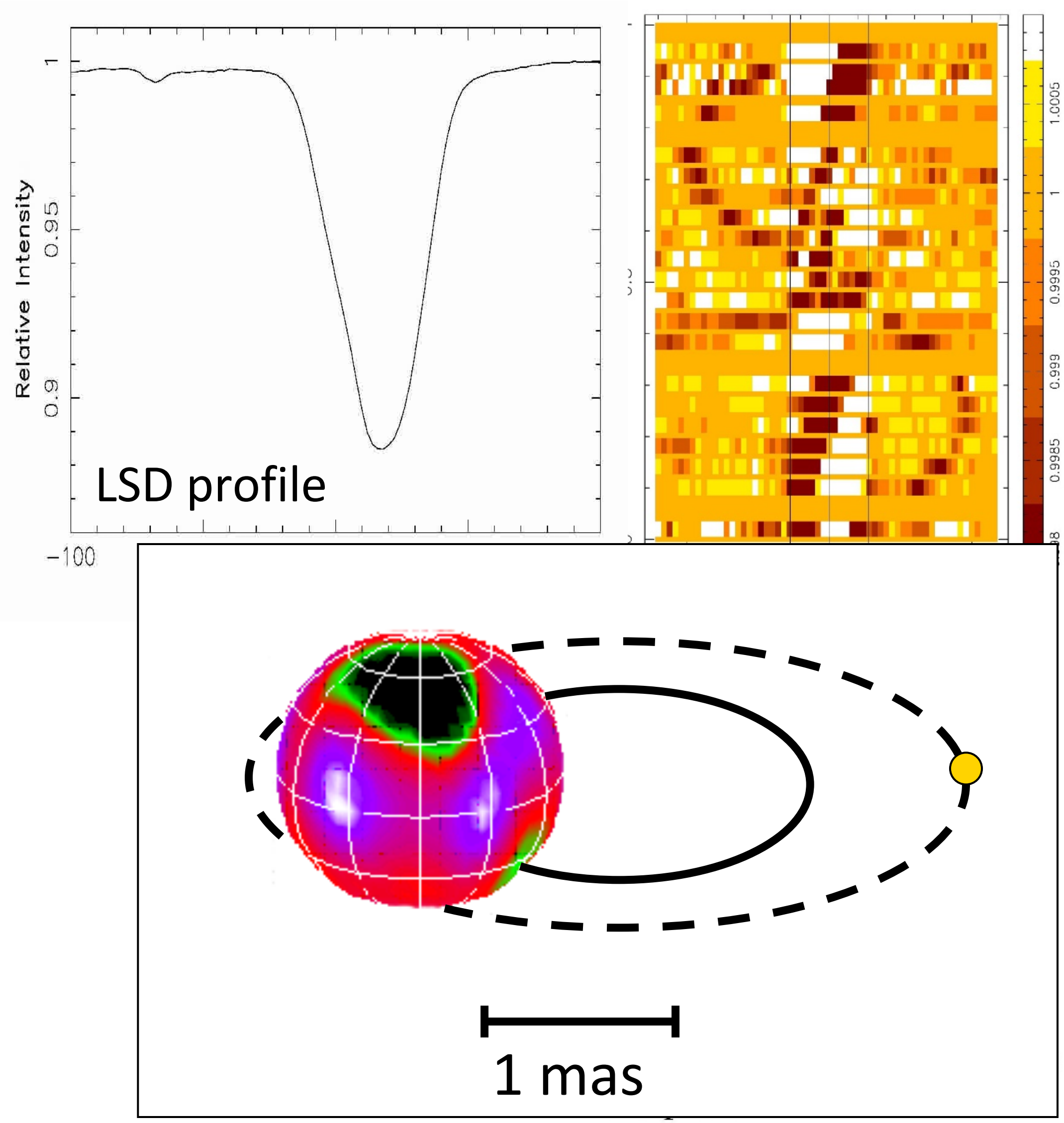




First detection of the secondary star

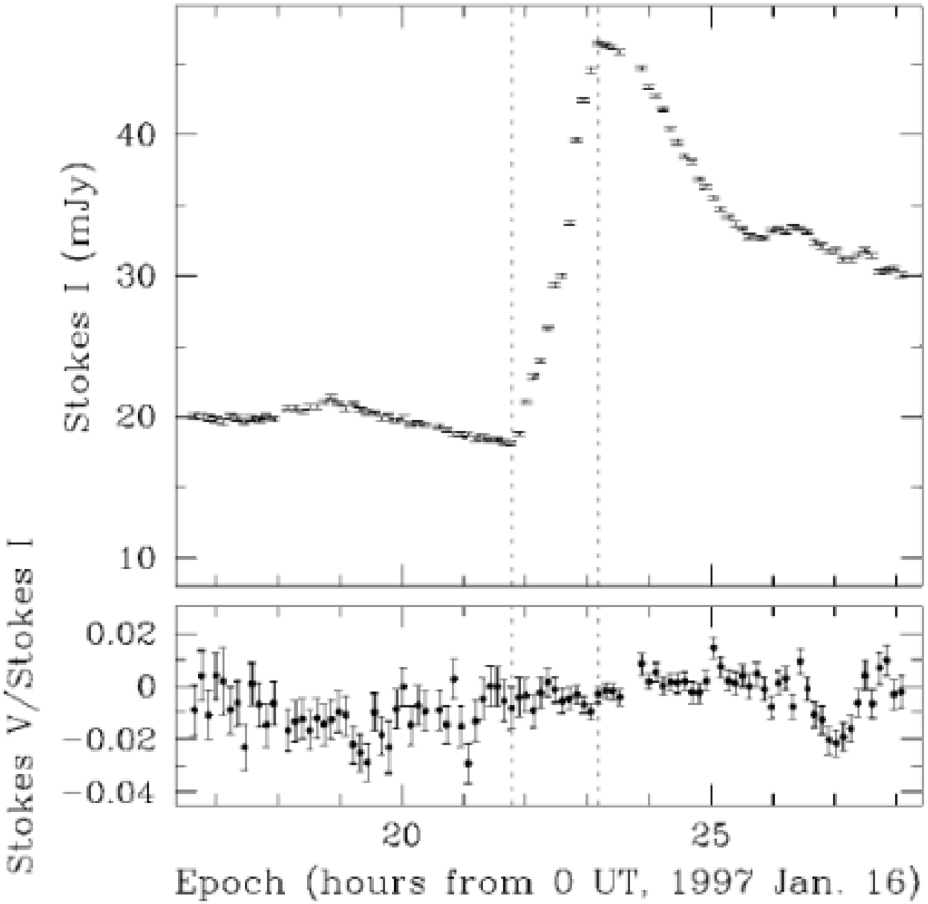
Marsden, Berdyugina, et al. (2005)

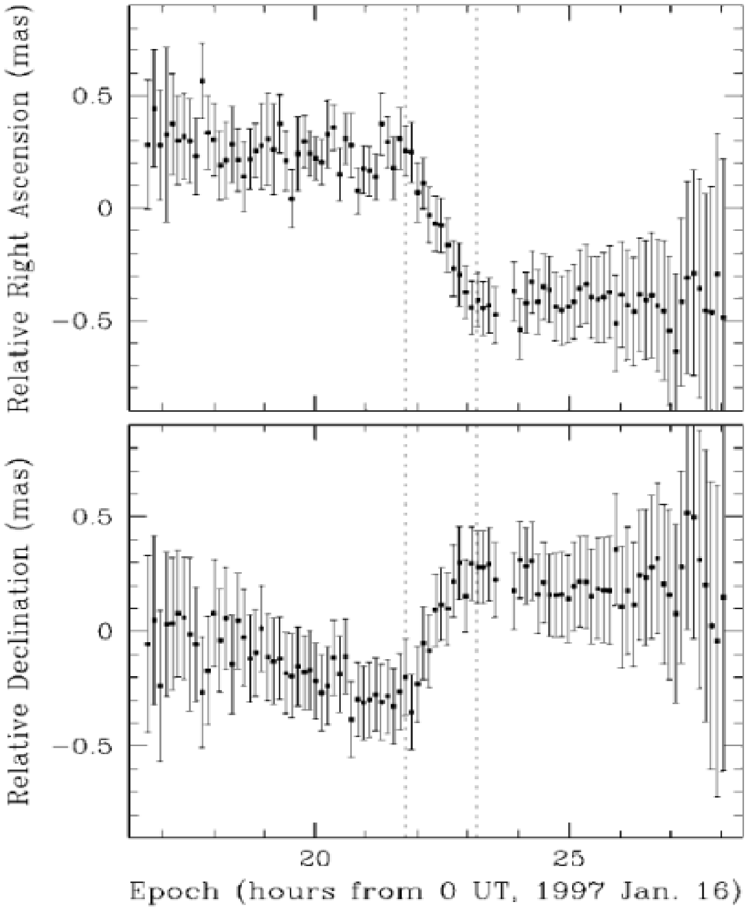
- **Binary**
  - P= 24.64877 ± 0.00003 d
  - M_2/M_1 = 0.550 ± 0.001
  - i_{orb} = 68° ± 9° (VLBI)
- **Primary: K2 III**
  - M= 1.8 ± 0.2 M_{SUN}
  - R= 13.3 ± 0.6 R_{SUN}
  - *v*sin*i* = 27.0 ± 0.5 km/s
  - i = 70° ± 10° (DI)
- **Secondary: G2 V**
  - M= 1.0 ± 0.1 M_{SUN}
  - R= 1.00 ± 0.07 R_{SUN}
  - Teff = 5650 ± 200 K
  - L= 0.9 ± 0.3 L_{SUN}



IM Peg radio astrometry

- VLBI, 3.6 cm, radio flare, shift $(\Delta\alpha,\Delta\delta)=(-0.68,+0.55)$ mas



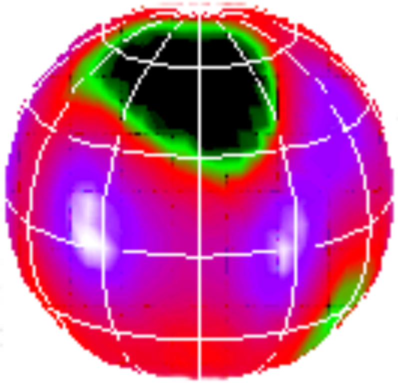


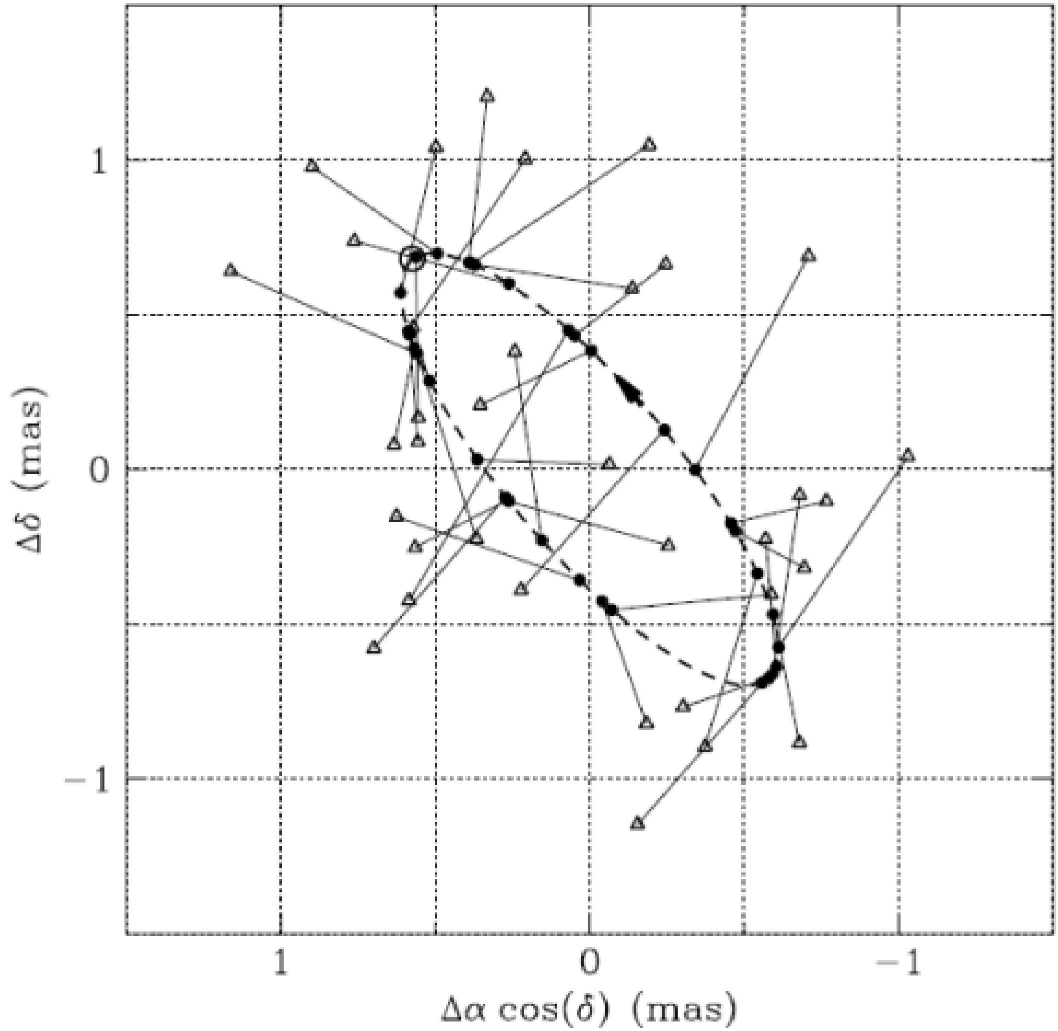
Lebach et al. (1999)

IM Peg radio astrometry

- **VLBI astrometry:**
  - orbital motion
  - orbit inclination
  - activity

Ransom et al. (2012)

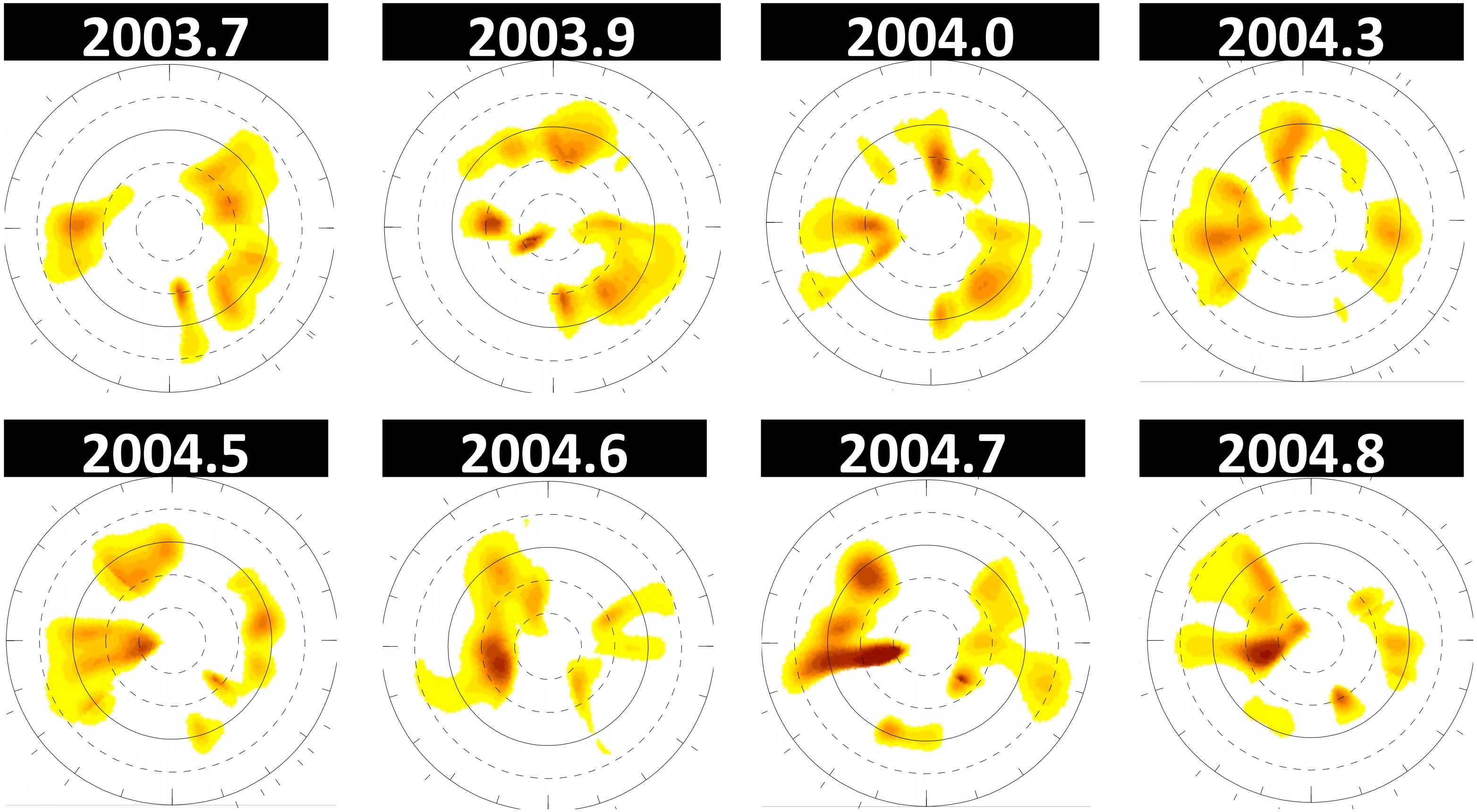




IM Peg starspots

Marsden, Berdyugina, et al. (2007)

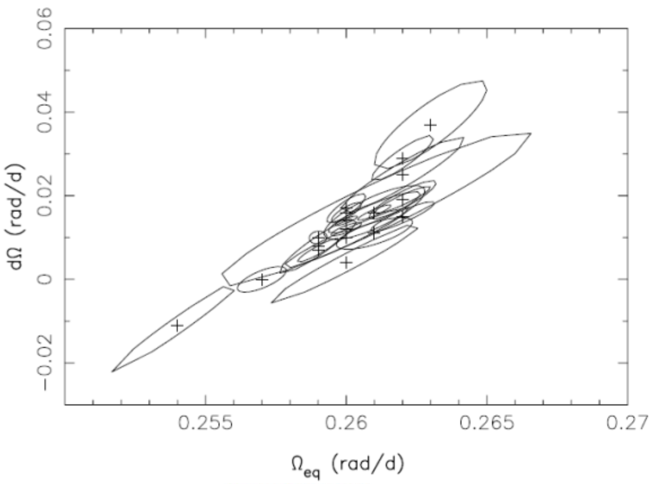
- **Doppler Imaging 2003-2005**
  - 5 telescopes (NOT, AST, CAT, CrAO, AAT), >700 spectra
  - 2 DI methods (Berdyugina 1998; Donati et al. 1997), 30 images

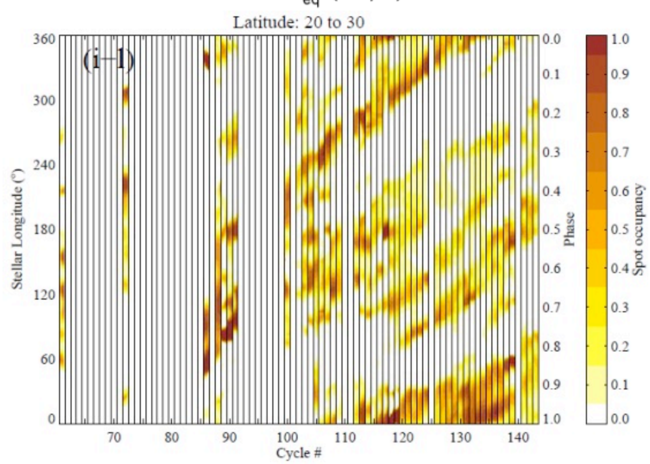


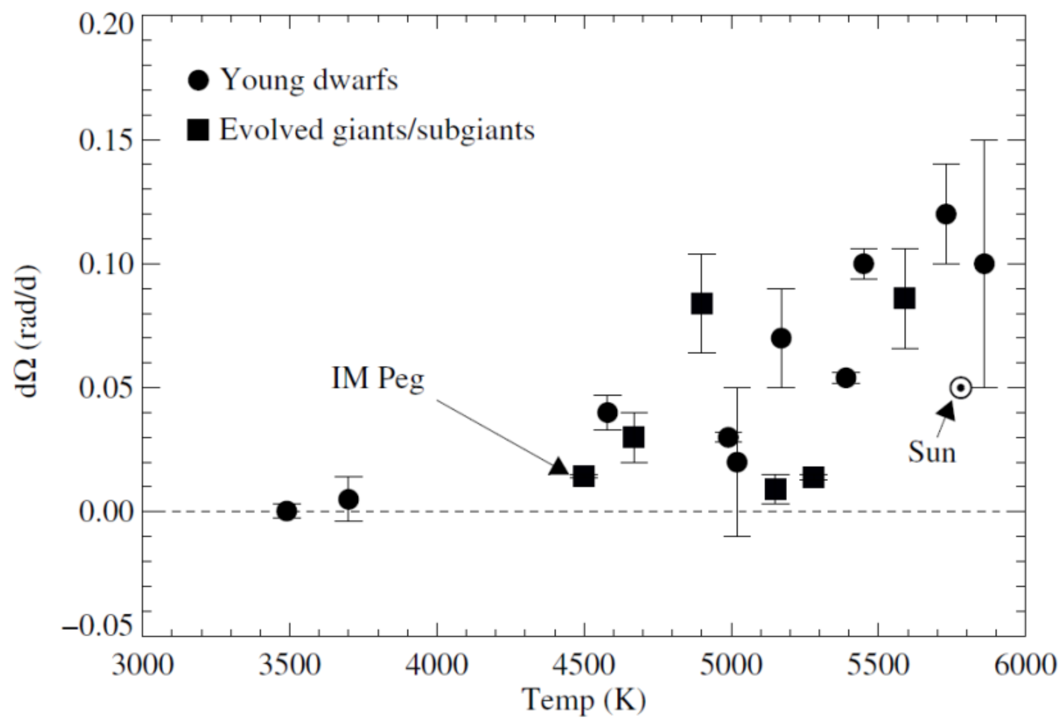
IM Peg differential rotation

- A solar-like dif.rot: $\Omega(?) = \Omega_{eq} - d\Omega \sin^2 ?$
  - $\Omega_{eq} = 0.2606 \pm 0.0002$ rad/d
  - $d\Omega = 0.0142 \pm 0.0007$ rad/d

Marsden, Berdyugina, et al. (2007)

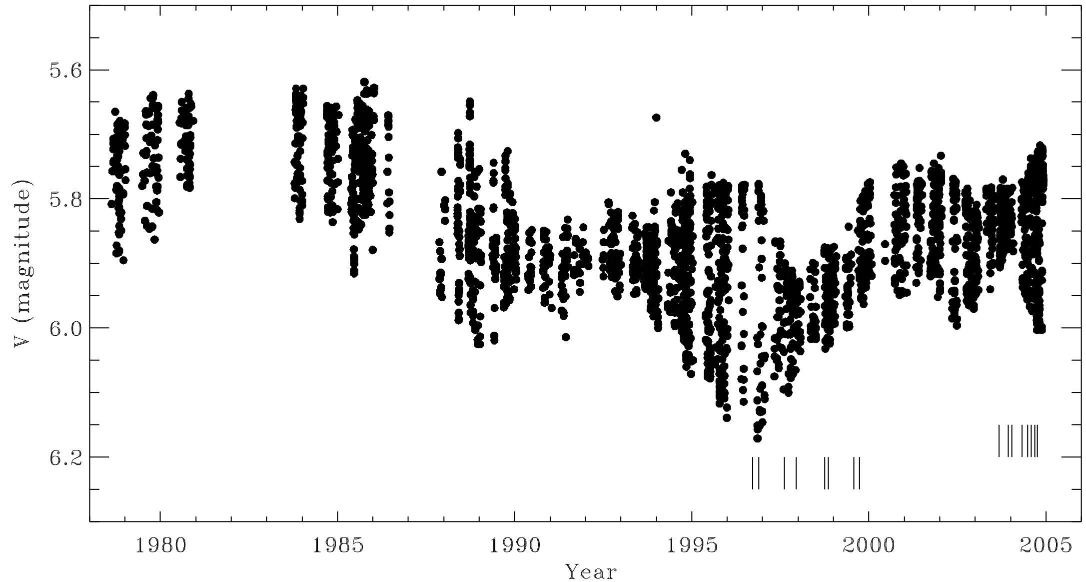


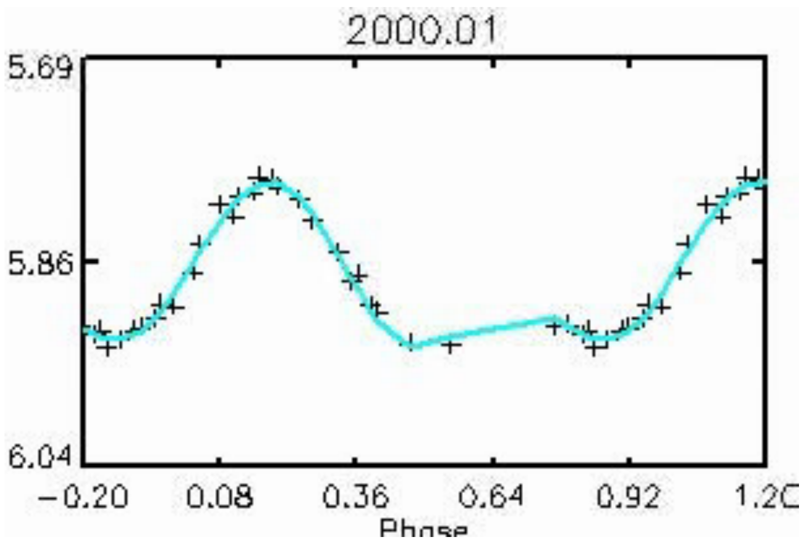




IM Peg cycles and flip-flops

- **Photometry**
  - APT (Arizona)
  - ~30 yr cycle: mean mag
  - ~11 yr cycle: flip-flops
- **Flip-flops**
  - preferred longitudes 180° apart
  - one longitude is usually more active
  - the longitude which is active can swap to the opposite side
  - In 2004, a new flip-flop occurred (seen in DI)

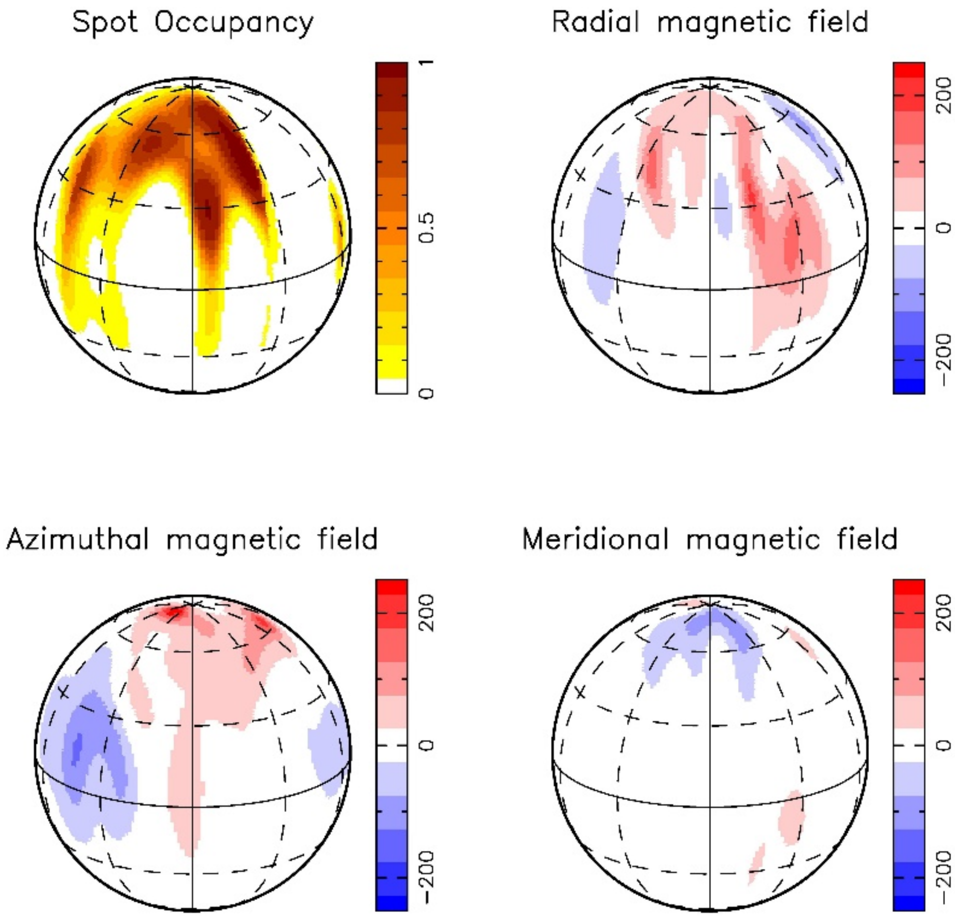


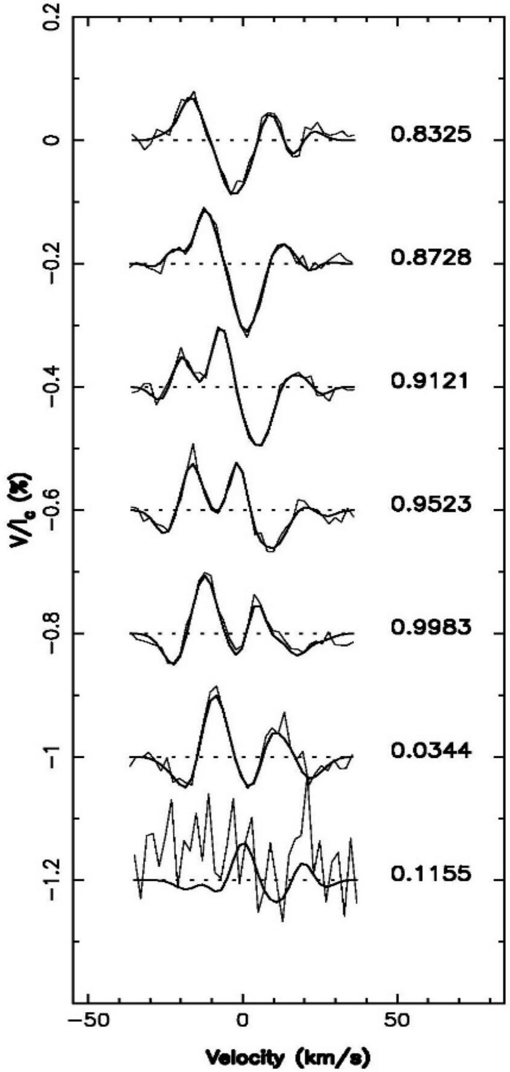


First IM Peg magnetic field image

- Zeeman-Doppler Imaging:
  - AAT, Stokes V, 8 nights, Sep 2004

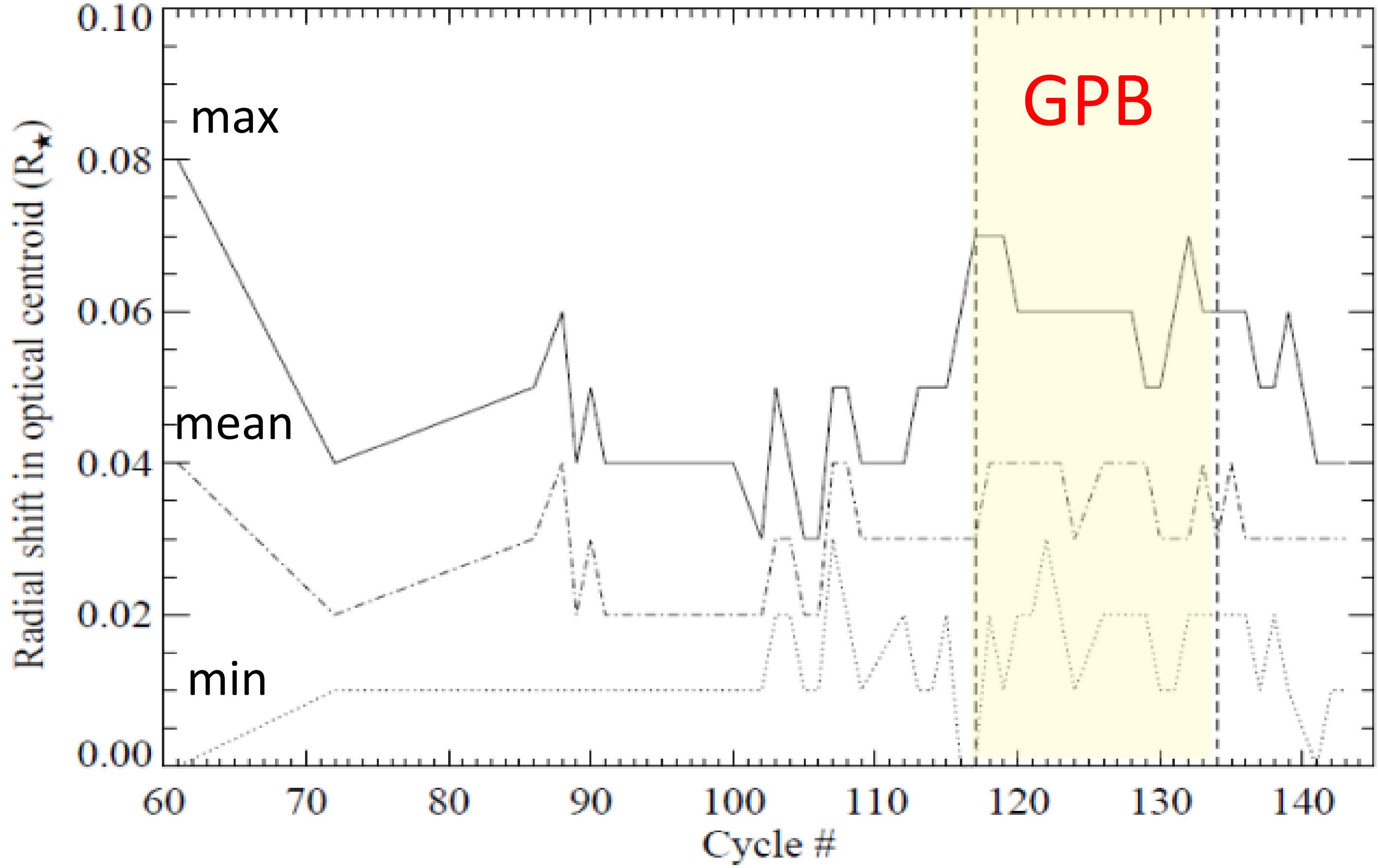
Berdyugina & Marsden (2006)





IM Peg optical centroid shifts

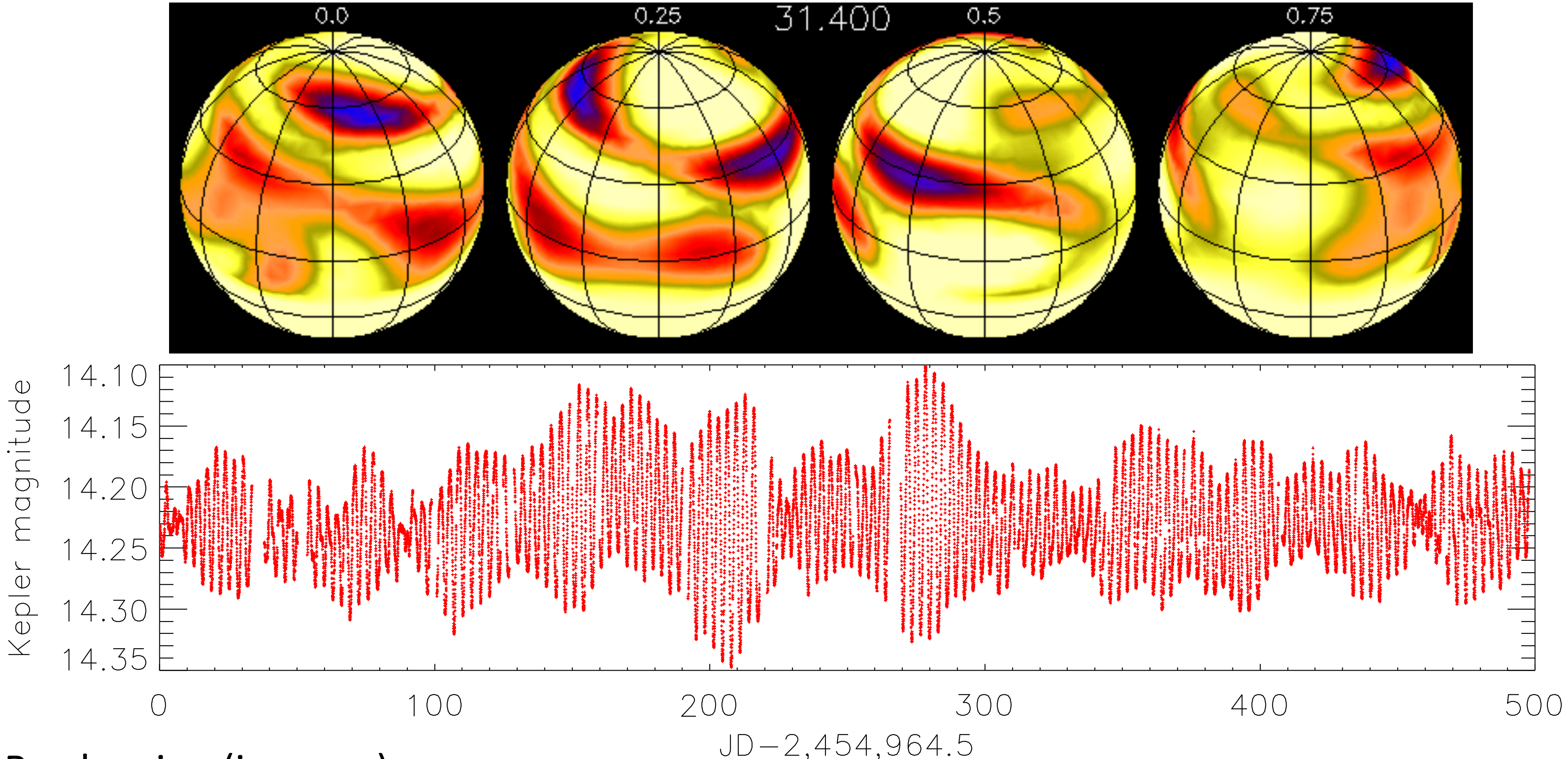
- Maximum centroid shifts < 0.08 R_* [?] < 0.1 mas (100 μas)
  - GPB



Berdyugina et al. (2007), report to GPB

Light-curve inversions

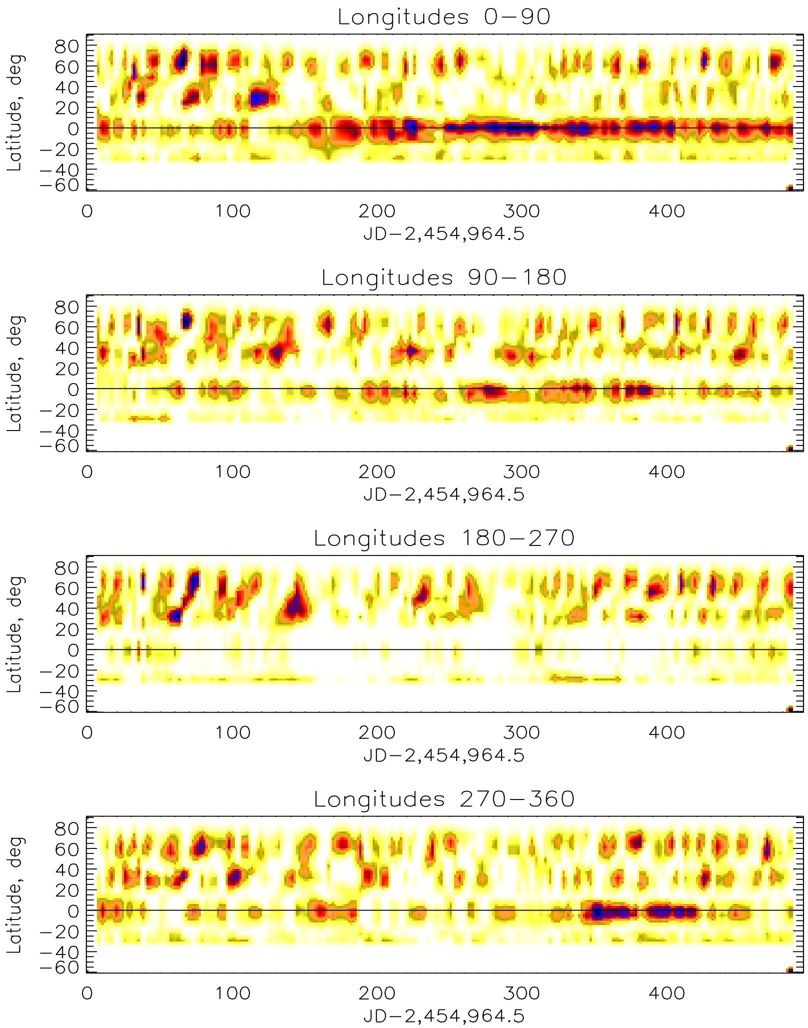
- *Kepler* "young sun" G2 V: new inversion technique
  - Spot longitudes & latitudes can be recovered in slowly rotating stars, such as Alpha Cen A, B, Proxima, etc.



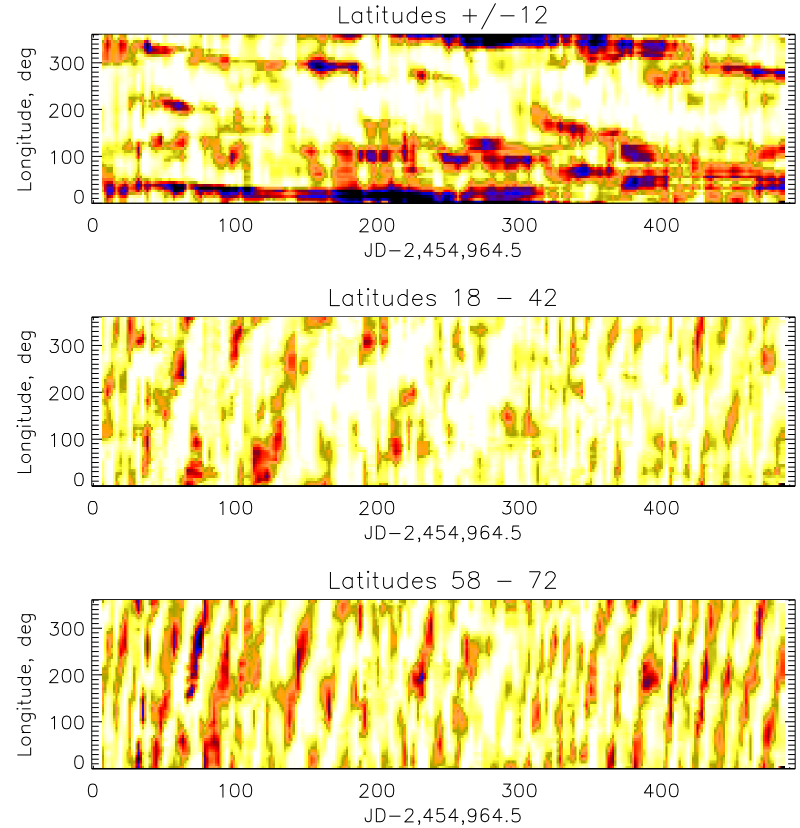
Berdyugina (in prep.)

Starspot Synoptic Maps

- Spot latitudes

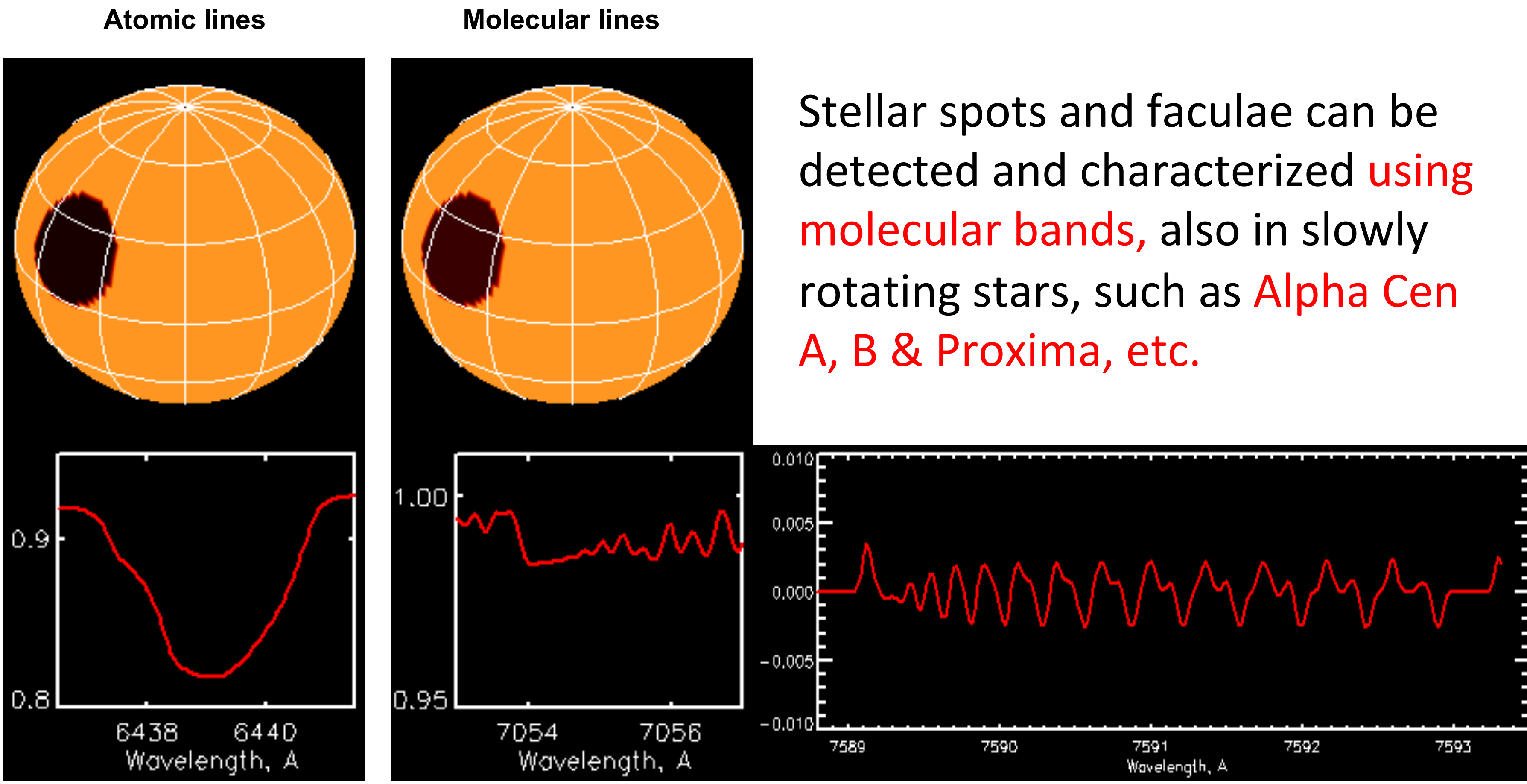


- Spot longitudes



Stellar activity in molecular lines

- Increase spatial resolution with molecular lines



Stellar spots and faculae can be detected and characterized using molecular bands, also in slowly rotating stars, such as Alpha Cen A, B & Proxima, etc.

Berdyugina et al. (2002, 2006)

TOLIMAN mission

- Alpha Cen A
  - G2 V, P~22d, R=1.22, Vsini~2.5 km/s
- Alpha Cen B
  - K1 V, P~36d, R=0.86, Vsini~2km/s
- Starspot & Faculae monitoring during the mission:
  - Spectroscopy in molecular bands -> Tstar, Tspot, Tfacul
  - Photometry (BVR) -> 2D spot maps
  - Ca II K -> 2D faculae maps
- Test observations and modeling before the mission!

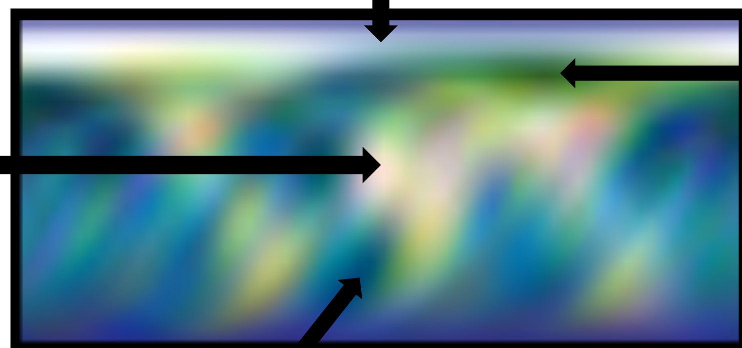
Earth in Alpha Cen

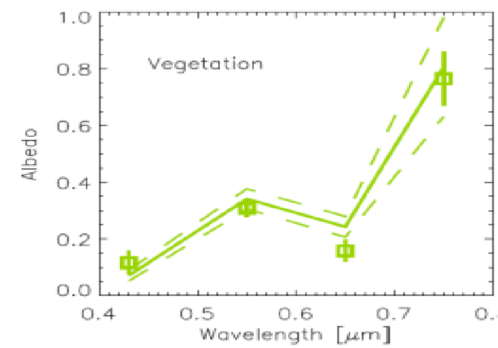
Berdyugina & Kuhn (2017)

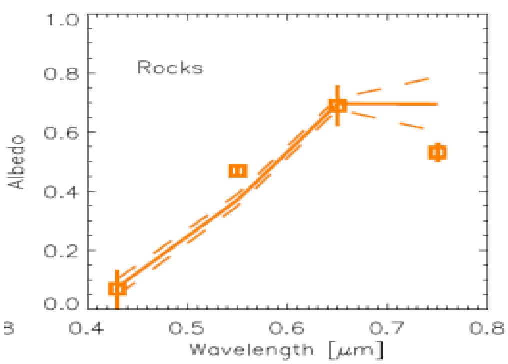
Ice cap

Forest

Desert







Deep Ocean