The Solar-Stellar Connection

Part 1 - The Sun and helioseismology

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Guy R. Davies

The Sun and helioseismology

Solar activity and helioseismology

Stellar activity

The solar-stellar connection

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The gentle Sun

Living with a star

Towards the deep interior

Helioseismology

Results

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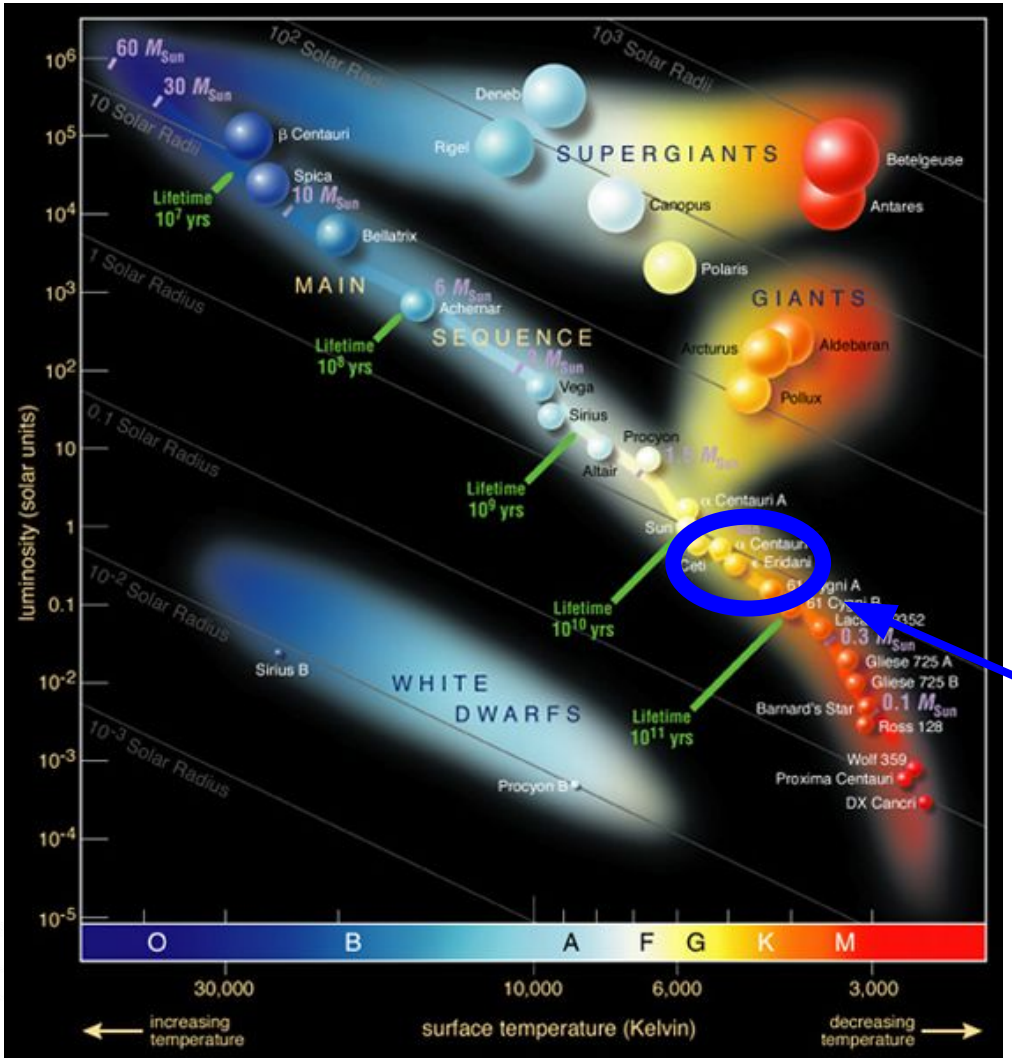

Sun-like stars!

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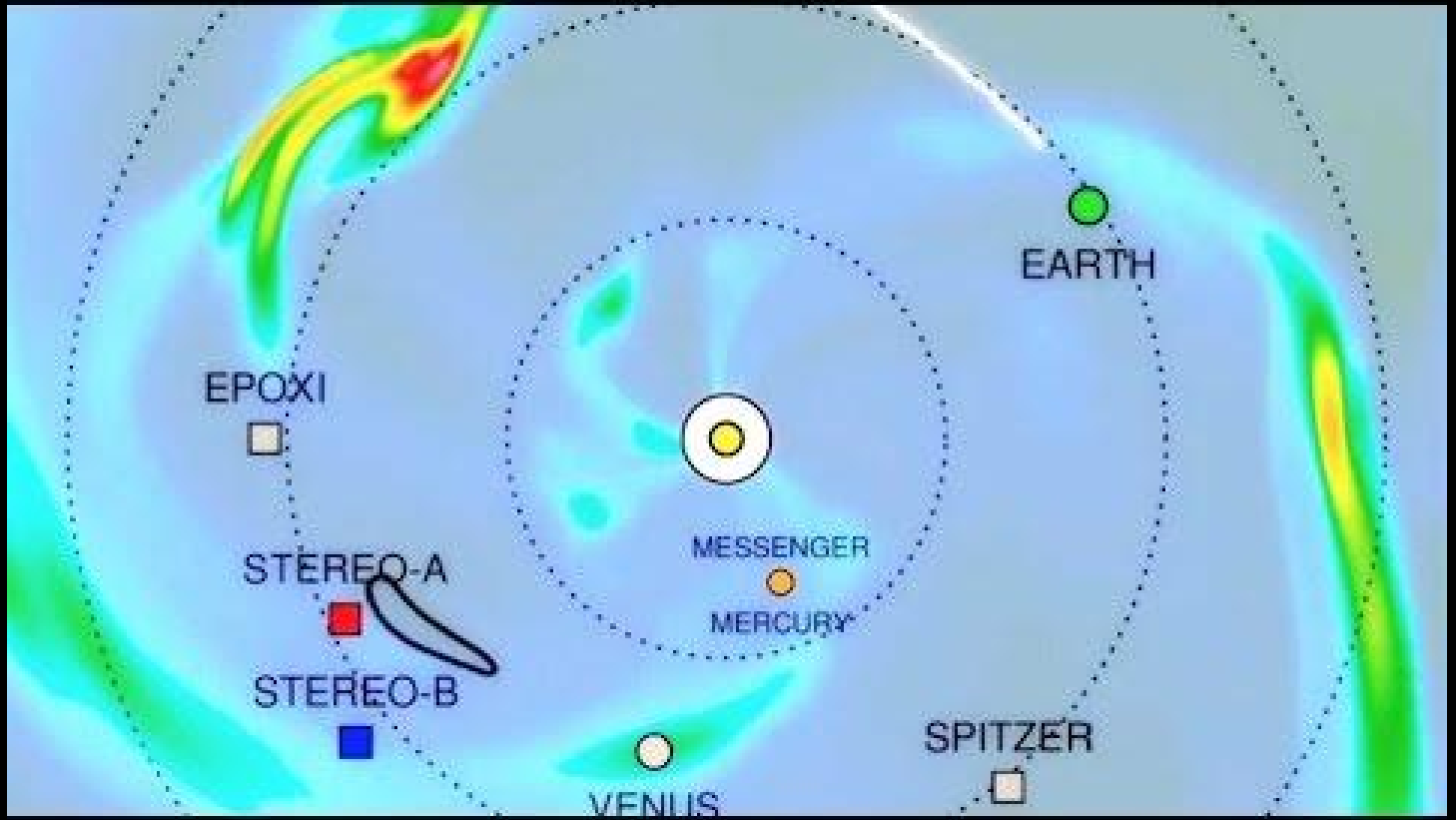
- **Rotation**
- **Magnetism**


EARTH
EPOXI
MESSENGER
MERCURY
STEREO-A
STEREO-B
SPITZER
VENUS

- **Rotation**
- **Magnetism**
- **Stellar winds**
- **Transient events**


NASA SDO

- Rotation
- Magnetism
- Stellar winds
- Transient events
- Carrington level events

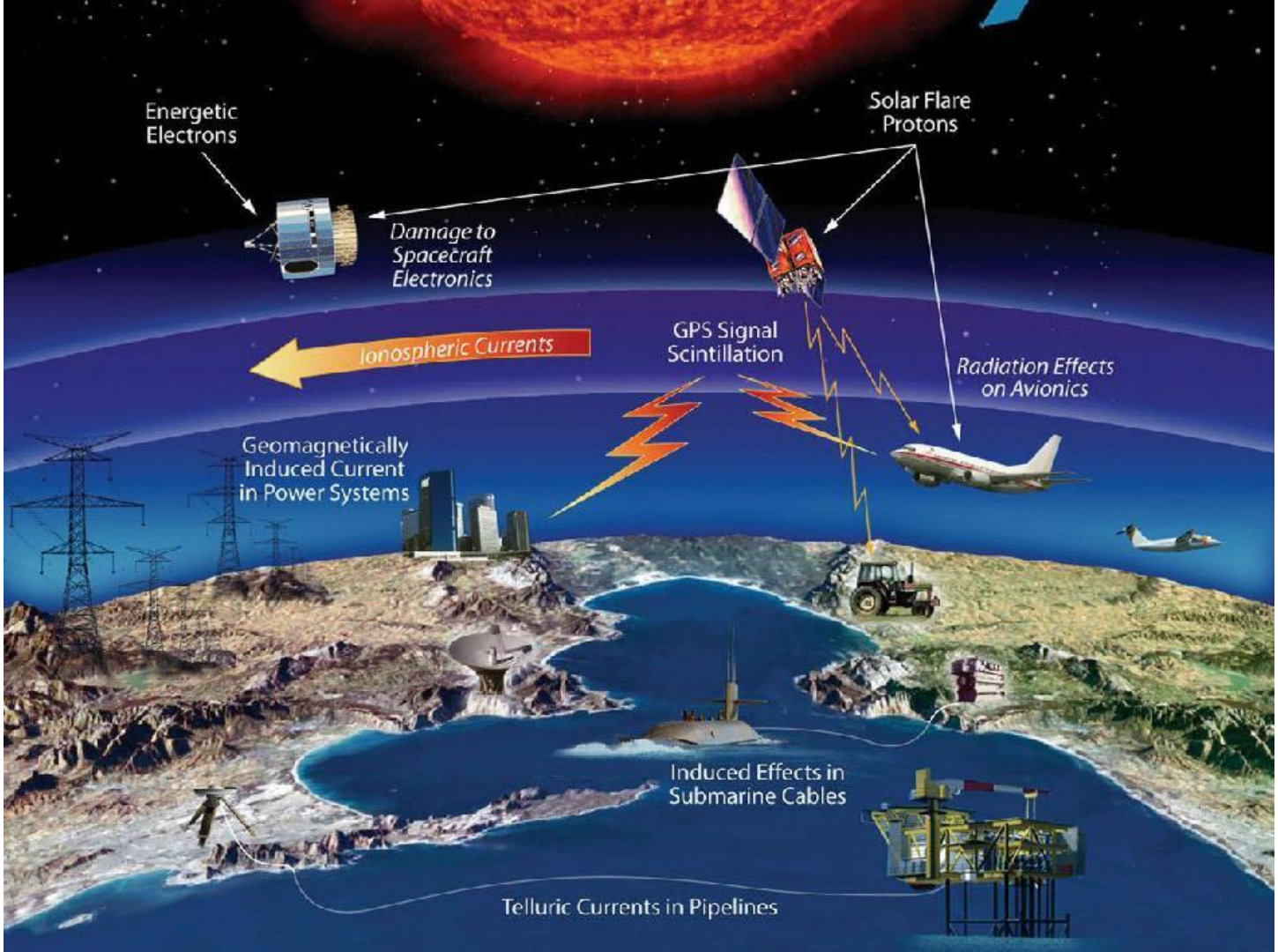


Image: NASA heliophysics

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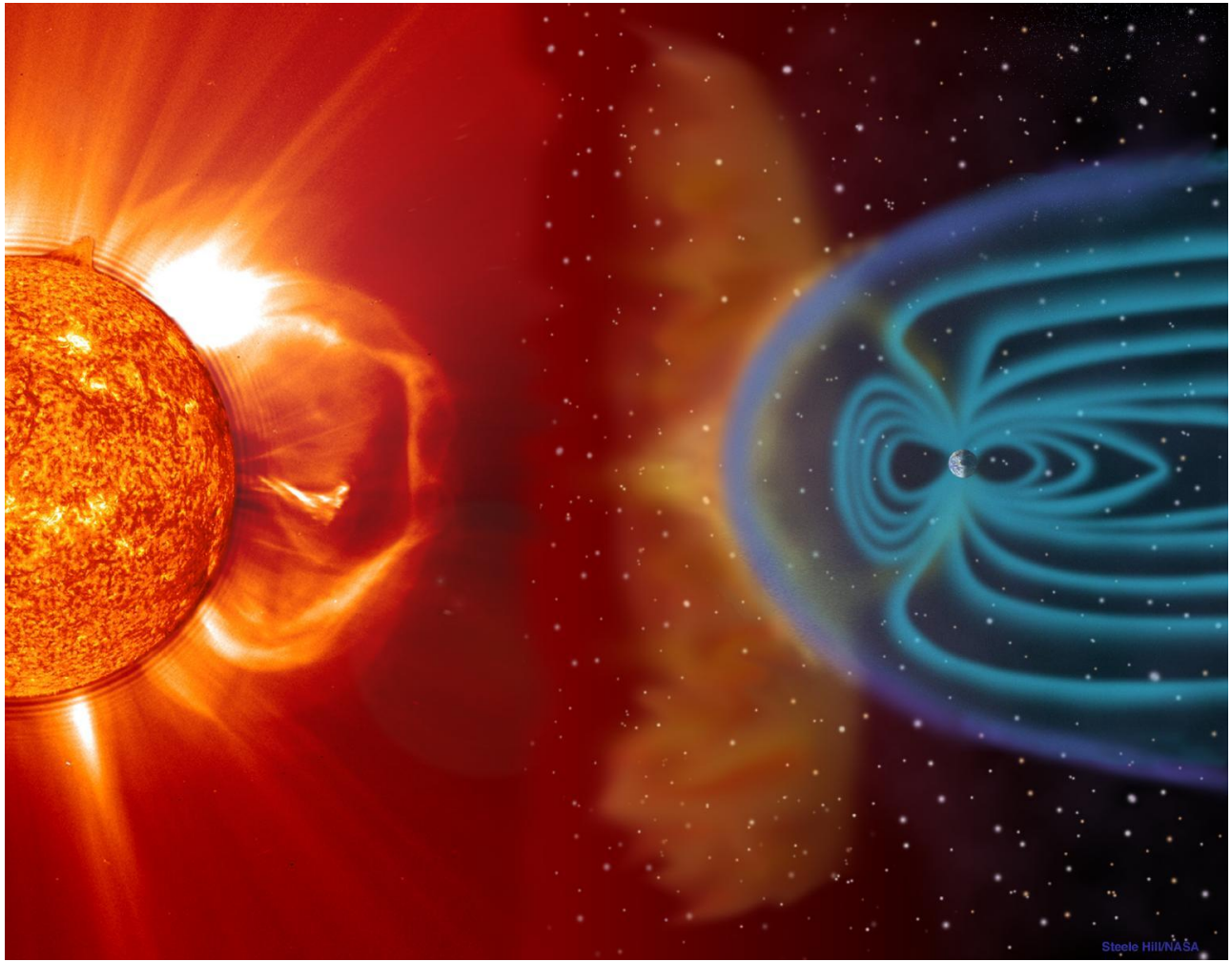

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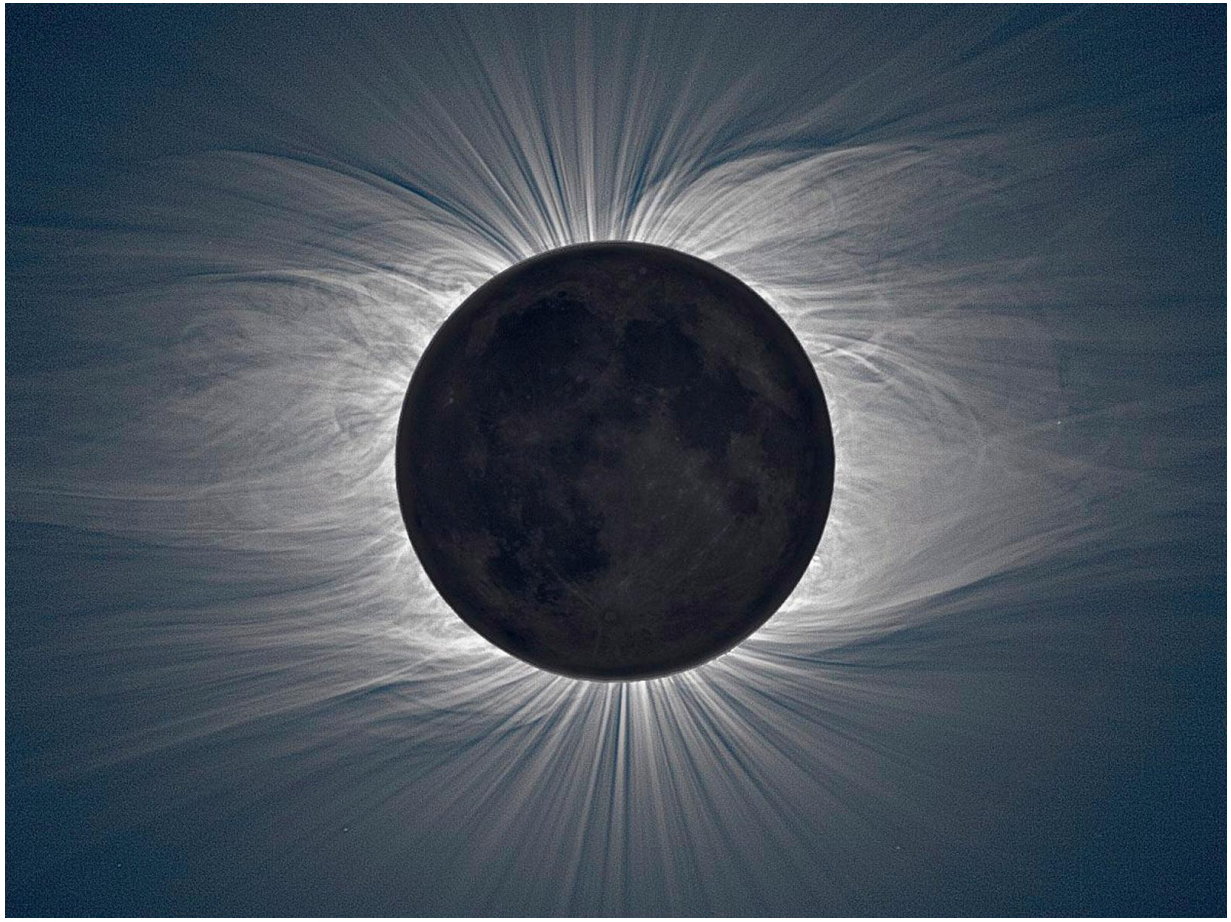

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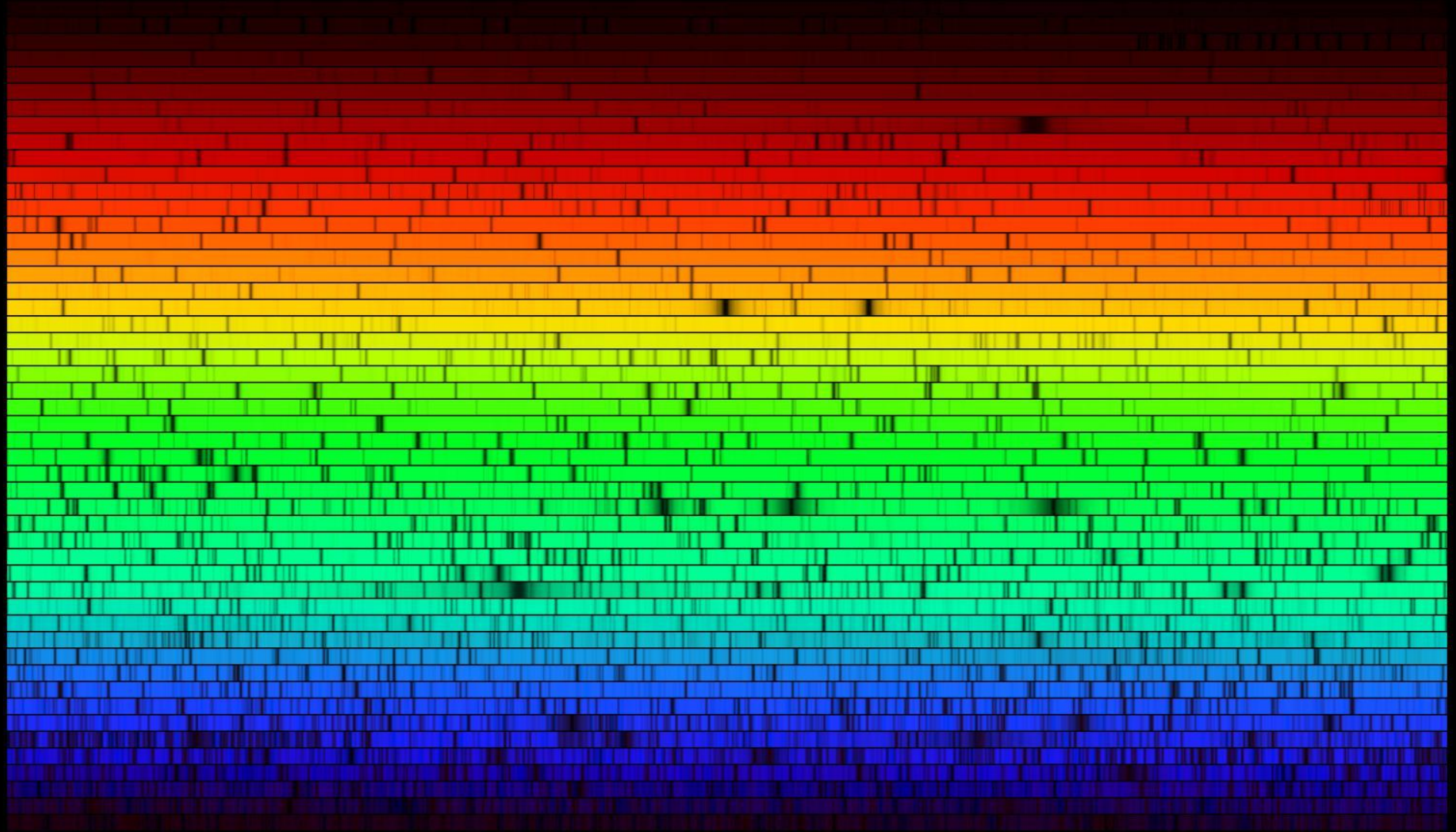
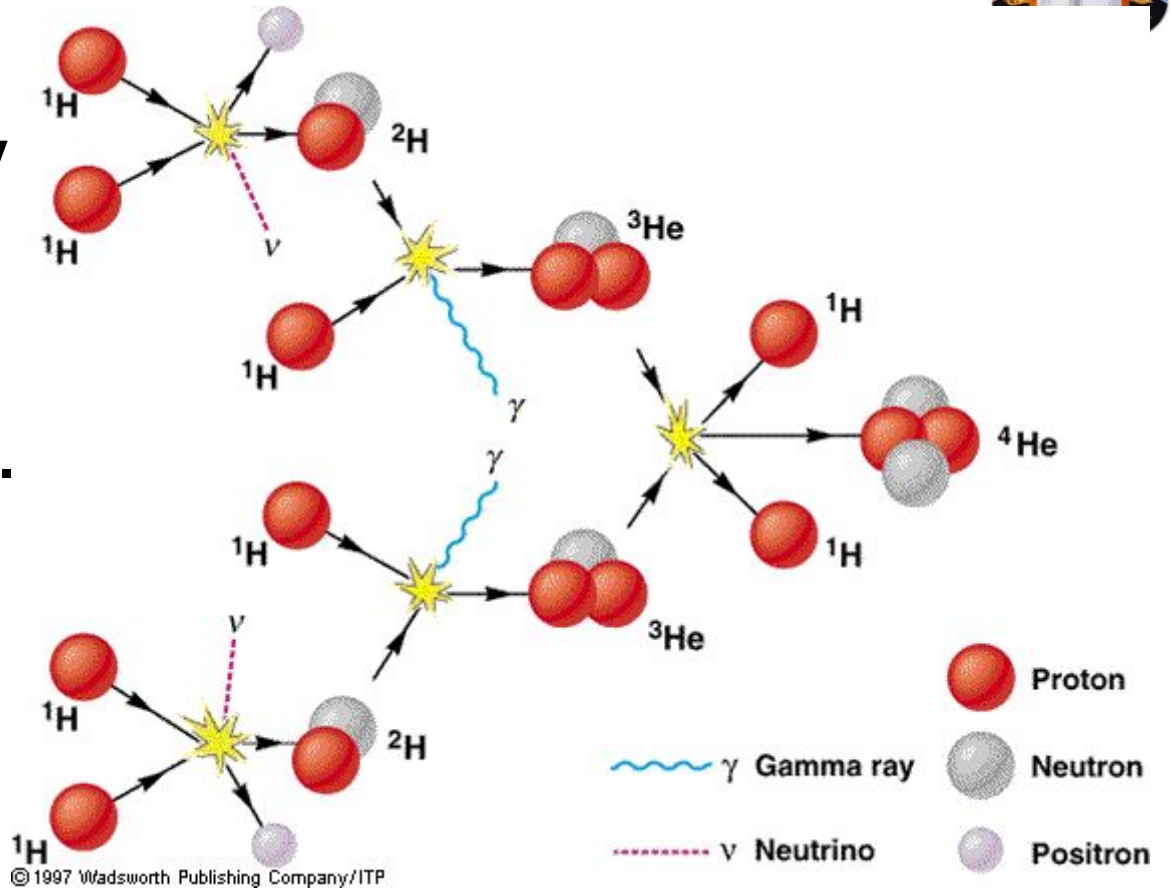


The Unseen Interior

''At first sight it would seem that the deep interior of the sun and stars is less accessible to scientific investigation than any other region of the universe. Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is hidden beneath substantial barriers? What appliance can pierce through the outer layers of a star and test the conditions within?''

A. S. Eddington, 'The Internal Constitution of the Stars ', 1926, Cambridge Uni. Press, p.

Every second of every day, the Sun converts 700 million tons of Hydrogen into 695 million tons of Helium.



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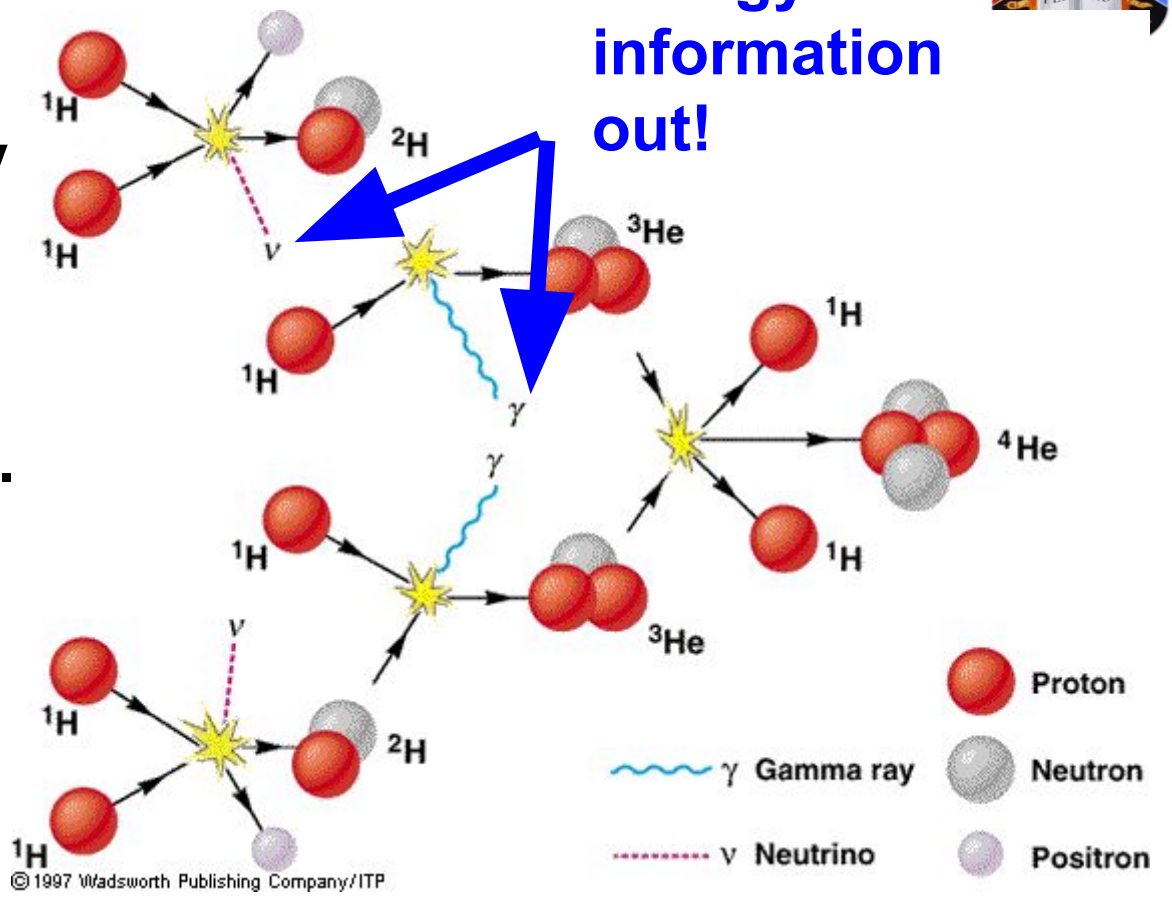

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Helioseismology

Results

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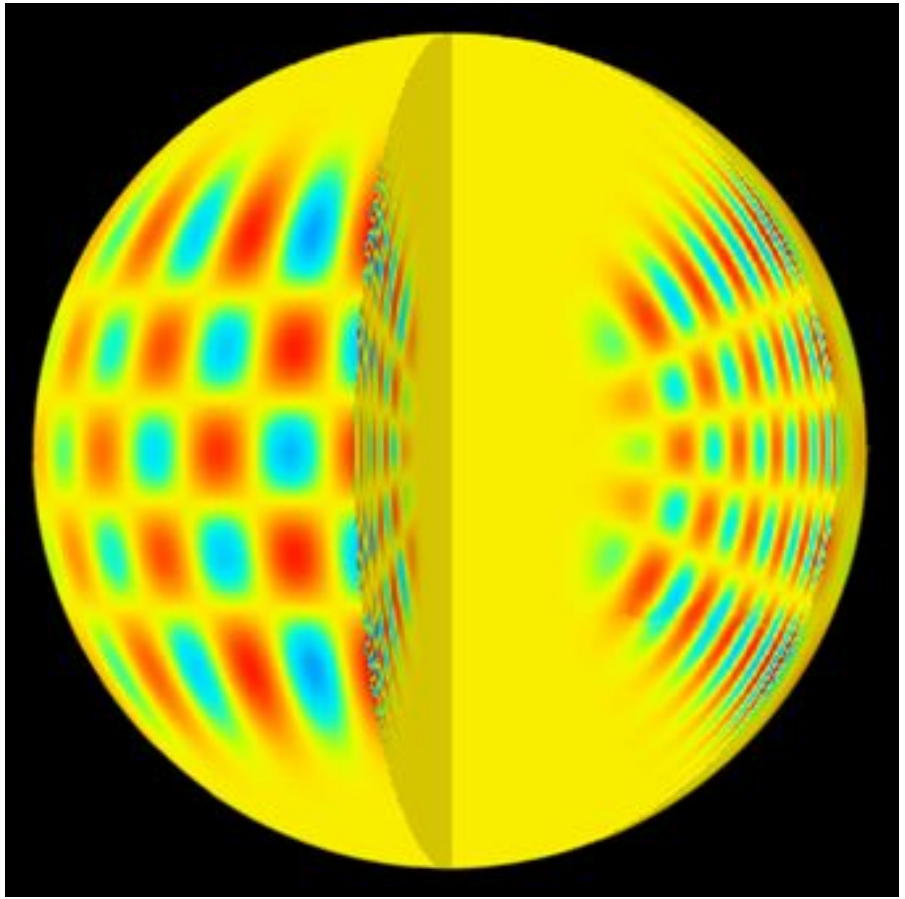
Helioseismology is the study of the propagation of wave oscillations, particularly acoustic pressure waves, in the Sun.



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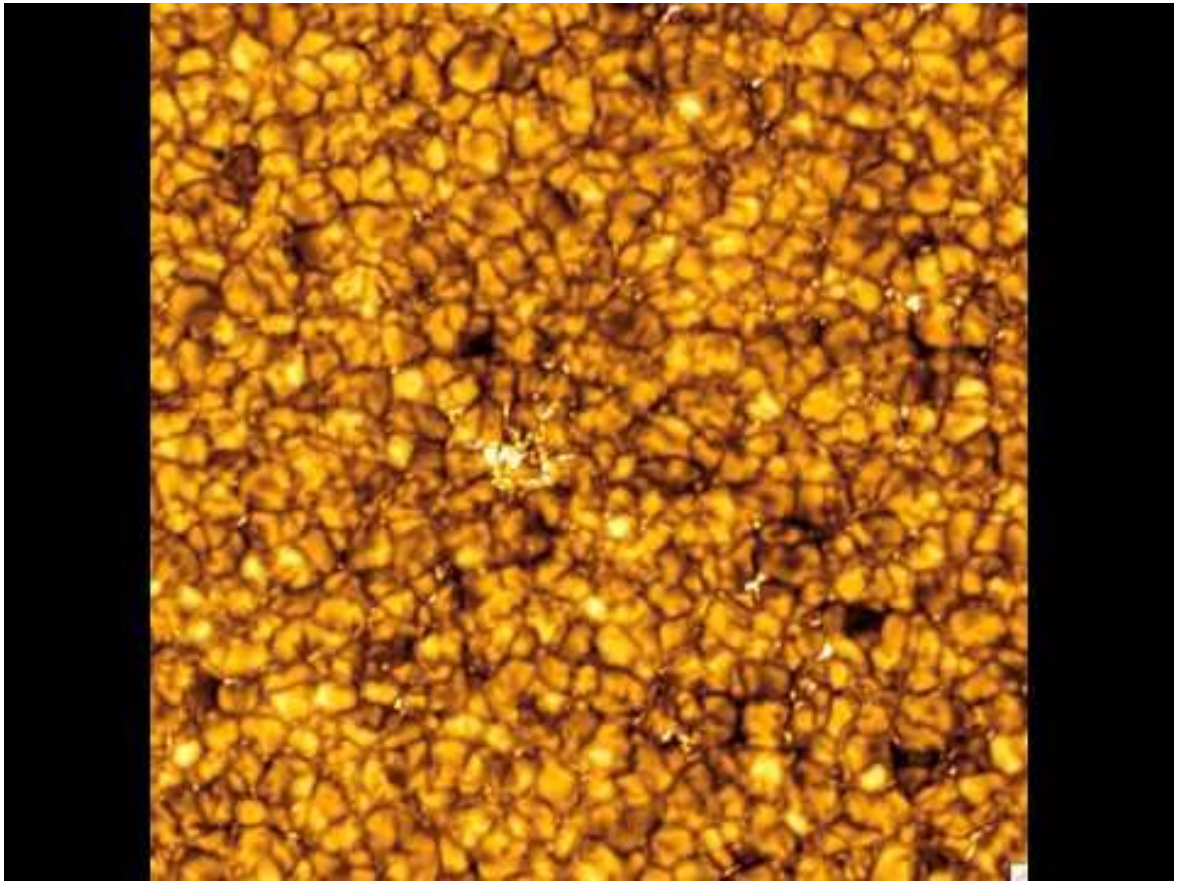

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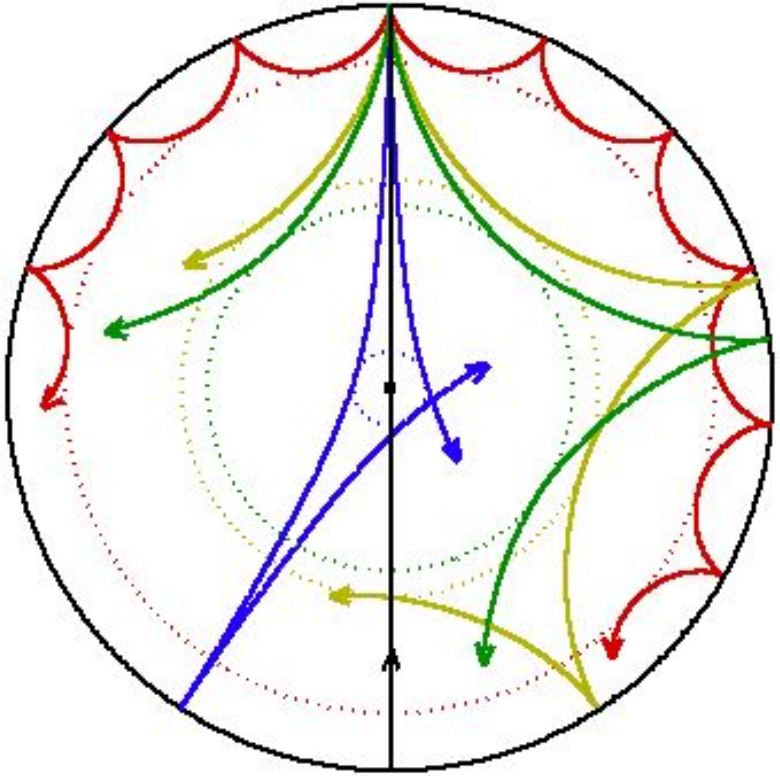
Credit: Swedish 1m Solar Telescope

What are solar-like pulsations?



Rays of propagation.

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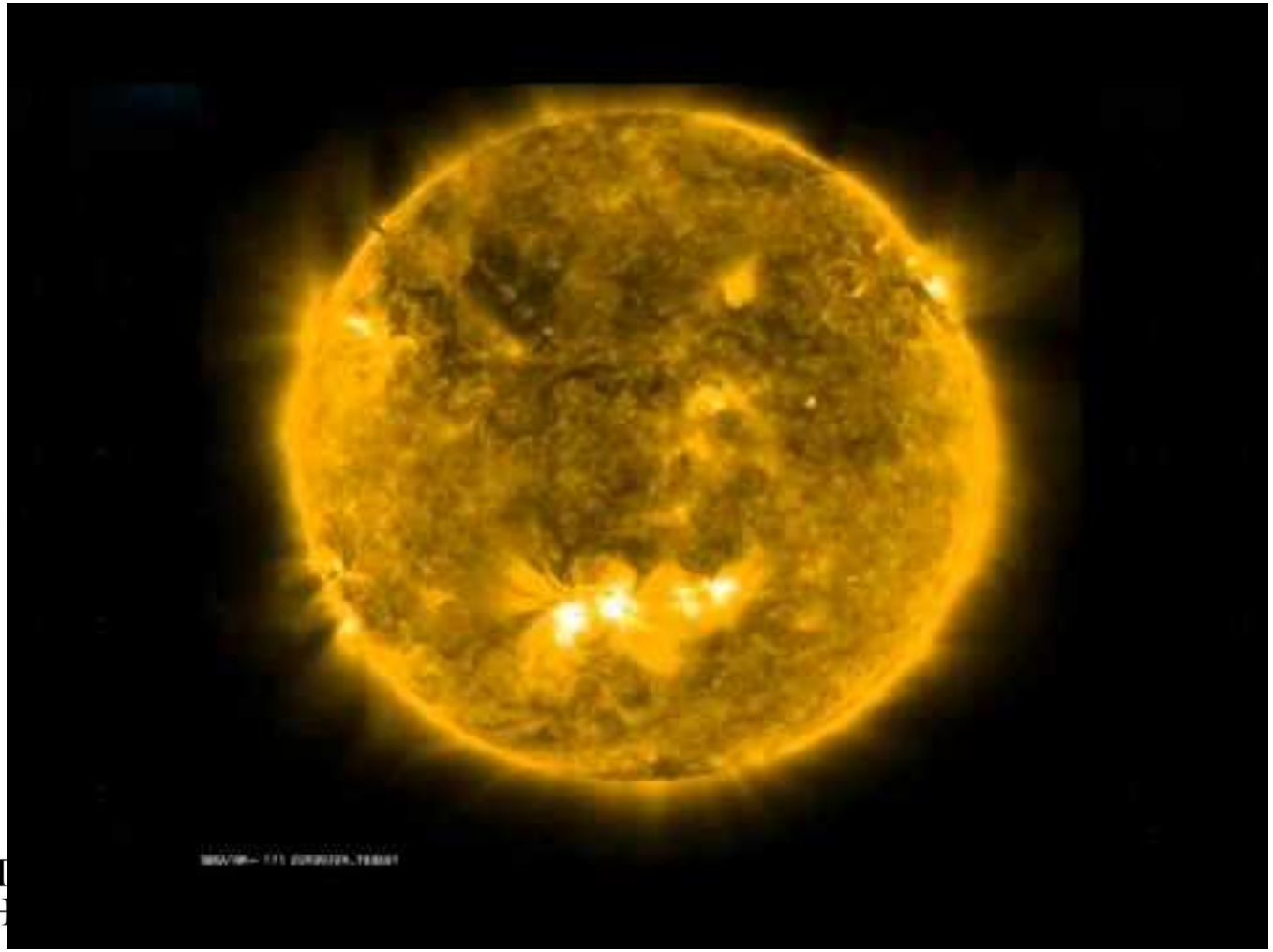

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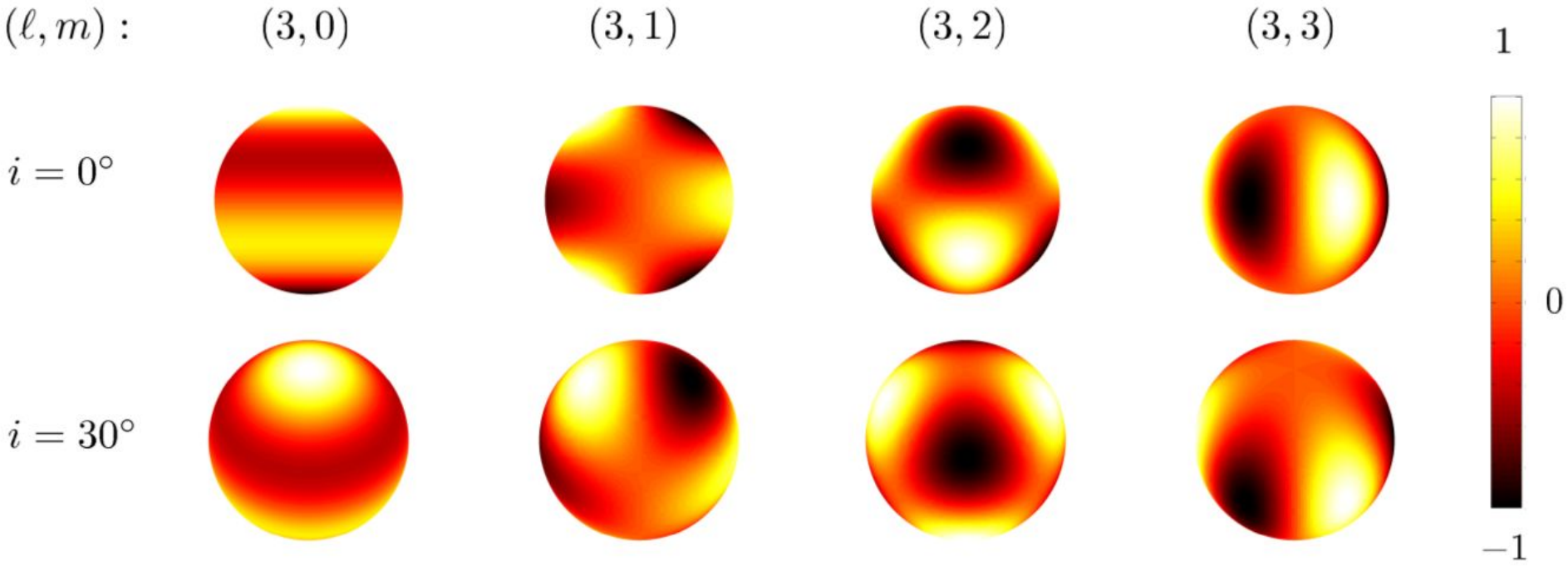
Oscillations produce variations in intensity



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The Sun as a star

Birmingham Solar Oscillations Network (BiSON)

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BiSON: Sun as a star

- **Ground based 6 station network**
- **1978 to present**
- **1985 onwards three or more stations**
- **Radial velocity using resonant scattering spectrometers**
- **Calibrated data are freely available!**

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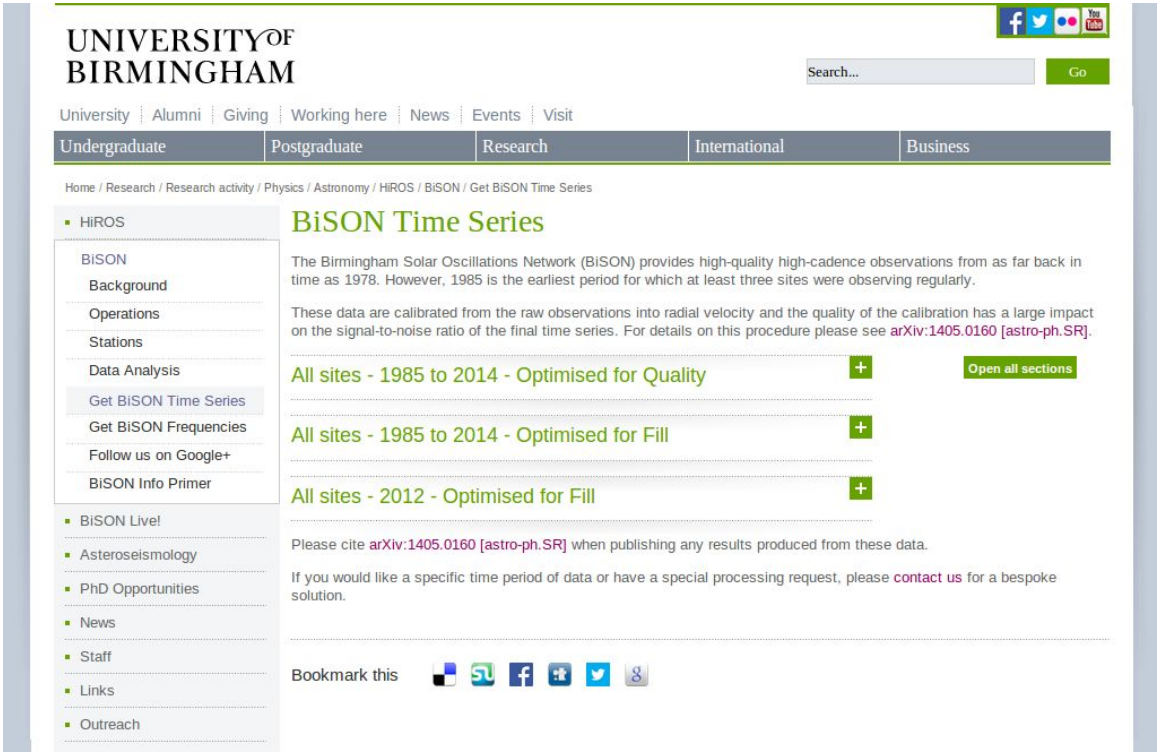
BiSON: Get the data



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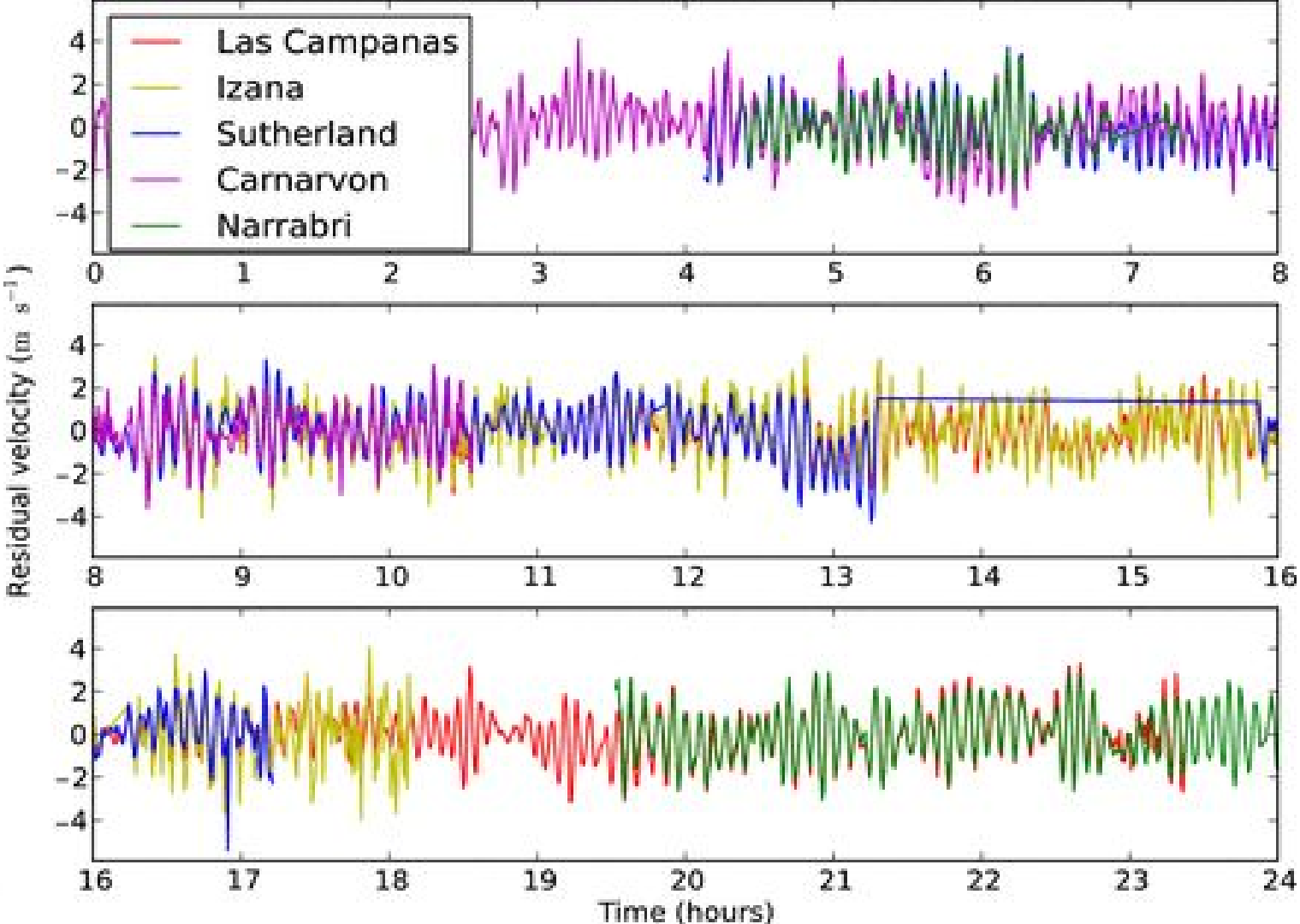
http://bison.ph.bham.ac.uk/index.php?page=bison,timeseries


Las Campanas
Izana
Sutherland
Carnarvon
Narrabri
Residual velocity (m s^{-1})
Time (hours)

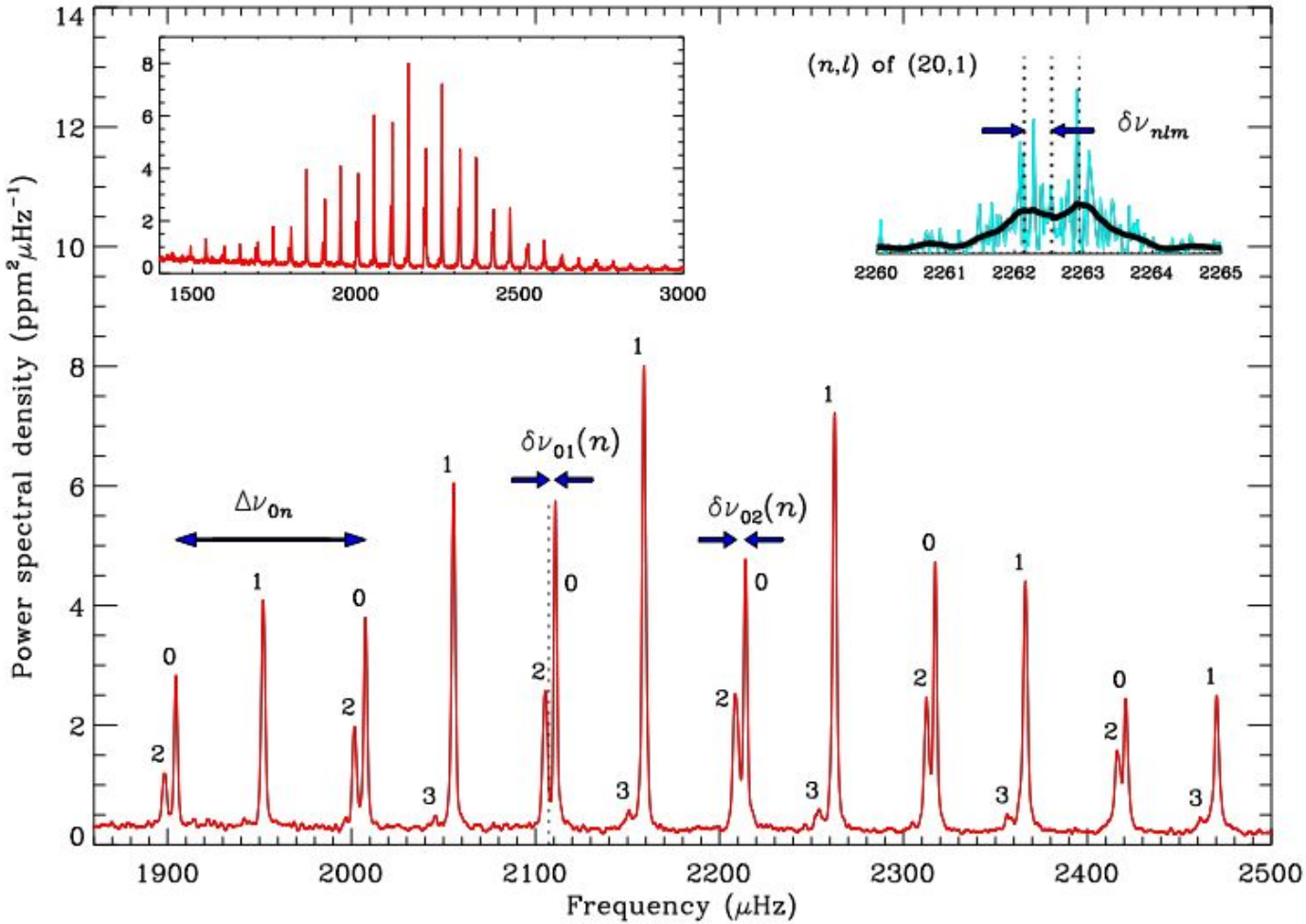
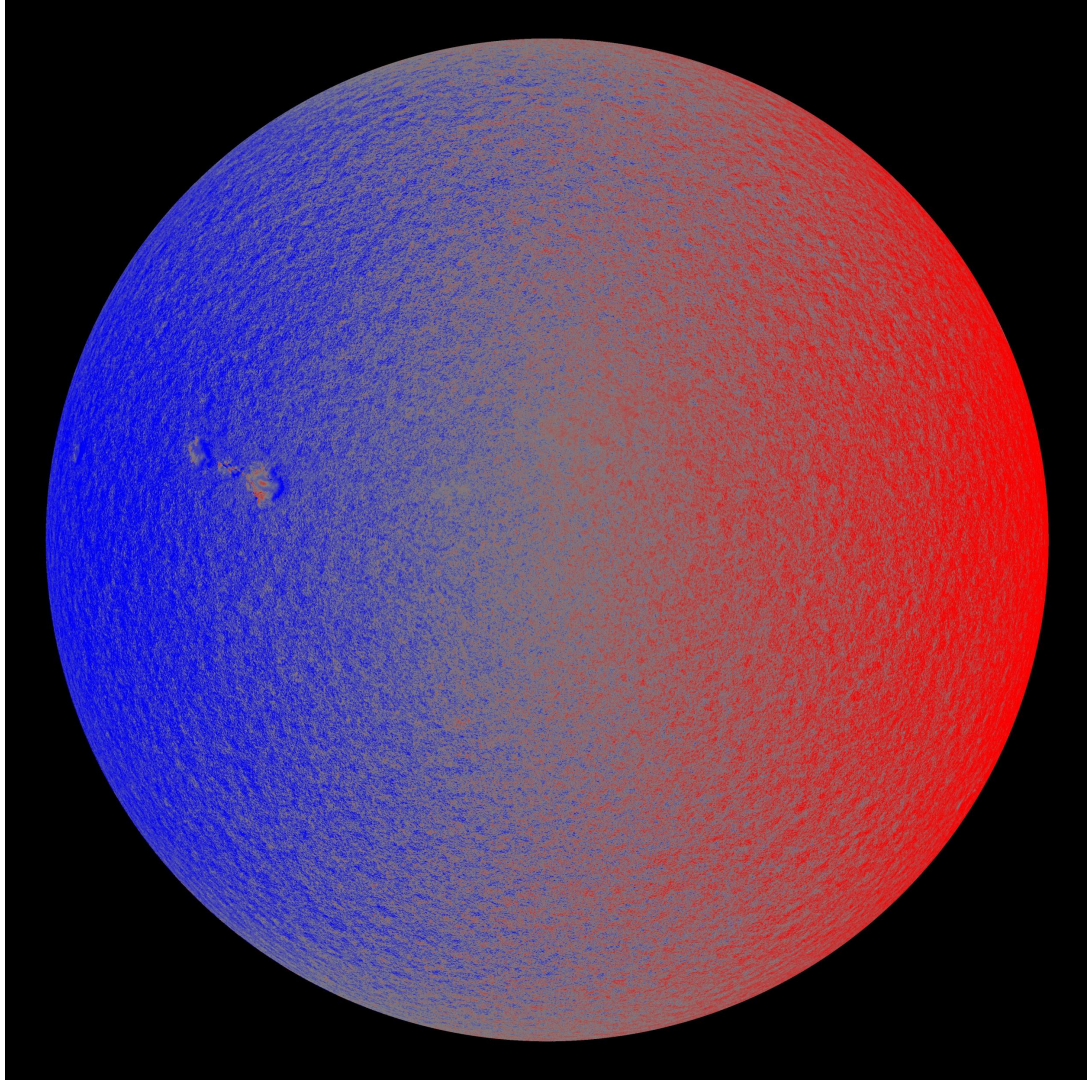

Power spectral density (ppm^2 μHz^{-1})
Frequency (μHz)
$\Delta\nu_{0n}$
$\delta\nu_{01}(n)$
$\delta\nu_{02}(n)$
(n,l) of (20,1)
$\delta\nu_{nlm}$

Image: SDO doppler grams



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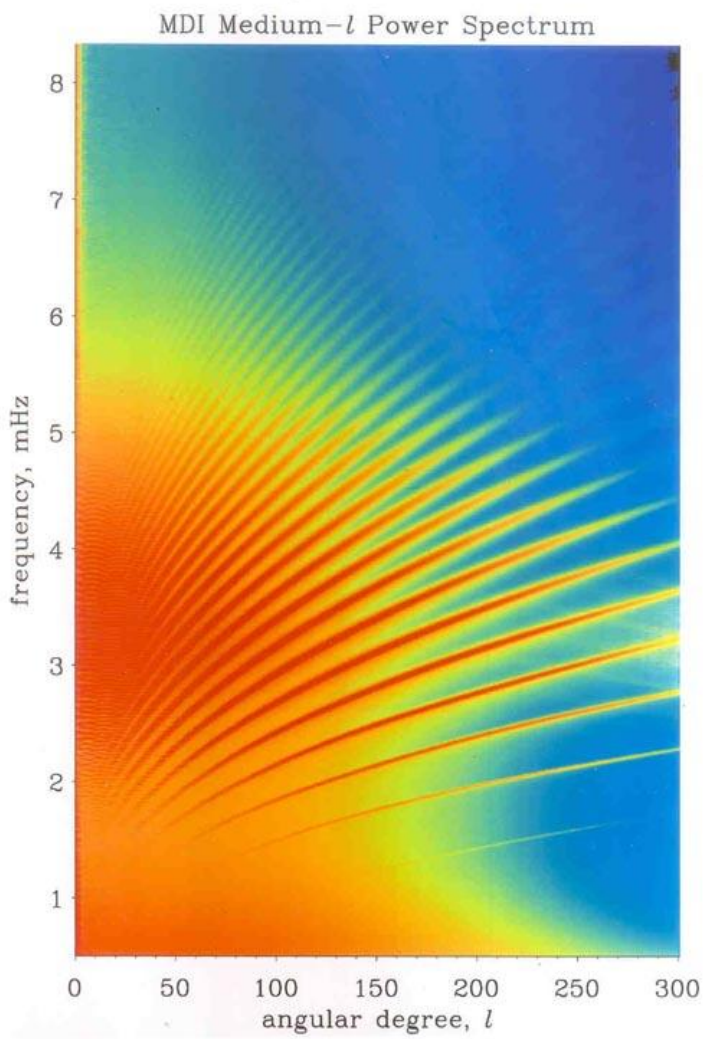

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Helioseismology

Results

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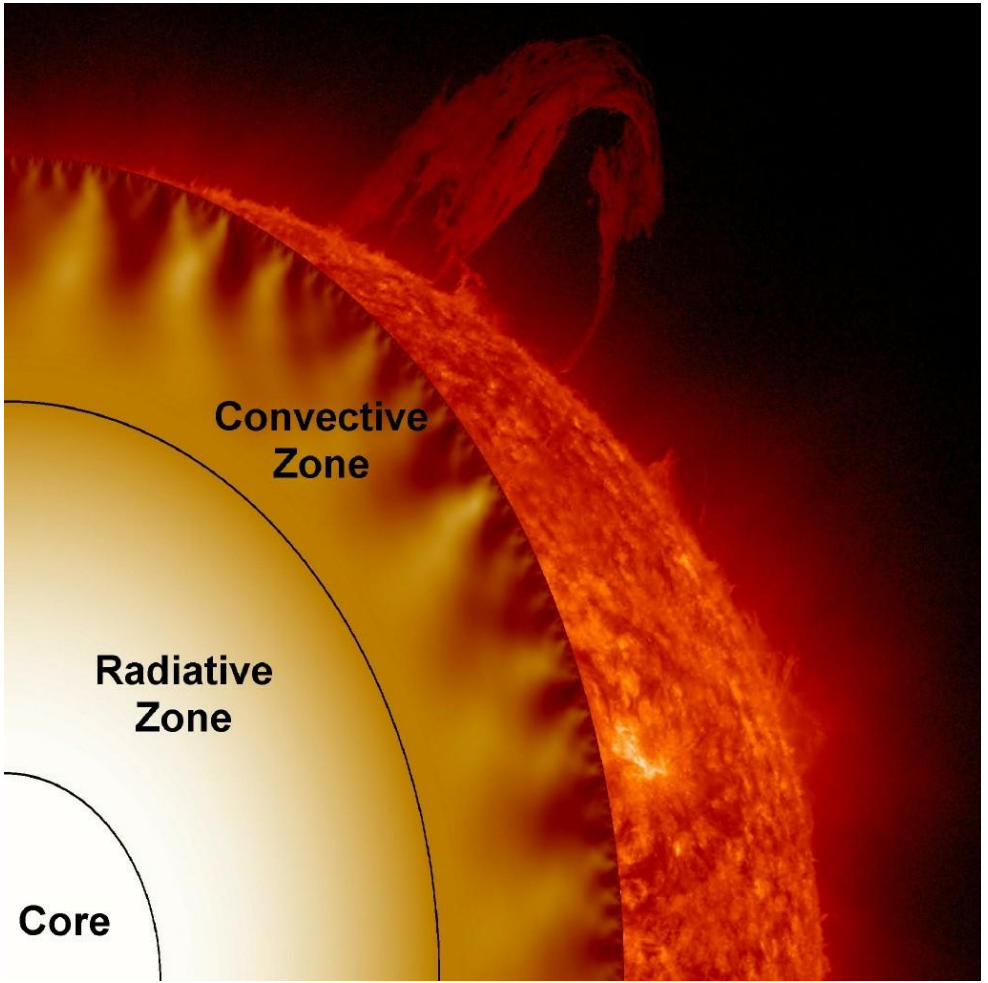
Convective zone: outer 30%

Radiative zone: inner 70%

The deep core - the engine room of the Sun

Temperature: 15 million K

Pressure: 260 billion times Earth's atmospheric pressure



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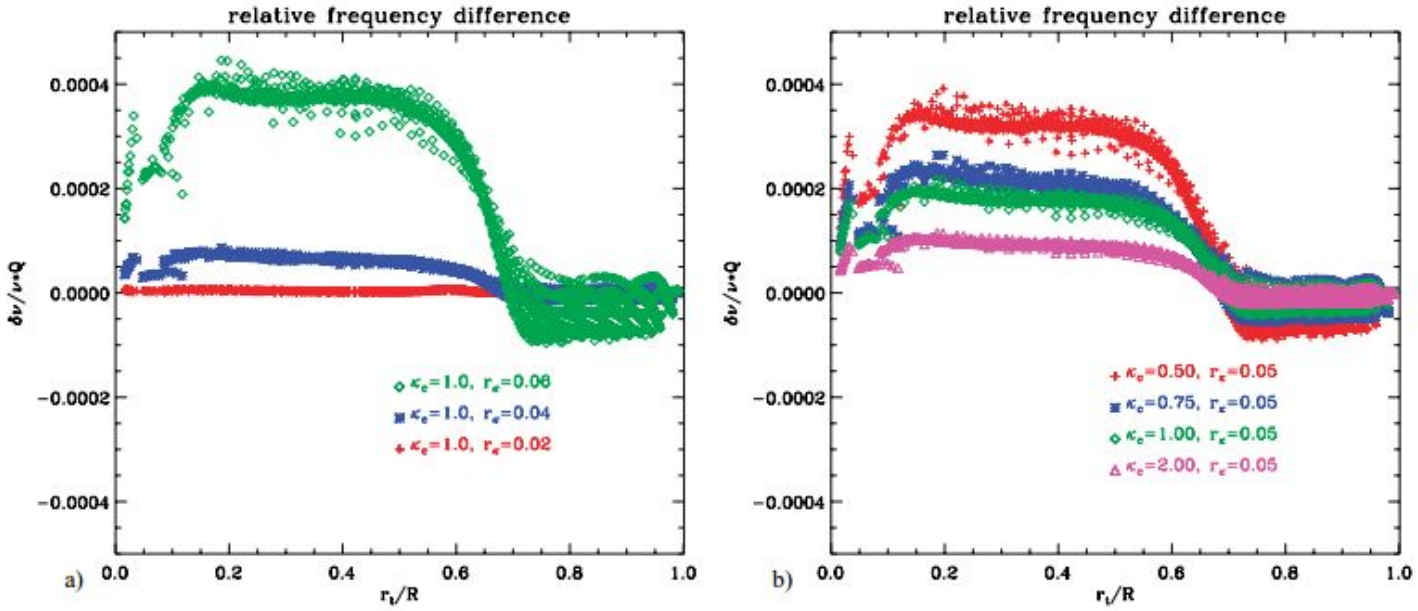

Figure 2. Relative frequency differences, scaled with mode inertia Q, between the dark matter solar models and the standard solar model as a function of radius r_t of the inner turning point for: a) models with varying scale height (Models B-D), and b) the models with varying dark matter opacity (Models E–H).

Hamerly+ 2011

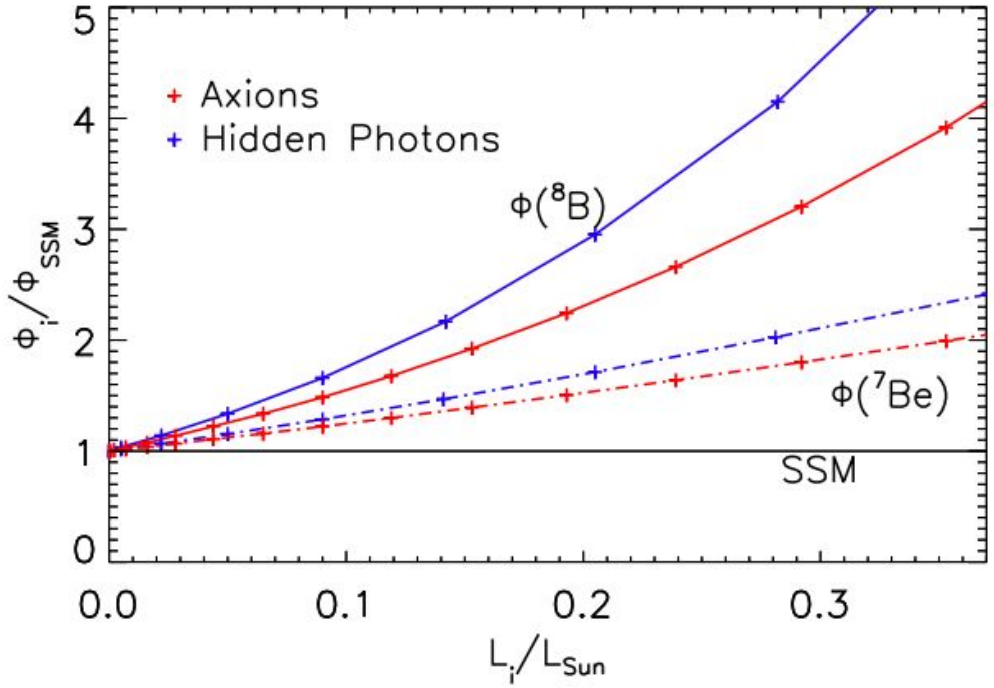

Figure 4: Relative changes of the neutrino fluxes with respect to SSM prediction as function of the luminosity contribution of axions (red line) and hidden photons (blue line).

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Vinyoles+ 2015

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Part 2 - Solar activity and helioseismology

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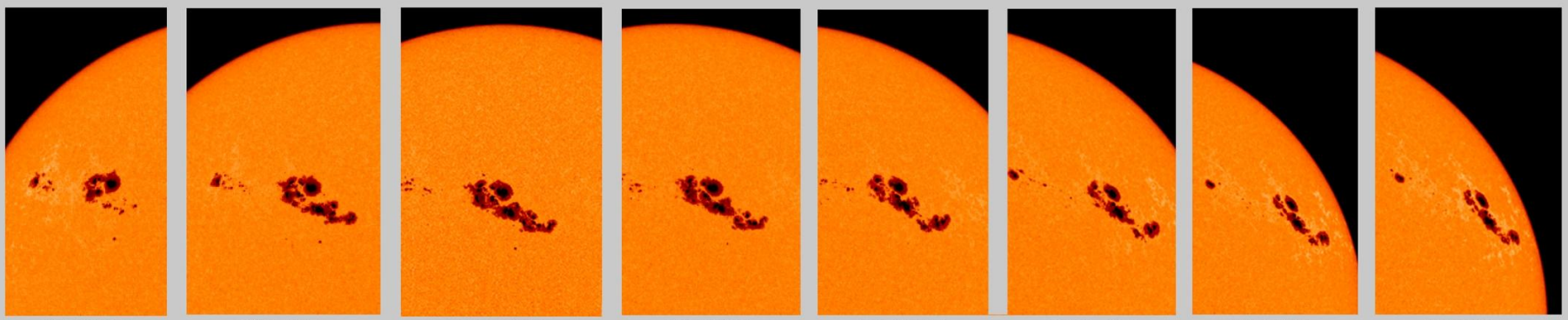
Solar rotation

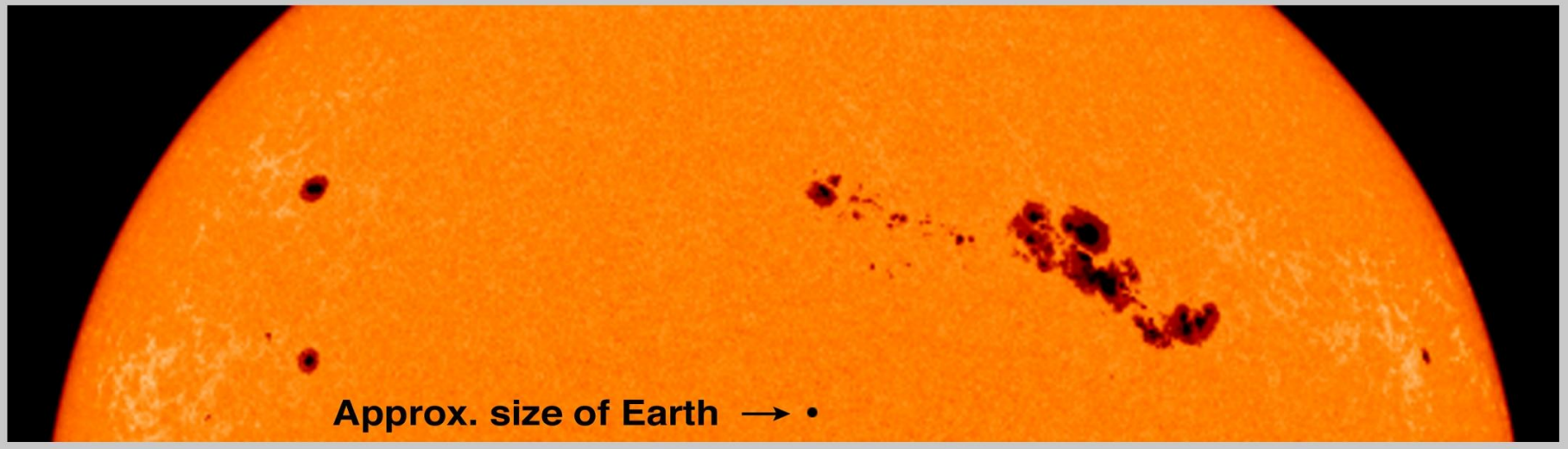
Helioseismology

Solar activity

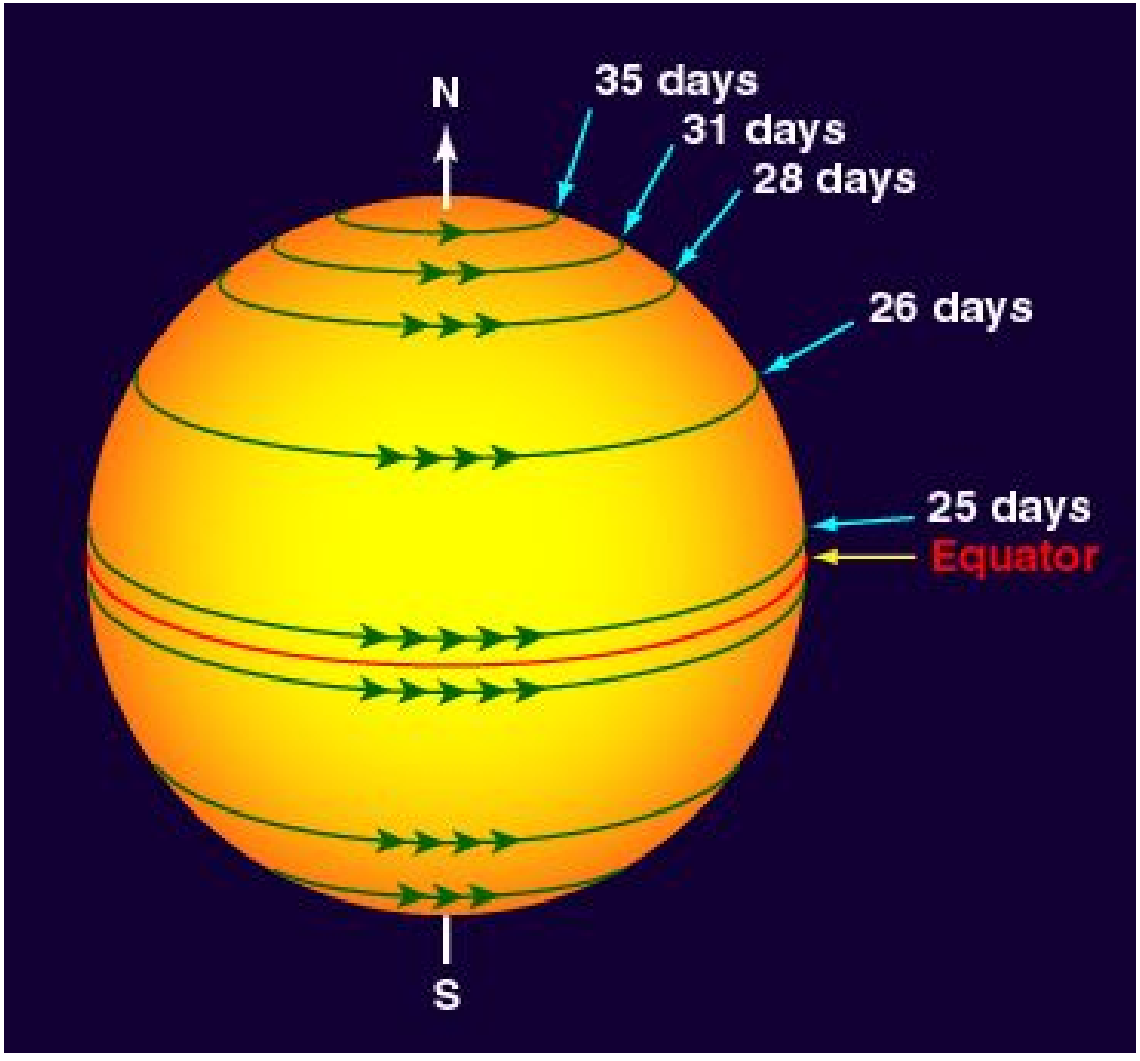
Solar cycle

Helioseismology





March 30, 2001



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Solar rotation

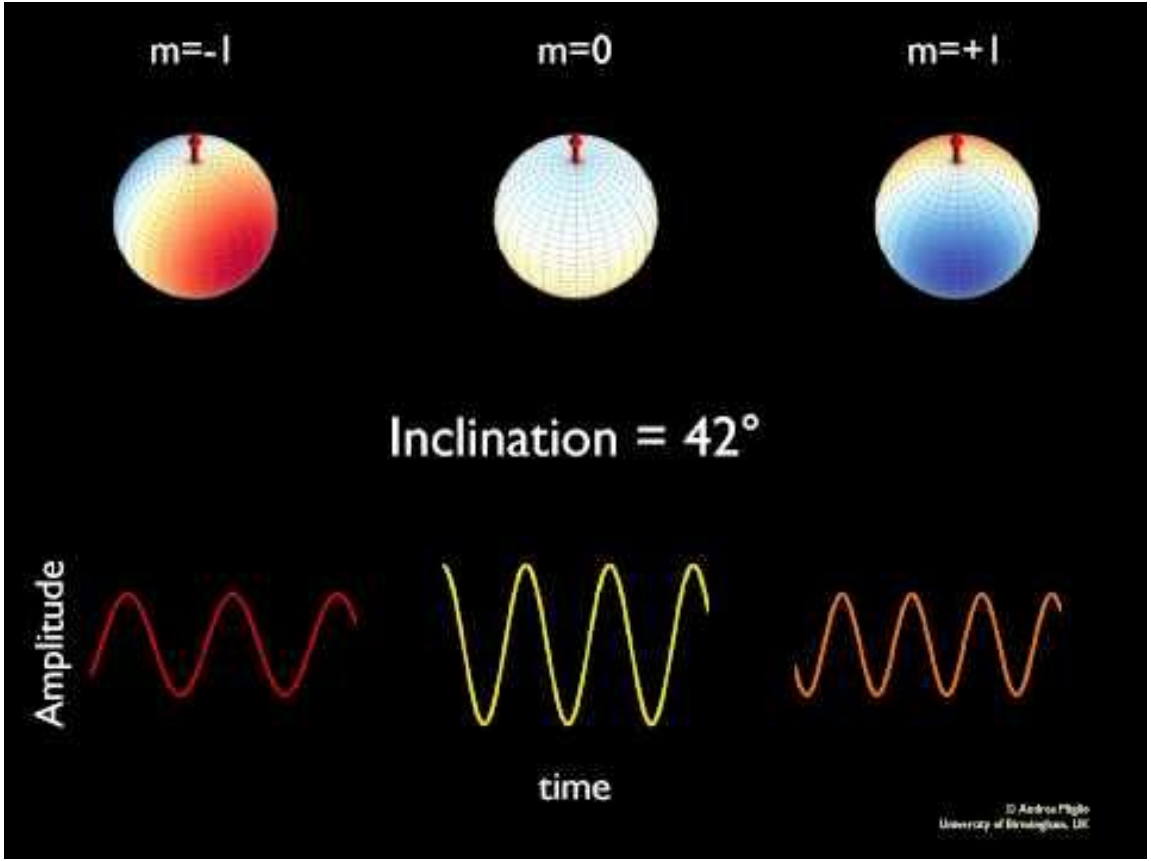
Helioseismology

Solar activity

Solar cycle

Helioseismology

How do we measure rotation using solar-like oscillations?



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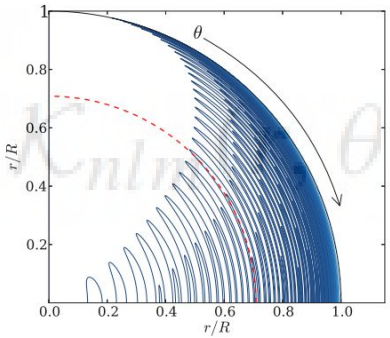
How do we measure rotation using solar-like oscillations?

$$\delta\nu_{nlm} = \int_0^{\pi}\int_0^{R} \mathcal{K}_{nlm}(r,\theta)\mathcal{N}(r,\theta) r\,dr\,d\theta.$$

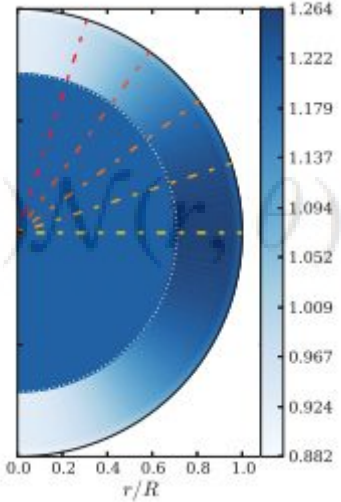
How do we measure rotation using solar-like oscillations?

$$\delta\nu_{nlm} = \int_0^{\pi}\int_0^{R} K_{nlm}(r,\theta)\,\Omega(r,\theta)\,r\,dr\,d\theta.$$

Observed frequency splitting



How the mode of oscillation is sensitive to the interior of the star



Rotation profile

Lund+ 2014

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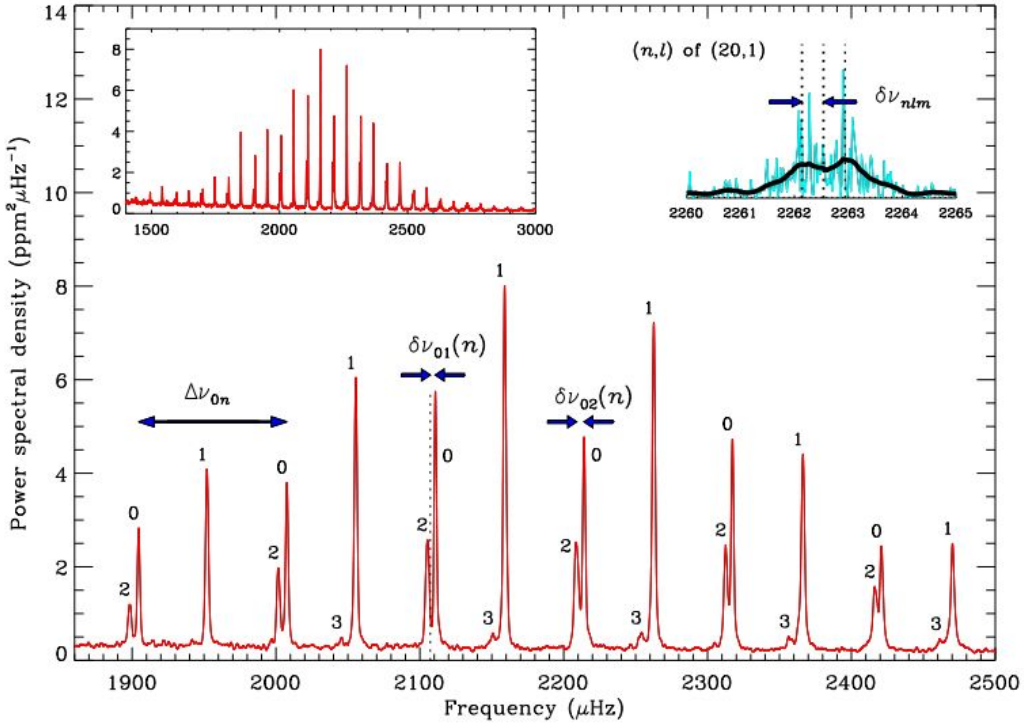

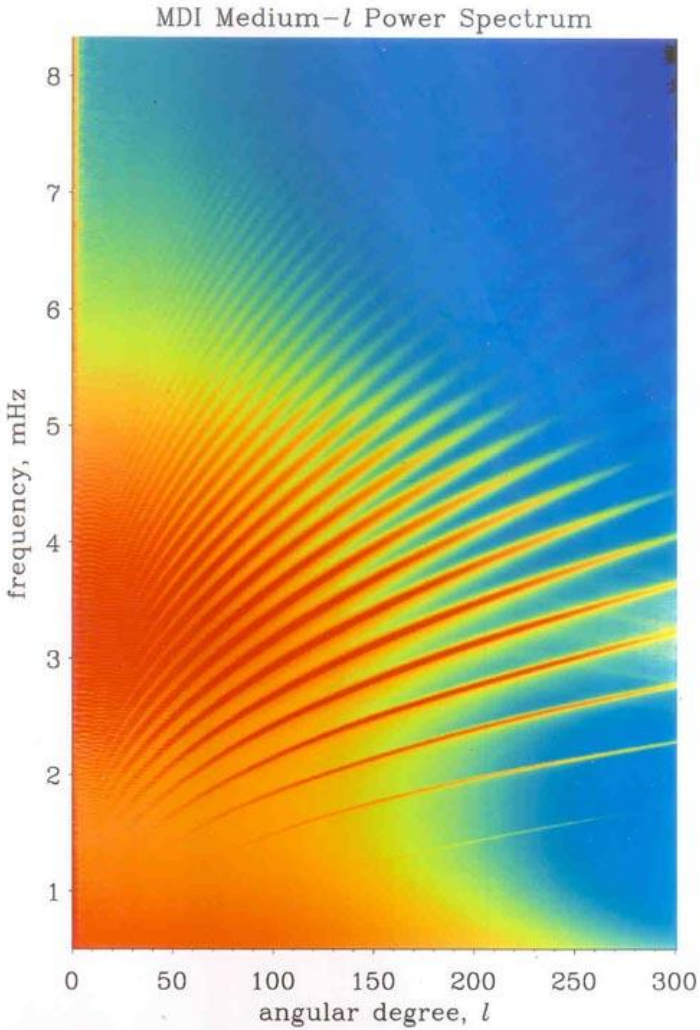

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How do we measure rotation using solar-like oscillations?

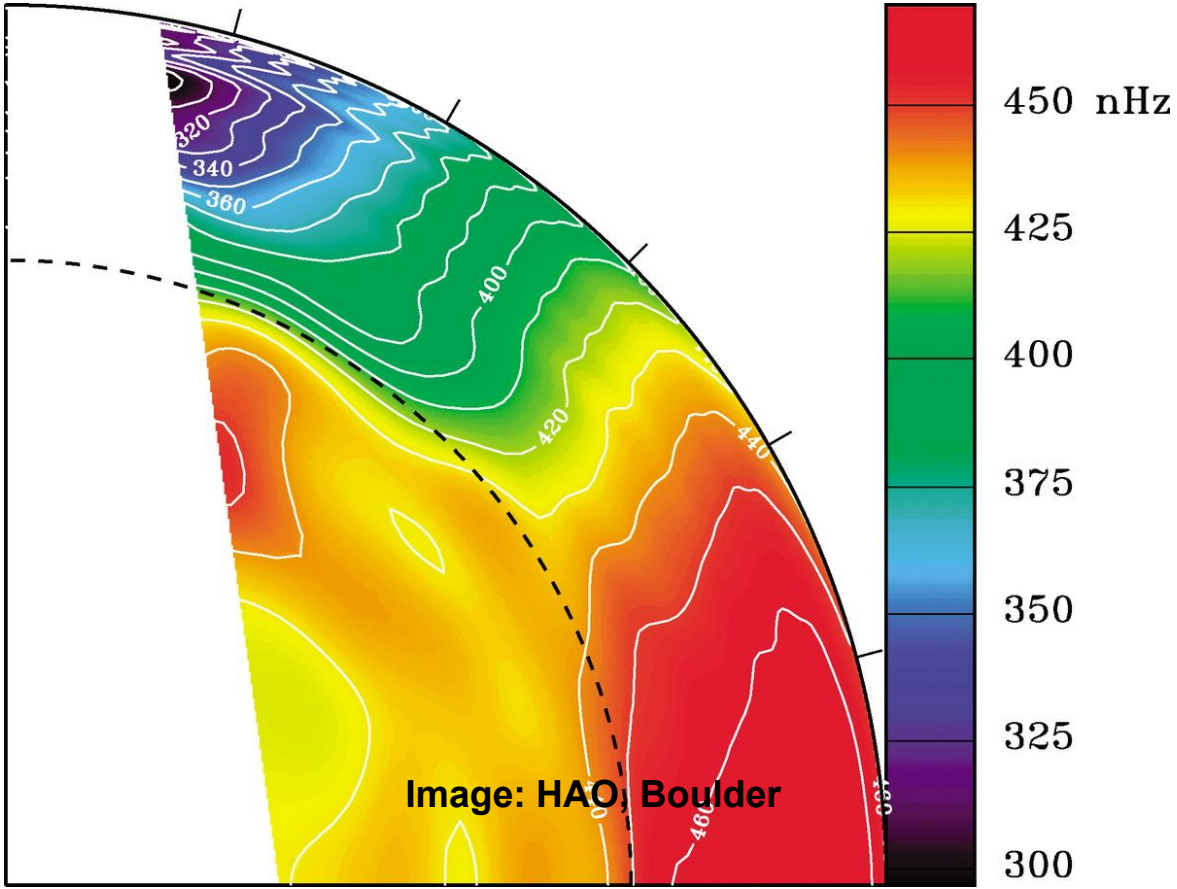

Image: HAO, Boulder

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Solar rotation

Helioseismology

Solar activity

Solar cycle

Helioseismology

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Discussion:

Discuss the types and timescales of solar activity or evolution!

3 minutes

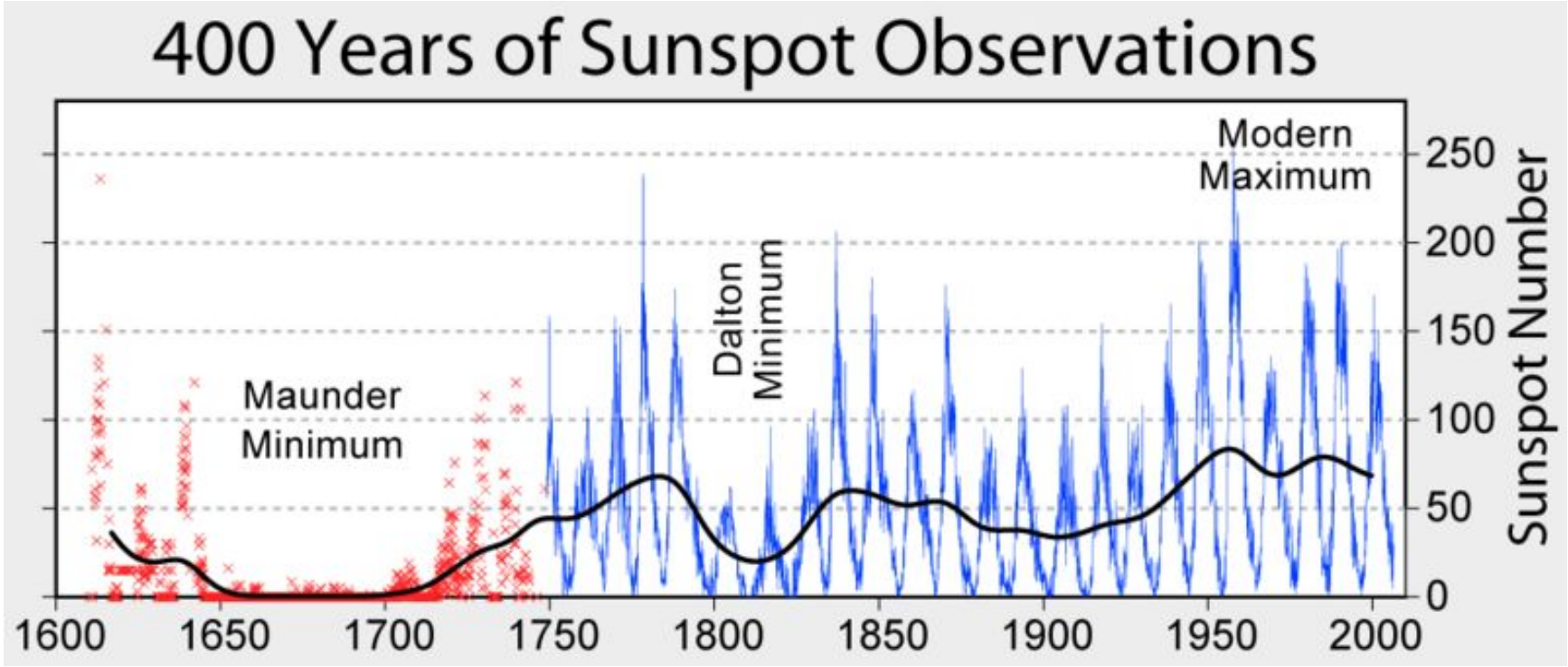
Solar rotation

Helioseismology

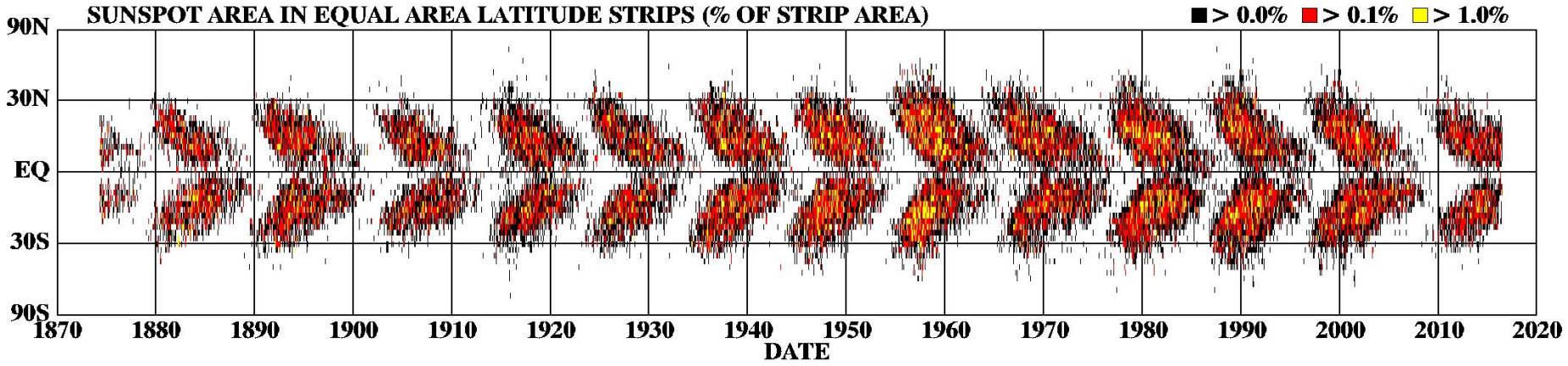
Solar activity

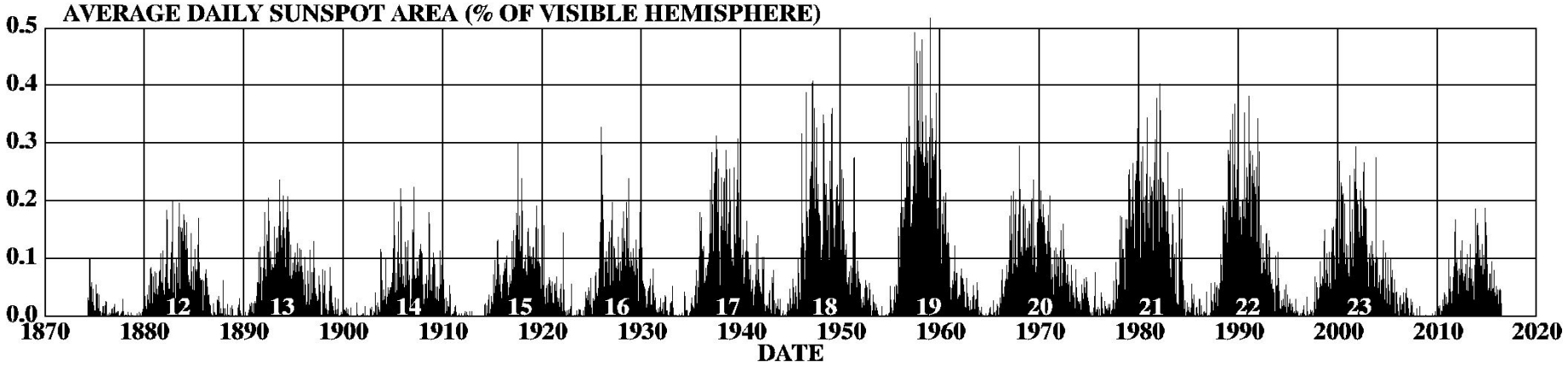
Solar cycle

Helioseismology


400 Years of Sunspot Observations
Modern
Maximum
Dalton
Minimum
Maunder
Minimum
250
200
150
100
50
0
Sunspot Number
1600
1650
1700
1750
1800
1850
1900
1950
2000

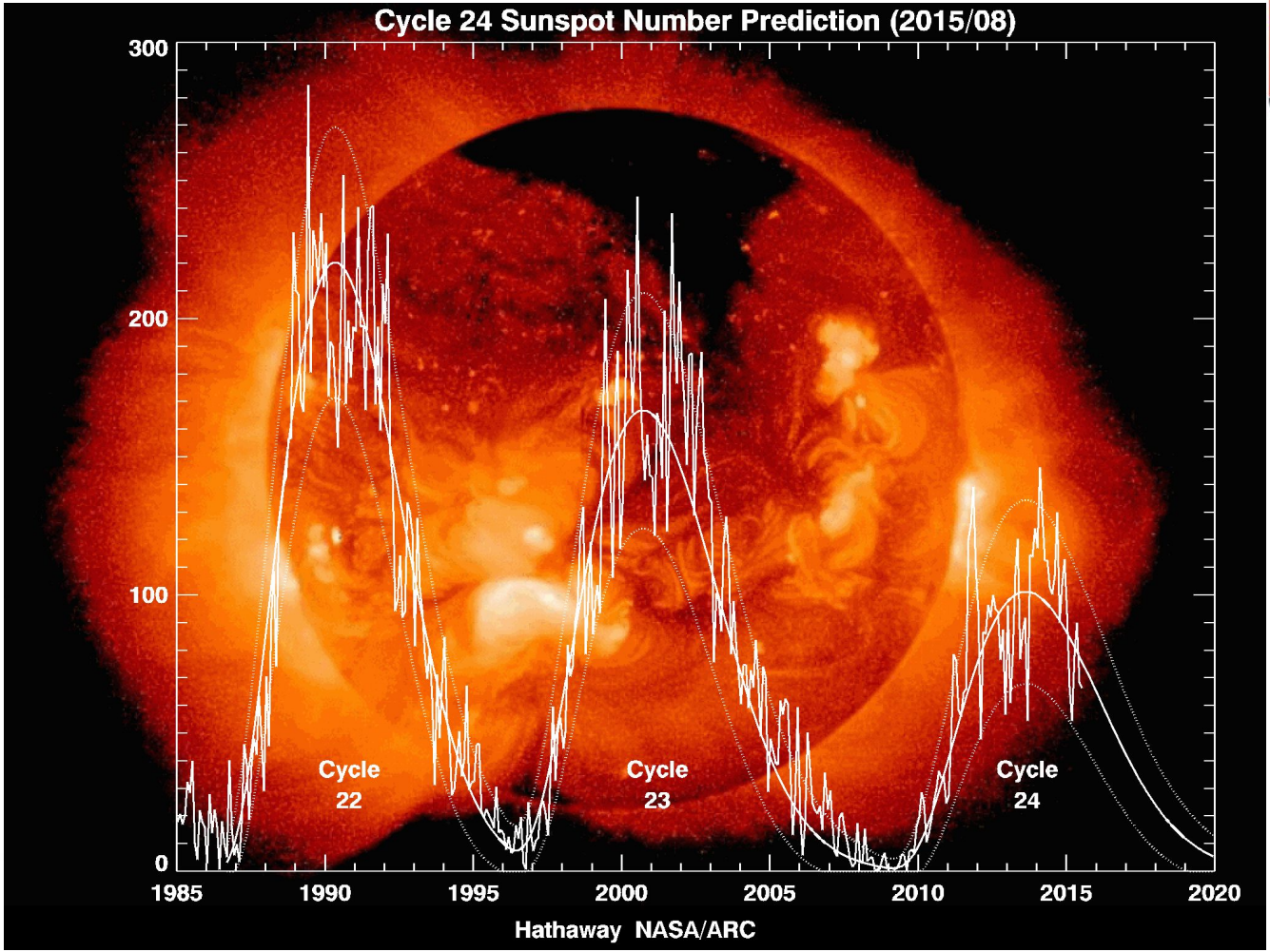
DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS





http://solarscience.msfc.nasa.gov/

HATHAWAY NASA/ARC 2016/07



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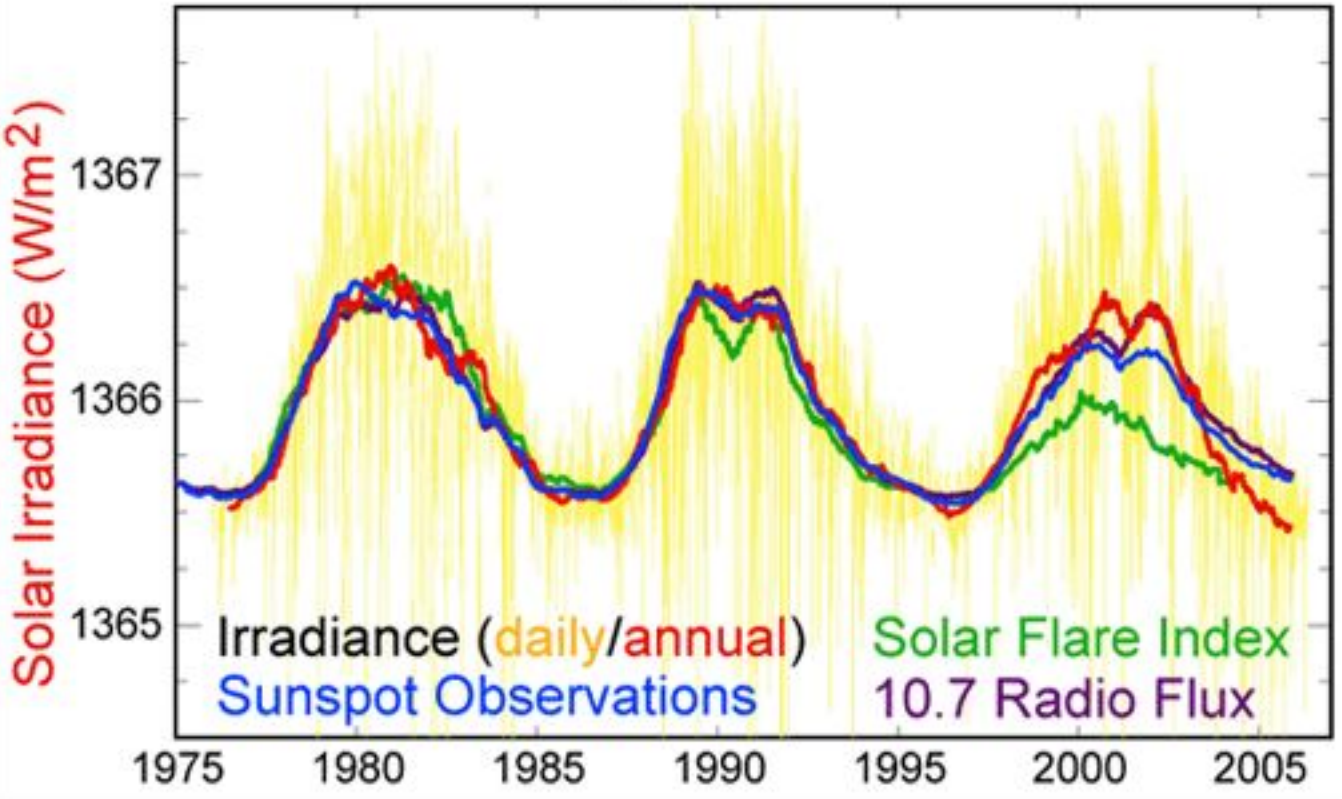
Solar Cycle Variations



Solar rotation

Helioseismology

Solar activity

Solar cycle

Helioseismology

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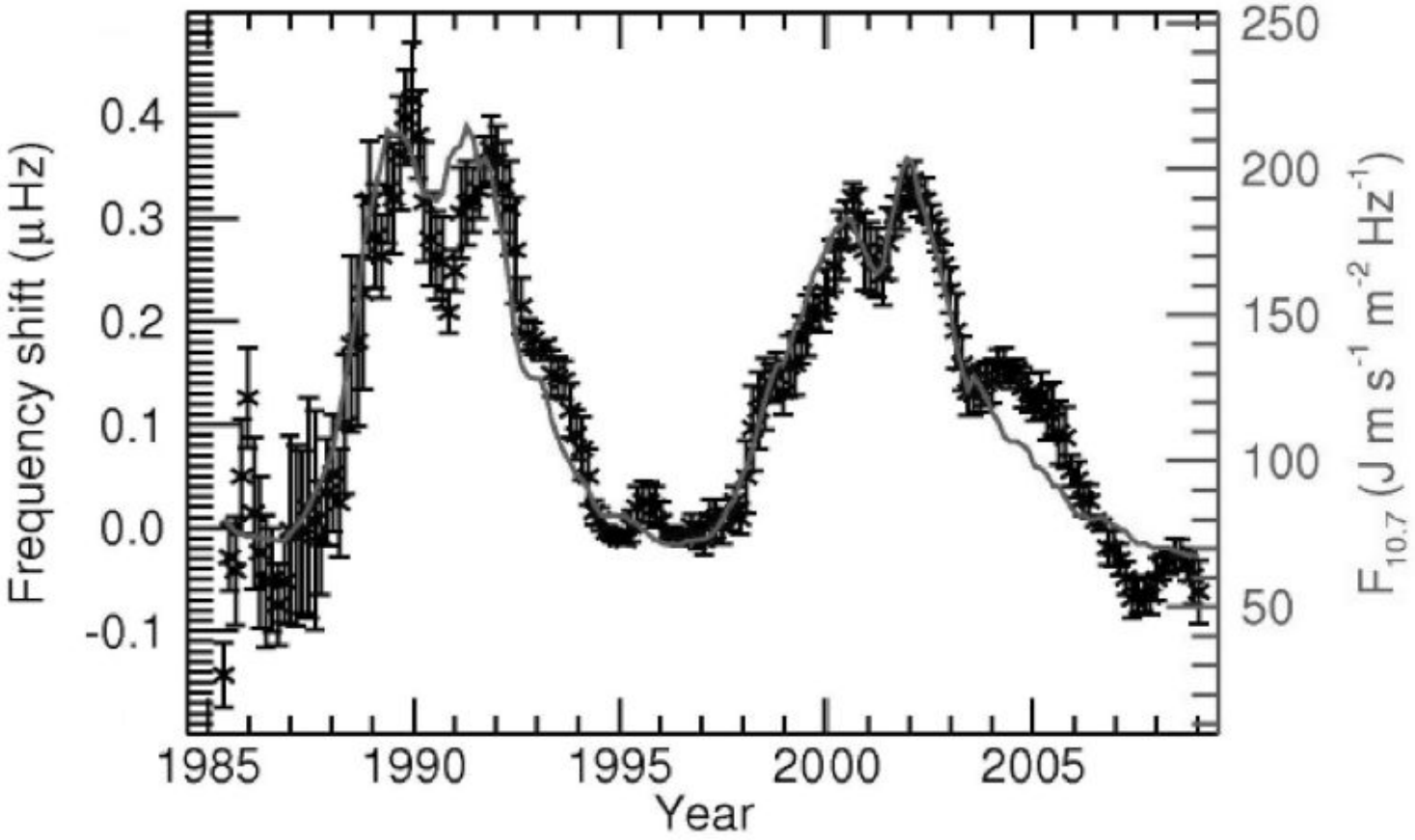

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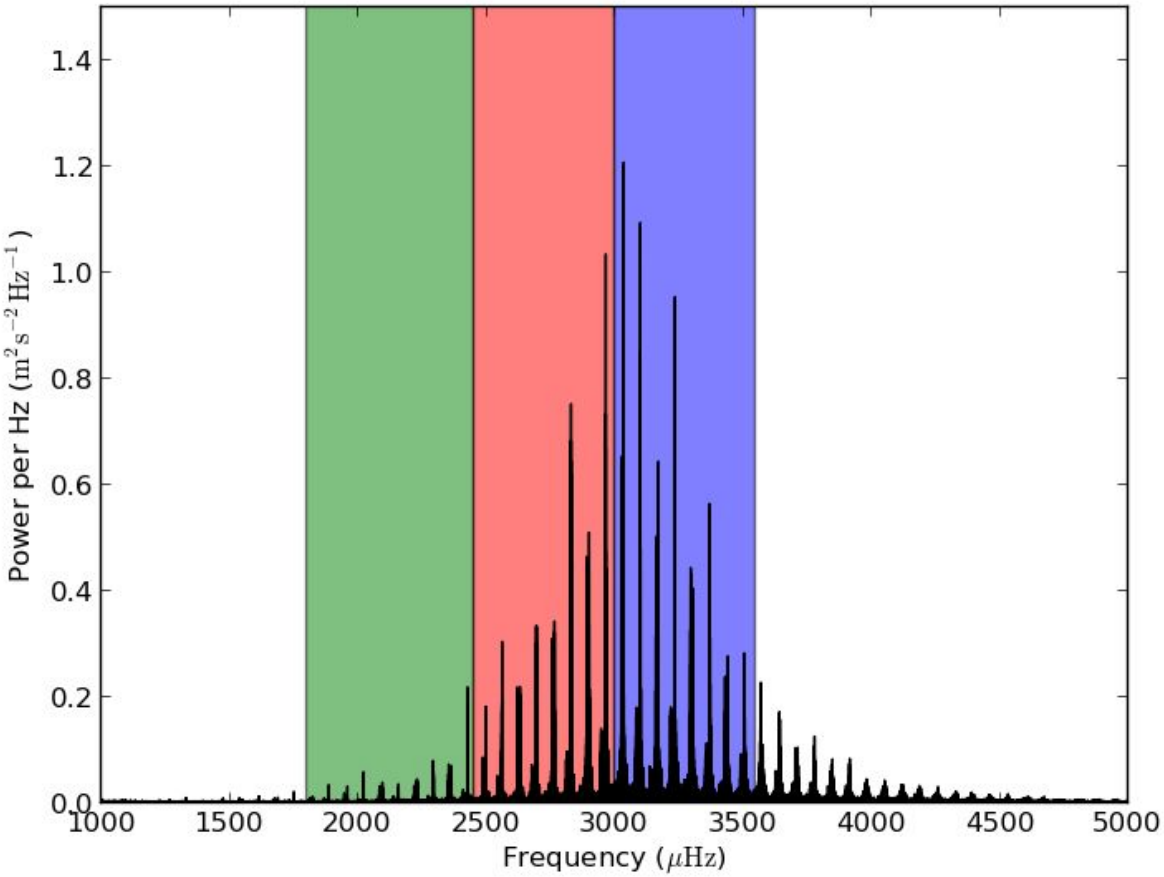
Fig. Broomhall+ 2012



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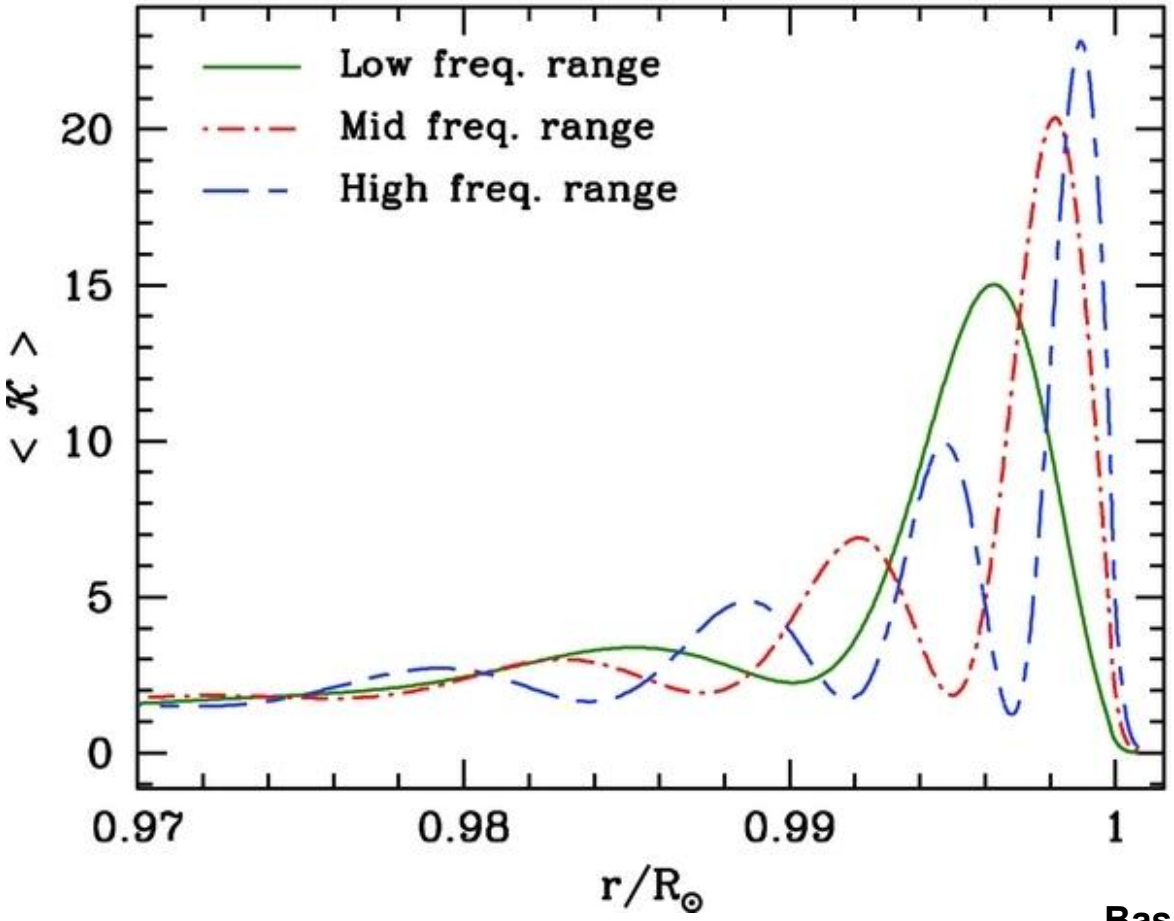

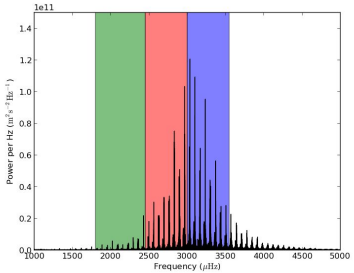

Basu+ 2012

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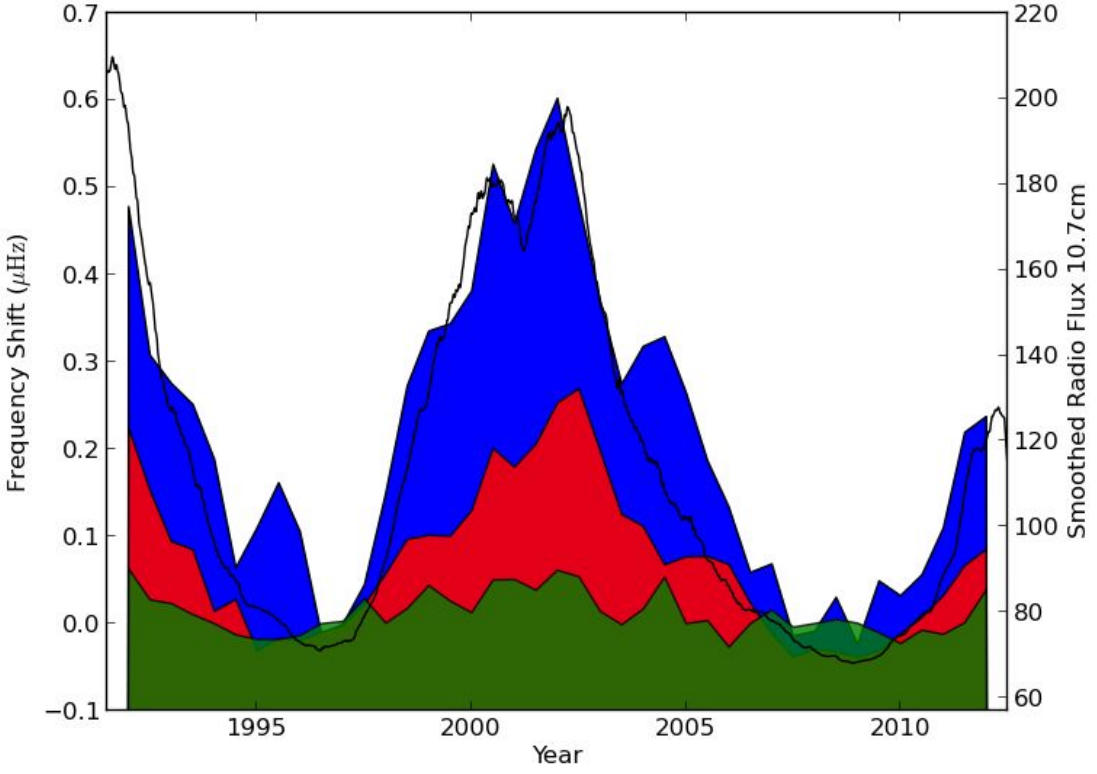

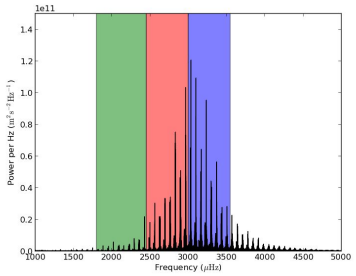

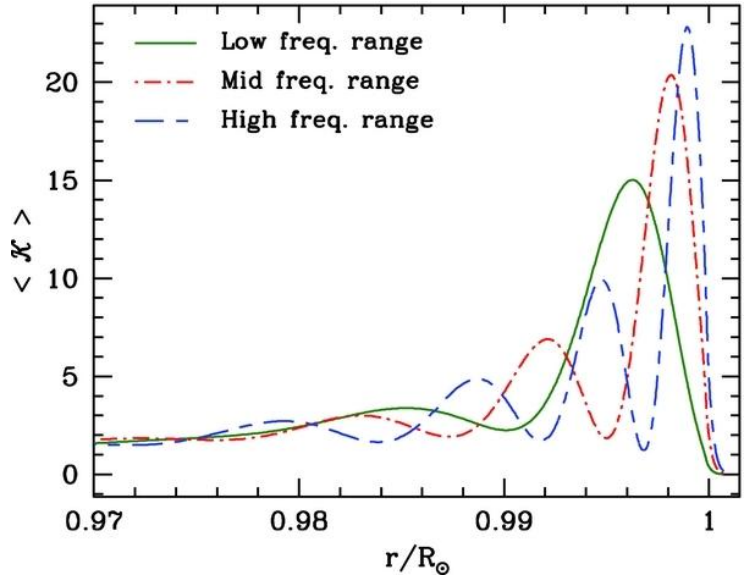

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“Thing” that causes the frequency shift is located at a depth > 0.996 R_sol

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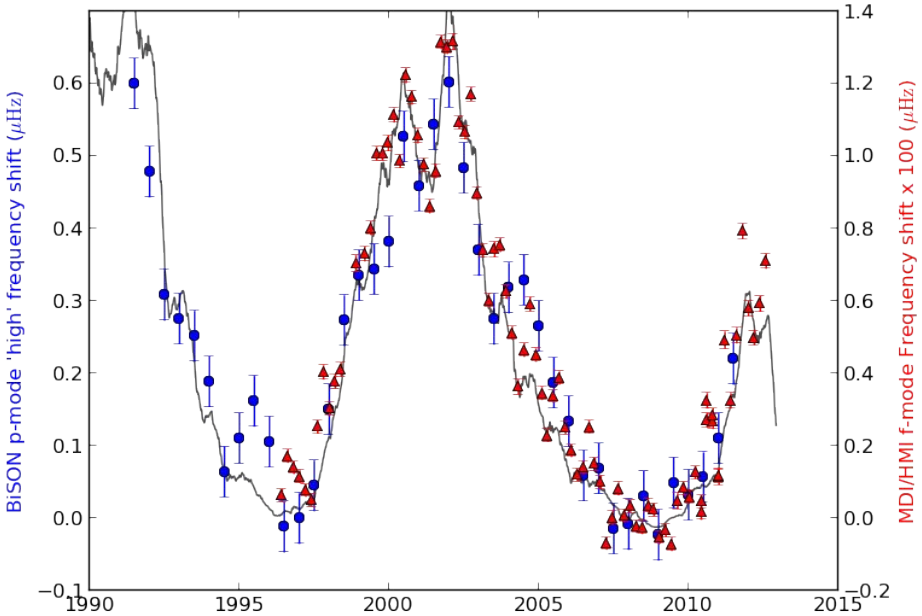
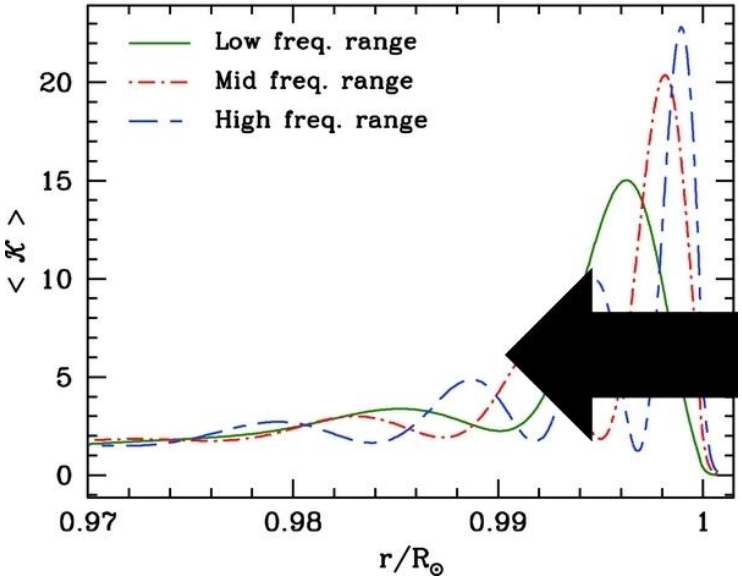
Basu et al. 2012

BiSON: Solar cycle + f mode





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The Sun and helioseismology

Solar activity and helioseismology

Tomorrow ...

Stellar activity

The solar-stellar connection

The Sun and helioseismology

Solar activity and helioseismology

Stellar activity

The solar-stellar connection

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Solar rotation

Helioseismology

Solar activity cycle

Solar dynamo

Results

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The Solar-Stellar Connection

Part 3 - Stellar activity

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Guy R. Davies

The Sun and helioseismology

Solar activity and helioseismology

Stellar activity

The solar-stellar connection

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Stellar activity

Magnetic field

Empirical relations

Spin down

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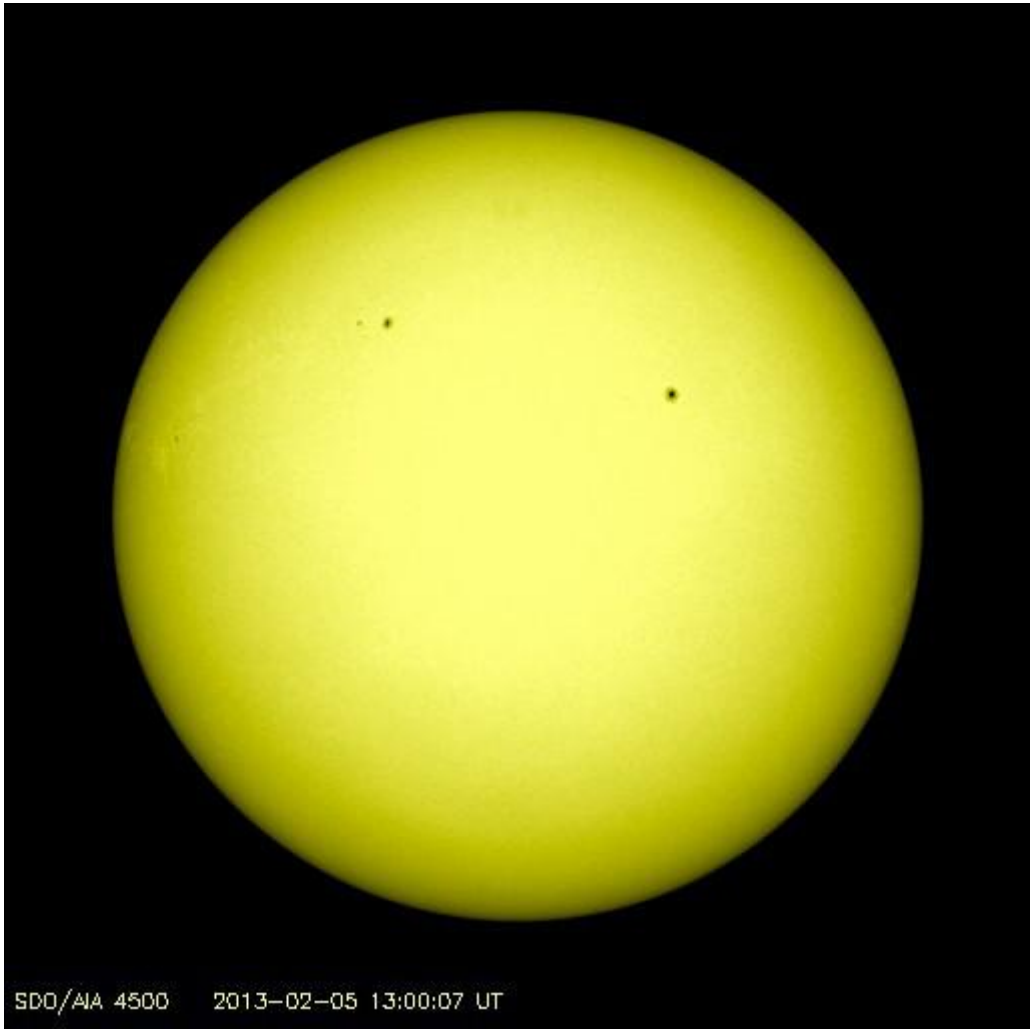

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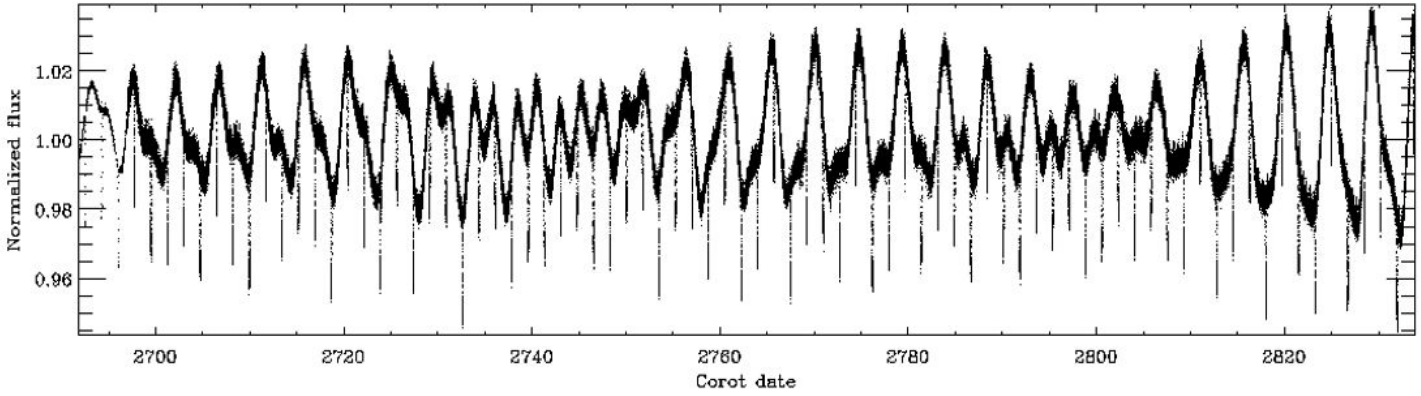
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0.96
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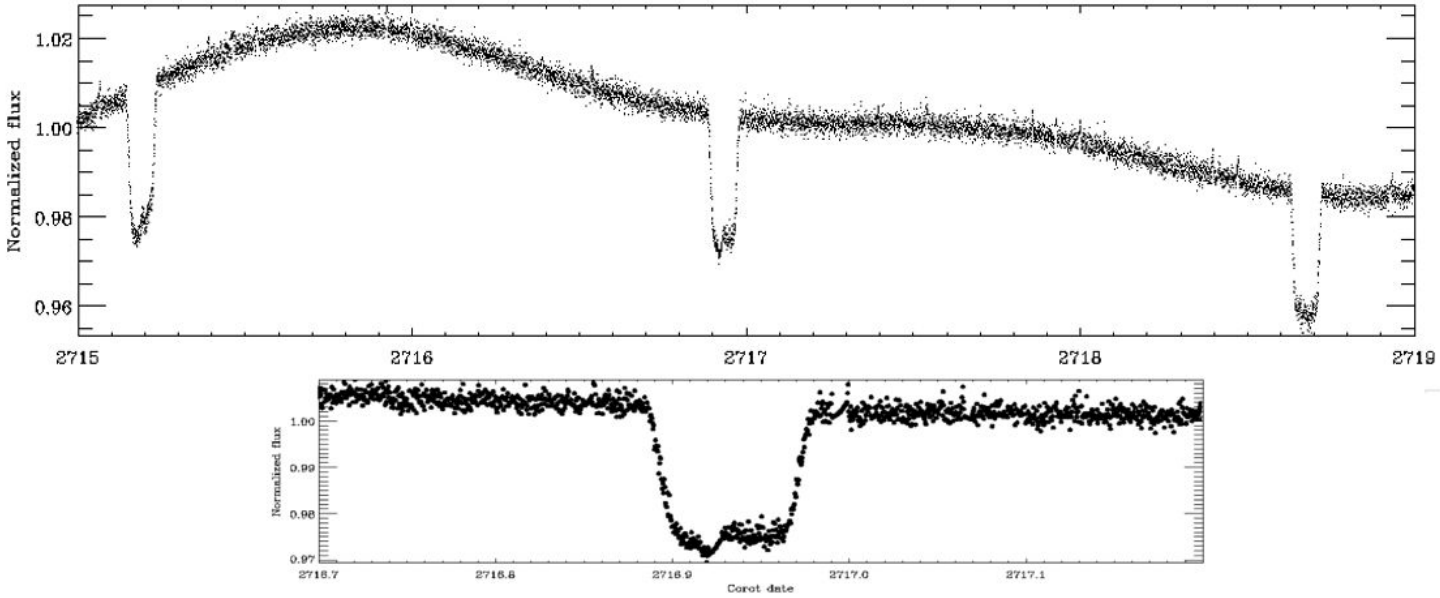
2800
2820
Corot date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0.98
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2716
2717
2718
2719
Normalized flux
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0.97
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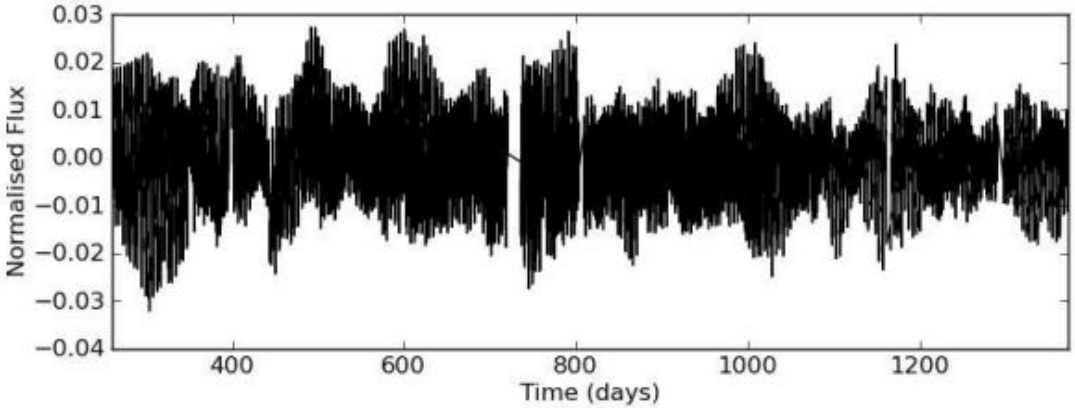
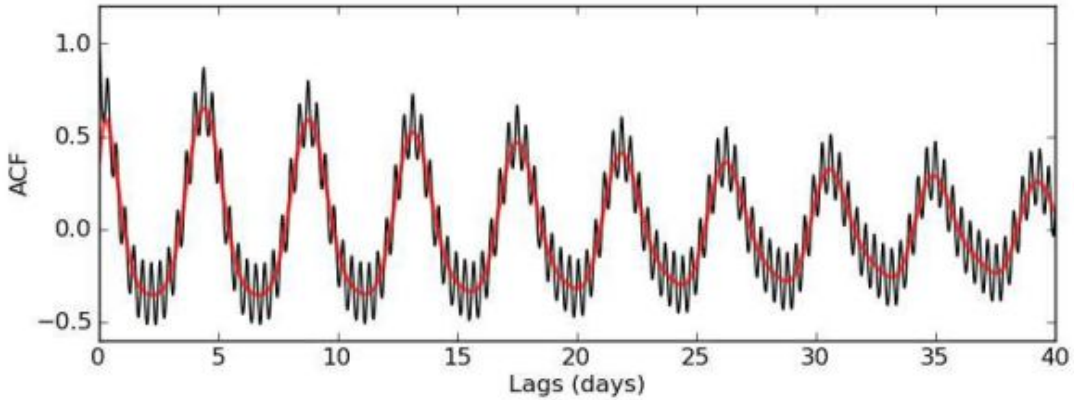
2716.9
2717.0
2717.1
Corot date

CoRoT-2b





McQuillan+ 2014

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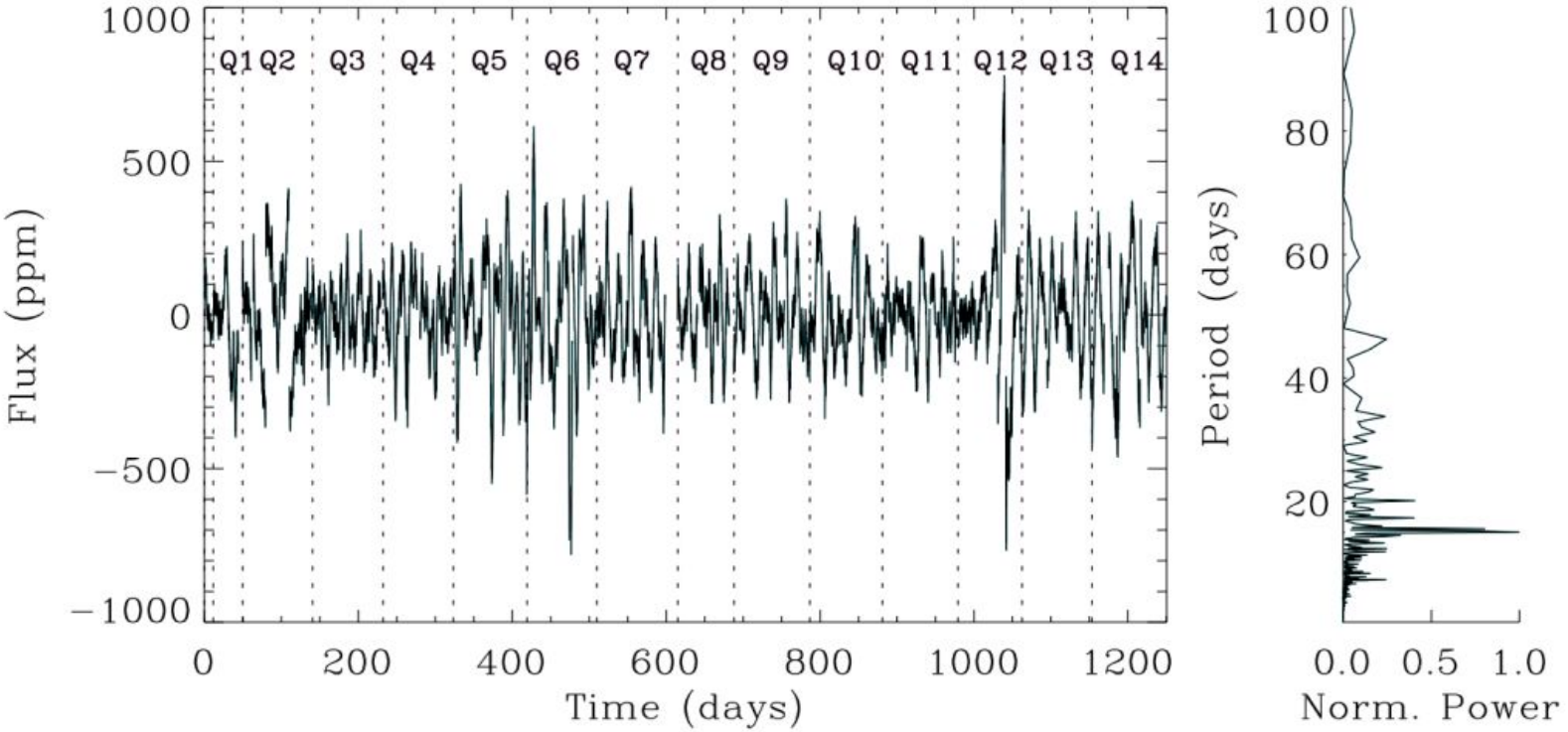

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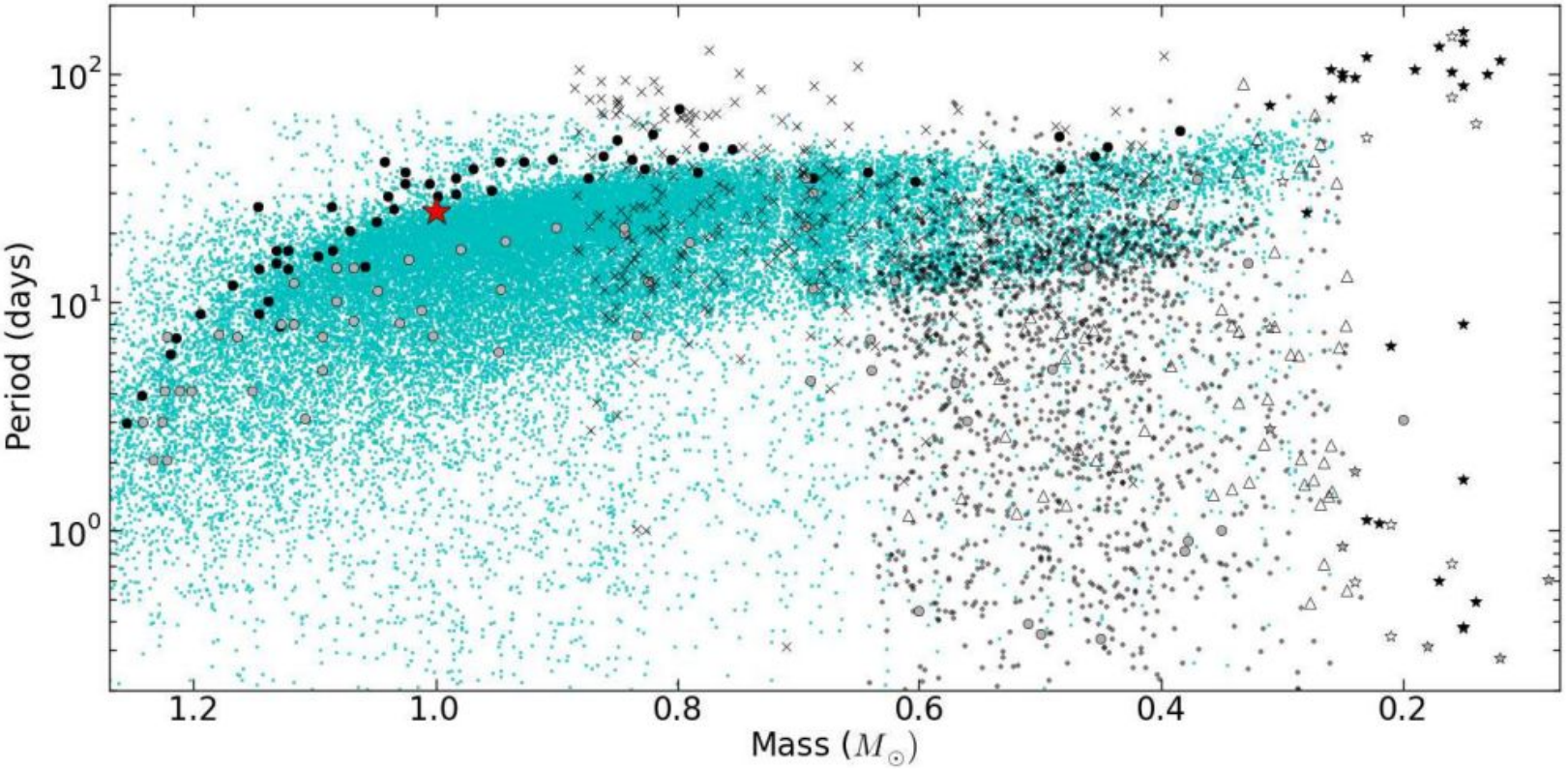
Garcia+ 2014



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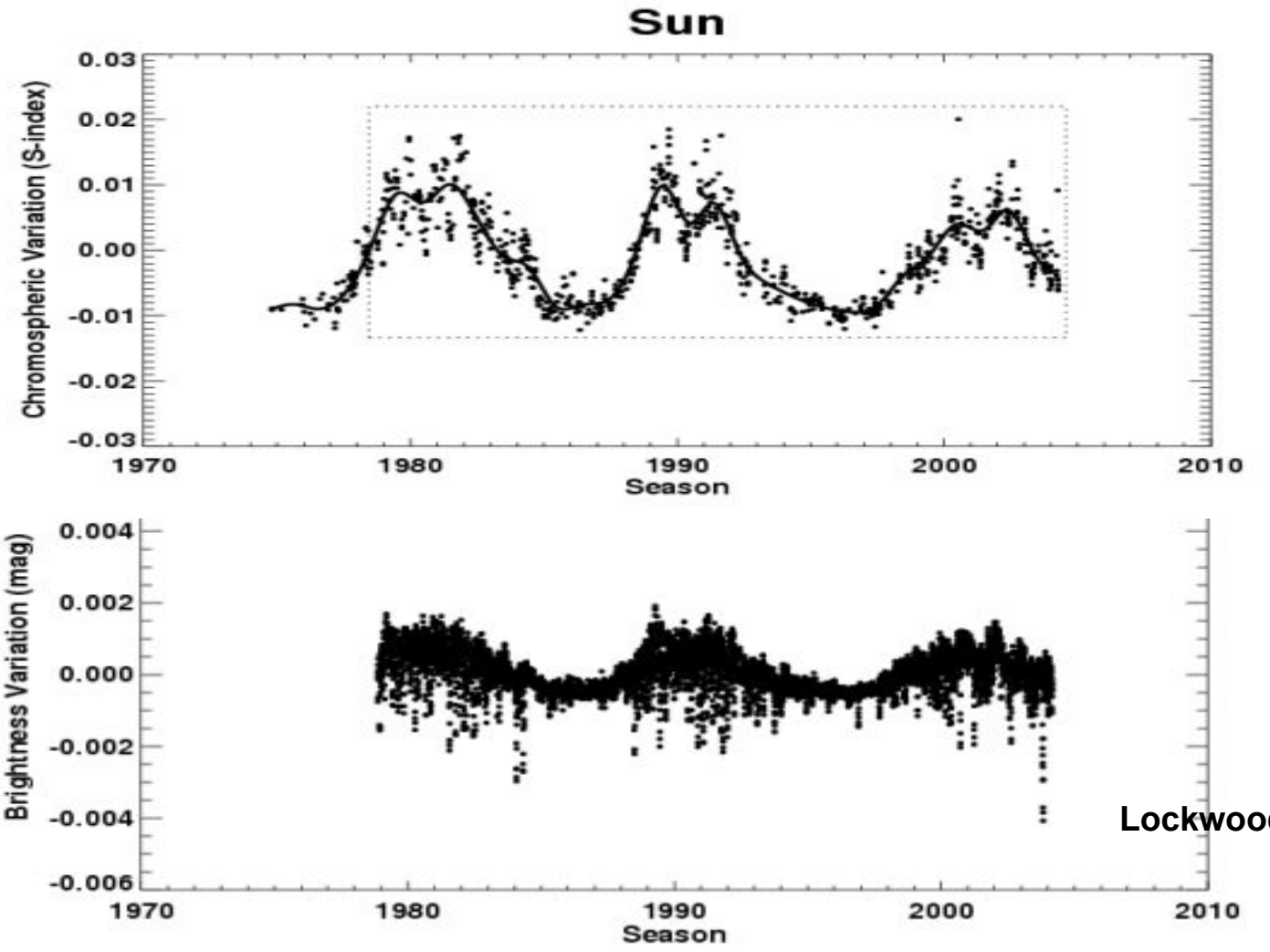
McQuillan+ 2014



Lockwood+ 2007

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Spots or faculae?

Well ....

It’s a little bit complicated!

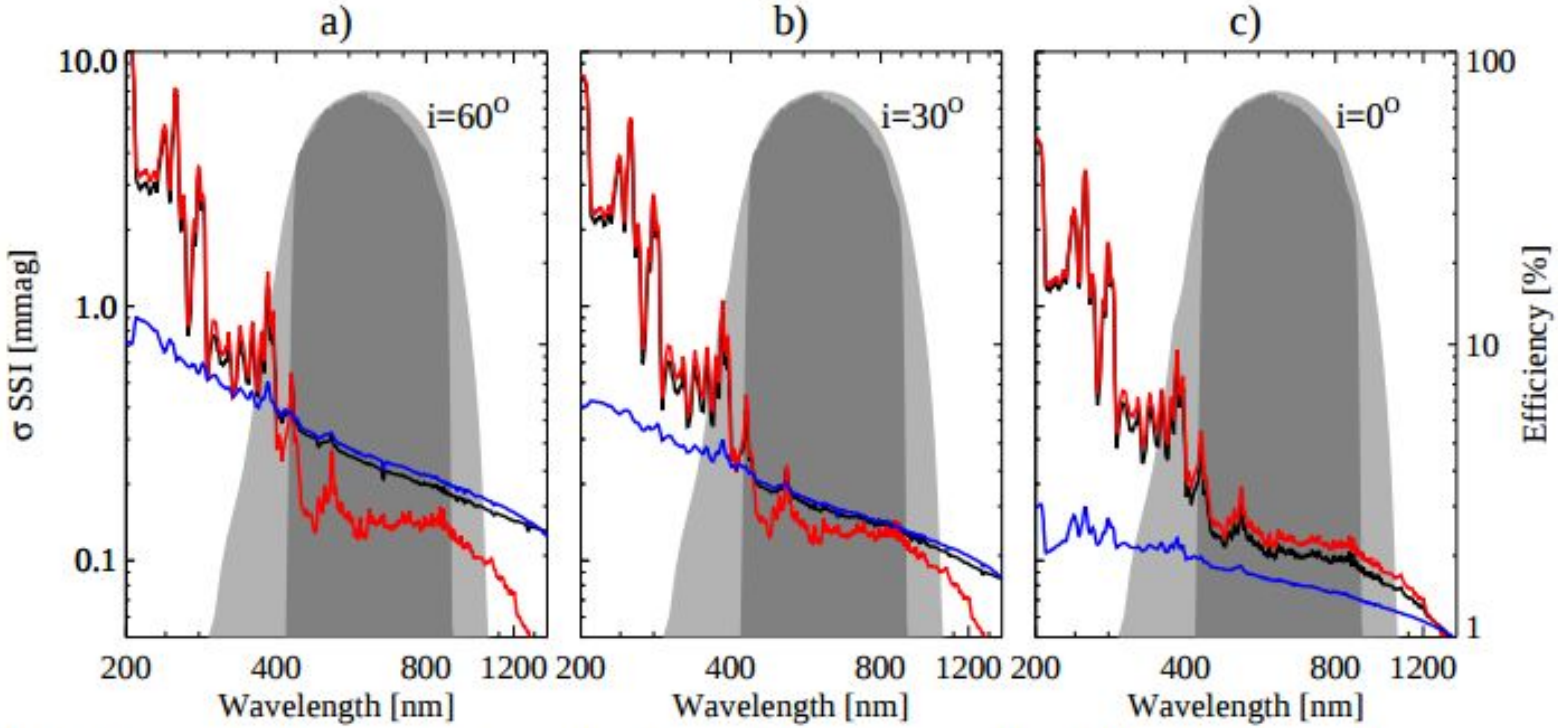

Fig. 6. The amplitude of the rotational solar brightness variability (black curves) and its facular (red) and spot (blue) components calculated for the 1999-2014 period at three values of the inclination: 60° (panel a), 30° (panel b), and 0° (panel c). The dark (light) shaded areas show Kepler (CoRoT) total spectral efficiency.

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Shapiro+ 2016

Stellar activity

Magnetic field

Empirical relations

Spin down

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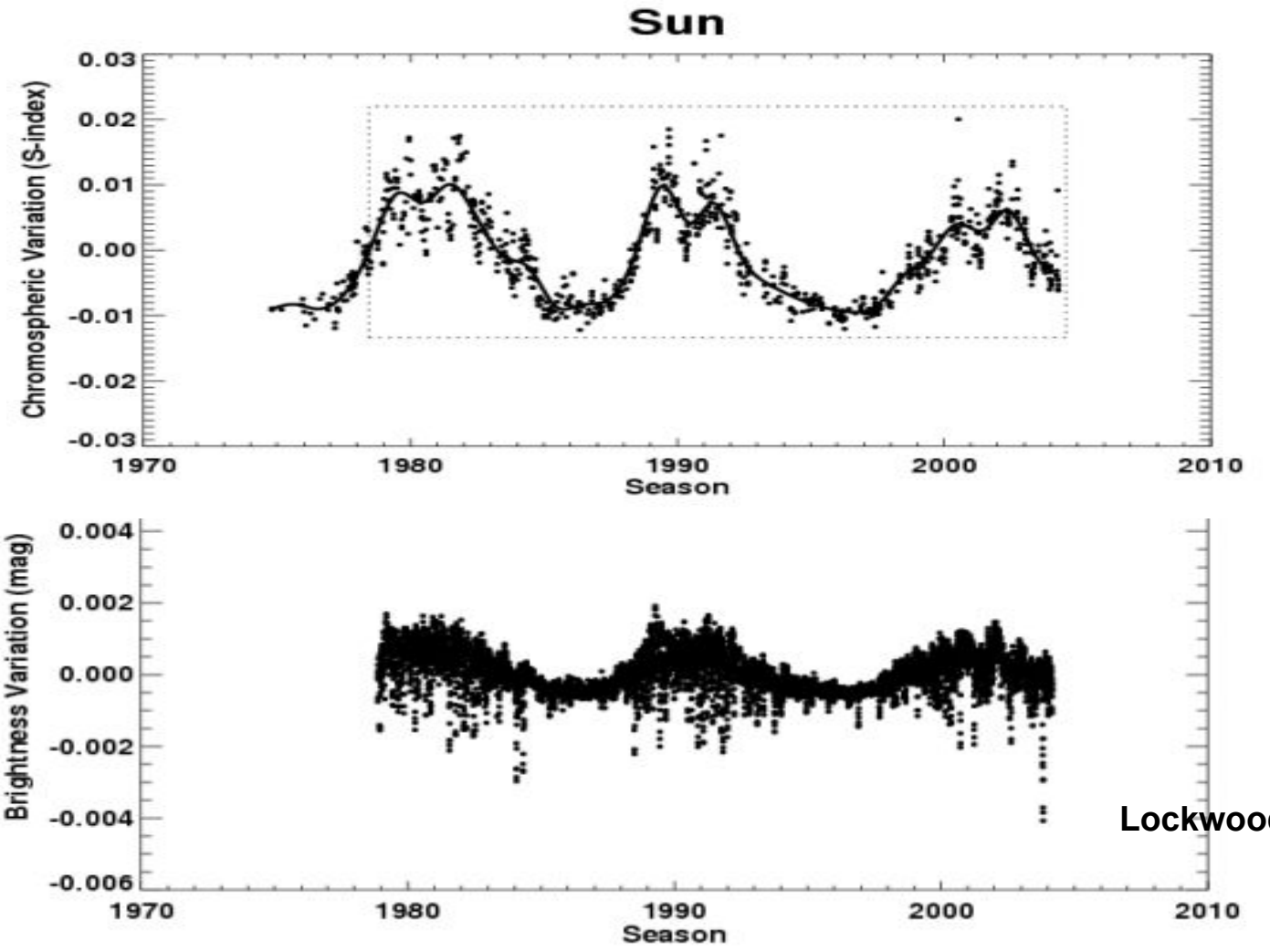
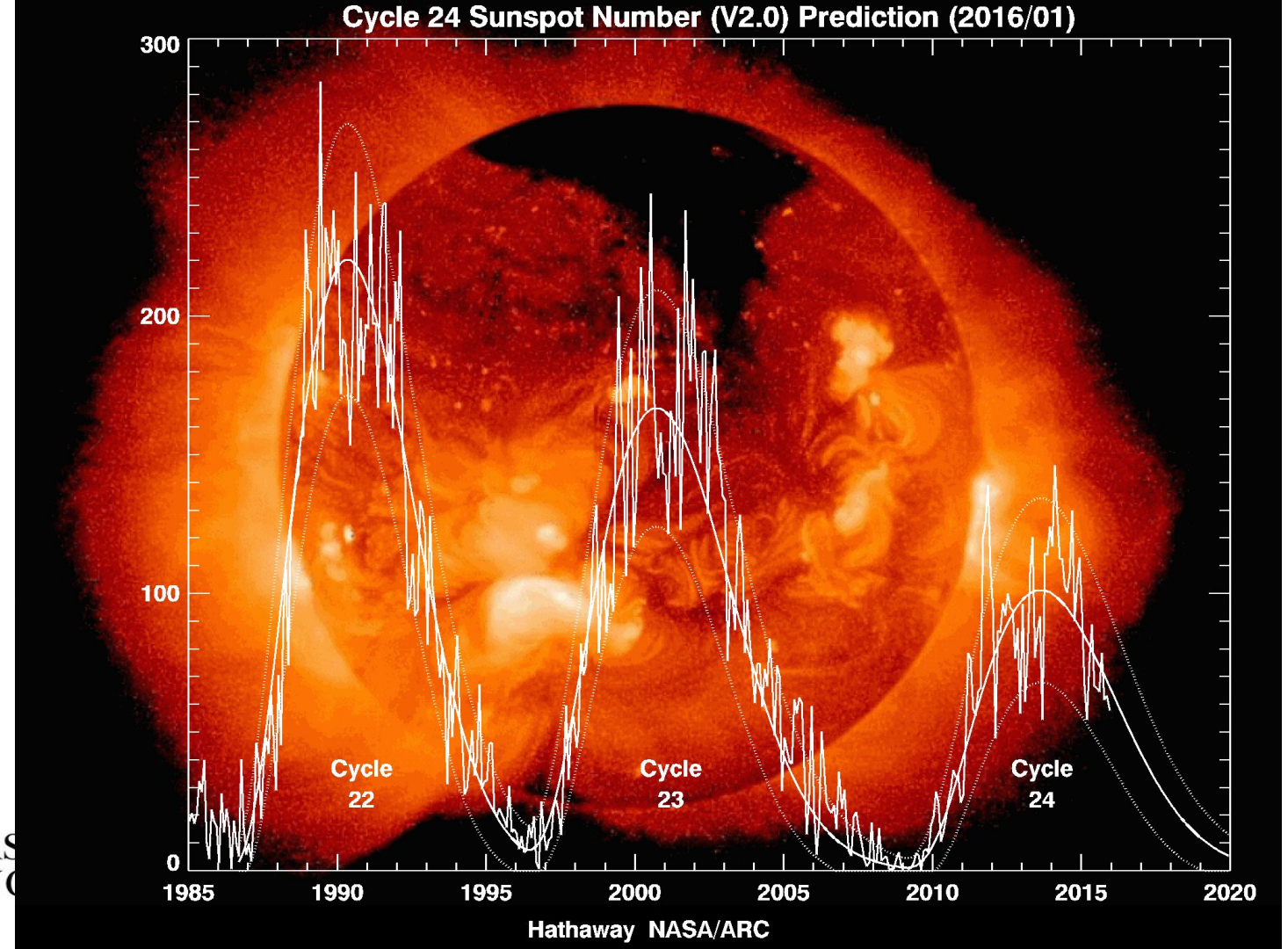


Lockwood+ 2007

UNIVERS
BIRMINC



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Stellar activity

Magnetic field

Empirical relations

Spin down

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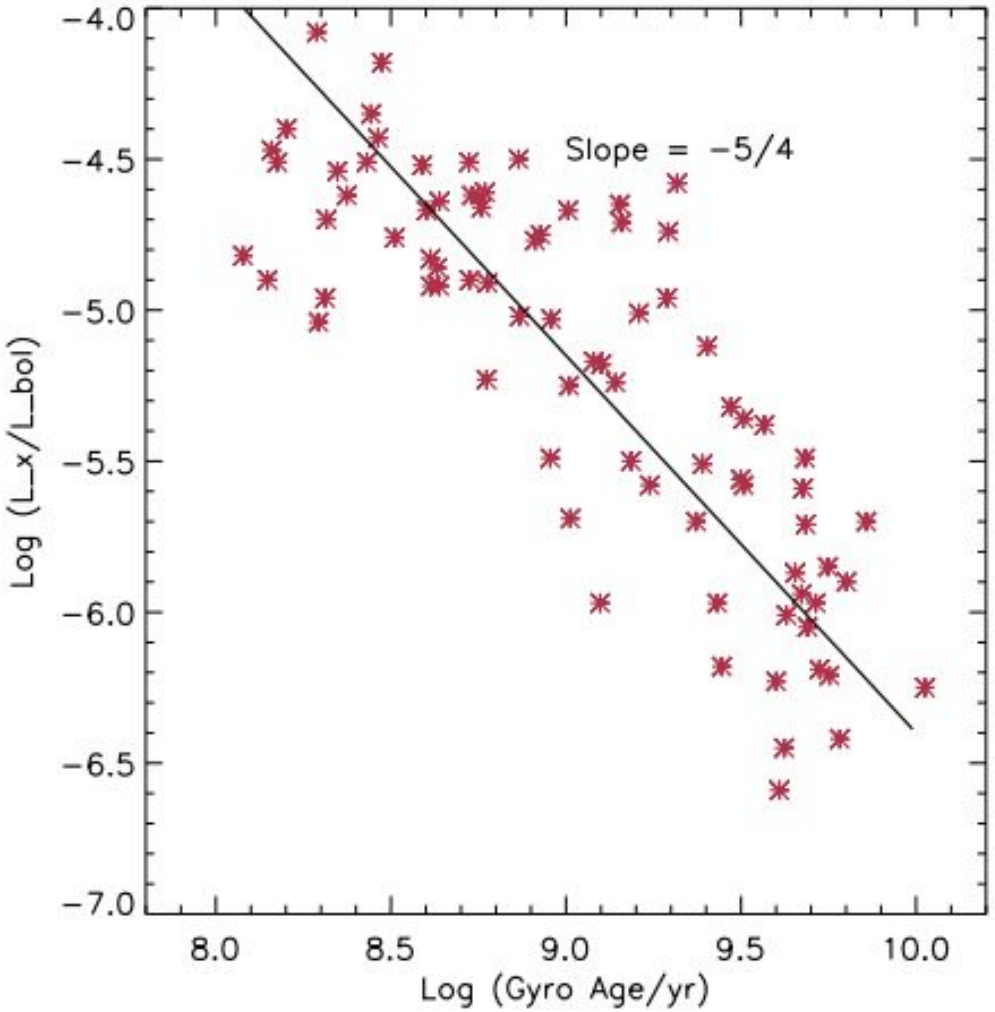
Today's top tip:

You can go a long way in astronomy by plotting things against other things!



Barnes 2007

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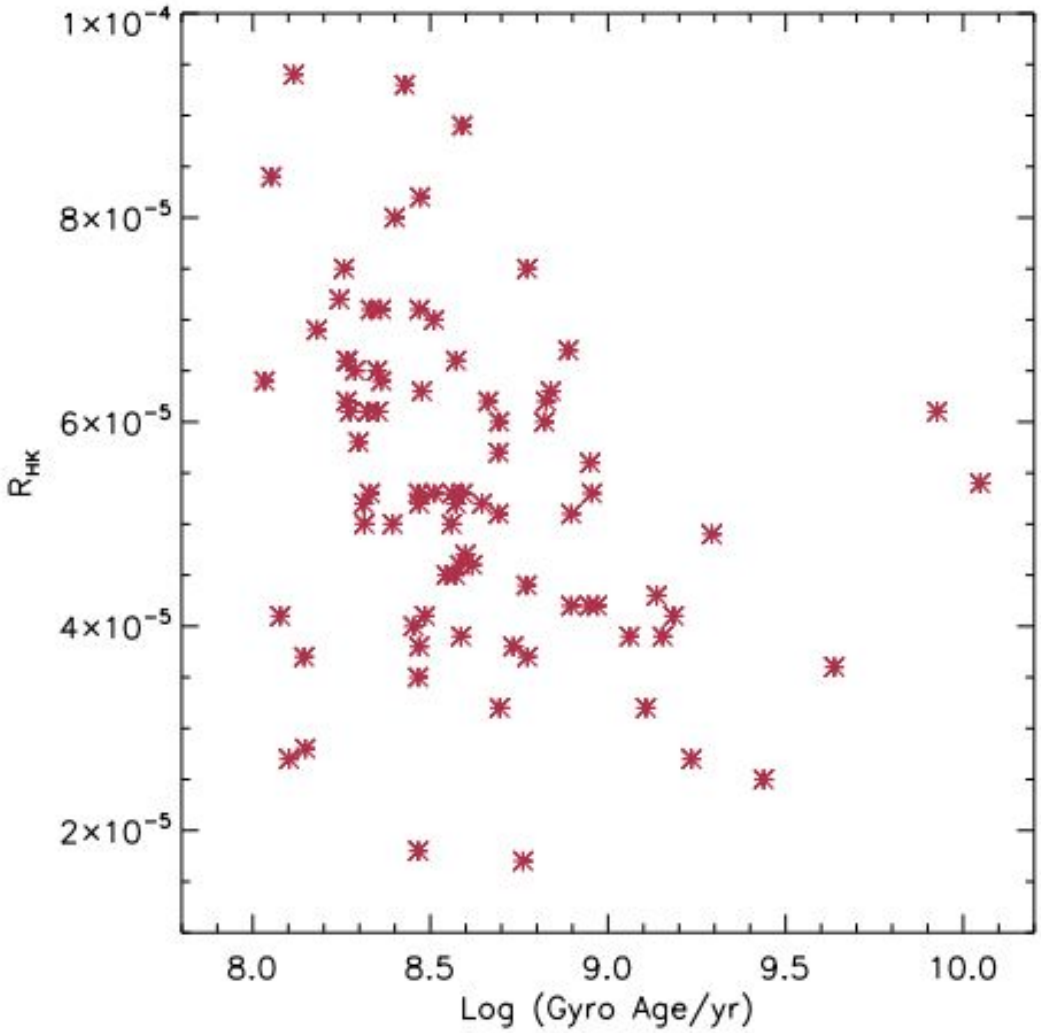


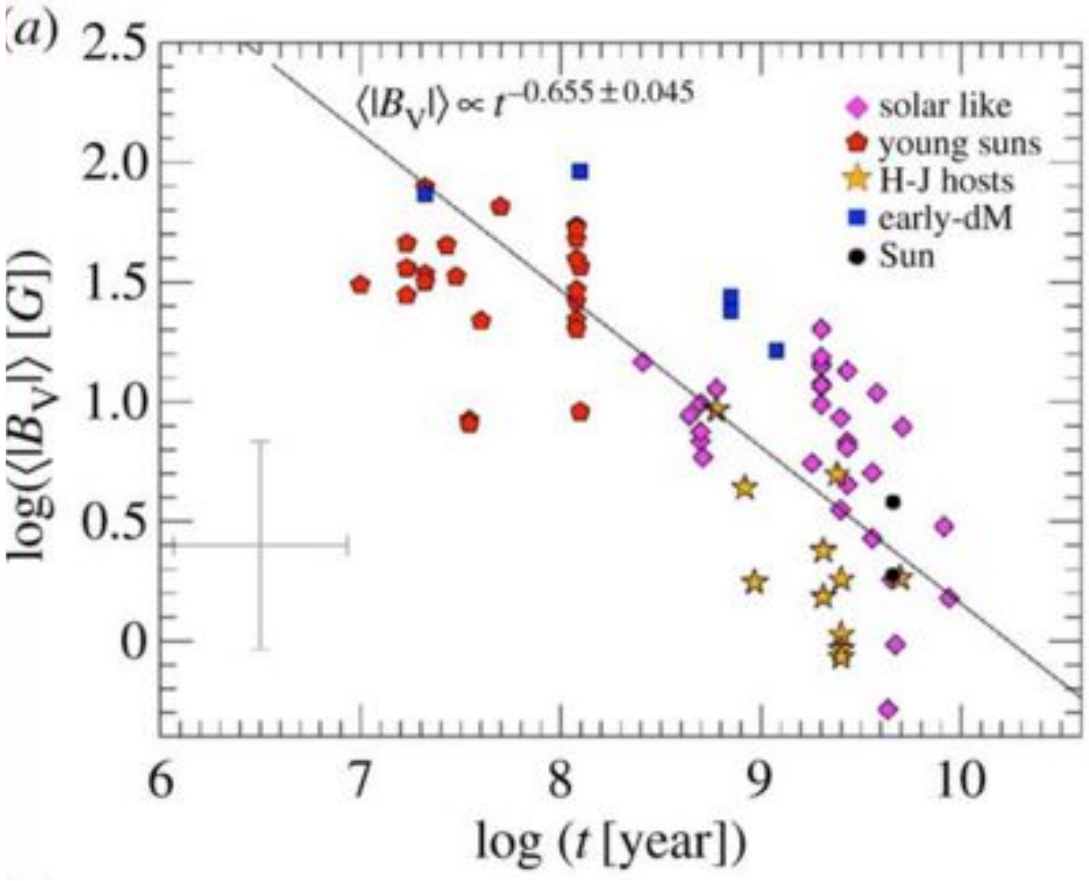
Barnes 2007

UNIVERSITY OF BIRMINGHAM

Today's top tip:

You can go a long way in astronomy by plotting things against other things!

Even better, plot some things in a different color!



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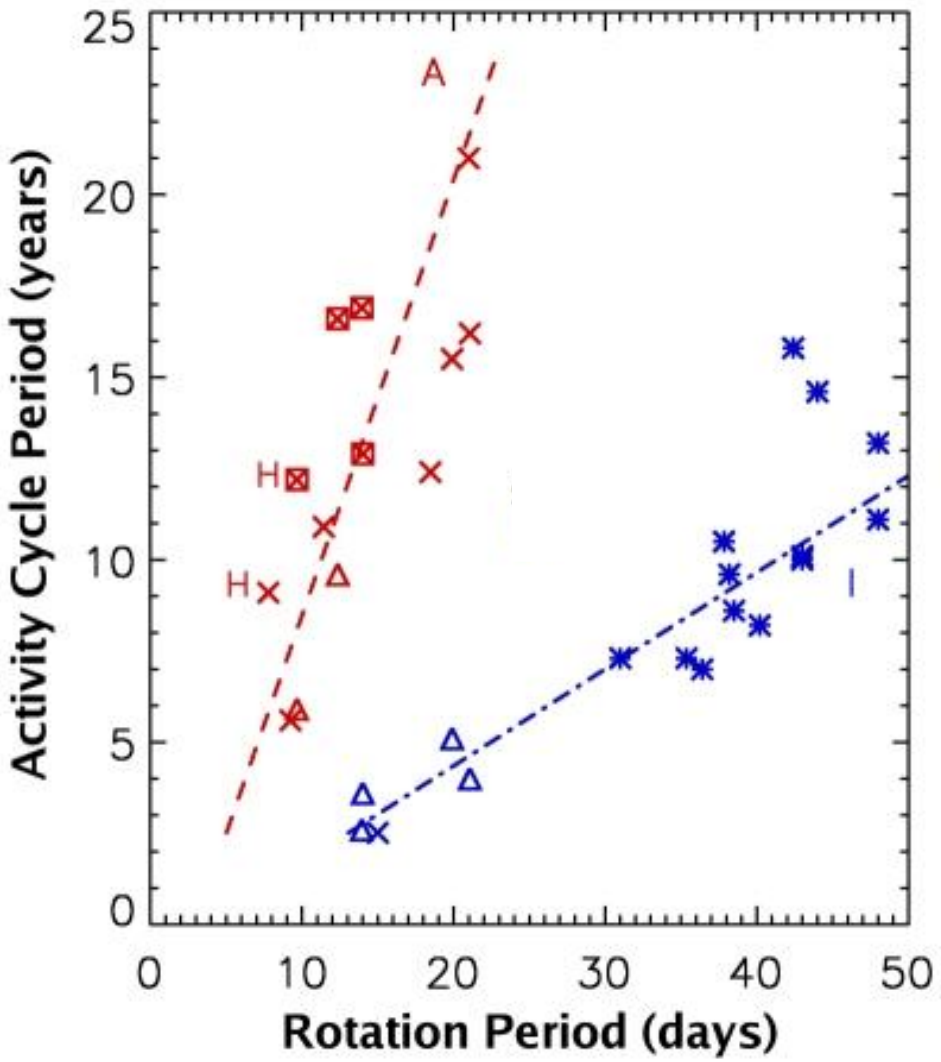
Vidotto 2011

Today's top tip:

You can go a long way in astronomy by plotting things against other things!

Even better, plot some things in a different color!

Even better, find two populations!



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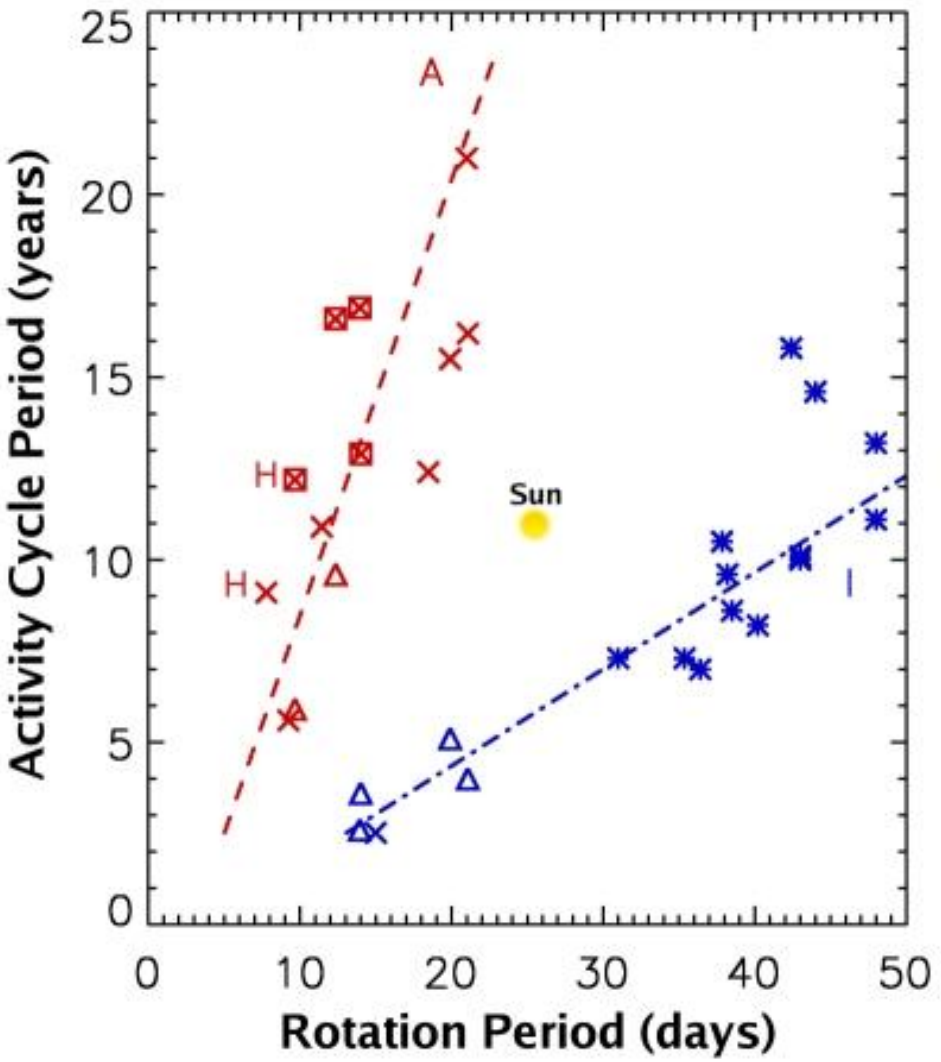
Bohm Vitense 2007



Is the Sun a typical star?

Bohm Vitense 2007

Today's top tip:

You can go a long way in astronomy by plotting things against other things!

Even better - use theory!

Even better, plot some things in a different color!

Even better, use shapes!

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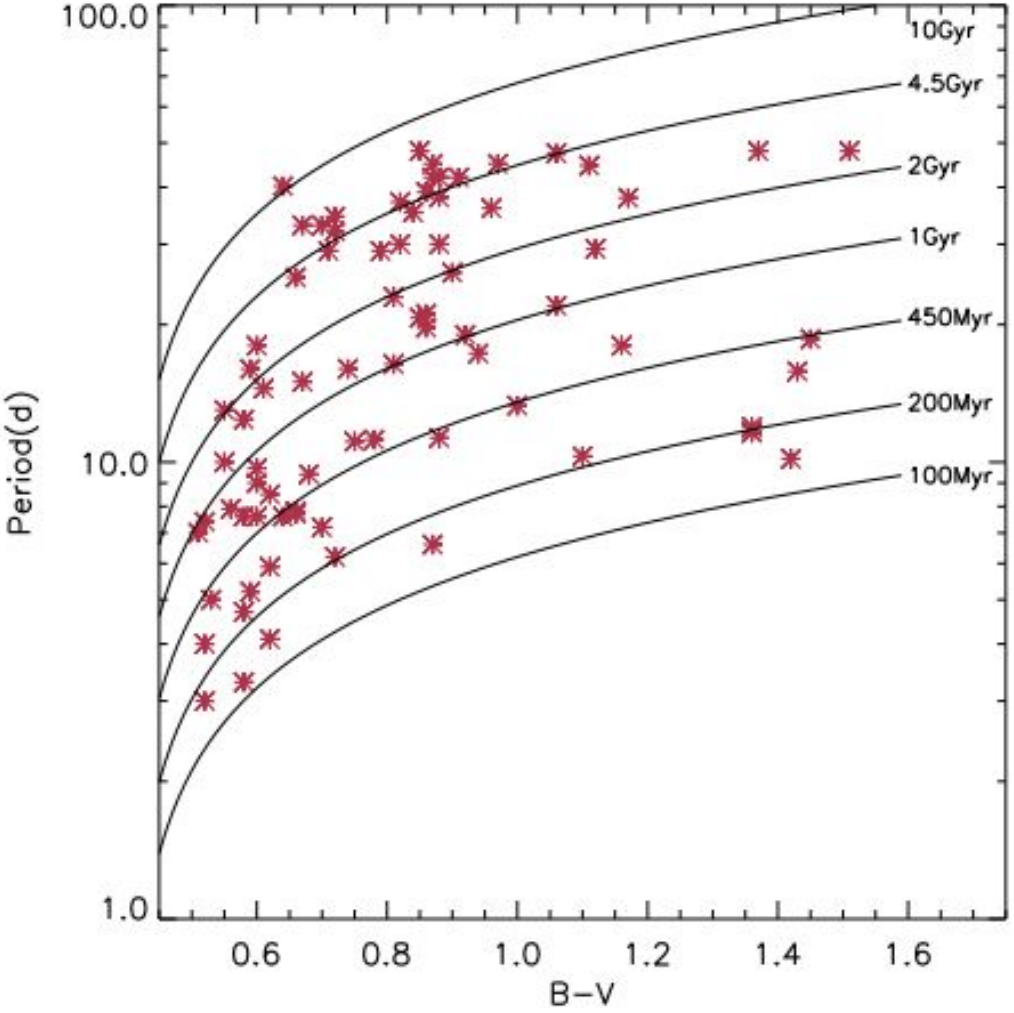

Barnes 2007

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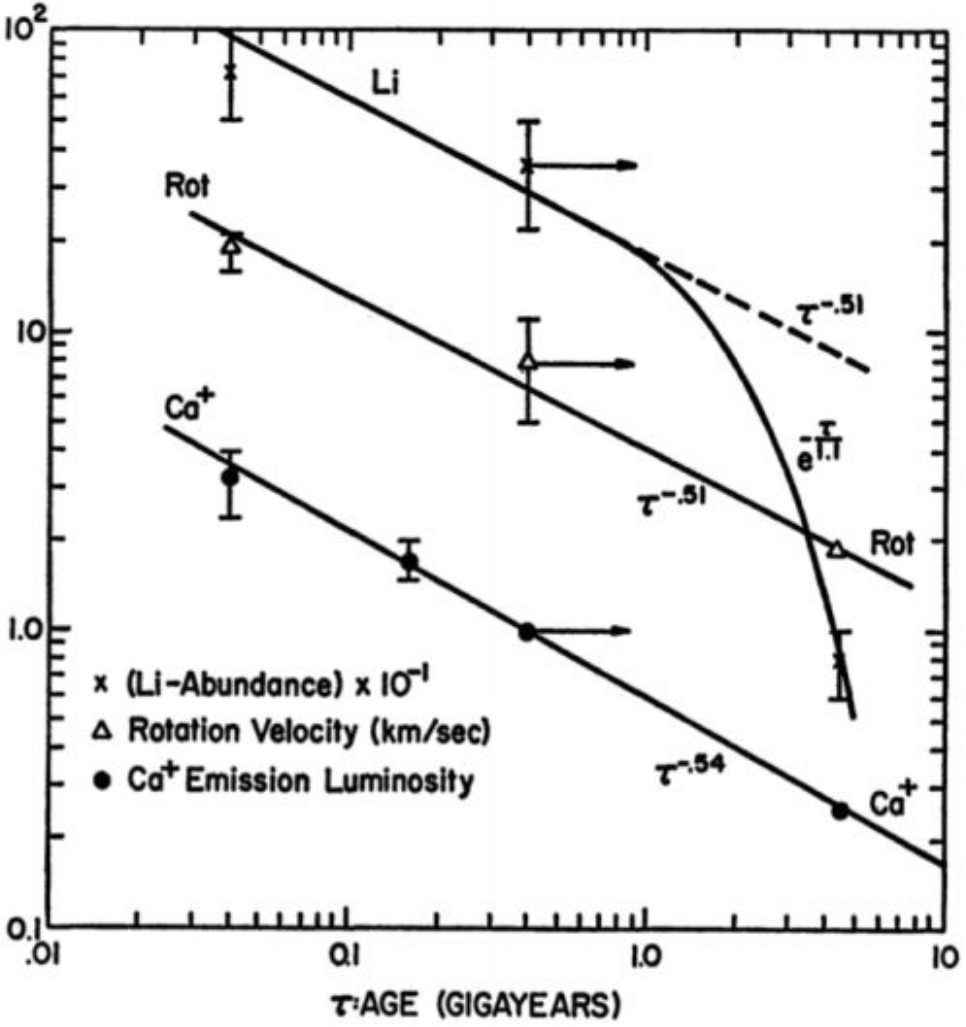
Stellar activity

Magnetic field

Empirical relations

Spin down



Skumanich 1972

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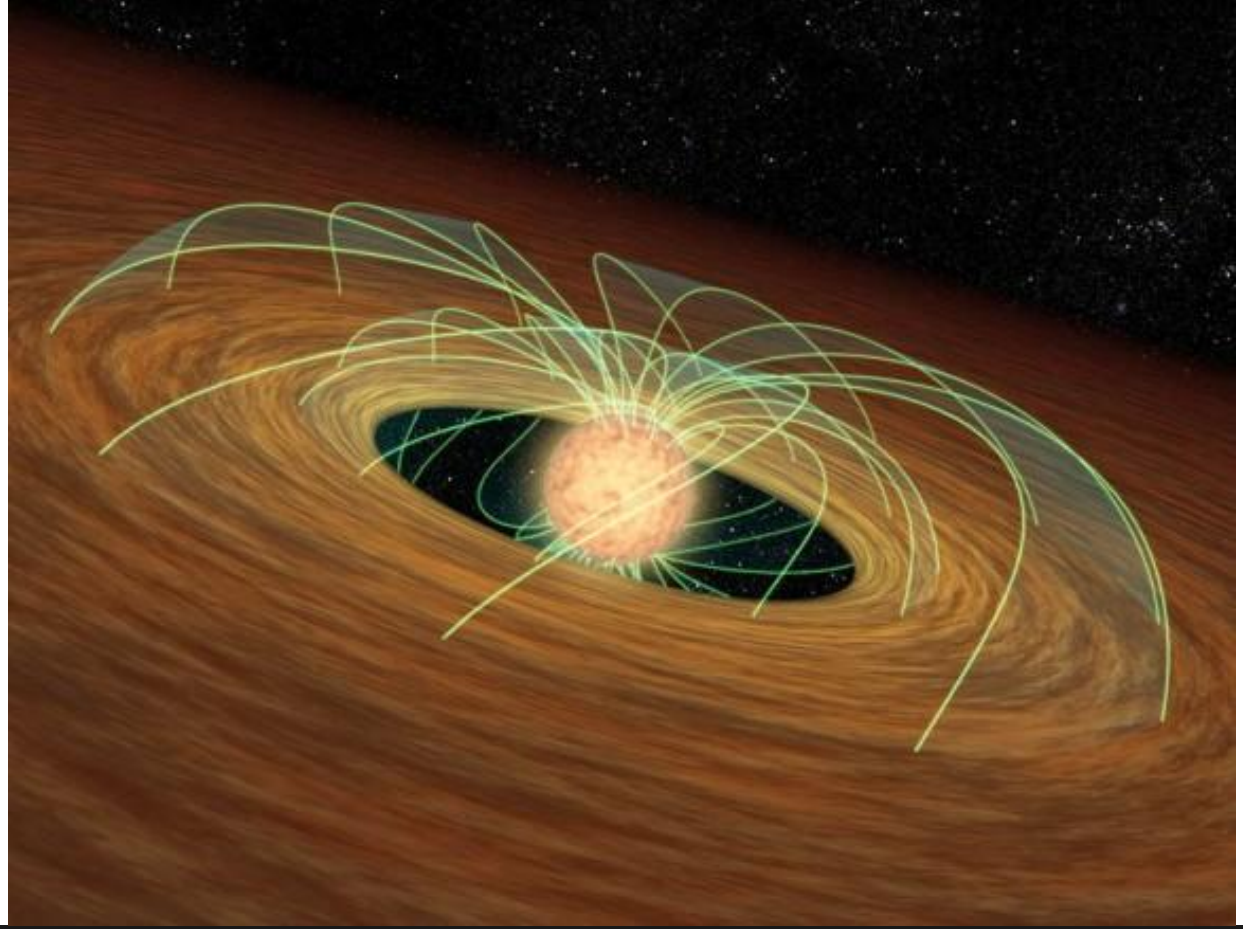

Credit: NASA/JPL-Caltech/R. Hurt (SSC).

Magnetic braking

Conservation of angular momentum: $$\frac{\partial J(t)}{\partial t} = 0$$

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Angular momentum = Moment of Inertia * Angular Velocity

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Moment of inertia: $$I = \int_Q r^2 \mathrm{d}m$$ **Where Q is total mass.**

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Angular momentum = Moment of Inertia * Angular Velocity

Moment of inertia: $$I = \int_Q r^2 \mathrm{d}m$$

Where Q is total mass.

Example: Main Sequence to Red Giant

$$\frac{dJ}{dt} = \frac{2}{3}\frac{dM}{dt} R^2 \Omega \left[\left(\frac{r_A}{R}\right)_{\text{dipole}}\right]^1$$

$$\frac{dJ}{dt} = \frac{2}{3}\frac{dM}{dt} R^2 \Omega \left[\left(\frac{r_A}{R}\right)_{\text{dipole}}\right]^1$$

Exponent defined by the field topology.

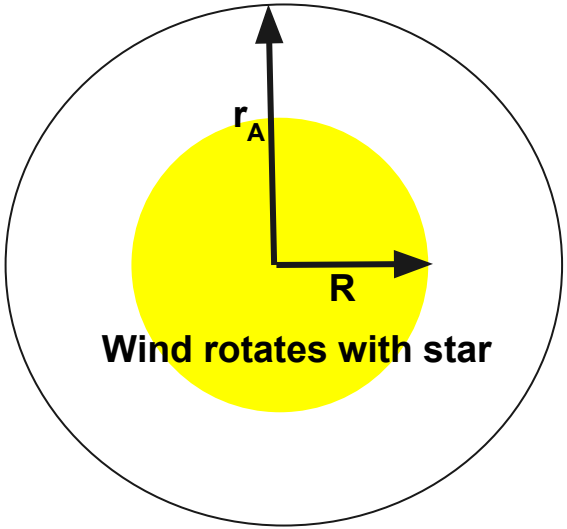
Angular momentum loss

Mass loss

Rotation

Wind co-rotates with star untill mass passes through point r_A

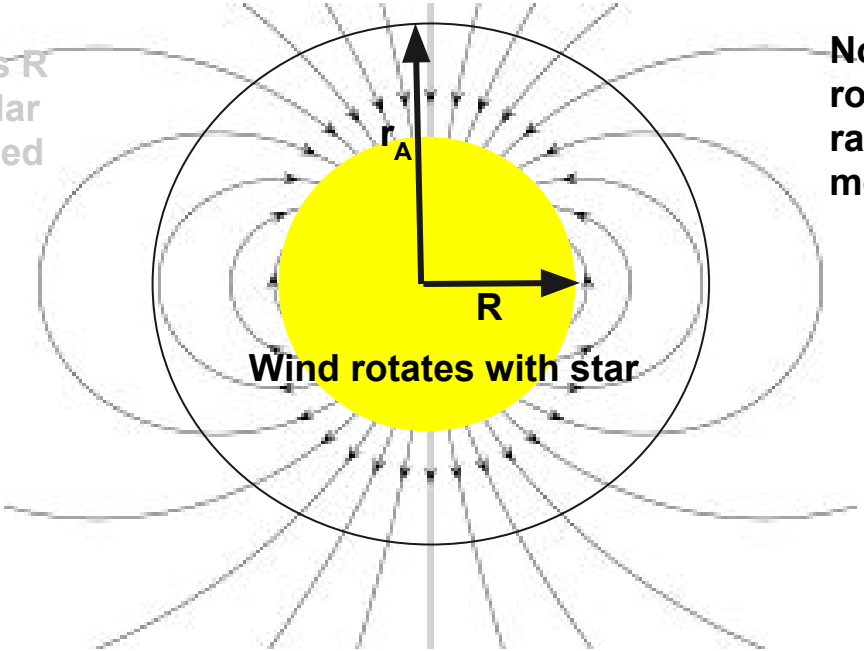
$$\frac{dJ}{dt} = \frac{2}{3}\frac{dM}{dt} R^2 \Omega \left[\left(\frac{r_A}{R}\right)_{\text{dipole}}\right]^1$$



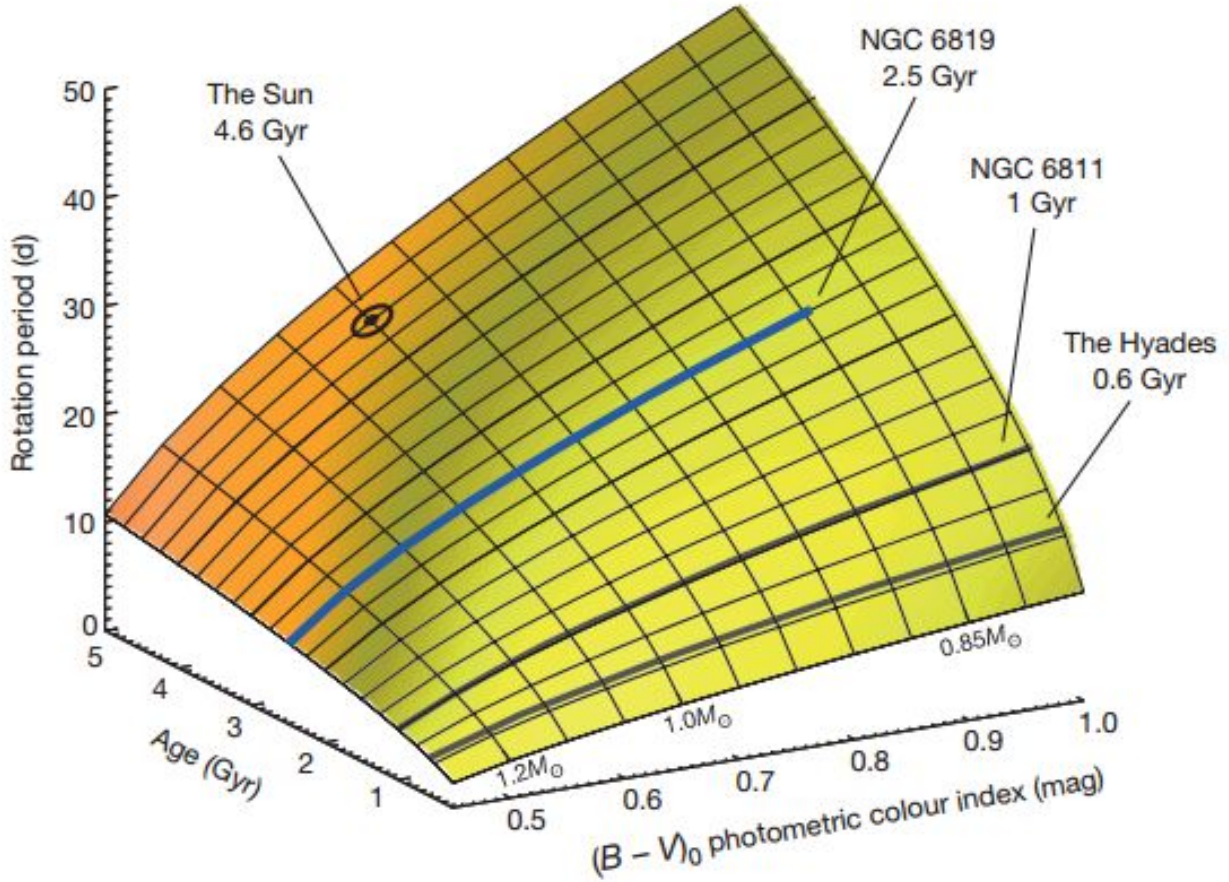
Wind slows down as R increases and angular momentum conserved

$$\frac{dJ}{dt} = \frac{2}{3}\frac{dM}{dt} R^2 \Omega \left[\left(\frac{r_A}{R}\right)_{\text{dipole}}\right]^1$$

Wind slows down as R increases and angular momentum conserved



Now couple wind to the stellar rotation via the magnetic field - rapid transfer of angular momentum.



Meibom + 2015

Gyrochronology

The Solar-Stellar Connection

Part 4 - The Solar-Stellar Connection

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Guy R. Davies

Context - Solar activity

Gyrochronology

Measurement - rotation

Measurement - age

Results

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Solar physics ...

“If the Sun did not have a magnetic field, it would be as uninteresting a star as most astronomers believe it to be.”

R. B. Leighton
(of Feynman Leighton Sands)

Context - Solar activity

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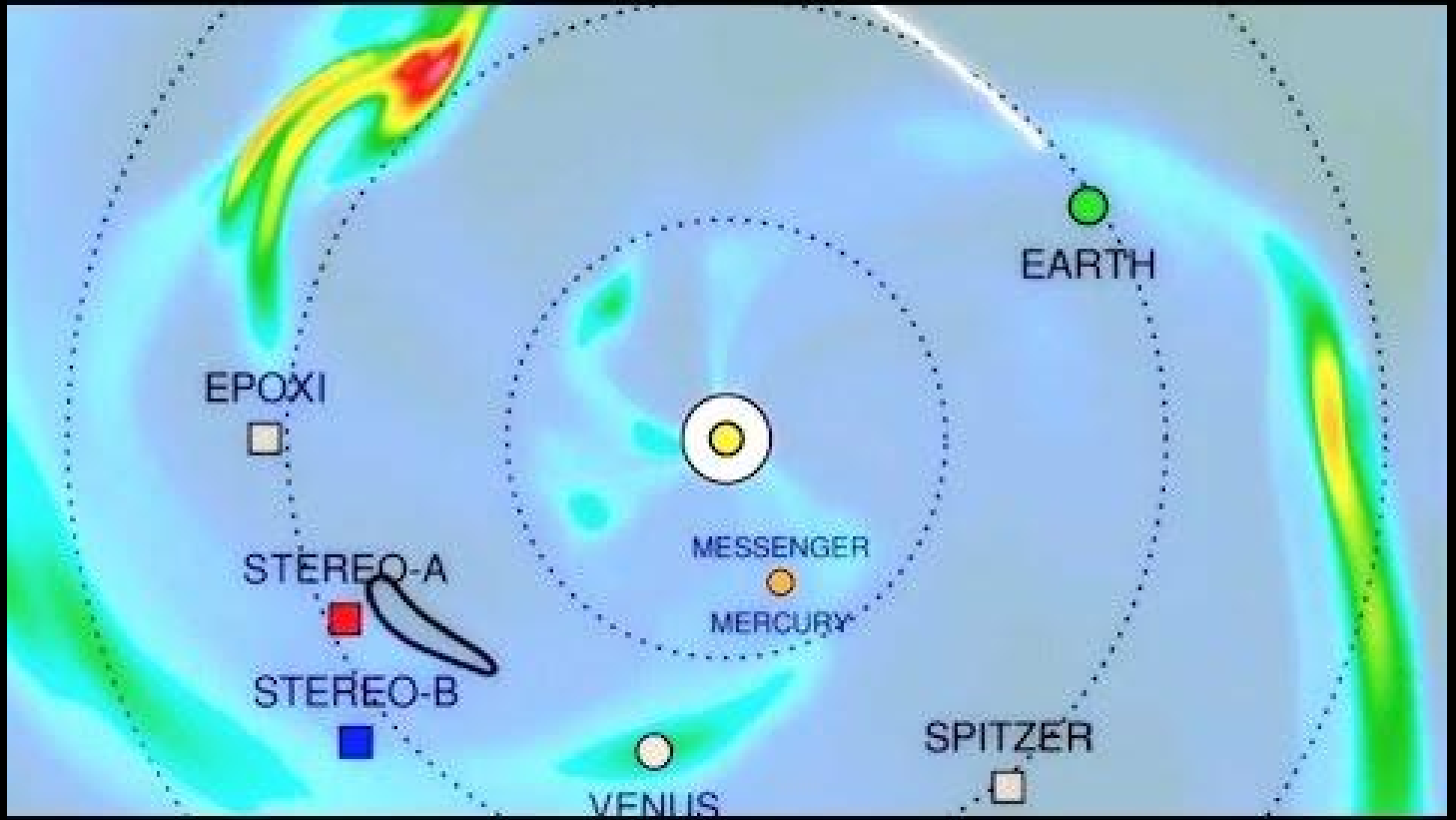
EARTH
EPOXI
MESSENGER
MERCURY
STEREO-A
STEREO-B
SPITZER
VENUS

Context - Solar activity

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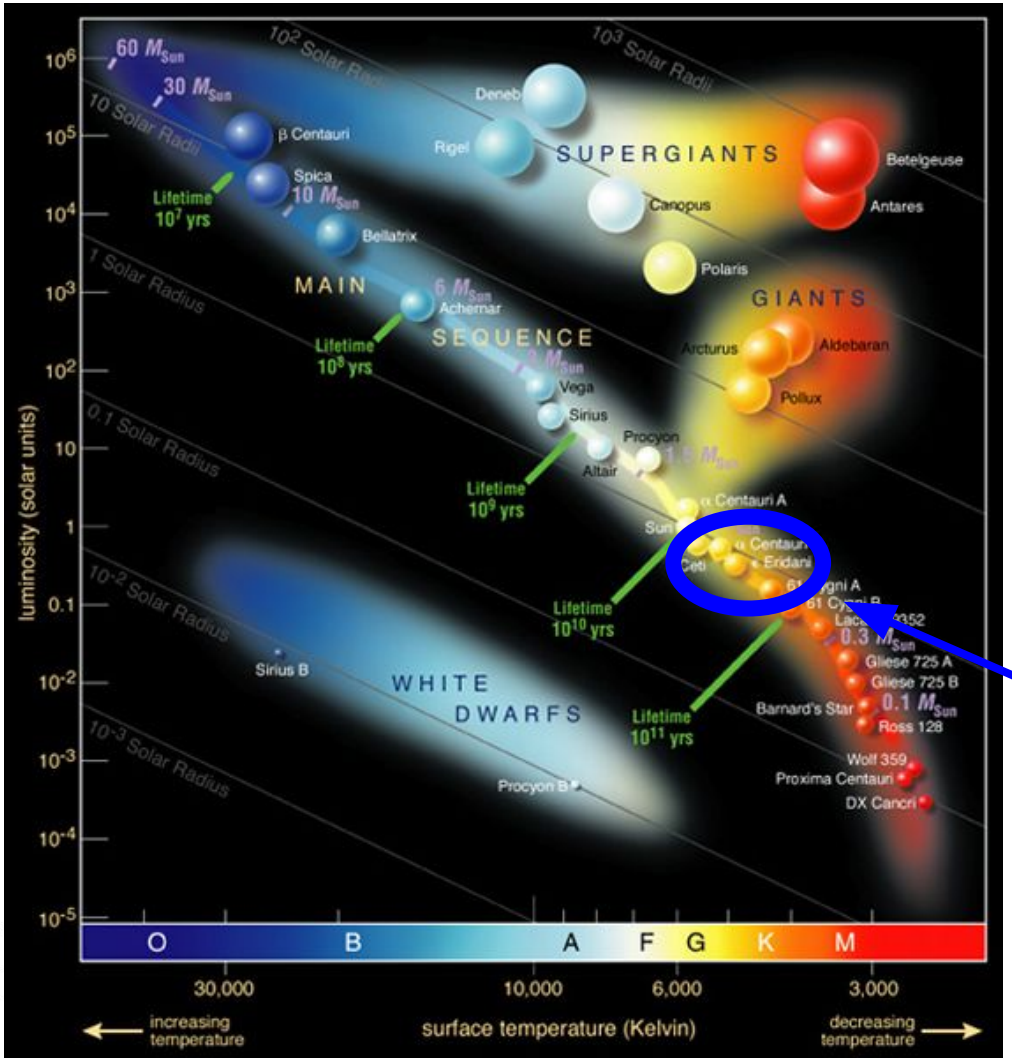

Sun-like stars!

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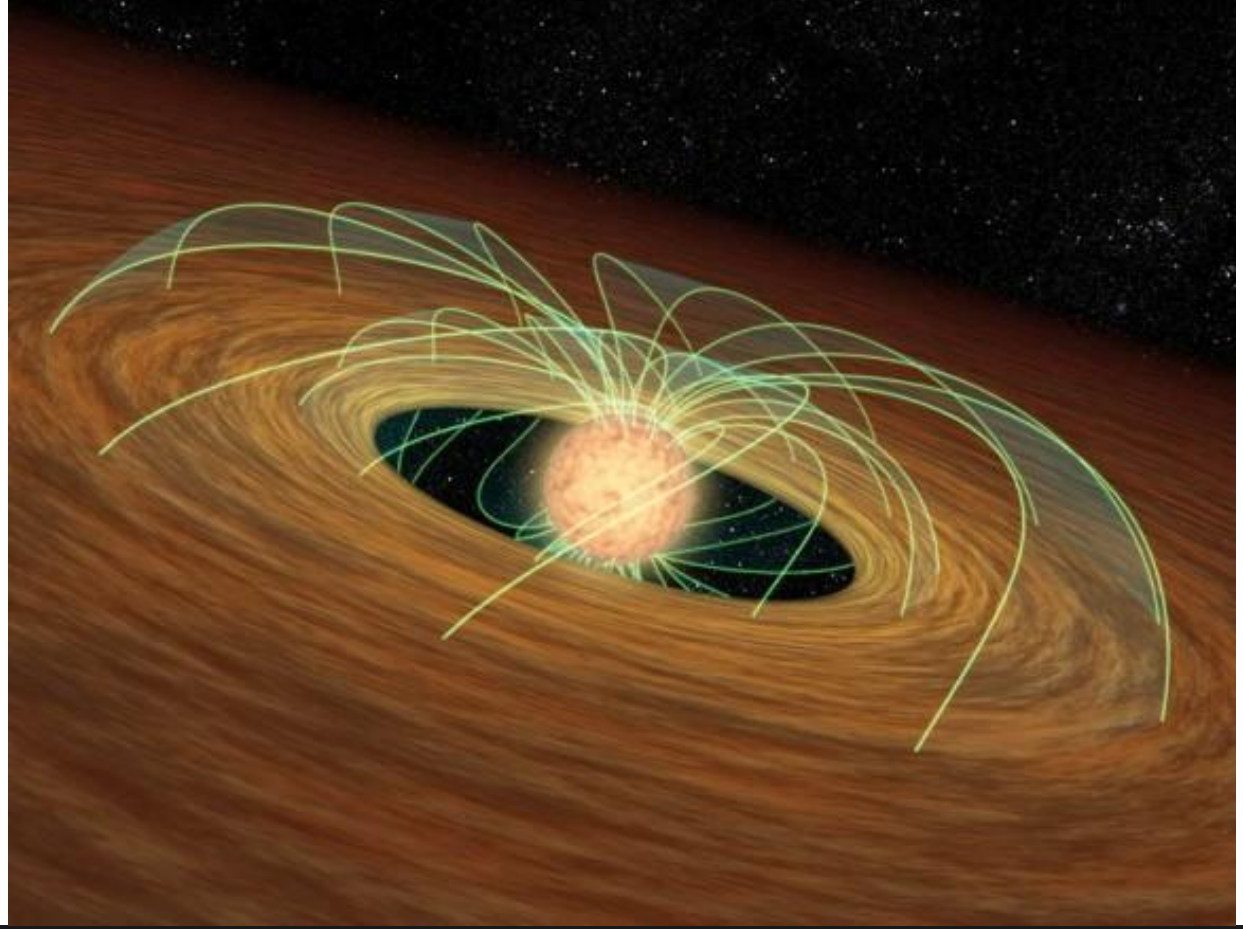
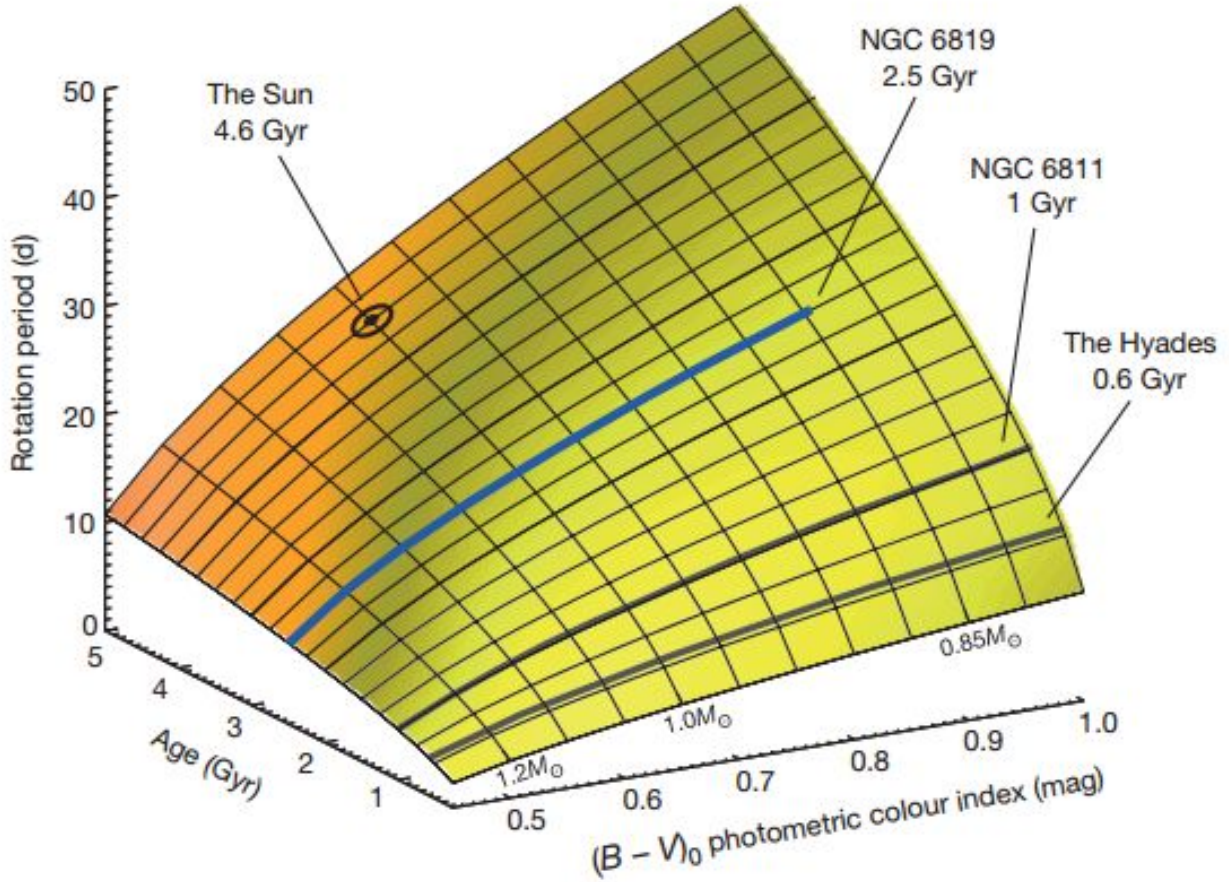


Credit: NASA/JPL-Caltech/R. Hurt (SSC).

Magnetic braking

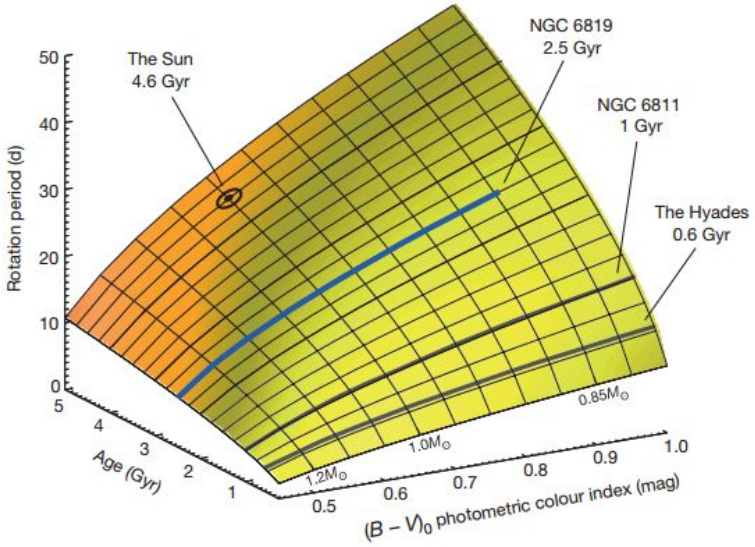


Meibom + 2015

Gyrochronology

A spin-down clock for cool stars from observations of a 2.5-billion-year-old cluster

Søren Meibom[1], Sydney A. Barnes[2], Imants Platais[3], Ronald L. Gilliland[4], David W. Latham[1], Robert D. Mathieu[5]



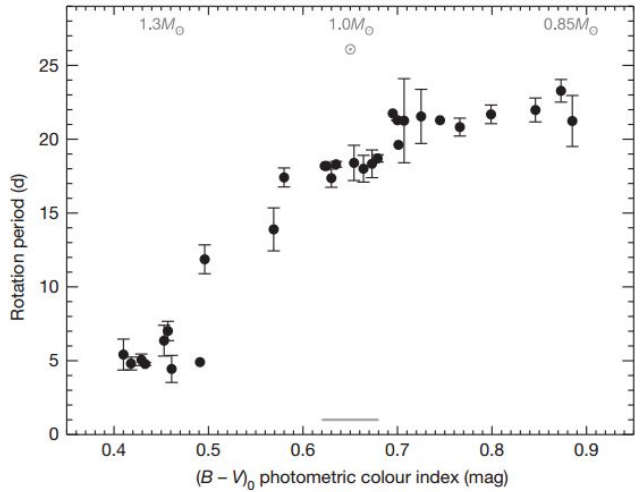


Figure 2 | The colour–period diagram for NGC 6819. The distribution of rotation periods as a function of de-reddened colour index $(B\text{-}V)_0$ for 30 cool photometric, proper-motion, and radial-velocity members of the 2.5 Gyr open star cluster NGC 6819. The measurements define a tight dependence of rotation period on colour (mass). The symbols and error bars respectively indicate the means and standard deviations of multiple measurements for the same star when available. The location of the Sun (4.56 Gyr) in the diagram is marked with a grey solar symbol. Stellar masses in solar units are given along the top horizontal axis at the corresponding colours. Solar-mass stars with $(B\text{-}V)_0$ between 0.62 and 0.68 mag (interval marked by grey line near the bottom horizontal axis) have a mean period of 18.2 d with a standard deviation of 0.4 d.

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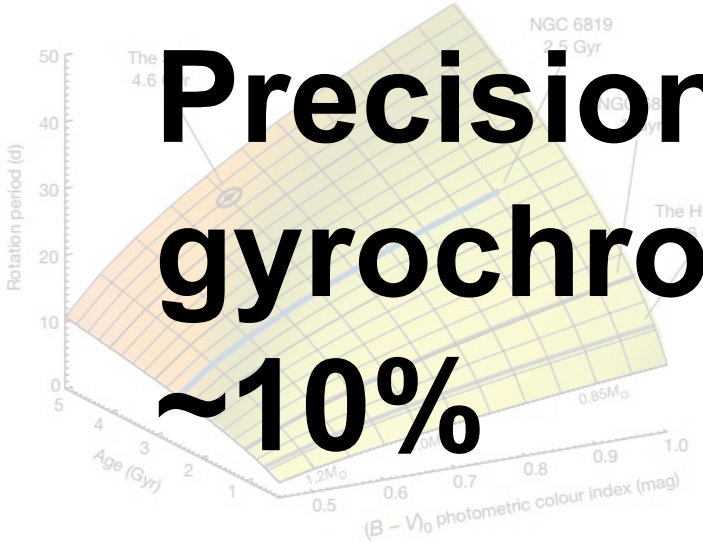
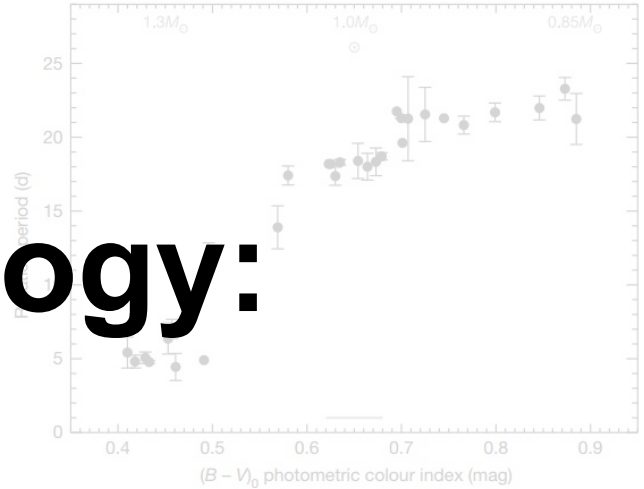


Precision of gyrochronology: ~10%



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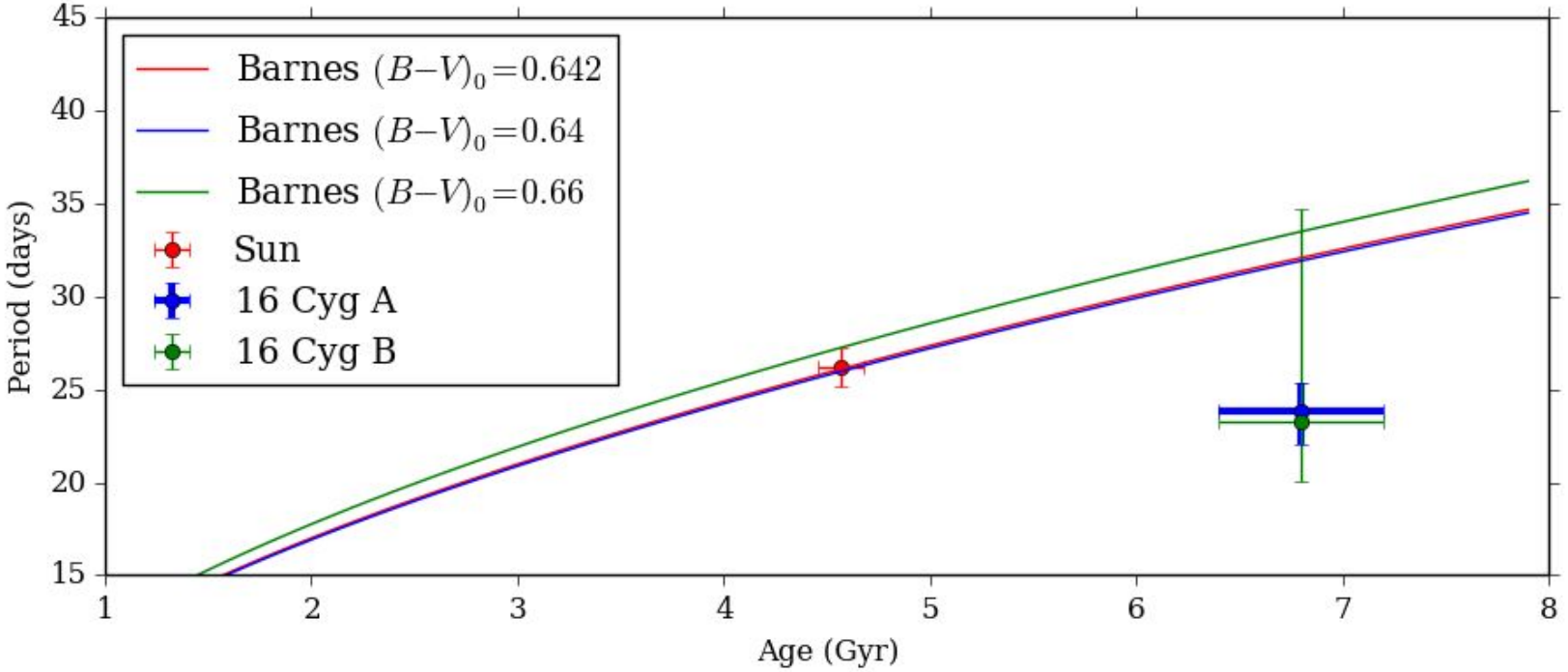

Davies + 2015

Gyrochronology on old stars

Calibrating Gyrochronology using Kepler Asteroseismic targets

Ruth Angus,[1⋆] Suzanne Aigrain,[1] Daniel Foreman-Mackey,[2] and Amy McQuillan[3]
[1] *Department of Physics, University of Oxford, UK*
[2] *Centre for Cosmology and Particle Physics, New York University, New York, NY, USA*
[3] *School of Physics and Astronomy, Raymond and Beverly Sackler, Faculty of Exact Sciences, Tel Aviv University, 69978, Tel Aviv, Israel*

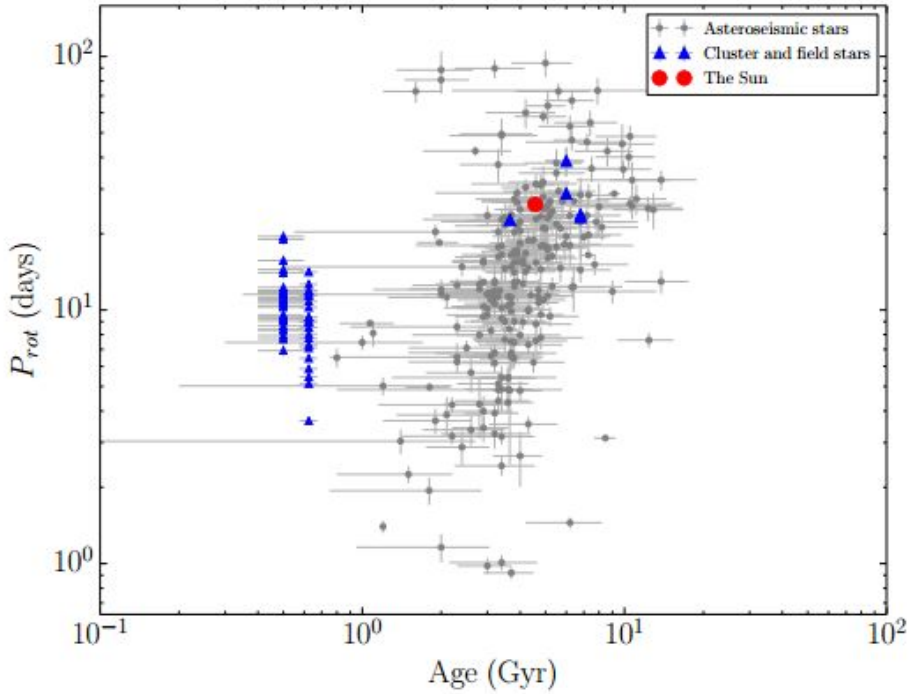

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Figure 1. Photometric rotation period vs age for 310 *Kepler* targets (grey circles) plus cluster and field stars (blue triangles). The Sun is shown as a red circle.

Calibrating Gyrochronology using Kepler Asteroseismic targets

Ruth Angus,[1⋆] Suzanne Aigrain,[1] Daniel Foreman-Mackey,[2] and Amy McQuillan[3]
[1] *Department of Physics, University of Oxford, UK*
[2] *Centre for Cosmology and Particle Physics, New York University, New York, NY, USA*
[3] *School of Physics and Astronomy, Raymond and Beverly Sackler, Faculty of Exact Sciences, Tel Aviv University, 69978, Tel Aviv, Israel*

Markov Chain Monte Carlo methods were used to explore the posterior probability distribution functions of the gyrochronology parameters and we carefully checked the effects of leaving out parts of our sample, leading us to find that no single relation beween rotation period, colour and age can adequately describe all the subsets of our data. The *Kepler* asteroseismic stars, cluster stars and local field stars are [illegible] but described by the [illegible] relation. The *Kepler* asteroseismic [illegible] clusters show unexpected deviations from the predicted behaviour, providing concerns for the overall reliability of gyrochro[illegible]

“leading us to find that no single relation between rotation period, colour and age can adequately describe all the subsets of our data”

Precision of gyrochronology: ?

Figure 1. Photometric rotation period vs age for 310 *Kepler* targets (grey circles) plus cluster and field stars (blue triangles). The Sun is shown as a red circle.

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Context - Solar activity

Gyrochronology

Measurement - rotation

Measurement - age

Results

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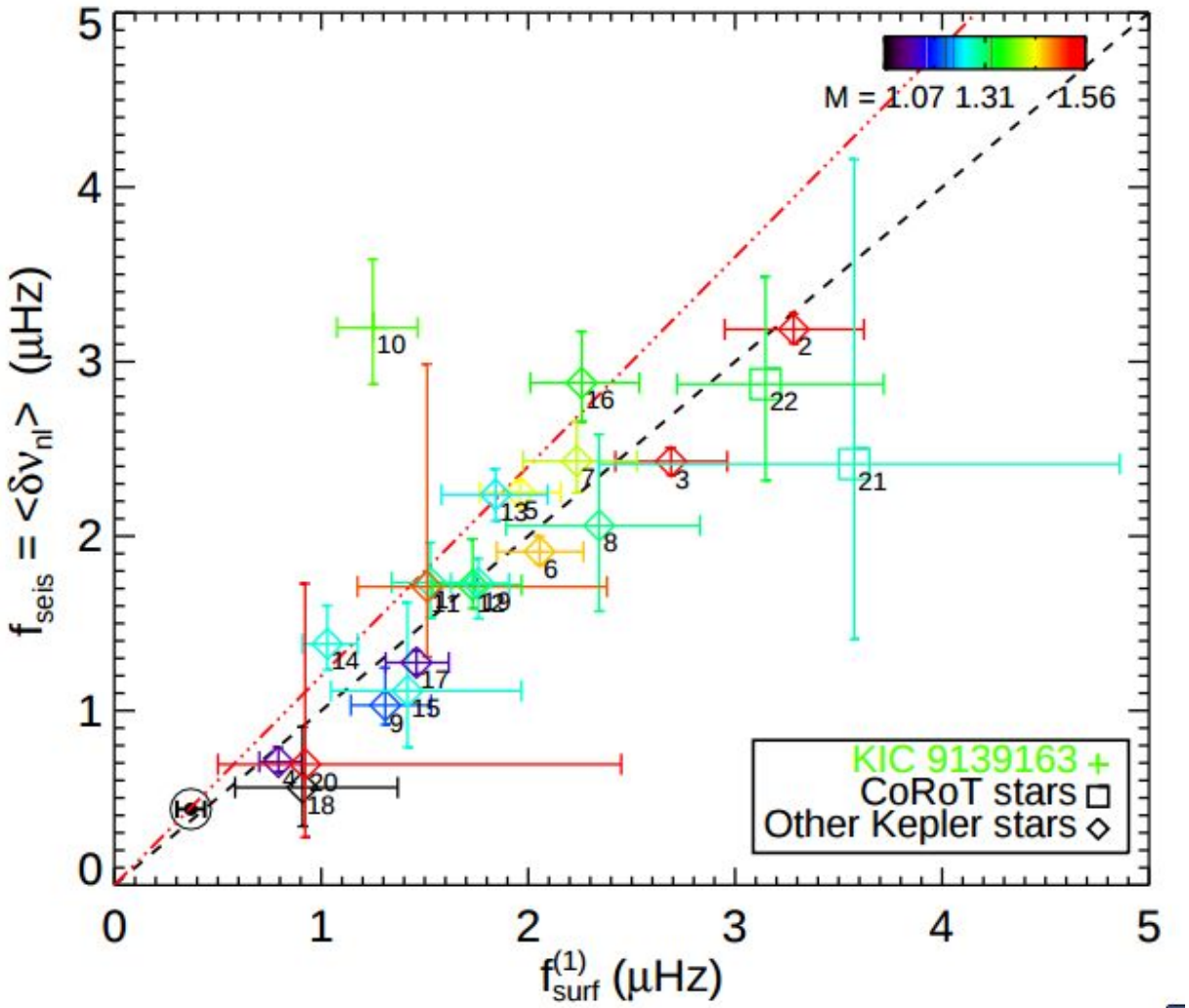

Benomar+ 2015

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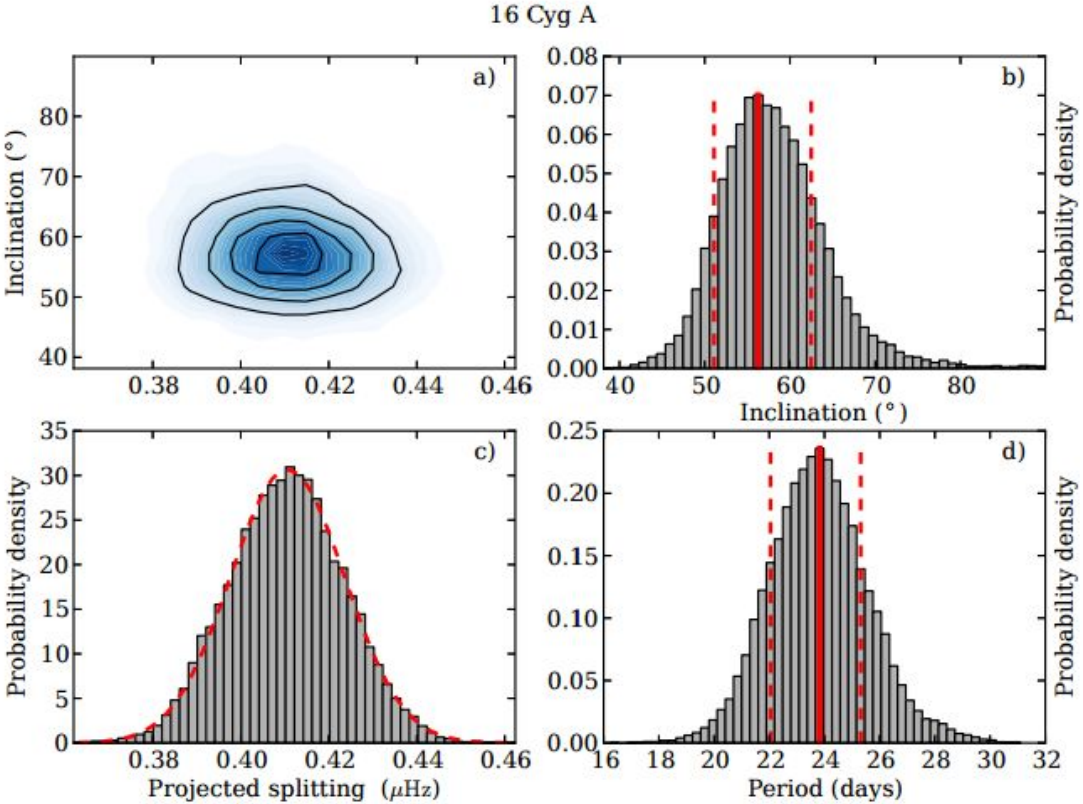
Asteroseismic inference on rotation, gyrochronology and planetary system dynamics of 16 Cygni

G.R. Davies[1,2,3], W.J. Chaplin[2,3], W.M. Farr[2], R.A. García[1], M.N. Lund[3], S. Mathis[1], T.S. Metcalfe[4,3], T. Appourchaux[5], S. Basu[6], O. Benomar[7], T.L. Campante[2], T. Ceillier[1], Y. Elsworth[2], R. Handberg[2,3], D. Salabert[1], D. Stello[8,3]



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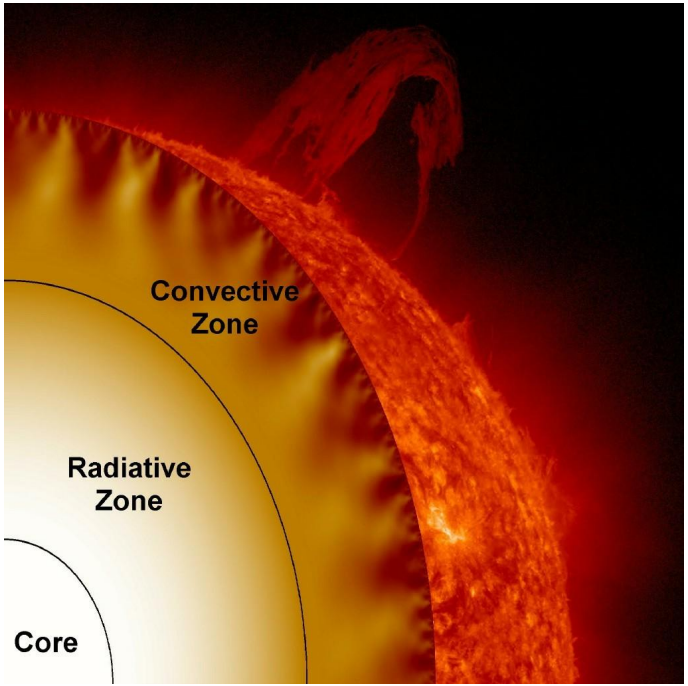

Astrophysics: The inner lives of red giants

Travis S. Metcalfe

Nature **471**, 580–581 (31 March 2011) | doi:10.1038/471580a

“Just as in Hollywood, the age of a star is not always obvious if you look only at the surface”

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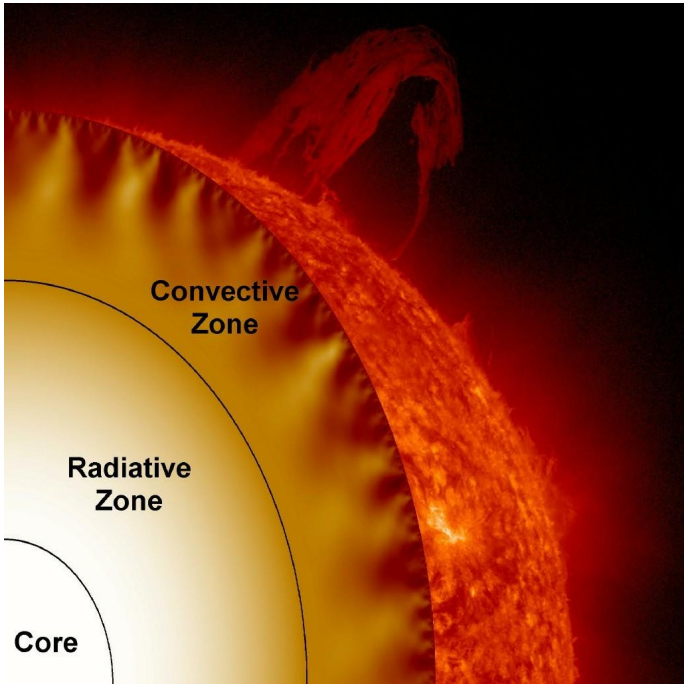

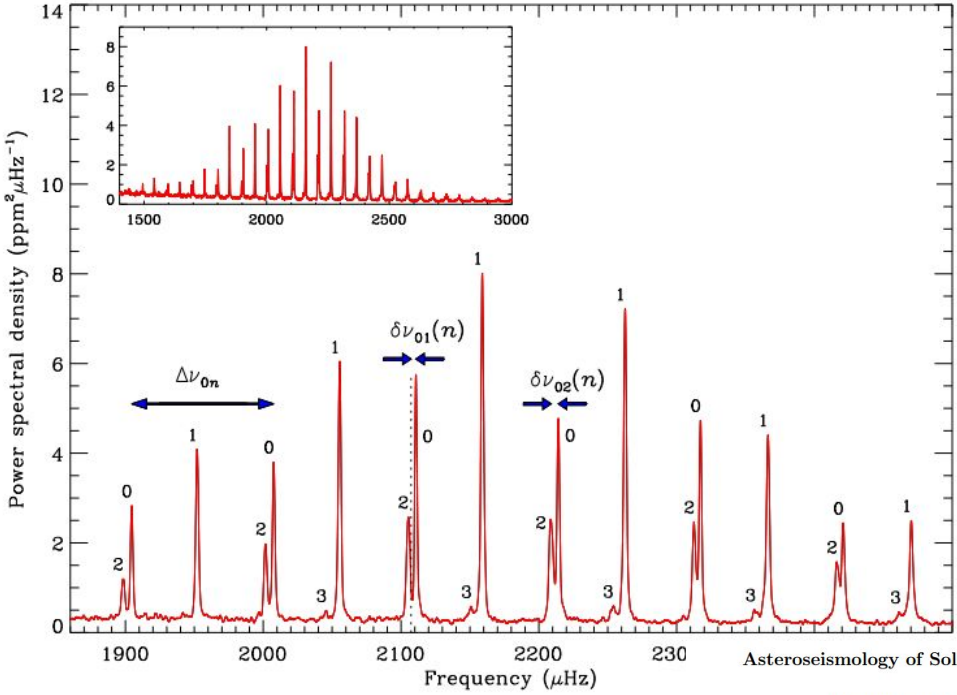

Asteroseismology of Solar-Type and Red-Giant Stars

William J. Chaplin, Andrea Miglio

School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

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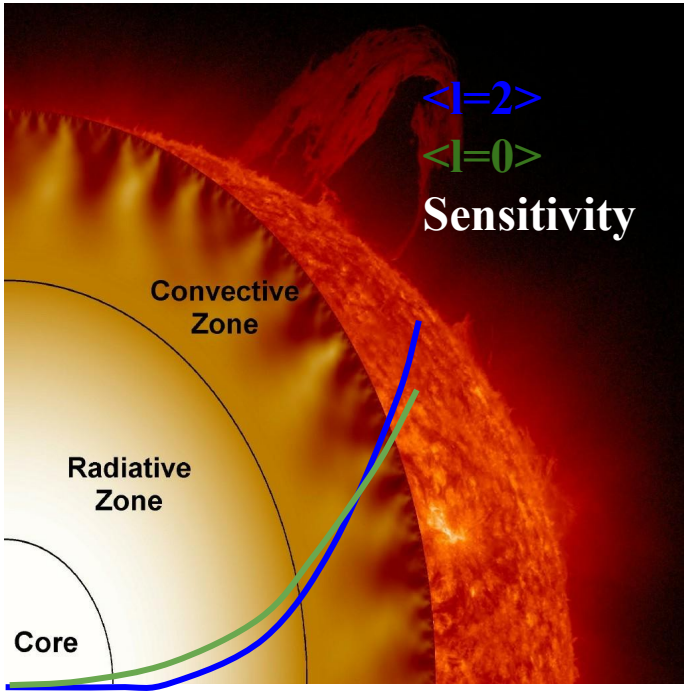

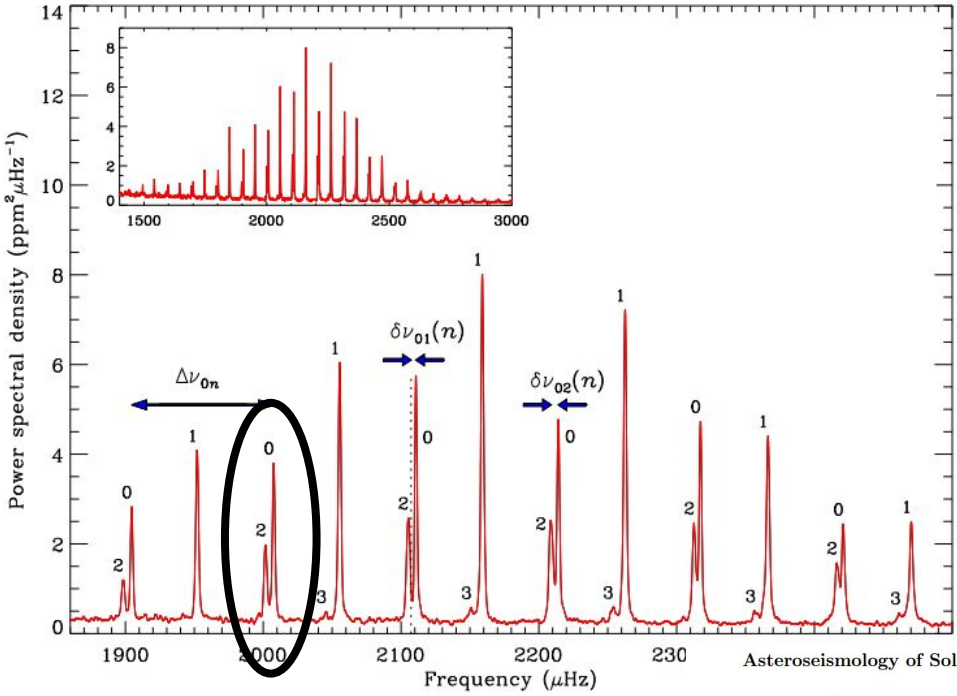

Asteroseismology of Solar-Type and Red-Giant Stars

William J. Chaplin, Andrea Miglio
School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

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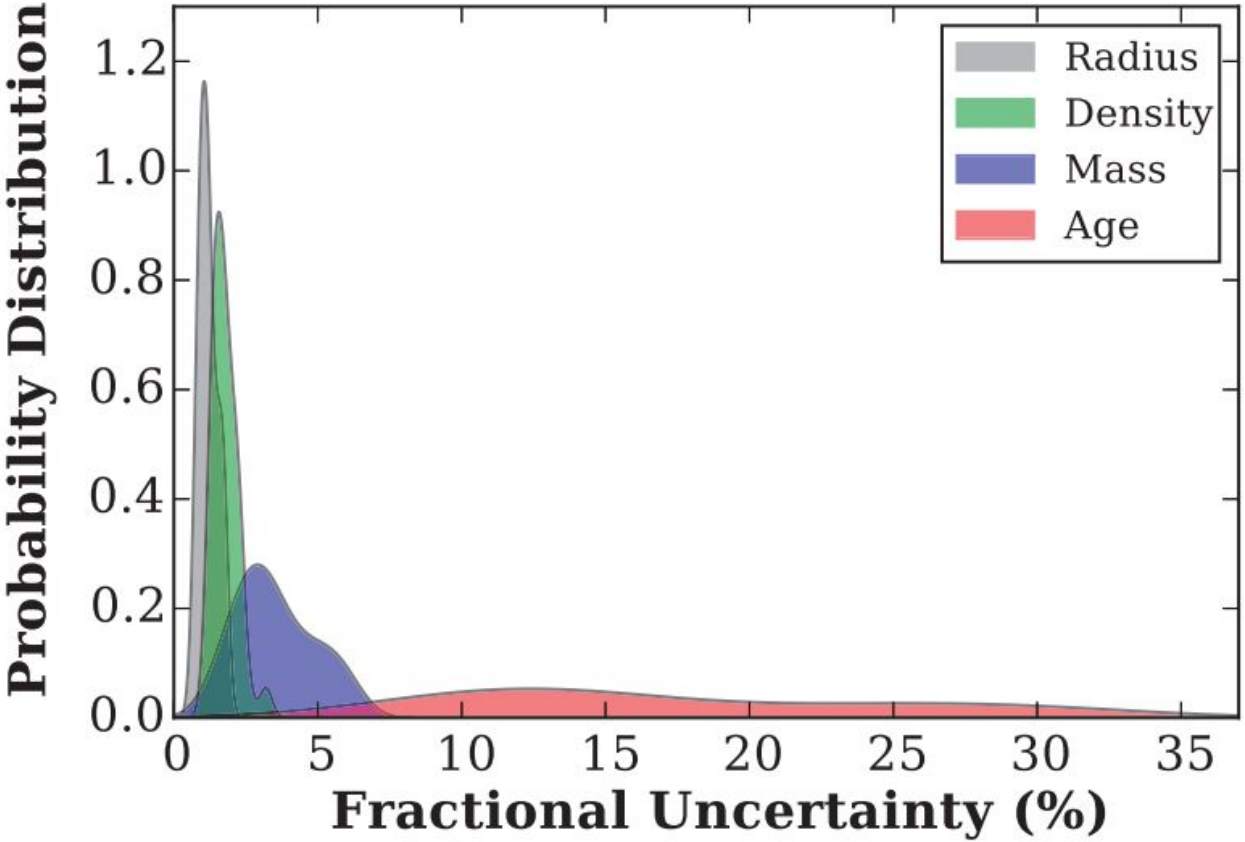

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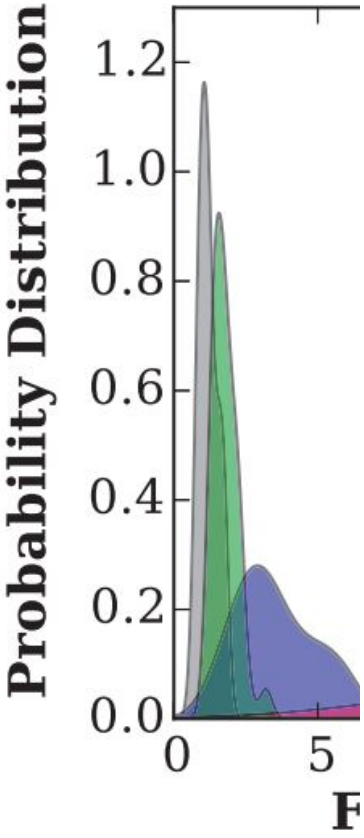
Silva Aguirre, Davies+ 2015
Davies, Silva Aguirre+ 2016



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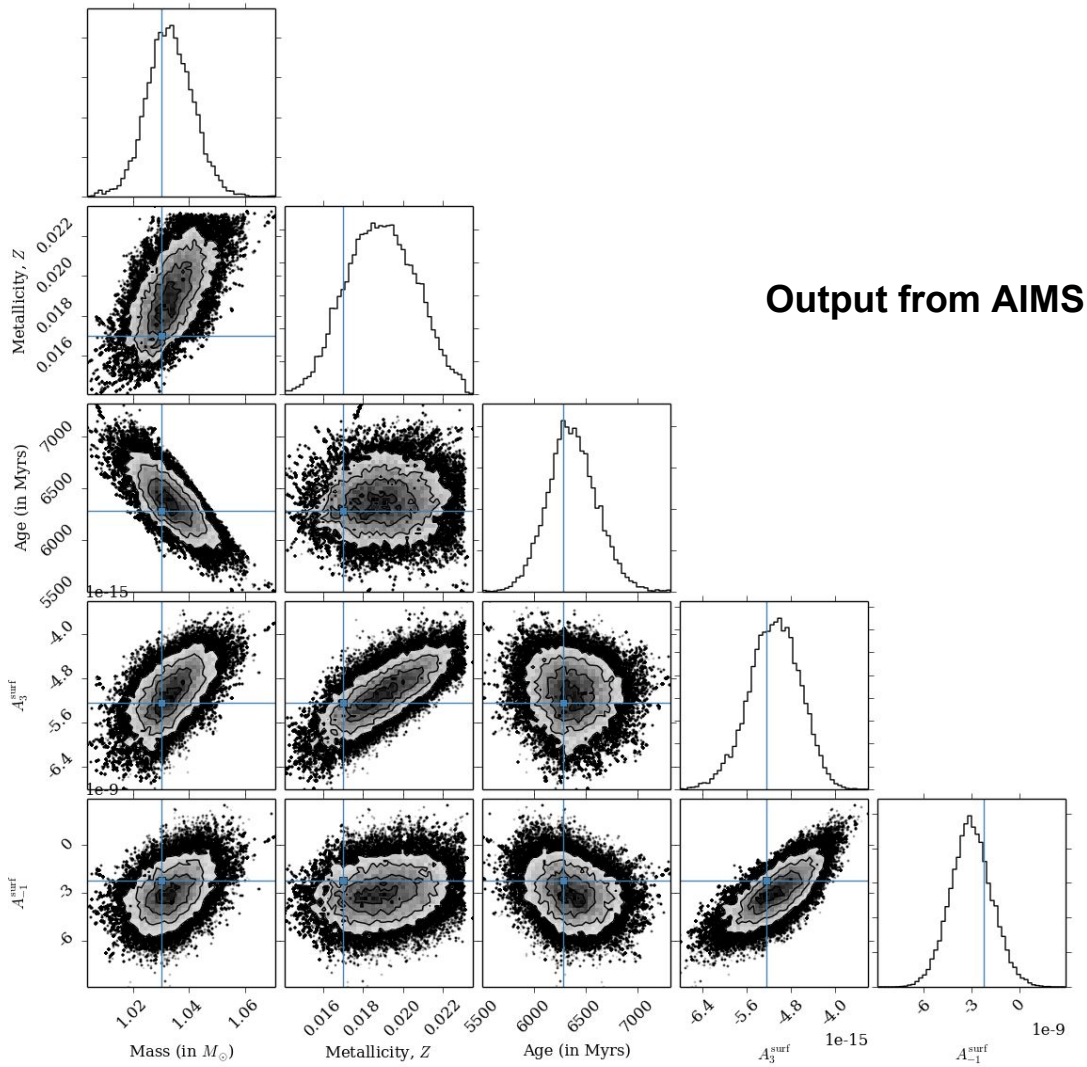
Output from AIMS



Context - Solar activity

Gyrochronology

Measurement - rotation

Measurement - age

Results

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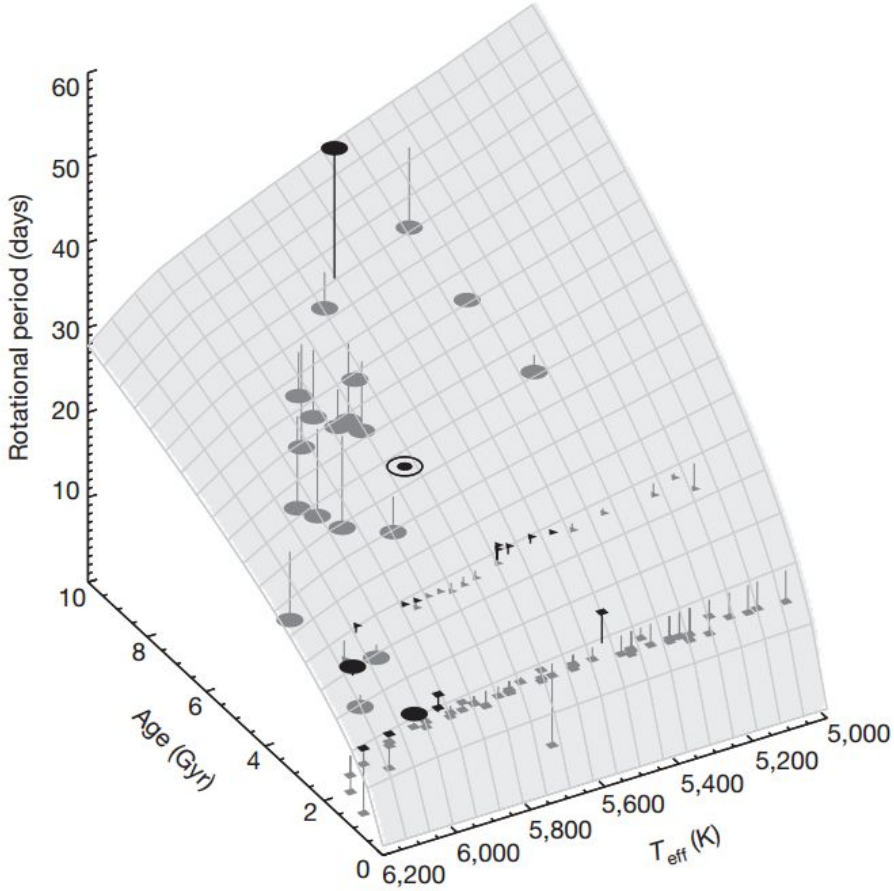

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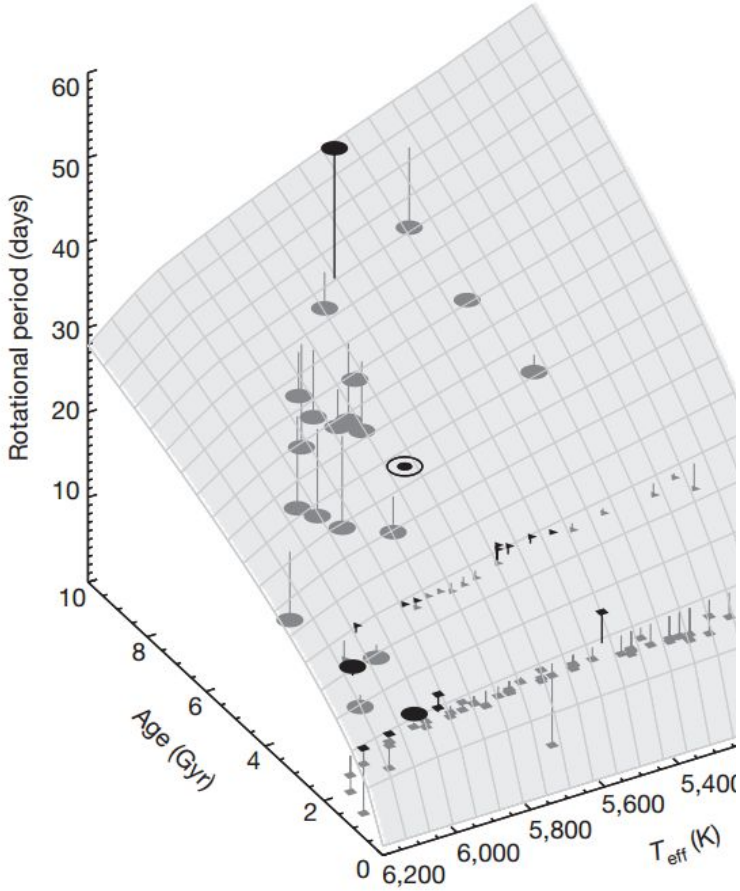
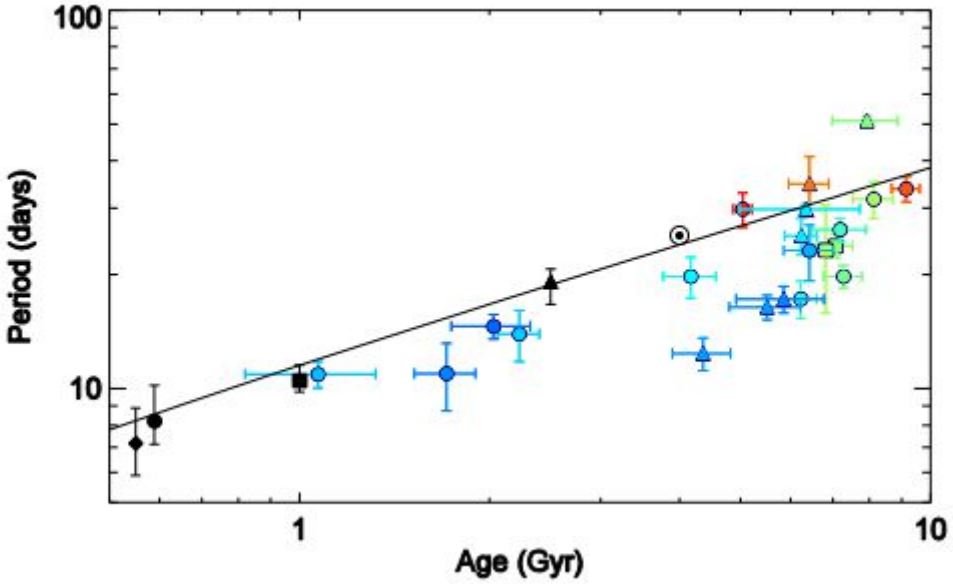
van Saders, Davies + Nature 2016





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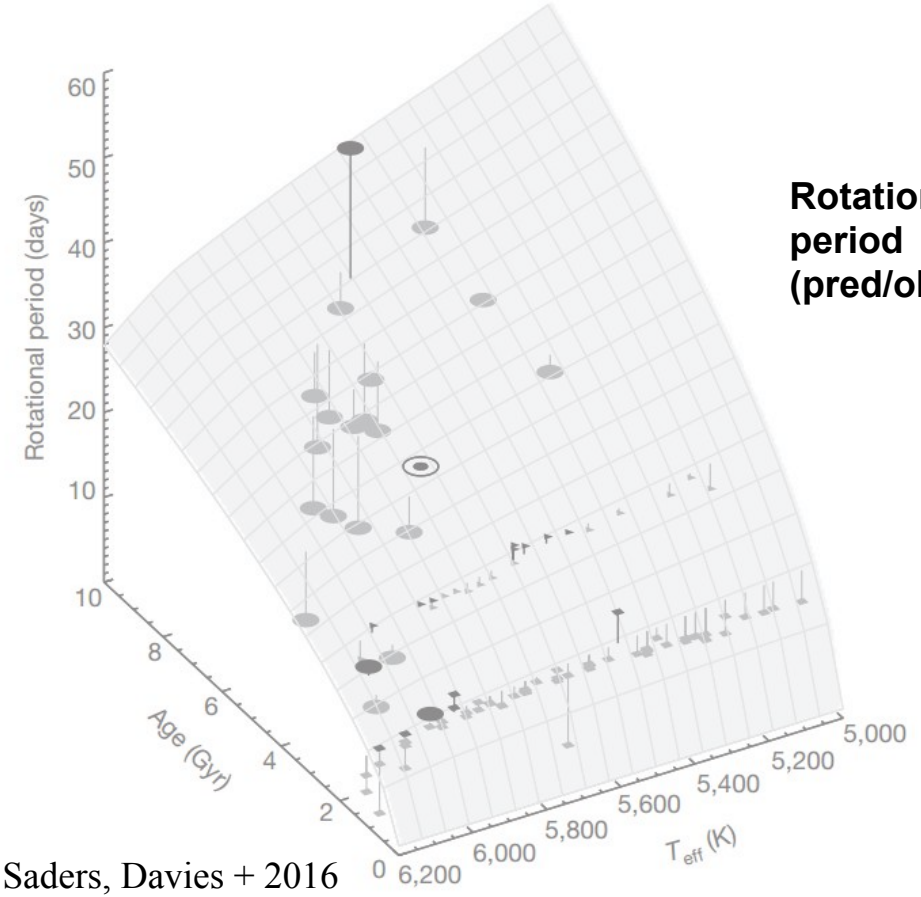
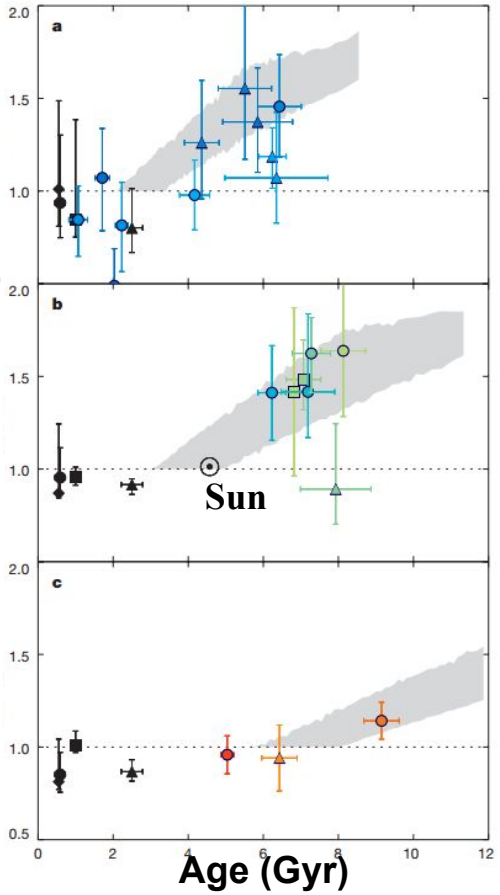
van Saders, Davies + Nature 2016



van Saders, Davies + 2016

Rotation period (pred/obs)



Stellar temperature or mass

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Rossby Number (Ro)

Definition: Period of rotation / convective turnover timescale

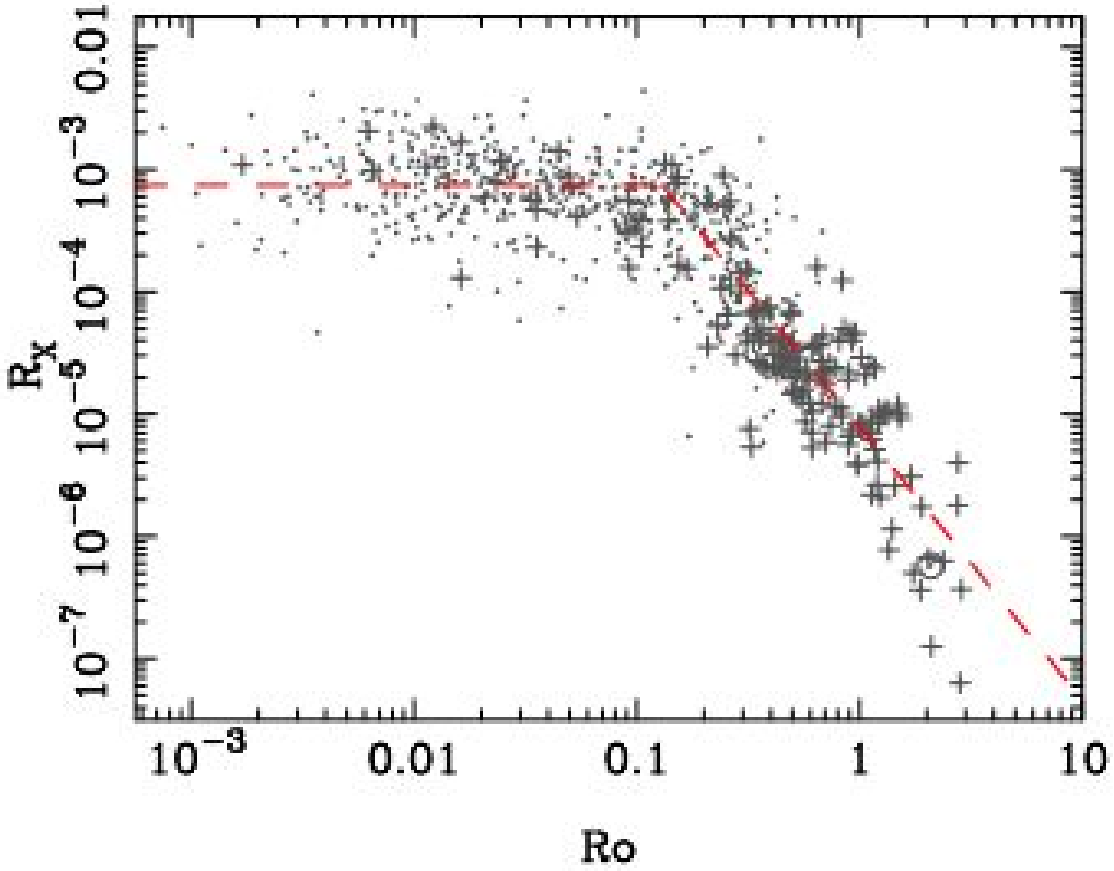
$$Ro = P_{\mathrm{rot}} / \tau_{\mathrm{c}}$$

Why use this?

It is *the* parameter of dynamo theory.

Links rotation and convection - important ingredients of solar dynamo theory (other dynamo theories are available).

Importantly linked to magnetic field strength.



Wright+ 2011

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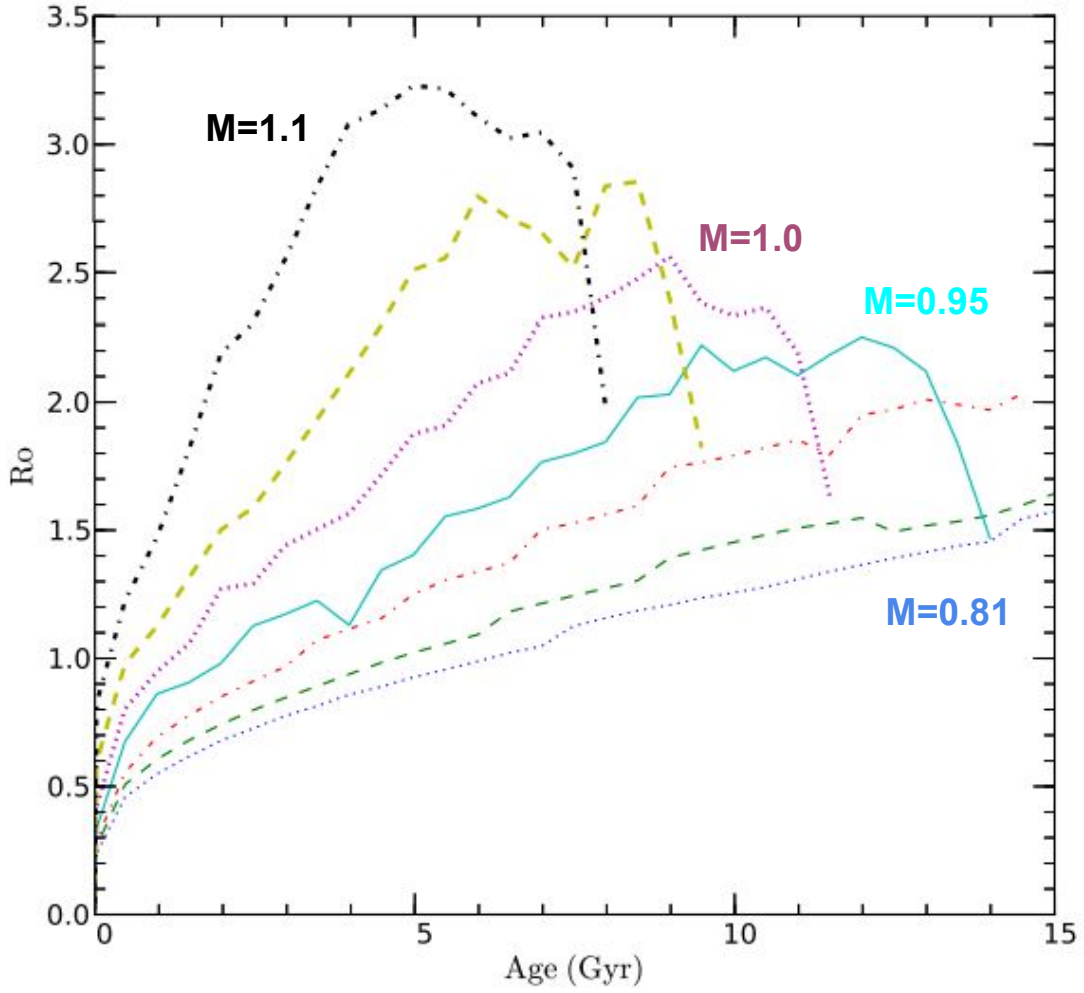
Rossby number evolution



Castro + 2013

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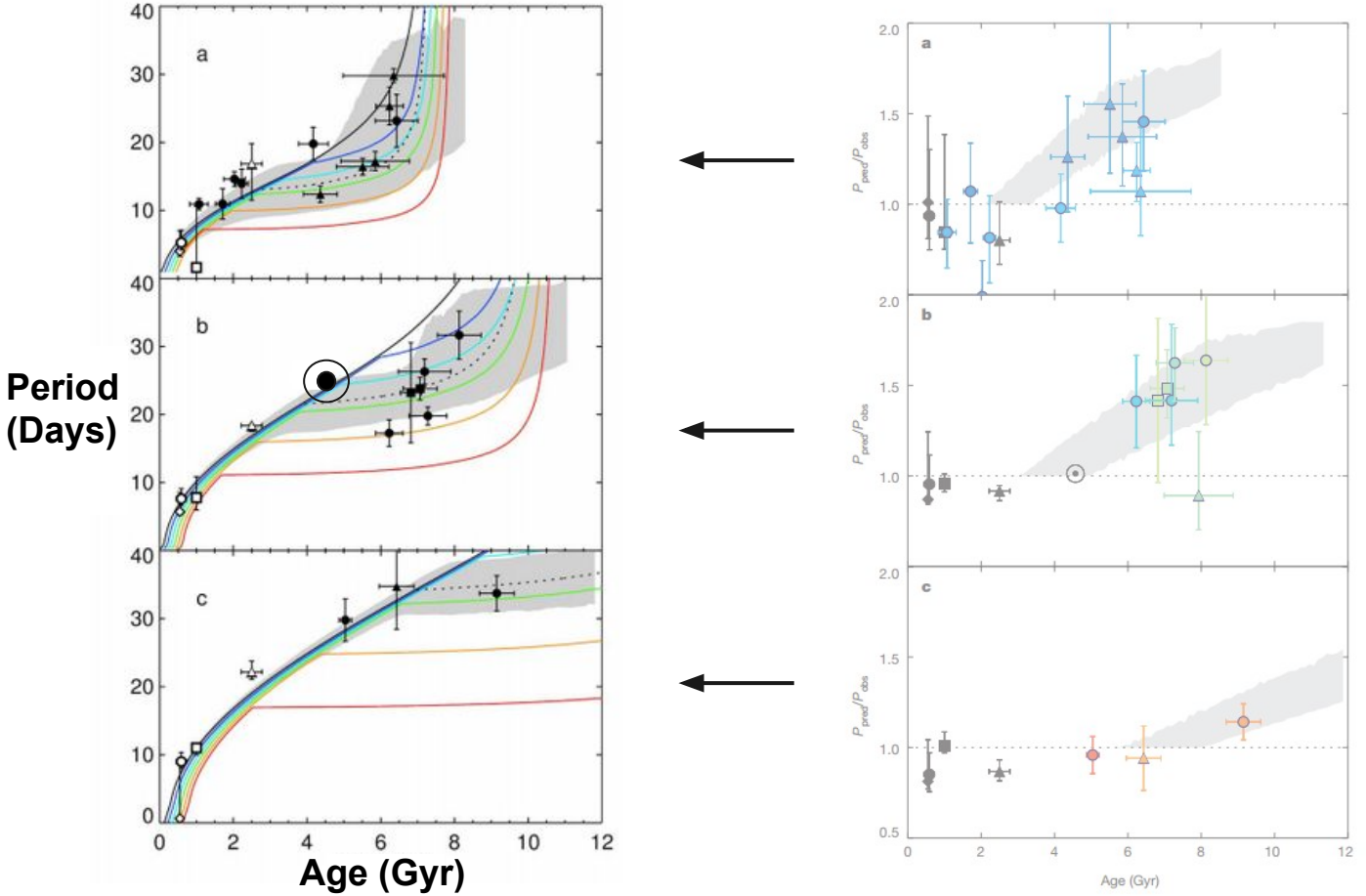

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van Saders, Davies + Nature 2016

What happens if … reduced solar magnetic activity?

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What happens if … reduced solar magnetic activity?

“If the Sun did not have a magnetic field, it would be as uninteresting a star as most astronomers believe it to be.”

R. B. Leighton
(of Feynman Leighton Sands)

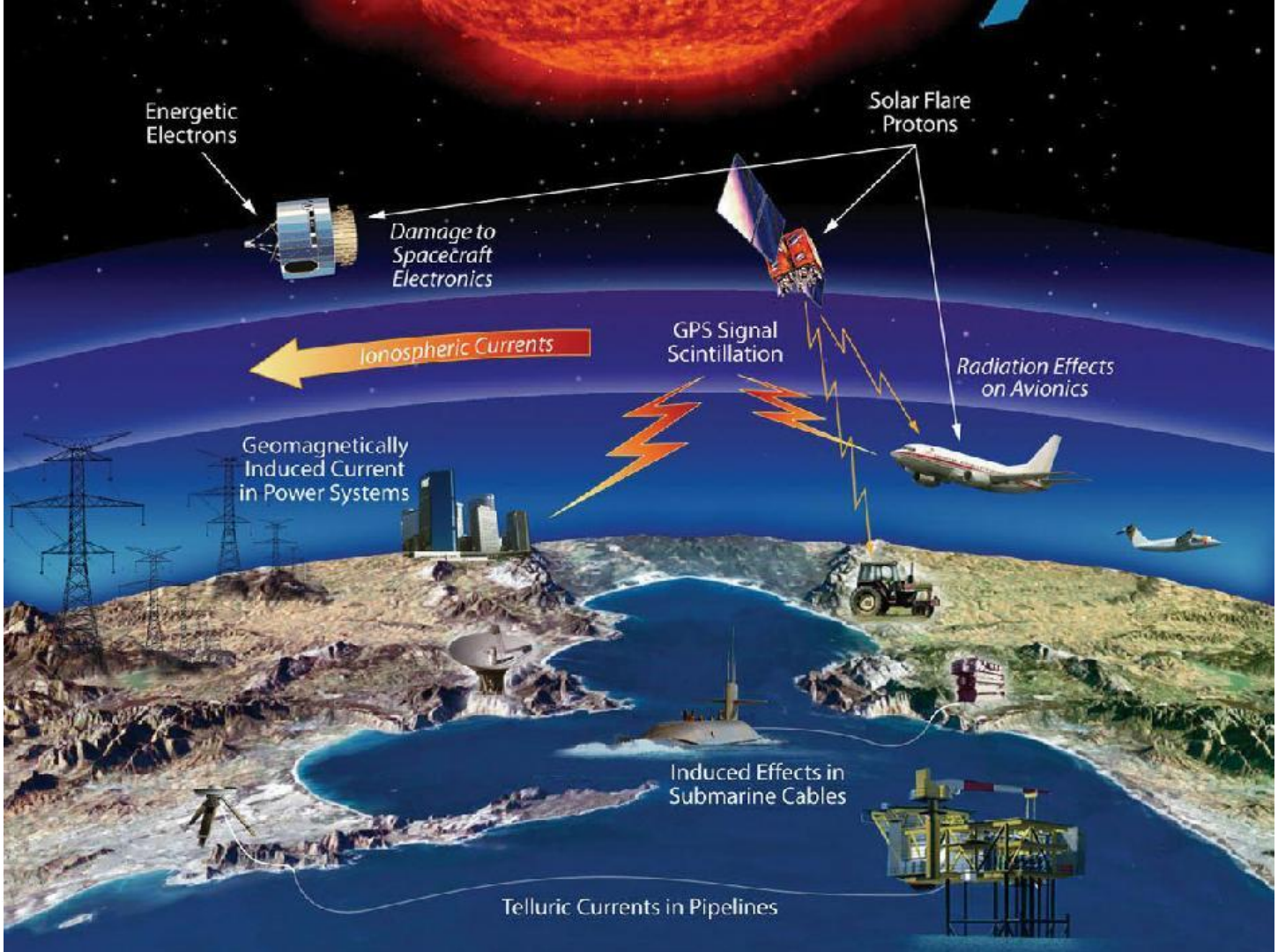
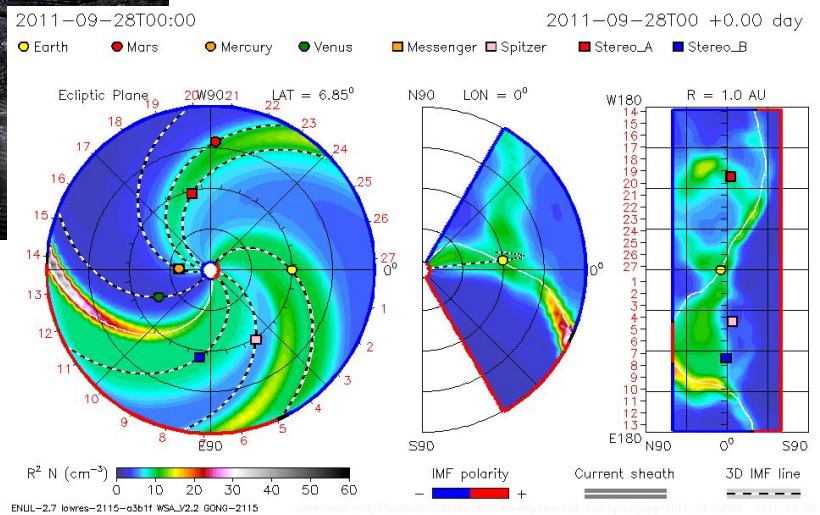


Image: NASA heliophysics



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