Asteroseismology of magnetic stars

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Stars with a stable magnetic field: from pre-main sequence to compact remnants
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Magnetic field - pulsation:

W. Unno, Y. Osaki, H. Ando, and H. Shibahashi. *Nonradial oscillations of stars.* 1989

Magnetic field - pulsation:

Equation of motion:

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla \Phi - \frac{1}{\rho} \nabla p$$

W. Unno, Y. Osaki, H. Ando, and H. Shibahashi. *Nonradial oscillations of stars.* 1989

Magnetic field - pulsation:

Equation of motion in the presence of a rotation and magnetic field:

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + 2\boldsymbol{\Omega}_0 \times \mathbf{v} + \boldsymbol{\Omega}_0 \times \boldsymbol{\Omega}_0 \times \mathbf{r}$$

$$= -\nabla\Phi - \frac{1}{\rho}\nabla p + \frac{1}{4\pi\rho}(\nabla \times \mathbf{B}) \times \mathbf{B}$$

W. Unno, Y. Osaki, H. Ando, and H. Shibahashi. *Nonradial oscillations of stars*. 1989

Magnetic field - pulsation:

Equation of motion in the presence of a rotation and magnetic field:

Coriolis force

Centrifugal force

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + 2\boldsymbol{\Omega}_0 \times \mathbf{v} + \boldsymbol{\Omega}_0 \times \boldsymbol{\Omega}_0 \times \mathbf{r}$$

Lorence force

$$= -\nabla\Phi - \frac{1}{\rho}\nabla p + \frac{1}{4\pi\rho}(\nabla \times \mathbf{B}) \times \mathbf{B}$$

W. Unno, Y. Osaki, H. Ando, and H. Shibahashi. *Nonradial oscillations of stars.* 1989

Magnetic field - pulsation:

Linearization:

$$\mathscr{L}(\xi) - \sigma^2\xi + \sigma\mathbf{M}(\xi) + \mathbf{N}(\xi) + \mathbf{B}(\xi)$$

where

$\mathscr{L}$ - describes the linear, adiabatic oscillations without rotation and magnetic field.

Rotation effects (first order):

$$\mathbf{M}(\xi) = 2\mathrm{i}\left[\mathbf{\Omega}_0 \times \xi + (\mathbf{v}\cdot\nabla)\xi\right]$$

Rotation effects (second order):

$$\mathbf{N}(\xi) = (\mathbf{v}\cdot\nabla)^2\xi - 2\mathbf{\Omega}_0 \times \left[(\xi\cdot\nabla)\mathbf{v} - (\mathbf{v}\cdot\nabla)\xi\right] - (\xi\cdot\nabla)(\mathbf{v}\cdot\nabla)\mathbf{v}$$

Magnetic field effects (second order):

$$\mathbf{B}(\xi) = \frac{1}{4\pi}\left[\left[\frac{1}{\rho}(\xi\cdot\nabla)\rho + \nabla\cdot\xi\right]\mathbf{B}\times(\nabla\times\mathbf{B}) - \left[(\nabla\times\mathbf{B}')\times\mathbf{B} + (\nabla\times\mathbf{B})\times\mathbf{B}'\right]\right]$$

Oblique pulsator model

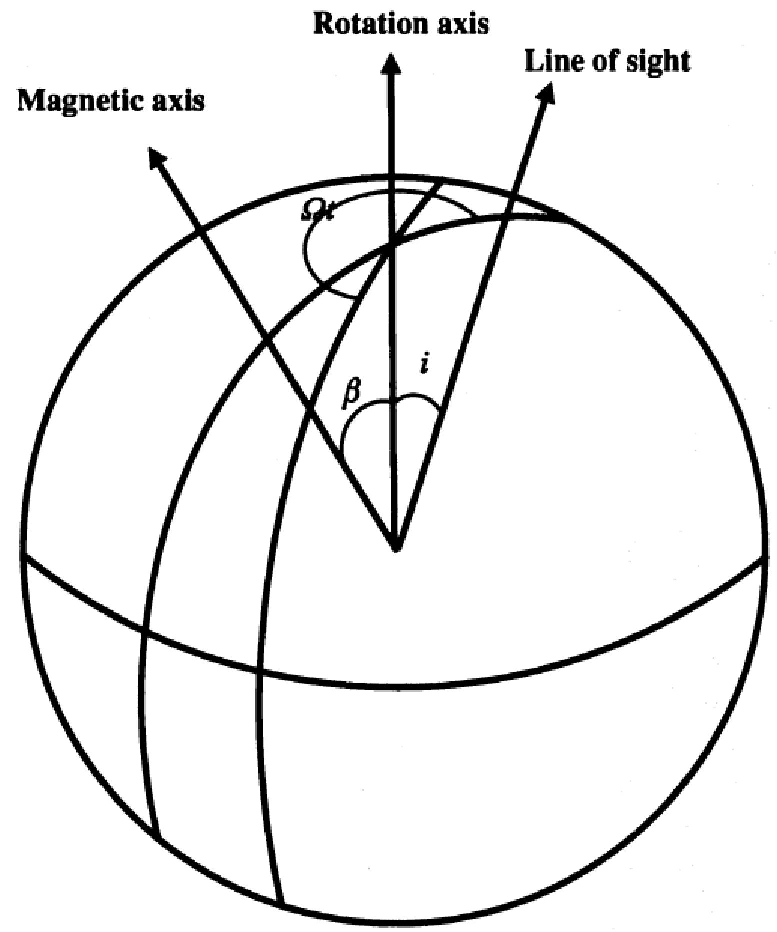


Fig. 1. Geometrical configuration of the magnetic axis, the rotation axis, and the line-of-sight. The magnetic axis is oblique to the rotation axis by the angle β. The angle between the line of sight and the rotation axis is denoted by i.

H. Shibahashi and M. Takata. Theory for the distorted dipole modes of the rapidly oscillating AP stars: A refinement of the oblique pulsator model. *PASJ*, 45:617–641, August 1993.

Oblique pulsator model

ℓ=0

$$\left[Y_0^0(\theta_B,\phi_B)+\alpha Y_2^0(\theta_B,\phi_B)\right]\exp i\omega t$$

H. Shibahashi. What's New in the Theory of Stellar Nonradial Oscillations. In R. K. Ulrich, E. J. Rhodes, Jr., and W. Dappen, editors, *GONG 1994. Helio- and Astro-Seismology from the Earth and Space*, volume 76 of *Astronomical Society of the Pacific Conference Series*, page 618, 1995.

H. Shibahashi. Asteroseismology of magnetic stars. In A. Wilson and P. L. Pallé, editors, *SOHO 10/GONG 2000 Workshop: Helio- and Asteroseismology at the Dawn of the Millennium*, volume 464 of *ESA Special Publication*, pages 457–460, January 2001.

Oblique pulsator model

ℓ=0

$$\left[Y_0^0(\theta_B,\phi_B)+\alpha Y_2^0(\theta_B,\phi_B)\right]\exp i\omega t$$

Quintuplet in the oscillation spectrum

H. Shibahashi. What's New in the Theory of Stellar Nonradial Oscillations. In R. K. Ulrich, E. J. Rhodes, Jr., and W. Dappen, editors, *GONG 1994. Helio- and Astro-Seismology from the Earth and Space*, volume 76 of *Astronomical Society of the Pacific Conference Series*, page 618, 1995.

H. Shibahashi. Asteroseismology of magnetic stars. In A. Wilson and P. L. Pallé, editors, *SOHO 10/GONG 2000 Workshop: Helio- and Asteroseismology at the Dawn of the Millennium*, volume 464 of *ESA Special Publication*, pages 457–460, January 2001.

Oblique pulsator model

ℓ=0

$$\frac{A_2 + A_{-2}}{A_1 + A_{-1}} = \frac{1}{4} |\tan\beta \tan i|$$

H. Shibahashi. What's New in the Theory of Stellar Nonradial Oscillations. In R. K. Ulrich, E. J. Rhodes, Jr., and W. Dappen, editors, *GONG 1994. Helio- and Astro-Seismology from the Earth and Space*, volume 76 of *Astronomical Society of the Pacific Conference Series*, page 618, 1995.

H. Shibahashi. Asteroseismology of magnetic stars. In A. Wilson and P. L. Pallé, editors, *SOHO 10/GONG 2000 Workshop: Helio- and Asteroseismology at the Dawn of the Millennium*, volume 464 of *ESA Special Publication*, pages 457–460, January 2001.

Oblique pulsator model

ℓ=1

$$\left[Y_1^0(\theta_B, \phi_B) + \sum_{m=\pm 1} \alpha_m Y_1^m(\theta_B, \phi_B) \right.$$
$$\left. + \sum_{m=0,\pm 1} \alpha'_m Y_3^m(\theta_B, \phi_B) \right] \exp i\omega t$$

H. Shibahashi. What's New in the Theory of Stellar Nonradial Oscillations. In R. K. Ulrich, E. J. Rhodes, Jr., and W. Dappen, editors, *GONG 1994. Helio- and Astro-Seismology from the Earth and Space*, volume 76 of *Astronomical Society of the Pacific Conference Series*, page 618, 1995.

H. Shibahashi. Asteroseismology of magnetic stars. In A. Wilson and P. L. Pallé, editors, *SOHO 10/GONG 2000 Workshop: Helio- and Asteroseismology at the Dawn of the Millennium*, volume 464 of *ESA Special Publication*, pages 457–460, January 2001.

Oblique pulsator model

ℓ=1

$$\left[Y_1^0(\theta_B, \phi_B) + \sum_{m=\pm 1} \alpha_m Y_1^m(\theta_B, \phi_B) + \sum_{m=0,\pm 1} \alpha'_m Y_3^m(\theta_B, \phi_B) \right] \exp i\omega t$$

Septuplet in the oscillation spectrum

H. Shibahashi. What's New in the Theory of Stellar Nonradial Oscillations. In R. K. Ulrich, E. J. Rhodes, Jr., and W. Dappen, editors, *GONG 1994. Helio- and Astro-Seismology from the Earth and Space*, volume 76 of *Astronomical Society of the Pacific Conference Series*, page 618, 1995.

H. Shibahashi. Asteroseismology of magnetic stars. In A. Wilson and P. L. Pallé, editors, *SOHO 10/GONG 2000 Workshop: Helio- and Asteroseismology at the Dawn of the Millennium*, volume 464 of *ESA Special Publication*, pages 457–460, January 2001.

Oblique pulsator model

ℓ=1

$$\frac{A_1^1 + A_1^{-1}}{A_1^0} = \tan\beta \tan i,$$

$$\frac{A_1^1 - A_1^{-1}}{A_1^1 + A_1^{-1}} = \frac{C_{n1}\Omega}{\sigma_{|m|=0}^{(1)mag} - \sigma_{|m|=1}^{(1)mag}}$$

Oblique pulsator model

ℓ=2

$$\frac{A_2^2 + A_2^{-2}}{A_2^0} = \frac{3\sin^2\beta\sin^2 i}{(3\cos^2\beta - 1)(3\cos^2 i - 1)}$$

$$\frac{A_2^2 - A_2^{-2}}{A_2^2 + A_2^{-2}} = \frac{2C_{n2}\Omega}{\sigma_{|m|=0}^{(1)mag} - \sigma_{|m|=1}^{(1)mag}}.$$

$$\frac{A_2^1 + A_2^{-1}}{A_2^0} = \frac{12\sin\beta\cos\beta\sin i\cos i}{(3\cos^2\beta - 1)(3\cos^2 i - 1)}$$

$$\frac{A_2^1 - A_2^{-1}}{A_2^1 + A_2^{-1}} = \frac{C_{n2}\Omega}{\sigma_{|m|=0}^{(1)mag} - \sigma_{|m|=1}^{(1)mag}}.$$

Oblique pulsator model

ℓ=2

$$\frac{A_2^2 + A_2^{-2}}{A_2^0} = \frac{3\sin^2\beta\sin^2 i}{(3\cos^2\beta - 1)(3\cos^2 i - 1)}$$

$$\frac{A_2^2 - A_2^{-2}}{A_2^2 + A_2^{-2}} = \frac{2C_{n2}\Omega}{\sigma_{|m|=0}^{(1)mag} - \sigma_{|m|=1}^{(1)mag}}.$$

$$\frac{A_2^1 + A_2^{-1}}{A_2^0} = \frac{12\sin\beta\cos\beta\sin i\cos i}{(3\cos^2\beta - 1)(3\cos^2 i - 1)}$$

$$\frac{A_2^1 - A_2^{-1}}{A_2^1 + A_2^{-1}} = \frac{C_{n2}\Omega}{\sigma_{|m|=0}^{(1)mag} - \sigma_{|m|=1}^{(1)mag}}.$$

Nonuplet in the oscillation spectrum

Ap stars
Chemically peculiar A-type Stars

- Non-Ap stars do not have surface magnetic fields (Shorlin et al. 2002, Bagnulo et al. 2006)
- All Ap stars do posses surface magnetic fields (Auriere et al. 2007)

Shorlin S. L. S., Wade G. A., Donati J.-F. et al. 2002, A&A, 392, 637
Aurière M., Wade G. A., Silvester J., et al. 2007, A&A, 475, 1053
Bagnulo S., Landstreet J. D., Mason E., et al. 2006, A&A, 450, 777

roAp stars:

Rapidly oscillating Ap Stars can be found near the classical instability strip, close to the δ Scuti stars. These stars are of spectral type A or F with a peculiar chemical composition of the outer layers caused by atomic diffusion. roAp stars were discovered by Kurtz (1982).

Light variation of roAp stars is caused by pulsations in high-order magneto-acoustic modes, which are driven in the hydrogen ionisation region. Many modes show frequency multiplets interpreted as being caused by a rotational amplitude modulation.

Typical pulsation periods are in the range of 5-22 min and the amplitudes are usually lower than 6 mmag. Radial velocity variations are smaller than 5000 ms^{-1}.

D. W. Kurtz. Rapidly oscillating AP stars. *MNRAS*, 200:807–859, September 1982

roAp stars:

roAp stars exhibit strong abundance anomalies (especially of rare earth elements). The abundances are non-uniform in both directions: horizontal (spots) and vertical (stratification) .The global magnetic fields has a typical strength several kG.

roAp stars:

In roAp stars magnetic effect dominates over the rotation effect. The oscillation symmetric axis coincides with the magnetic axis which is inclined to the rotational axis (the oblique pulsator model, Stibbs 1950, Kurtz 1982).

Stibbs D. W. N., 1950, MNRAS, 110, 395

D. W. Kurtz. Rapidly oscillating AP stars. *MNRAS*, 200:807–859, September 1982

roAp stars:

Rotation connected with the oscillation alongside with the magnetic field symmetric axis causes splitting of the single frequency peak in the power spectrum into $2\ell+5$ components.

roAp stars:

The relative amplitudes of a multiplet components depend on different properties of a star. It means that the observations of the fine structure of the oscillation frequencies can be used as a diagnosis of the rotation and internal magnetic field. In this sense, the observations of roAp stars open a new aspect of asteroseismology.

W. Dziembowski and P. R. Goode. Frequency splitting in AP stars. *ApJ*, 296:L27–L30, September 1985.

W. Dziembowski and P. R. Goode. Asterseismology for certain AP stars. In D. O. Gough, editor, *NATO Advanced Science Institutes (ASI) Series C*, volume 169 of *NATO Advanced Science Institutes (ASI) Series C*, pages 441–451, 1986.

roAp stars: HR 1217

The first discovered roAp star was HR 1217 (Kurtz 1982). It was a target of a lot of observations (including multi-site campaigns) The star is one of the coolest known Ap star. It is also relatively close to the Sun (~50 pc, Hipparcos parallax)

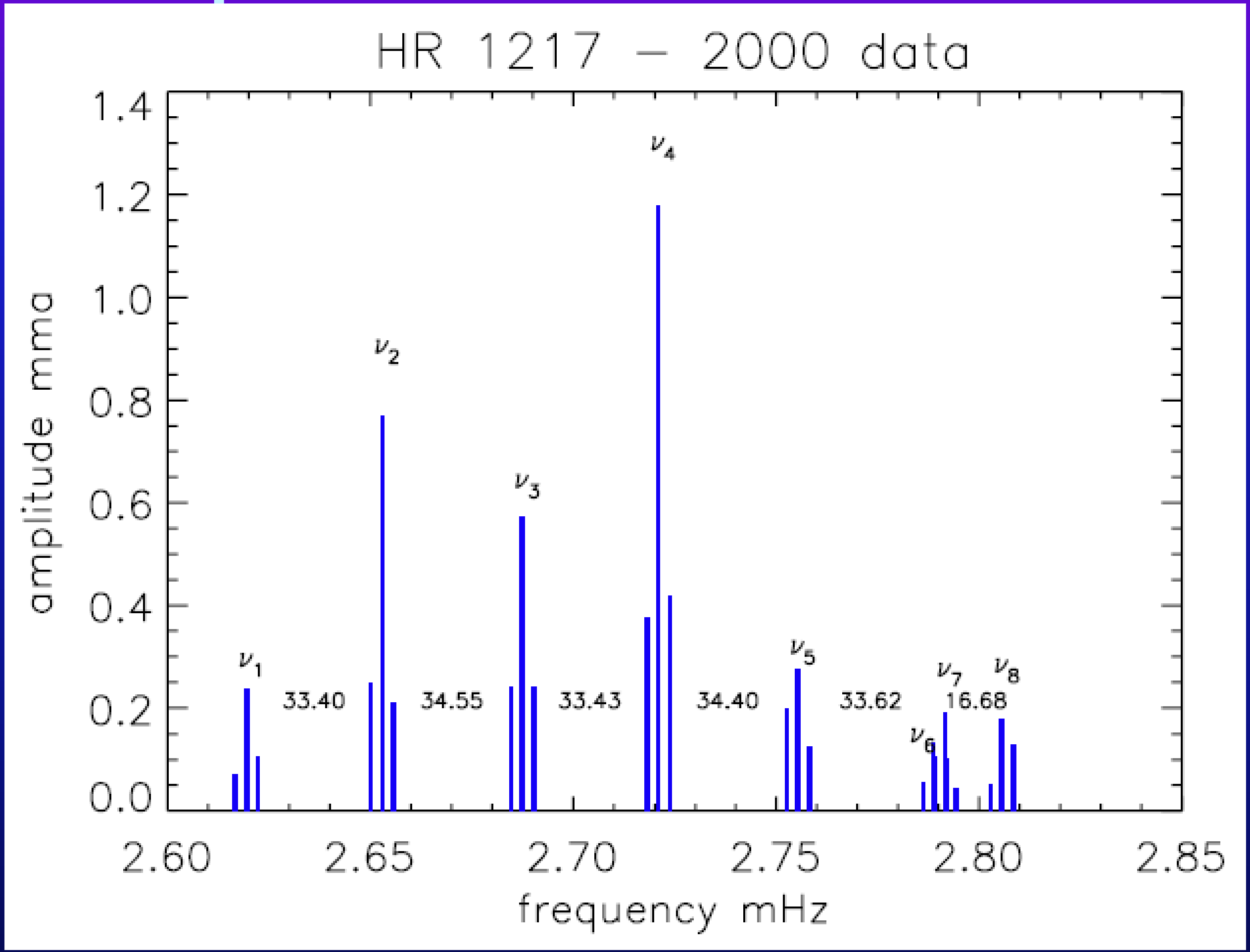
Kurtz D. W., 1981, "Discovery of 6.15 Minute Oscillations in the Cool Magnetic Ap Star HD 24712", *Information Bulletin on Variable Stars*, **1915**, 1 – 4

D. W. Kurtz. Rapidly oscillating AP stars. *MNRAS*, 200:807–859, September 1982.

Kurtz D. W., Seeman J., 1983, "Frequency analysis of the rapidly oscillating Ap star HR 1217 (HD 24712)", *Monthly Notices of the Royal Astronomical Society*, **205**, 11 – 22

Kurtz D. W., Matthews J. M., Martinez P., Seeman J., Cropper M., Clemens J. C., Kreidl T. J., Sterken C., Schneider H., Weiss W. W., Kawaler S. D., Kepler S. O., 1989, "The high-overtone p-mode spectrum of the rapidly oscillating Ap star HR 1217 (HD 24712) - Results of a frequency analysis of 324 HR of multi-site photometric observations obtained during a 46-d time-span in 1986", *Monthly Notices of the Royal Astronomical Society*, **240**, 881 – 915

roAp stars: HR 1217



Kurtz D. W., Kawaler S. D., Riddle R. L., Reed M. D., Cunha M. S., Wood M., Silvestri N., Watson T. K., Dolez N., Moskalik P., Zola S., Pallier E., Guzik J. A., Metcalfe T. S., Mukadam A. S., Nather R. E., Winget D. E., Sullivan D. J., Sullivan T., Sekiguchi K., Jiang X., Shobbrook R., Ashoka B. N., Seetha S., Joshi S., O'Donoghue D., Handler G., Mueller M., Gonzalez Perez J. M., Solheim J.-E., Johannessen F., Ulla A., Kepler S. O., Kanaan A., da Costa A., Fraga L., Giovannini O., Matthews J. M., 2002, "Discovery of the 'missing' mode in HR 1217 by the Whole Earth Telescope", *Monthly Notices of the Royal Astronomical Society,* **330**, L57 – L61

Kurtz D. W., Cameron C., Cunha M. S., Dolez N., Vauclair G., Pallier E., Ulla A., Kepler S. O., da Costa A., Kanaan A., Fraga L., Giovannini O., Wood M. A., Silvestri N., Kawaler S. D., Riddle R. L., Reed M. D., Watson T. K., Metcalfe T. S., Mukadam A., Nather R. E., Winget D. E., Nitta A., Kleinman S. J., Guzik J. A., Bradley P. A., Matthews J. M., Sekiguchi K., Sullivan D. J., Sullivan T., Shobbrook R., Jiang X., Birch P. V., Ashoka B. N., Seetha S., Girish V., Joshi S., Moskalik P., Zola S., O'Donoghue D., Handler G., Mueller M., Perez J. M. G., Solheim J.-E., Johannessen F., Bigot L., 2005a, "Pushing the ground-based limit: 14-μmag photometric precision with the definitive Whole Earth Telescope asteroseismic data set for the rapidly oscillating Ap star HR1217", *Monthly Notices of the Royal Astronomical Society,* **358**, 651 – 664

roAp stars: HR 1217

Cunha M. S., Gough D., 2000, "Magnetic perturbations to the acoustic modes of roAp stars", *Monthly Notices of the Royal Astronomical Society*, **319**, 1020 – 1038

Cunha M. S., 2006, "Improved pulsating models of magnetic Ap stars - I. Exploring different magnetic field configurations", *Monthly Notices of the Royal Astronomical Society*, **365**, 153 – 164

roAp stars: HR 1217

P_{rot}=12.46 d

i=137°

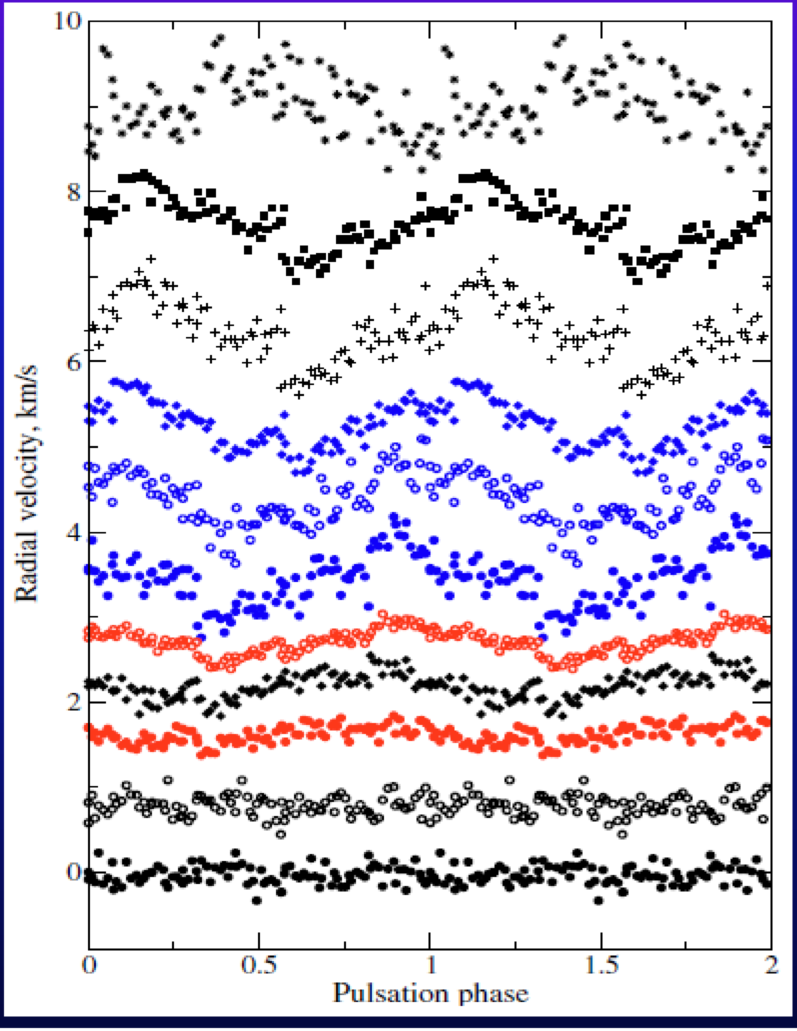
β=150°

Bagnuolo W. G., Jr., Gies D. R., 1991, "Tomographic separation of composite spectra - The components of the O-star spectroscopic binary AO Cassiopeiae", *Astrophysical Journal,* **376,** 266 – 271

T. Ryabchikova, G. A. Wade, M. Aurière, S. Bagnulo, J.-F. Donati, S. V. Jeffers, N. Johnson, J. D. Landstreet, F. Lignières, T. Lueftinger, S. Marsden, D. Mouillet, F. Paletou, P. Petit, P. Reegen, J. Silvester, S. Strasser, and N. Toque. Rotational periods of four roAp stars. *A&A*, 429:L55–L58, January 2005.

Kurtz D. W., Cameron C., Cunha M. S., Dolez N., Vauclair G., Pallier E., Ulla A., Kepler S. O., da Costa A., Kanaan A., Fraga L., Giovannini O., Wood M. A., Silvestri N., Kawaler S. D., Riddle R. L., Reed M. D., Watson T. K., Metcalfe T. S., Mukadam A., Nather R. E., Winget D. E., Nitta A., Kleinman S. J., Guzik J. A., Bradley P. A., Matthews J. M., Sekiguchi K., Sullivan D. J., Sullivan T., Shobbrook R., Jiang X., Birch P. V., Ashoka B. N., Seetha S., Girish V., Joshi S., Moskalik P., Zola S., O'Donoghue D., Handler G., Mueller M., Perez J. M. G., Solheim J.-E., Johannessen F., Bigot L., 2005a, "Pushing the ground-based limit: 14-μmag photometric precision with the definitive Whole Earth Telescope asteroseismic data set for the rapidly oscillating Ap star HR1217", *Monthly Notices of the Royal Astronomical Society,* **358,** 651 – 664

roAp stars: HR 1217



The lines are presented in the order that their line-forming layers occur in the atmosphere. Thus this figure clearly shows the increasing pulsation amplitude with height and the phase shift to later times of pulsation maximum with height, hence an outwardly running wave component to the pulsation

Ryabchikova T., Sachkov M., Weiss W. W., Kallinger T., Kochukhov O., Bagnulo S., Ilyin I., Landstreet J. D., Leone F., Lo Curto G., Lüftinger T., Lyashko D., Magazzù A., 2007b, "Pulsation in the atmosphere of the roAp star HD 24712. I. Spectroscopic observations and radial velocity measurements", *Astronomy and Astrophysics*, **462**, 1103 – 1112

roAp stars

- determination of magnetic field geometry
- inference the upper atmospheric properties at levels that cannot be observed in any star but the Sun.
- directly resolve the radial nodes in the atmosphere and demonstrated the depth structure of the pulsation and of the stratified abundances of the elements

B-type main sequence pulsators

MiMeS (Magnetism in Massive Stars, (Wade et al. 2014, 2016)

BinaMIcS (Binarity and Magnetic Interactions in various classes of stars, Alecian et al. 2015)

BOB (B fields in OB stars, Morel et al. 2014, 2015, Hubrig et al. 2014, 2015, Fossati et al. 2015, Schöller et al. 2017)

BRITE spectropolarimetric survey (Neiner et al. 2014, 2016)

B-type main sequence pulsators

Known pulsating B-type stars with magnetic fields:

- β Cep (Shibahashi & Aerts 2000, Henrichs et al. 2013)
- ξ^1 CMi (Shultz et al. 2017)
- V2052 Oph (Briquet et al. 2012, Handler et al. 2012)
- HD 96446 (Jarvinen et al. 2017)
- β CMa (Fossati et al. 2015)
- HD 43317 (Buysschaert et al. 2017)

B-type main sequence pulsators

β Cep

TABLE 1

Observed Frequencies of Spectral Line Variations

Mode	Frequency (day^{-1})	Amplitude
f_3	4.923	6.89×10^{-4}
f_4	5.082	1.10×10^{-3}
f_1	5.250	1.00
f_2	5.380	1.41×10^{-3}
f_5	5.417	1.40×10^{-3}
f_6 [a]	5.583	1.62×10^{-4}

Aerts, C., Mathias, P., Gillet, D., & Waelkens, C. 1994, A&A, 286, 109

Telting, J. H., Aerts, C., & Mathias, P. 1997, A&A, 322, 493

Henrichs, H. F., Bauer, F., Hill, G. M., Kaper, L., Nichols Bohlin, J. S., & Veen, P. M. 1993, in Proc. IAU Colloq. 139, New Perspectives on Stellar Pulsation and Pulsating Variable Stars, ed. J. M. Nemec & J. M. Matthews (Cambridge: Cambridge Univ. Press), 295

Shibahashi, H. & Aerts, C. 2000, ApJ, 531, L143

B-type main sequence pulsators

β Cep

ASTEROSEISMOLOGY AND OBLIQUE PULSATOR MODEL OF β CEPHEI

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ABSTRACT

We discuss the oscillation features of β Cephei, which is a magnetic star in which the magnetic axis seems to be oblique to the rotation axis. We interpret the observed equidistant fine structure of the frequency spectrum as a manifestation of a magnetic perturbation of an eigenmode, which would be a radial mode in the absence of the magnetic field. Besides these frequency components, we interpret another peak in the frequency spectrum as an independent quadrupole mode. By this mode identification, we deduce the mass, evolutionary stage, rotational frequency, magnetic field strength, and geometrical configuration of β Cep.

Shibahashi, H. & Aerts, C. 2000, ApJ, 531, L143

B-type main sequence pulsators

β Cep

$V_{rot} \sin i = 25$ km/s

$P_{rot} = 6$ d

$i \approx 30^\circ$

$\beta \approx 100^\circ$

Shibahashi, H. & Aerts, C. 2000, ApJ, 531, L143

B-type main sequence pulsators

Discovery of the magnetic field in the pulsating B star β Cephei*,**

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ABSTRACT

Context. Although the star itself is not helium enriched, the periodicity and the variability in the UV wind lines of the pulsating B1 IV star β Cephei are similar to what is observed in magnetic helium-peculiar B stars, suggesting that β Cep is magnetic.
Aims. We searched for a magnetic field using high-resolution spectropolarimetry. From UV spectroscopy, we analysed the wind variability and investigated the correlation with the magnetic data.
Methods. We used 130 time-resolved circular polarisation spectra that were obtained from 1998 (when β Cep was discovered to be magnetic) to 2005, with the MuSiCoS échelle spectropolarimeter at the 2 m Télescope *Bernard Lyot*. We applied the least-square deconvolution method on the Stokes V spectra and derived the longitudinal component of the integrated magnetic field over the visible hemisphere of the star. We performed a period analysis on the magnetic data and on equivalent-width measurements of UV wind lines obtained over 17 years. We also analysed the short- and long-term radial velocity variations, which are due to the pulsations and the 90-year binary motion, respectively.
Results. β Cep hosts a sinusoidally varying magnetic field with an amplitude 97 ± 4 G and an average value −6 ± 3 G. From the UV wind line variability, we derive a period of 12.00075(11) days, which is the rotation period of the star, and is compatible with the observed magnetic modulation. Phases of maximum and minimum field match those of maximum emission in the UV wind lines, strongly supporting an oblique magnetic-rotator model. We discuss the magnetic behaviour as a function of pulsation behaviour and UV line variability.
Conclusions. This paper presents the analysis of the first confirmed detection of a dipolar magnetic field in an upper main-sequence pulsating star. Maximum wind absorption originates in the magnetic equatorial plane. Maximum emission occurs when the magnetic north pole points to the Earth. Radial velocities agree with the ~90-year orbit around its Be-star binary companion.

Key words. magnetic fields – stars: winds, outflows – binaries: spectroscopic – stars: oscillations – stars: early-type

B-type main sequence pulsators

β Cep

$V_{rot} \sin i = 27$ km/s

$P_{rot} = 12$ d

$i \approx 60^\circ$

$\beta \approx 96^\circ$

H. F. Henrichs, J. A. de Jong, E. Verdugo, R. S. Schnerr, C. Neiner, J.-F. Donati, C. Catala, S. L. S. Shorlin, G. A. Wade, P. M. Veen, J. S. Nichols, E. M. F. Damen, A. Talavera, G. M. Hill, L. Kaper, A. M. Tijani, V. C. Geers, K. Wiersema, B. Plaggenborg, and K. L. J. Rygl. Discovery of the magnetic field in the pulsating B star β Cephei. *A&A*, 555:A46, July 2013.

B-type main sequence pulsators

HD 96446

- β Cep type pulsations (Neiner et al. 2012)

Parameter	Value
Distance (pc)	471^{+167}_{-82}
$T_{\rm eff}$ (K)	$21\,600 \pm 800$
$\log g$	4.0
$E(B-V)$	0.12 ± 0.03
A_V (mag)	0.37 ± 0.1
BC (mag)	2.15 ± 0.2
$M_{\rm bol}$	-4.19 ± 0.52
$\log(L/L_\odot)$	3.58 ± 0.22
R ($R_\odot$)	4.45 ± 2.0
M ($M_\odot$)	8.2 ± 0.7
$v \sin i$ (km s^{-1})	3 ± 2
Inclination i (°)	4–15
Obliquity β (°)	35–60
$B_{\rm pol}$ (G)	5000–10 000

Notes. The distance was obtained from the newly reduced HIPPARCOS catalogue (van Leeuwen 2007). The temperature is from Netopil et al. (2008).

Neiner C., Landstreet J. D., Alecian E., Owocki S., Kochukhov O., Bohlender D., MiMeS Collaboration 2012, A&A, 546, A44

B-type main sequence pulsators

HD 96446

$<|B|> = 3.9 \pm 0.25$ kG

$V_{rot} \sin i = 3$ km/s

$P_{rot} = 23.4$ d

$i \approx 18 \pm 15^{\circ}$

$\beta \approx 40 \pm 25^{\circ}$

S. P. Järvinen, S. Hubrig, I. Ilyin, M. Schöller, and M. Briquet. The challenge of measuring magnetic fields in strongly pulsating stars: the case of HD 96446. *MNRAS*, 464:L85–L89, January 2017.

B-type main sequence pulsators

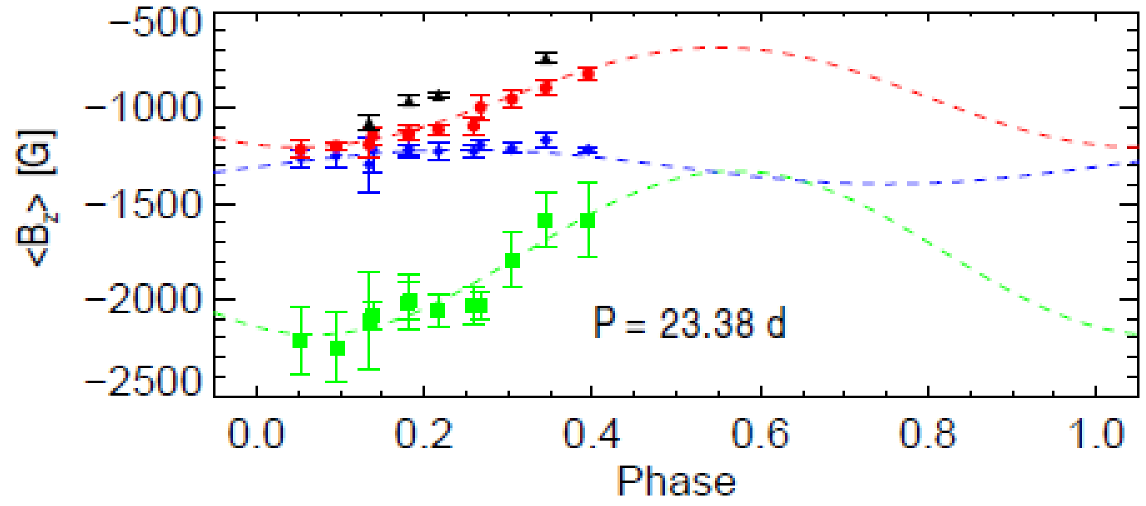


Figure 6. Magnetic field measurement distribution over the rotational phase using the ephemeris $T = 2\,455\,000.0 + 23^{\mathrm{d}}.38\ E$. Red filled circles represent values measured from all lines, green squares are from Si lines, and blue diamonds are from He lines. Dashed lines represent the fits. In addition, the values measured by Neiner et al. (2012) using only metal lines are denoted with black triangles.

S. P. Järvinen, S. Hubrig, I. Ilyin, M. Schöller, and M. Briquet. The challenge of measuring magnetic fields in strongly pulsating stars: the case of HD 96446. *MNRAS*, 464:L85–L89, January 2017.

B-type main sequence pulsators

HD 43317

β Cep/SPB pulsator (Pápics et al. 2012, Buysschaert et al. 2017)

Surface magnetic field ≈1-1.5 kG

Pápics, P. I., Briquet, M., Baglin, A., et al. 2012, A&A, 542, A55

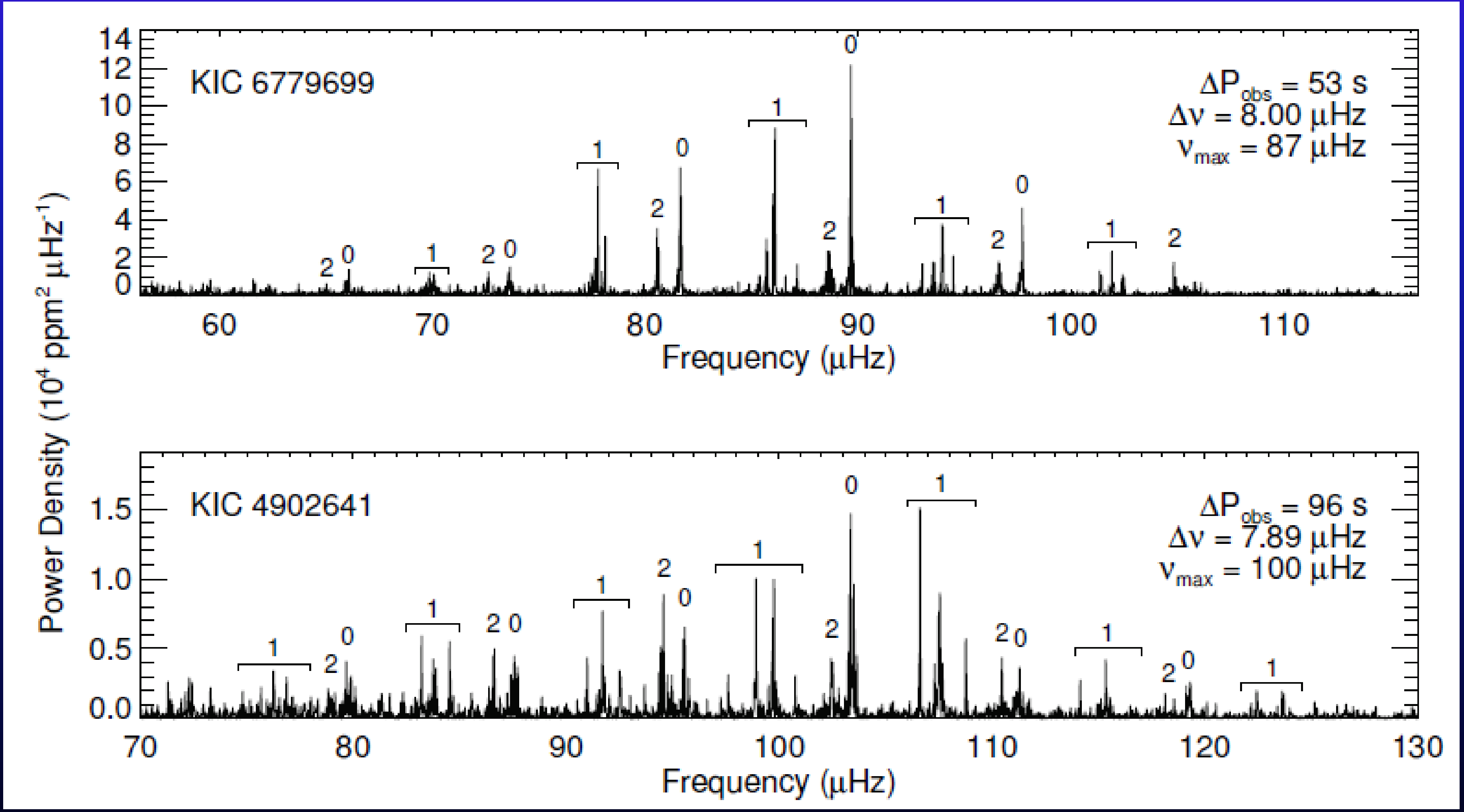
B. Buysschaert, C. Neiner, M. Briquet, and C. Aerts. Magnetic characterization of the SPB/β Cep hybrid pulsator HD 43317. *ArXiv e-prints*, July 2017.

Oscillating Red Giants

The oscillations of red giant stars are driven by turbulent motions in the outer convective envelope.

R. A. García, F. Pérez Hernández, O. Benomar, V. Silva Aguirre, J. Ballot, G. R. Davies, G. Doğan, D. Stello, J. Christensen-Dalsgaard, G. Houdek, F. Lignières, S. Mathur, M. Takata, T. Ceillier, W. J. Chaplin, S. Mathis, B. Mosser, R. M. Ouazzani, M. H. Pinsonneault, D. R. Reese, C. Régulo, D. Salabert, M. J. Thompson, J. L. van Saders, C. Neiner, and J. De Ridder. Study of KIC 8561221 observed by Kepler: an early red giant showing depressed dipolar modes. *A&A*, 563:A84, March 2014.

Oscillating Red Giants



Bedding, T. R., Mosser, B., Huber, D., et al. 2011, Nature, 471, 608

Oscillating Red Giants

Some stars exhibit unexpectedly small amplitudes of the dipole modes (about 20% of pulsating red giants). Also, it was noticed that the higher the ν_{max} the lower the amplitudes of the dipole modes. No clear correlations with stellar parameters were found, although a lower limit on the mass seems to exist at about $1.1 M_{sun}$

R. A. García, F. Pérez Hernández, O. Benomar, V. Silva Aguirre, J. Ballot, G. R. Davies, G. Doğan, D. Stello, J. Christensen-Dalsgaard, G. Houdek, F. Lignières, S. Mathur, M. Takata, T. Ceillier, W. J. Chaplin, S. Mathis, B. Mosser, R. M. Ouazzani, M. H. Pinsonneault, D. R. Reese, C. Régulo, D. Salabert, M. J. Thompson, J. L. van Saders, C. Neiner, and J. De Ridder. Study of KIC 8561221 observed by Kepler: an early red giant showing depressed dipolar modes. *A&A*, 563:A84, March 2014.

D. Stello, M. Cantiello, J. Fuller, D. Huber, R. A. García, T. R. Bedding, L. Bildsten, and V. Silva Aguirre. A prevalence of dynamo-generated magnetic fields in the cores of intermediate-mass stars. *Nature*, 529:364–367, January 2016.

Oscillating Red Giants

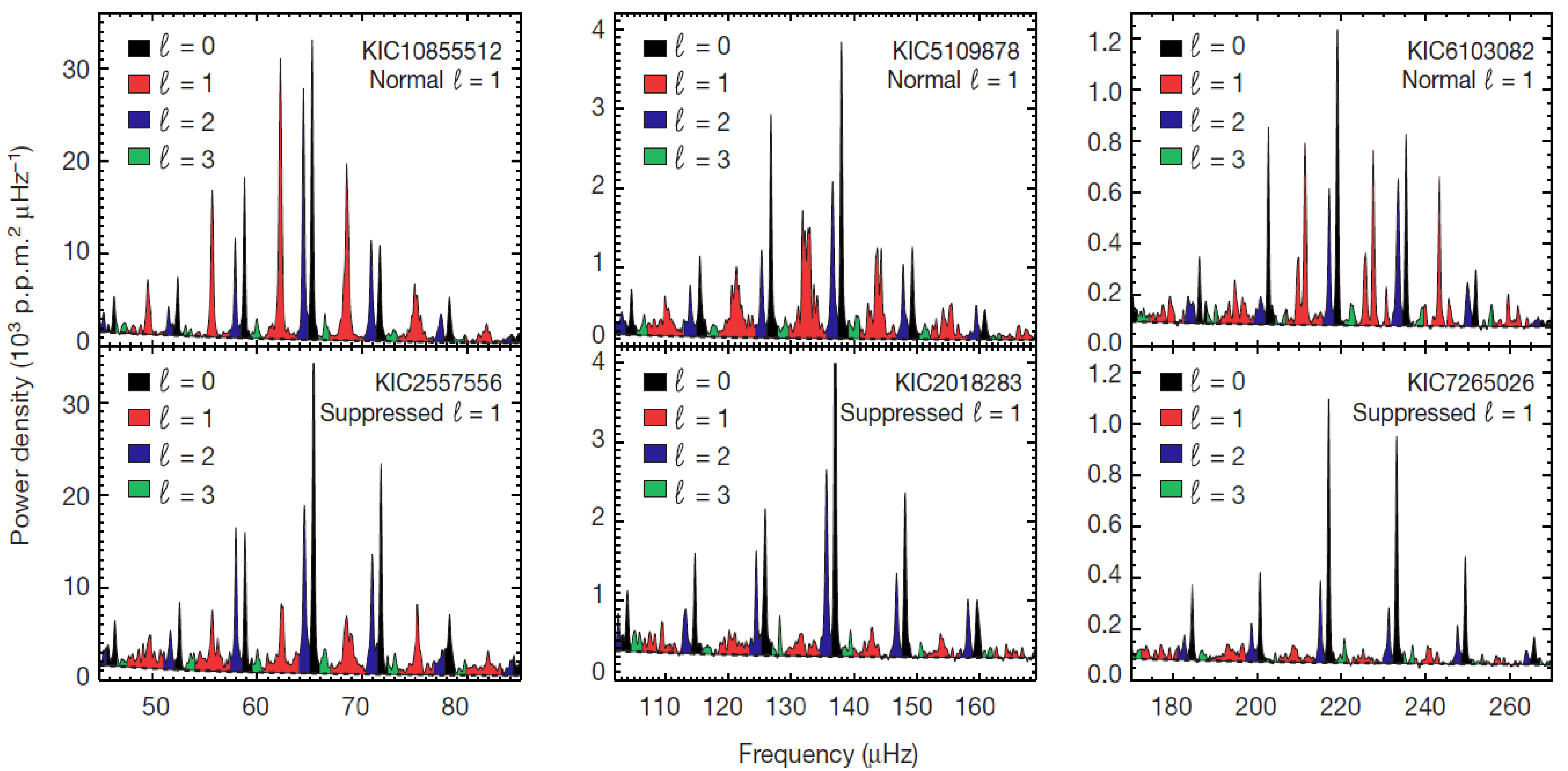
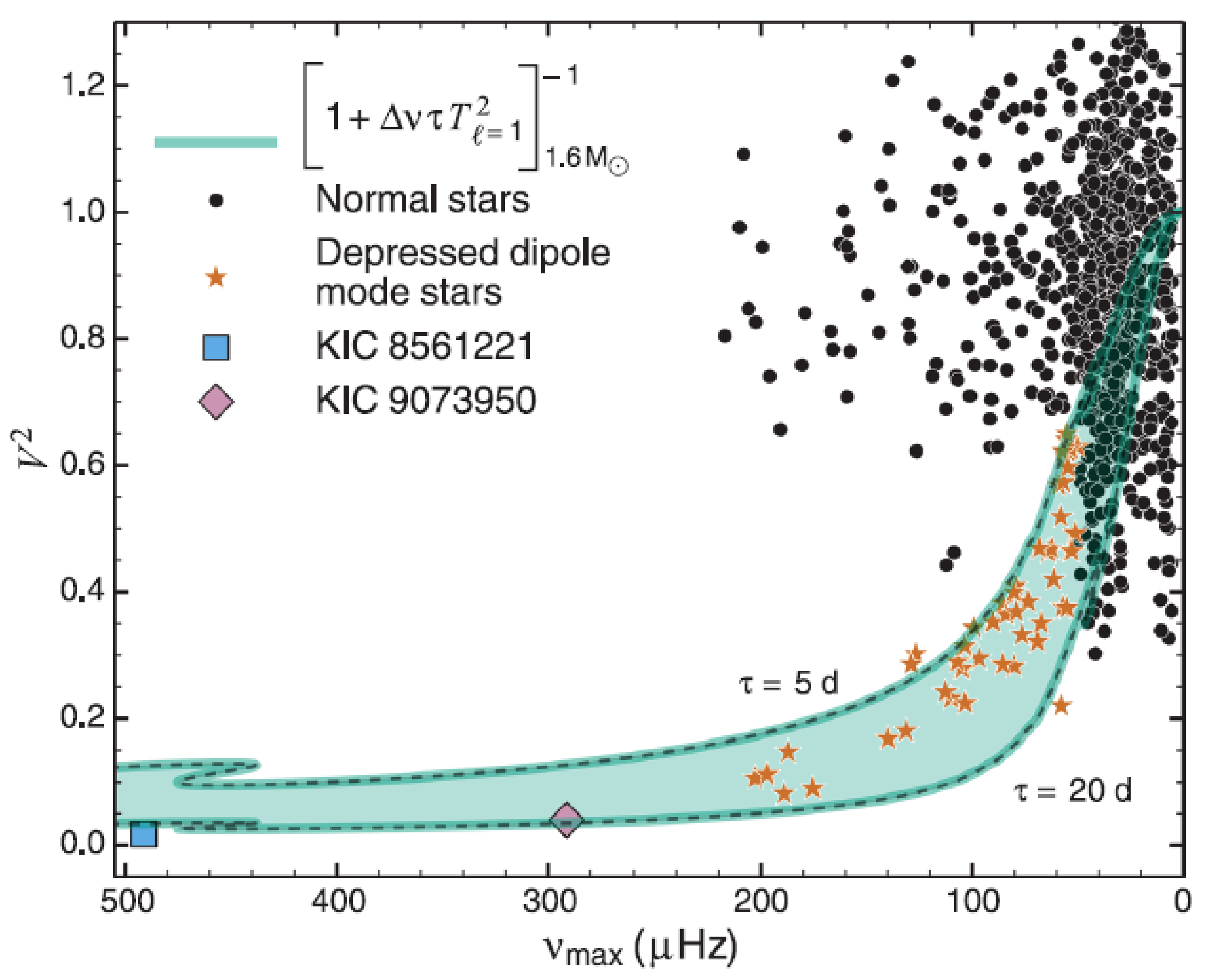


Figure 1 | Oscillation spectra of six red giants observed with Kepler. The stars are grouped into three pairs, each representing a different evolution stage ranging from the most evolved (lowest ν_{max}) on the left to the least evolved (highest ν_{max}) to the right. The coloured regions mark the power density dominated by modes of different degree $\ell = 0$–3. For clarity the spectra are smoothed by $0.03\Delta\nu$, which for the most evolved stars tends to create a single peak at each acoustic resonance, although each peak comprises multiple closely spaced mixed modes (red peaks in the left and centre panels). The slightly downward-sloping horizontal dashed line indicates the noise level.

D. Stello, M. Cantiello, J. Fuller, D. Huber, R. A. García, T. R. Bedding, L. Bildsten, and V. Silva Aguirre. A prevalence of dynamo-generated magnetic fields in the cores of intermediate-mass stars. *Nature*, 529:364–367, January 2016.

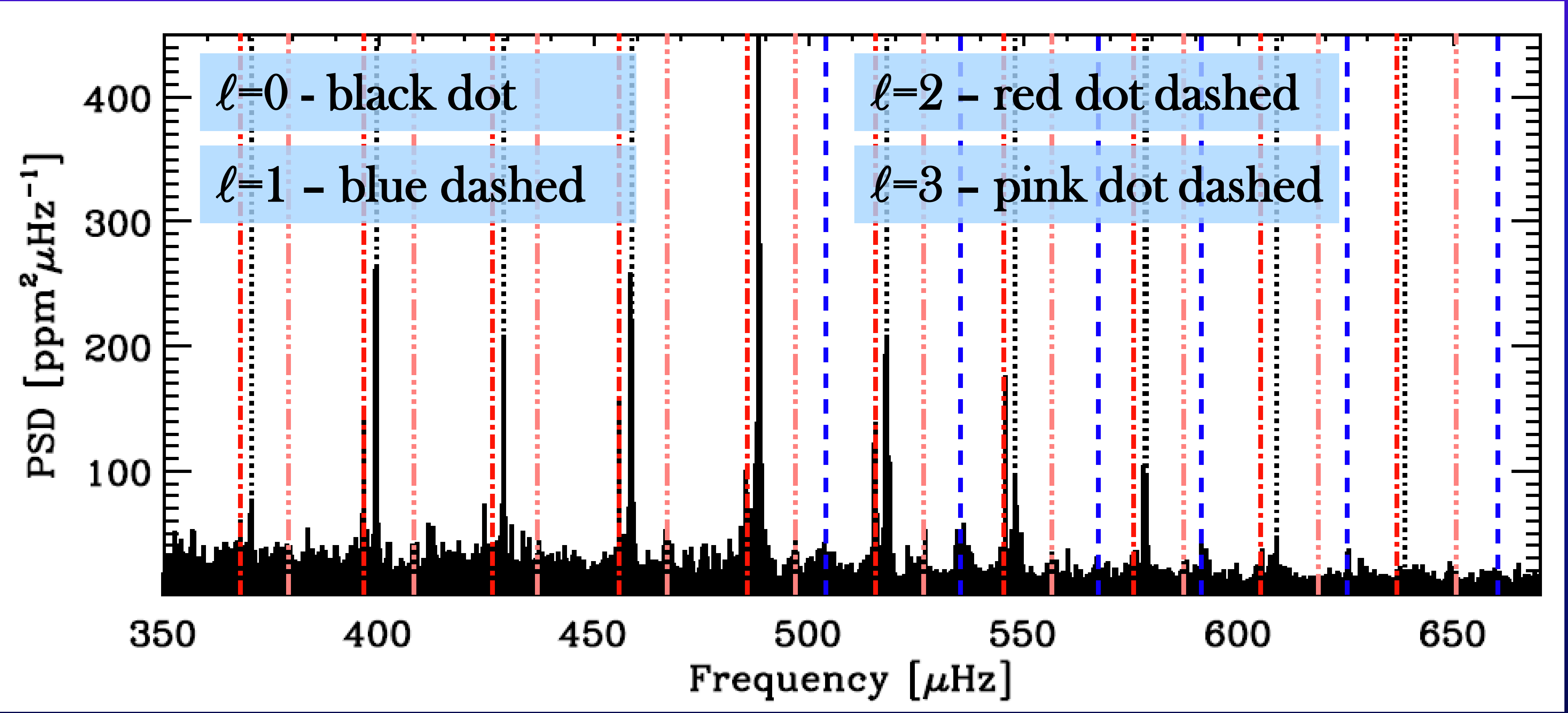
Oscillating Red Giants



Jim Fuller, Matteo Cantiello, Dennis Stello, Rafael A. Garcia, Lars Bildsten, 2015, Science 350 423-426

Oscillating Red Giants

KIC 8561221



R. A. García, F. Pérez Hernández, O. Benomar, V. Silva Aguirre, J. Ballot, G. R. Davies, G. Doğan, D. Stello, J. Christensen-Dalsgaard, G. Houdek, F. Lignières, S. Mathur, M. Takata, T. Ceillier, W. J. Chaplin, S. Mathis, B. Mosser, R. M. Ouazzani, M. H. Pinsonneault, D. R. Reese, C. Régulo, D. Salabert, M. J. Thompson, J. L. van Saders, C. Neiner, and J. De Ridder. Study of KIC 8561221 observed by Kepler: an early red giant showing depressed dipolar modes. *A&A*, 563:A84, March 2014.

Oscillating Red Giants

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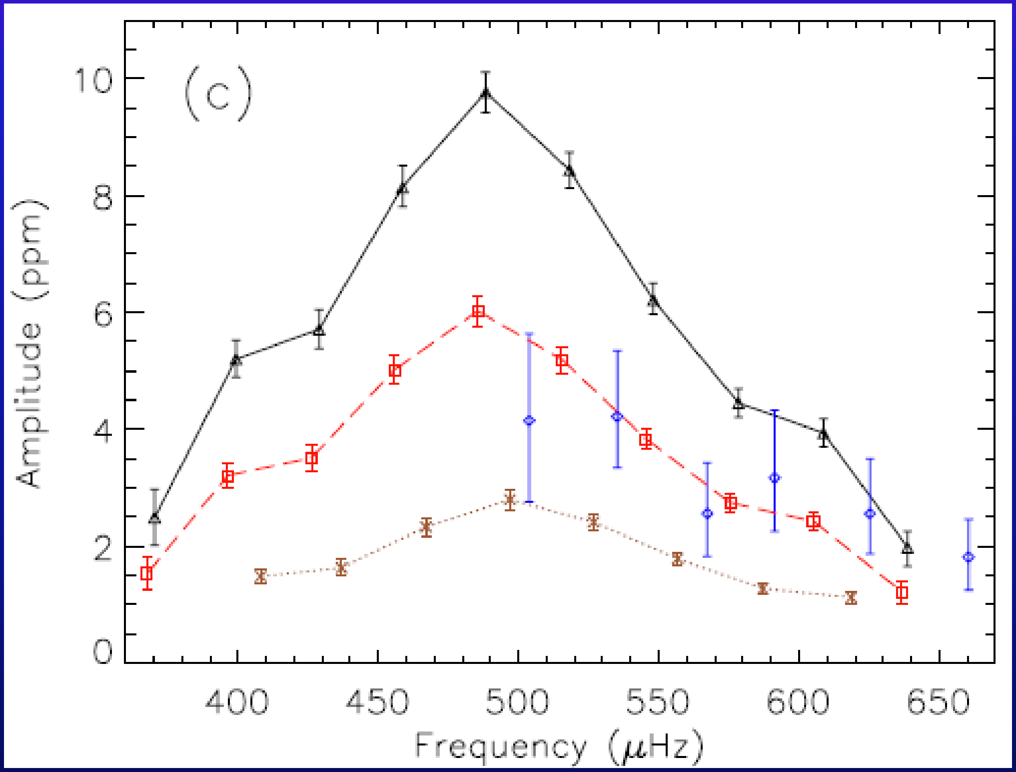

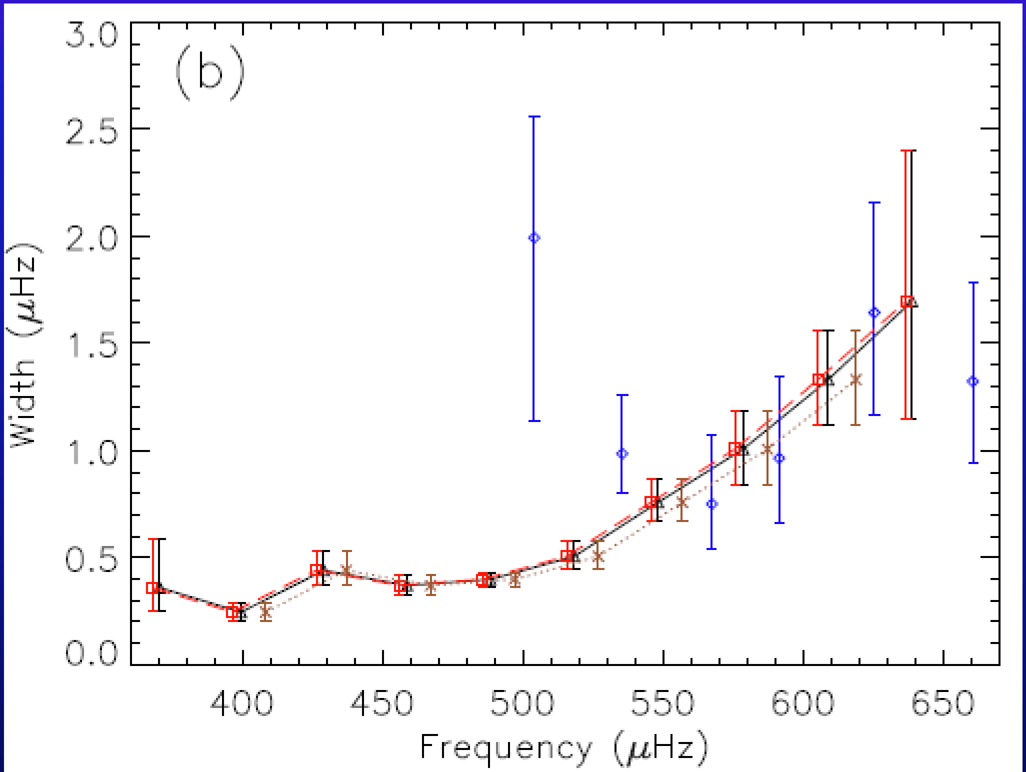

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Oscillating Red Giants

ASTEROSEISMOLOGY

Asteroseismology can reveal strong internal magnetic fields in red giant stars

Jim Fuller,[1,2*†] Matteo Cantiello,[2*†] Dennis Stello,[3,4] Rafael A. Garcia,[5] Lars Bildsten[2,6]

Internal stellar magnetic fields are inaccessible to direct observations, and little is known about their amplitude, geometry, and evolution. We demonstrate that strong magnetic fields in the cores of red giant stars can be identified with asteroseismology. The fields can manifest themselves via depressed dipole stellar oscillation modes, arising from a magnetic greenhouse effect that scatters and traps oscillation-mode energy within the core of the star. The Kepler satellite has observed a few dozen red giants with depressed dipole modes, which we interpret as stars with strongly magnetized cores. We find that field strengths larger than ~10^5 gauss may produce the observed depression, and in one case we infer a minimum core field strength of ≈10^7 gauss.

Oscillating Red Giants

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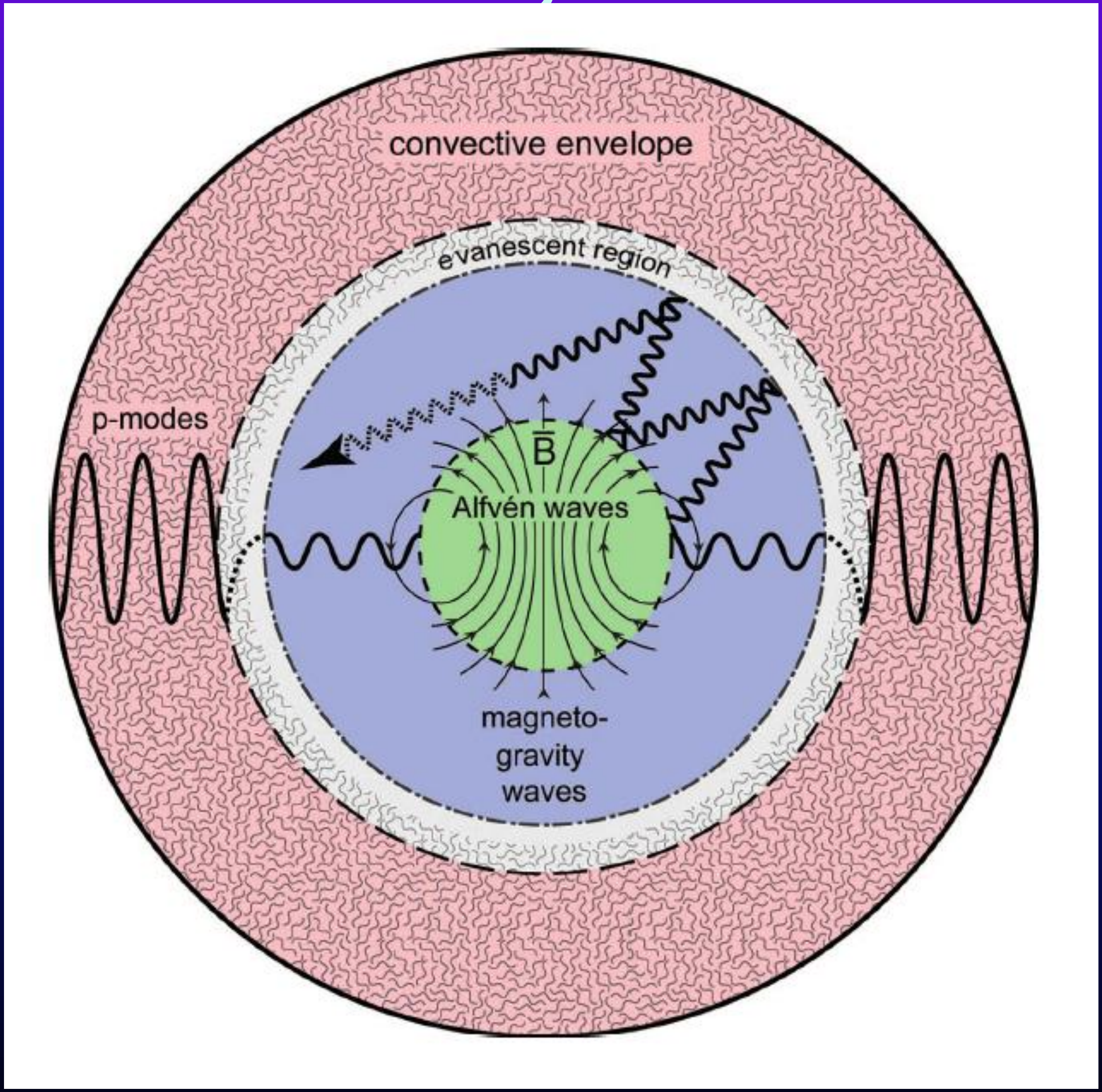
Oscillating Red Giants



Jim Fuller, Matteo Cantiello, Dennis Stello, Rafael A. Garcia, Lars Bildsten, 2015, Science 350 423-426

Oscillating Red Giants

$$B_c = \sqrt{\frac{\pi\rho}{2}}\frac{\omega^2 r}{N}$$

At which the Alfvén speed becomes larger than the radial group velocity of gravity waves.

Jim Fuller, Matteo Cantiello, Dennis Stello, Rafael A. Garcia, Lars Bildsten, 2015, Science 350 423-426

Oscillating Red Giants

Conversion of Internal Gravity Waves into Magnetic Waves

D. Lecoanet[1,2,3,4,5,6,7]*, G. M. Vasil[6], J. Fuller[7,8], M. Cantiello[7], & K. J. Burns[9]

[1] *Physics Department, University of California, Berkeley, CA 94720, USA*
[2] *Astronomy Department and Theoretical Astrophysics Center, University of California, Berkeley, CA 94720, USA*
[3] *IRPHE, Marseille, 13013, France*
[4] *Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544, USA*
[5] *Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA*
[6] *School of Mathematics & Statistics, University of Sydney, NSW 2006, Australia*
[7] *Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA*
[8] *TAPIR, Walter Burke Institute for Theoretical Physics, Mailcode 350-17, California Institute of Technology, Pasadena, CA 91125, USA*
[9] *Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

ABSTRACT

Asteroseismology probes the interiors of stars by studying oscillation modes at a star's surface. Although pulsation spectra are well understood for solar-like oscillators, a substantial fraction of red giant stars observed by Kepler exhibit abnormally low-amplitude dipole oscillation modes. Fuller et al. (2015) suggests this effect is produced by strong core magnetic fields that scatter dipole internal gravity waves (IGWs) into higher multipole IGWs or magnetic waves. In this paper, we study the interaction of IGWs with a magnetic field to test this mechanism. We consider two background stellar structures: one with a uniform magnetic field, and another with a magnetic field that varies both horizontally and vertically. We derive analytic solutions to the wave propagation problem and validate them with numerical simulations. In both cases, we find perfect conversion from IGWs into magnetic waves when the IGWs propagate into a region exceeding a critical magnetic field strength. Downward propagating IGWs cannot reflect into upward propagating IGWs because their vertical wavenumber never approaches zero. Instead, they are converted into upward propagating slow (Alfvénic) waves, and we show they will likely dissipate as they propagate back into weakly magnetized regions. Therefore, strong internal magnetic fields can produce dipole mode suppression in red giants, and gravity modes will likely be totally absent from the pulsation spectra of sufficiently magnetized stars.

Oscillating Red Giants

Conversion of Internal Gravity Waves into Magnetic Waves

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Oscillating Red Giants

Another important consequence of our results is that any strongly magnetized star will not exhibit g mode pulsations, because IGW will be converted into damped SM waves. Our specific examples give a critical magnetic field strength consistent (up to a factor of two) with Cantiello et al. (2016). This could explain why there are very few magnetic white dwarfs that are known g mode pulsators.[4] Additionally, g mode pulsations in γ-Doradus, sdB, or SPB stars can be totally suppressed by strong internal magnetic fields, and non-pulsating stars within these respective instability strips are good candidates for harboring internal fields.

D. Lecoanet, G. M. Vasil, J. Fuller, M. Cantiello, and K. J. Burns. Conversion of internal gravity waves into magnetic waves. *MNRAS*, 466:2181–2193, April 2017.

Summary

• Magnetic fields have been found in many different types of stars, i.e. Ap, Red Giants, B-type stars.

• Some magnetic stars pulsate, which gives a possibility of deriving constrains inaccessible in other ways.

• In general, the pulsation-magnetic fields interaction is very complicated.

• Long term spectropolarimetric observations are needed in order to characterize the stellar magnetic field.

•Long term photometric and spectroscopic observations are needed in order to characterize the stellar oscillations