ESO Between The Lines Workshop
Stellar atmospheres – an overview

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Overview

- What is the stellar atmosphere?
  - observational view
- Where are stellar atmosphere models needed today?
  - ... or why do we do this to us?
- How do we model stellar atmospheres?
  - admittedly sketchy presentation
  - which physical processes? which approximations?
- Next step: using model atmospheres as “background” to calculate the formation of spectral lines

What is the atmosphere?

- Light emitting surface layers of a star
  - directly accessible to (remote) observations
  - photosphere (dominant radiation source)
  - chromosphere
  - corona
  - wind (mass outflow, e.g. solar wind)
- Transition zone from stellar interior to interstellar medium
  - connects the star to the 'outside world'
- All energy generated in a star has to pass through the atmosphere
- Atmosphere itself usually does not produce additional energy!

The photosphere

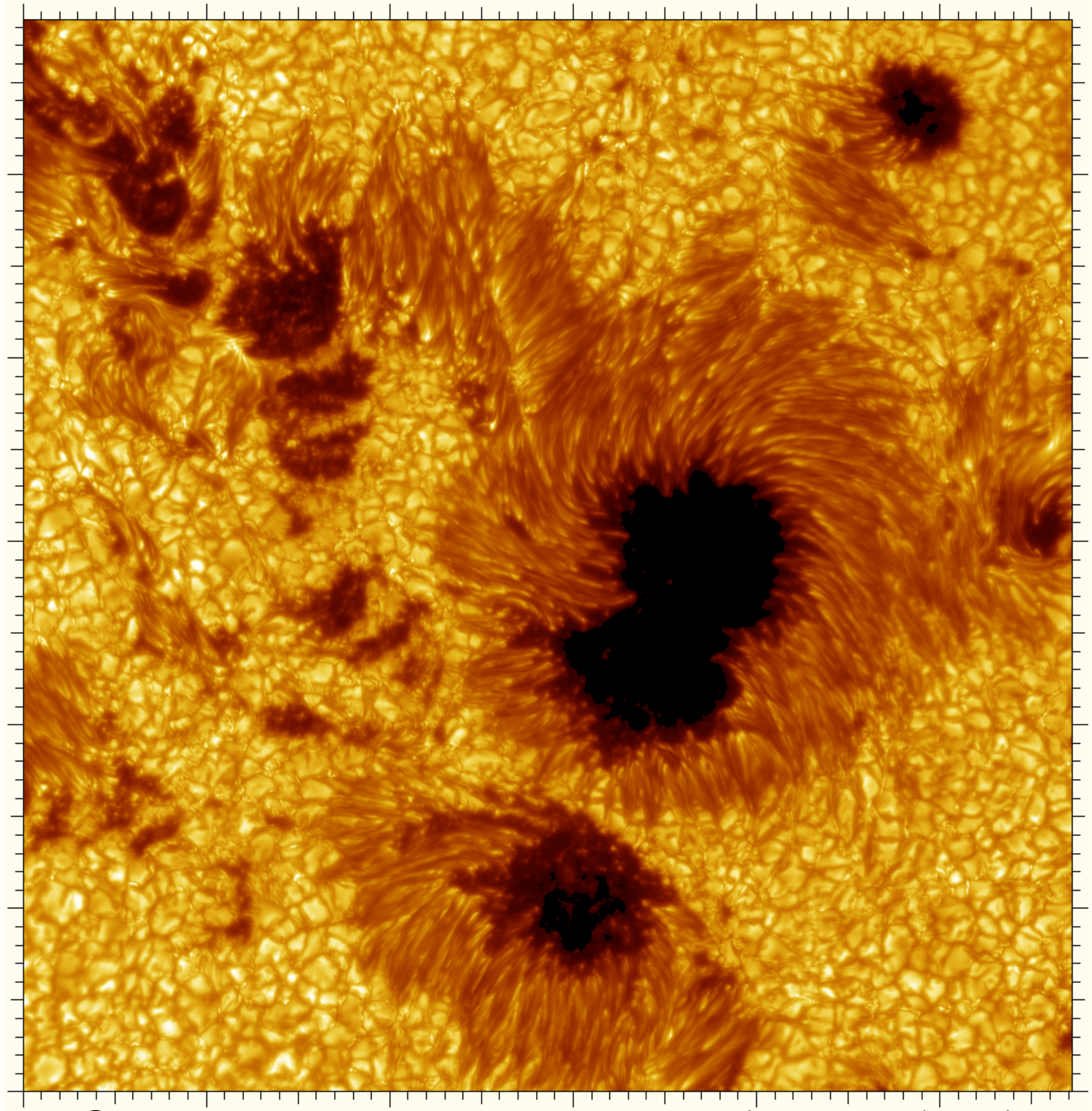
- Most light emitted by photosphere
  - stellar model atmospheres often focus on this layer
  - also focus of these lectures $\rightarrow$ chemical abundances

- Thickness Δh, some numbers:
  - Sun: $\Delta h \approx 1000\,\mathrm{km}$
    - $\star$ Sun appears to have a sharp limb
    - $\star$ curvature effects on the photospheric properties small
      solar surface almost 'flat'
  - white dwarf: $\Delta h \leq 100$ m
  - red super giant: $\Delta h / R \approx 1$

- Stellar evolution, often: atmosphere = photosphere = R($T = T_{\mathrm{eff}}$)

Solar photosphere: rather homogeneous but ...

Magnetically active region, optical spectral range, T$\approx 6000\,\mathrm{K}$



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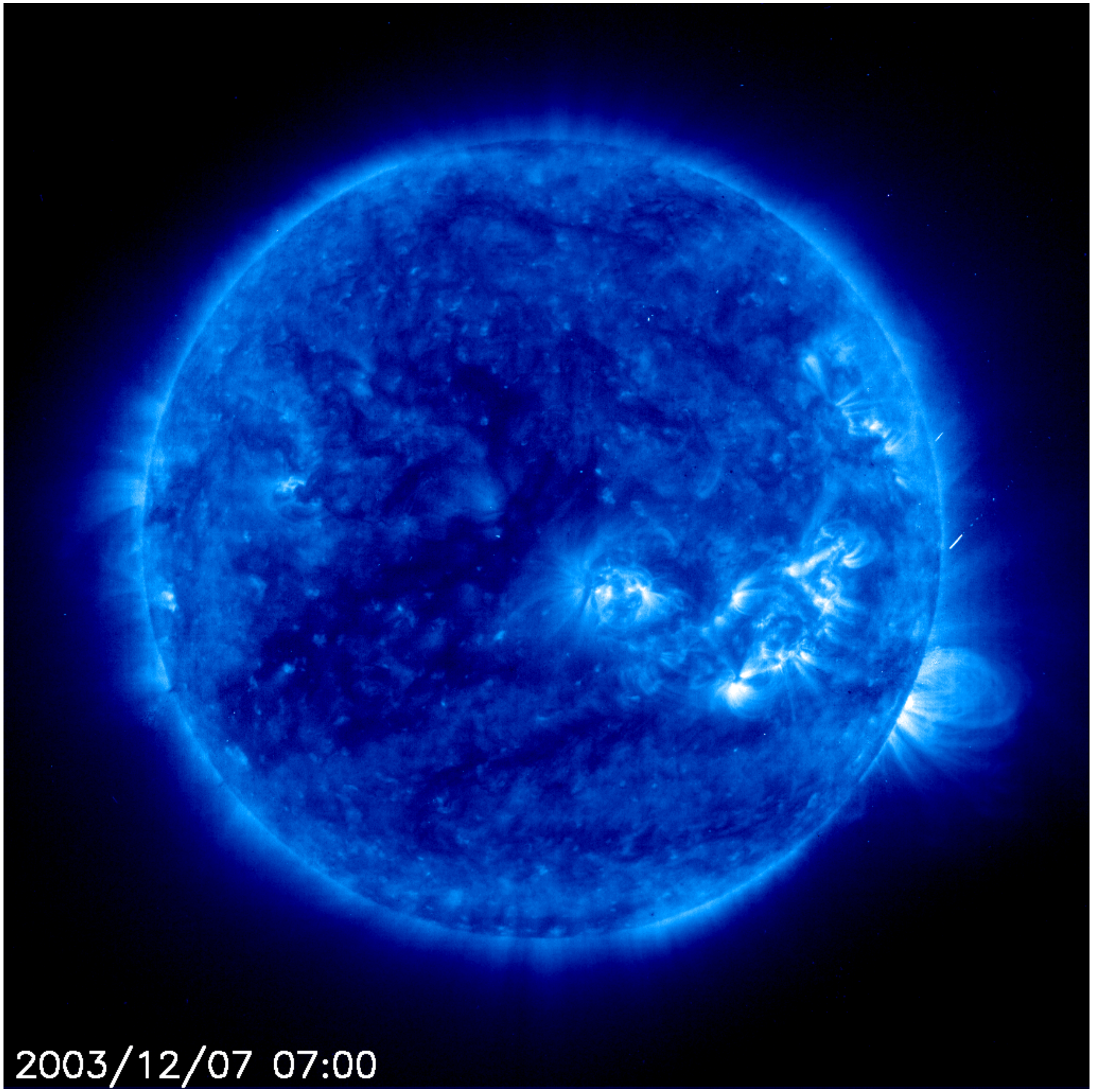
Corona, ultraviolet spectral range, T$\approx 10^6\,\mathrm{K}$ (Fe IX)



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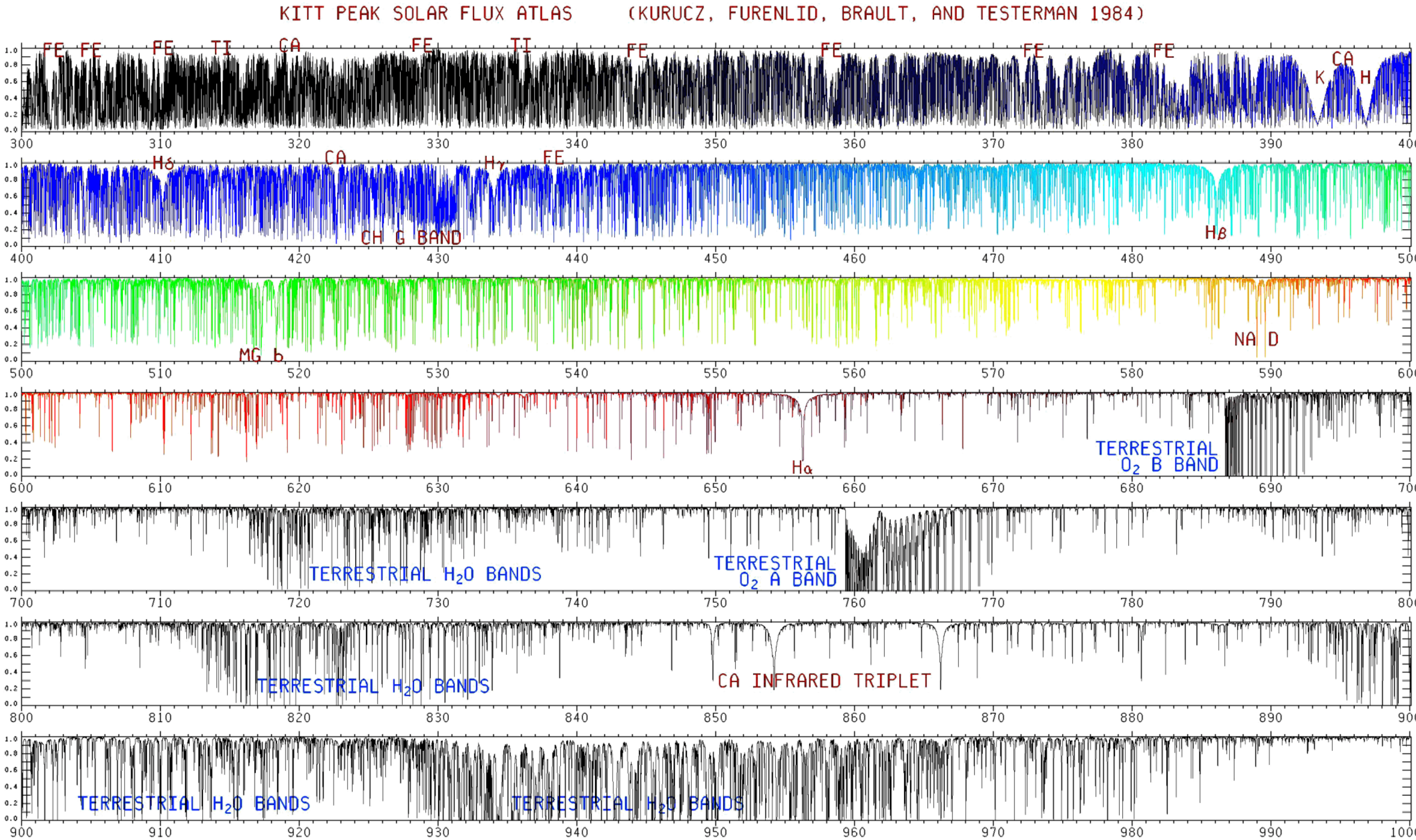
Model atmospheres: tool for the interpretation of stellar spectra



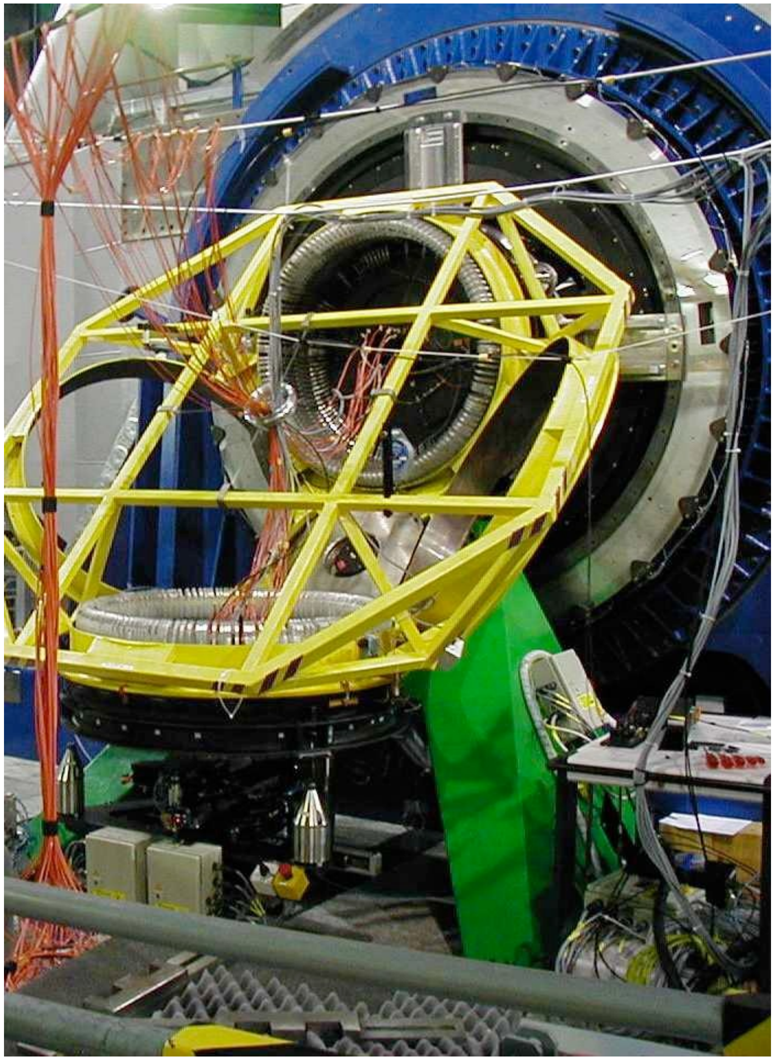
Model atmospheres: tool for the interpretation of stellar spectra

- Derivation of stellar properties
  - atmospheric parameters ($T_{\rm eff}$,$\log g$) $\rightarrow$ connection to luminosity, radius, mass
  - abundances $\rightarrow$ connection to nucleosynthesis processes and chemical evolution
  - radial velocity $\rightarrow$ kinematics

- Since year ≈ 2000 shift of perspective ...
  - increasing number of multiobject spectrographs operational
  - current record holder Chinese LAMOST facility: 4000 spectra per exposure
  - large number of stellar spectra produced $\rightarrow$ construction of analysis “pipelines” important activity
  - European GAIA satellite mission 2014–2024 has spawned further interest and demand

- Planet searches by radial velocity techniques additional source of spectra

Example multiobject spectrograph: FLAMES+GIRAFFE+UVES



- Installed at 8 m telescope at ESO Paranal, Nasmyth focus, robotic positioning of pick-ups, transfer via optical fibers, 130 low-res (GIRAFFE) and 8 high-res (UVES) spectra

Examples spectroscopic surveys (not complete list!)

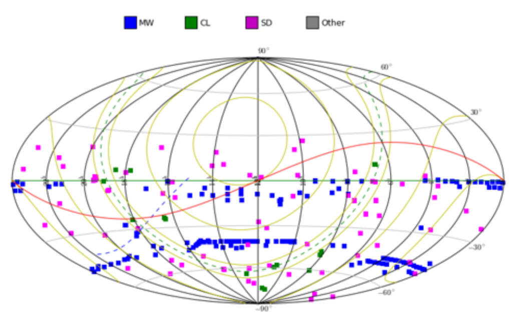
LAMOST

Xinglong Observing Station, National Astronomical Observatories, China

2012 – present

Gaia-ESO

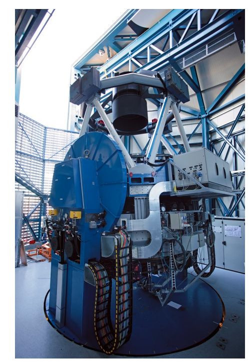
European Southern Observatory, Paranal, Chile



2012 – 2018

4MOST

ESO Paranal, Vista Telescope



2025 (?) – 2030 (?)

- Production of large number of stellar spectra ongoing / completed / planned

European Southern Observatory

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SPACE SCOOP

The Star That Should Not Exist

31 August 2011

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A team of European astronomers has used ESO's Very Large Telescope (VLT) to track down a star in the Milky Way that many thought was impossible. They discovered that this star is composed almost entirely of hydrogen and helium, with only remarkably small amounts of other chemical elements in it. This intriguing composition places it in the "forbidden zone" of a widely accepted theory of star formation, meaning that it should never have come into existence in the first place. The results will appear in the 1 September 2011 issue of the journal Nature.

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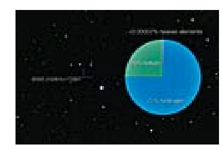
About the Release

Release No.:	eso1132
Name:	SDSS J102915+1729
Type:	• Milky Way : Star
Science data:	2011Natur.477...67C

Images

PR Image eso1132a
A star that should not exist

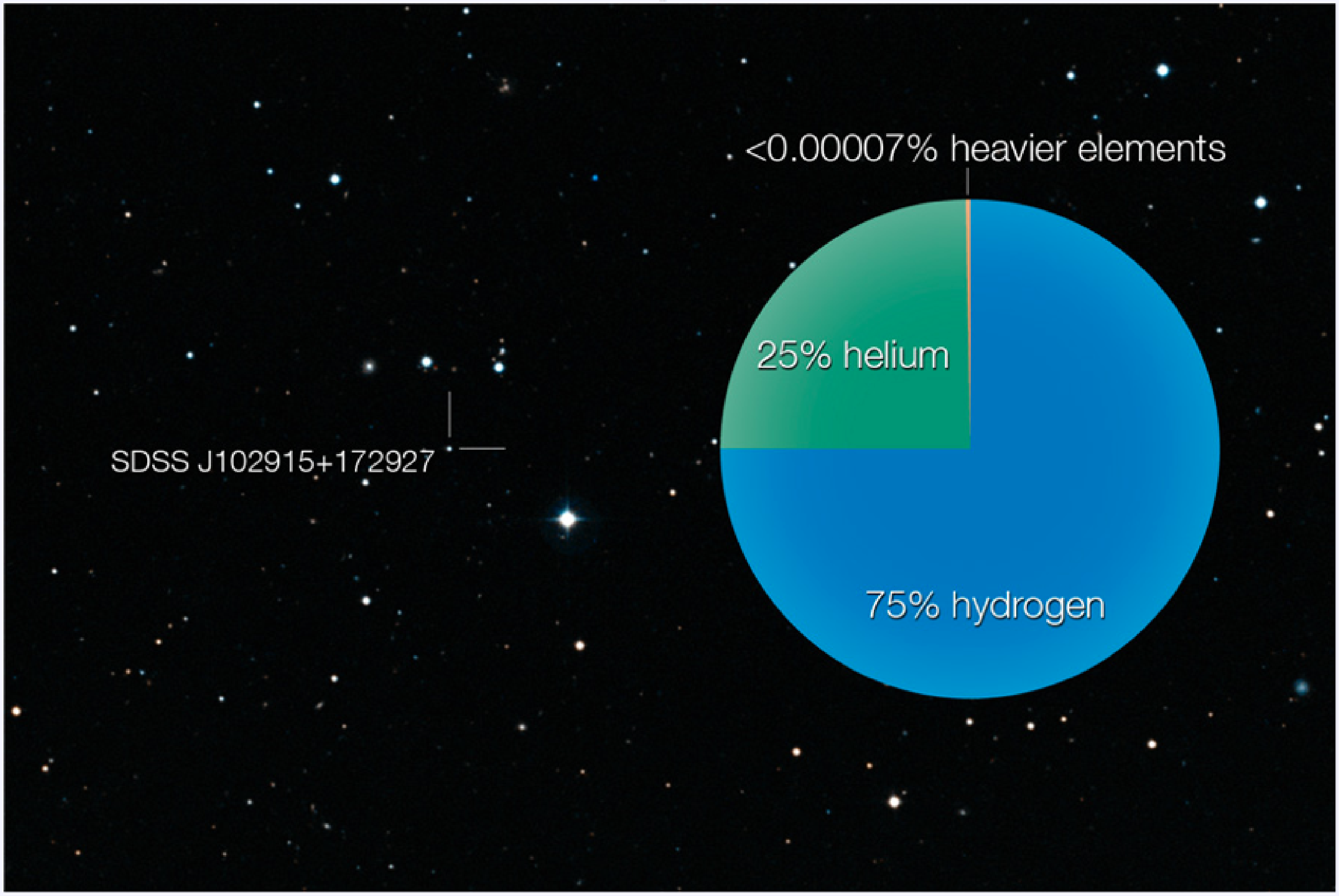


PR Image eso1132b
The composition of a

Astronomy Picture of the Day

Discover the cosmos! Each day a different image or photograph of our fascinating universe is featured, along with a brief explanation written by a professional astronomer.

2011 September 7



SDSS J102915+172927: A Star That Should Not Exist
Image Credit: ESO, DSS2

Chracterization of atmospheric abundances in spectroscopy

- Rarely interest in absolute amounts $\rightarrow$ relative numbers of atoms (not mass!)

- Usually: number of nuclei of of given chemical element X relative to 10^{12} hydrogen nuclei H (protons), logarithms!

$$\log \epsilon_{\mathrm{X}} = \log \epsilon(\mathrm{X}) = \mathrm{A}(\mathrm{X}) = \log(\mathrm{X}/\mathrm{H}) + 12 \tag{1}$$

  - $+12$ makes numbers usually positive; e.g., $\mathrm{A}(\mathrm{Fe})_{\odot} = 7.5$
  - nuclei: atoms might be ionized or bound in molecules which is ignored
  - hydrogen often most important contributor to continuous opacity

- Roughly, stellar abundances commonly scaled version of solar abundances $\rightarrow$ connecting stellar abundances to solar values

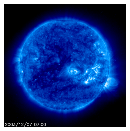
$$[\mathrm{X}/\mathrm{H}]_* = \log(\mathrm{X}/\mathrm{H})_* - \log(\mathrm{X}/\mathrm{H})_{\odot} \tag{2}$$

  - Example: $[\mathrm{O}/\mathrm{H}] = -1$ means that the star has 1/10 the ratio of oxygen to hydrogen nuclei as present in the solar atmosphere

- Depending on circumstances, sometimes other elements are chosen as reference (e.g., He, Si)

Processes & prescriptions 1

-  Photosphere & chromosphere: well described by continuum radiation-magneto-hydrodynamics

-  Corona & winds: depending on actual situation particle picture sometimes more adequate
  - low mass density, large mean free path of particles

- Energy transport
  - radiation $\rightarrow$ everywhere
  - gas currents, convection $\rightarrow$ cool star photosphere
  - waves $\rightarrow$ chromosphere, corona
  - heat conduction by electrons $\rightarrow$ corona

Processes & prescriptions 2

- Forces
  - gravity $\rightarrow$ (everywhere)
  - radiative force $\rightarrow$ 'radiation pressure', hot star photosphere, wind
  - gas pressure force $\rightarrow$ photosphere, chromosphere, wind
  - Lorentz force $\rightarrow$ magnetic environments, stellar spots, corona
  - momentum transport by waves $\rightarrow$ launching of winds
- Homogeneity? Mixing of matter
  - element diffusion $\rightarrow$ photospheres of A-type stars, magnetic fields
  - phase transitions $\rightarrow$ formation of 'dust clouds' in cool atmospheres (brown dwarfs, planets)

The shocking full R-MHD problem in Cartesian coordinates

$$\frac{\partial \rho}{\partial t} = -\vec{v}\,\nabla\rho - \rho\,\nabla\cdot\vec{v}$$ mass conservation

$$\rho\frac{\partial \vec{v}}{\partial t} = -\rho\vec{v}\cdot\nabla\vec{v} + \rho\vec{g} - \nabla P + \nabla\cdot\tau + \vec{K}_{\mathrm{Lorentz}} + \vec{K}_{\mathrm{rad}}$$ momentum conservation

$$\rho\frac{\partial e}{\partial t} = -\rho\vec{v}\,\nabla e - P\,\nabla\cdot\vec{v} + \rho\left(Q_{\mathrm{visc}} + Q_{\mathrm{Joule}} + Q_{\mathrm{rad}}\right)$$ energy conservation

$$\frac{\partial \vec{B}}{\partial t} = \nabla\times\left(\vec{v}\times\vec{B}\right) - \nabla\times\left(\eta\,\nabla\times\vec{B}\right)$$ induction equation

$$P = P(\rho, e)$$ equation of state

- ρ mass density, $\vec{v}$ velocity, $\vec{g}$ gravity vector, P gas pressure, $\vec{B}$ magnetic field, τ viscous stress tensor, $\vec{K}_{\mathrm{Lorentz}}(\vec{B})$ Lorentz force, $\vec{K}_{\mathrm{rad}}$ radiative force, η electric resistivity
- Q_{rad}, Q_{visc}, Q_{Joule} radiative, viscous, ohmic heating; functions of $f(\rho, e, \vec{v}, \vec{B})$
- homogeneous medium, no rotation, no mass diffusion

$\boxed{\textbf{Do we need all this?}}$

Do we need to tackle the full R-MHD problem?

- Well, yes and no . . ., observationally
  - limited spatial resolution
  - limited time resolution (stars are faint, collecting photons takes time)
- Pragmatic approach: restriction to what is needed to interpret the observations
- Nature (sometimes) helps by establishment of equilibria
  - physically: processes have enough time to reach a balance
  - micro-physically: (local) thermodynamic equilibrium (LTE, vs non-LTE or NLTE)
  - mathematically: seeking stationary solutions
- Stability of stationary solutions not always evident or guaranteed
  - pulsational instability (e.g., Cepheids, RR Lyrae)
  - convective instability ubiquitous in cool stars

Most stringent set of simplifying assumptions $\rightarrow$ std 1D models

- Isolated object (no binary causing external irradiation)

- 1D geometry: plane-parallel or spherical
  - all surface structure ignored (star-spots, granulation, active regions)

- Hydrostatic equilibrium, relatively short dynamical timescale
  - free-fall timescale $\ll$ evolutionary timescale
  - $\vec{v} \equiv 0$ or time-independent wind $v = v(r)$
  - gravitational force balanced by pressure force (and acceleration in wind)

- Thermal equilibrium, relatively short thermal timescale
  - Kelvin-Helmholtz timescale of surface layers $\ll$ evolutionary timescale
  - atmospheric heating and cooling processes balance each other
  - total energy flux $F_{\rm tot} = {\rm const}$, or $-\nabla \cdot F_{\rm tot} = Q_{\rm tot} = 0$

- No magnetic fields $\vec{B} = 0$

- Well mixed surface layers, chemically homogeneous

What remains of the full R-MHD problem

$$\frac{\partial \rho}{\partial t} = -\vec{v}\,\nabla\rho - \rho\,\nabla\cdot\vec{v} \equiv 0$$

$$\rho\frac{\partial \vec{v}}{\partial t} = -\rho\vec{v}\cdot\nabla\vec{v} + \rho\vec{g} - \nabla P + \nabla\cdot\tau + \vec{K}_{\mathrm{Lorentz}} + \vec{K}_{\mathrm{rad}} + \vec{K}_{\mathrm{conv}} = 0$$

$$\rho\frac{\partial e}{\partial t} = -\rho\vec{v}\,\nabla e - P\,\nabla\cdot\vec{v} + \rho\left(Q_{\mathrm{visc}} + Q_{\mathrm{Joule}} + Q_{\mathrm{rad}} + Q_{\mathrm{conv}}\right) = 0$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla\times\left(\vec{v}\times\vec{B}\right) - \nabla\times\left(\eta\,\nabla\times\vec{B}\right) \equiv 0$$

$$P = P(\rho, e)$$

- Normally written differently
  - radiative force written as gradient of 'radiative pressure' P_{rad}
  - convective force written as gradient of 'turbulent pressure' P_{turb}
- So-called mixing-length theory (rather recipe!) for treatment of convection

Standard equations describing a 1D stellar atmosphere plane-parallel geometry, radiative-convective equilibrium

$$\frac{dP_{\rm tot}}{dx} = \frac{d(P_{\rm gas} + P_{\rm rad} + P_{\rm turb} + \ldots)}{dx} = -\rho g$$

$$F_{\rm tot} = F_{\rm rad} + F_{\rm conv} = \mathrm{const} \quad \text{or} \quad Q_{\rm tot} = Q_{\rm rad} + Q_{\rm conv} = -\frac{d(F_{\rm rad} + F_{\rm conv})}{dx} = 0$$

$$P = P(\rho, T)$$

- Equation's simplicity deceptive: especially evaluation of $F_{\rm rad}$ complex
  - results from a solution of the radiative transport equation
  - complex wavelength dependence $\rightarrow$ many spectral lines
- Atmospheric parameters governing the physical conditions
  - effective temperature defined via $F_{\rm tot} = \sigma {T_{\rm eff}}^4$
  - surface gravity, usually given as $\log g$
  - chemical composition, 90+ numbers
  - total stellar mass or radius in the case of spherical models

Atmospheric parameters – some numbers

Star	Spec. Type	T_{eff} [K]	$\log g$ $[\mathrm{cm/s^2}]$	Radius $[10^3$km$]$	$H_{\mathrm{p}}^{\mathrm{surf}}$ $[10^3$km$]$
Sun	G2V	5 780	4.44	696	0.14
Procyon	F5IV	6 500	4.0	1 500	0.39
White Dwarf	DA	12 000	8.0	0.0075	0.00013
Red Giant	KII-III	3 700	1.0	66 000	240
Brown Dwarf	L	1 500	5.0	70	0.01
Earth	not yet	300(?)	2.99	6.378	0.0083

- Tremendous range in gravitational acceleration
- Only for extreme giants $H_{\mathrm{p}}^{\mathrm{surf}} \sim R$ so that sphericity effects become important

Steps for calculating a 1D model atmosphere

- Step 0: guess an initial temperature profile $T(x)$
- Step 1: hydrostatic equation + EOS to calculate $P(x)$
- Step 2: with known T, P and auxiliary quantities calculate $F_{\rm tot} = F_{\rm rad} + F_{\rm conv}$
- Step 3: $F_{\rm tot} = \rm const?$
  - yes: fine, we are done!
  - no: perform a temperature correction and repeat from Step 1
- T-correction important but still a bit of an 'alchemy' in present day codes
  - standard techniques: Unsöld-Lucy, Avrett-Krook, ...

Kurucz (1970, SAO Sepcial Report No. 309, p. 106):
It should be emphasized that the criterion for judging the effectiveness of a temperature correction is the total amount of computer time needed to calculate a model. Mathematical rigor is irrelevant. Any empirically derived tricks for speeding up convergence are completely justified.

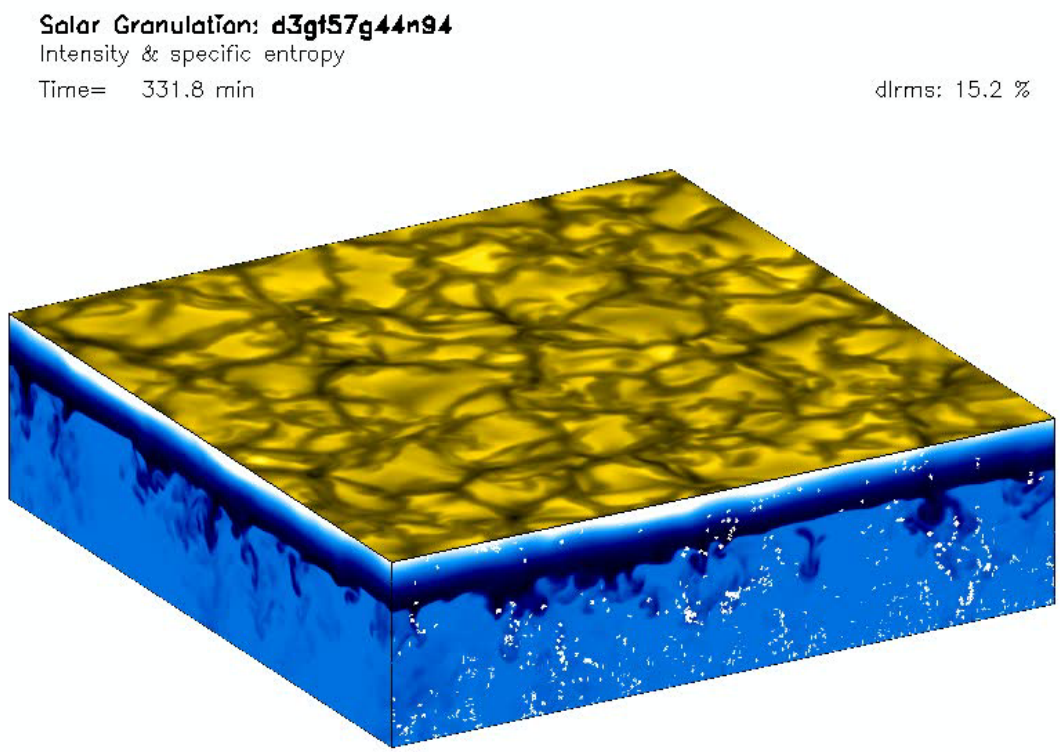
Example: ATLAS model of the solar atmosphere

TEFF 5777. LOG G 4.43770 [0.0] VTURB=1.0 KM/SEC L/H=1.25 NOVER ASPLUND ABUNDANCES ITERATION 45

	RHOX	TEMP	PRESSURE	DENSITY	HEIGHT (KM)	ROSSELAND DEPTH	FRACTION CONV FLUX	RADIATIVE ACCELERATION	PER CENT FLUX ERROR	PER CENT FLUX DERIV
1	4.727E-04	3682.4	1.295E+01	5.488E-11	0.000E+00	1.334E-07	0.000E+00	8.781E-02	0.003	-181.520
2	6.195E-04	3697.3	1.697E+01	7.165E-11	2.362E+01	1.778E-07	0.000E+00	9.797E-02	0.003	-15.161
3	7.905E-04	3716.7	2.166E+01	9.095E-11	4.495E+01	2.371E-07	0.000E+00	1.039E-01	0.003	-9.362
4	9.903E-04	3738.6	2.713E+01	1.133E-10	6.476E+01	3.162E-07	0.000E+00	1.068E-01	0.003	-6.422
5	1.224E-03	3762.1	3.353E+01	1.391E-10	8.335E+01	4.217E-07	0.000E+00	1.079E-01	0.003	-4.332
6	1.498E-03	3786.5	4.104E+01	1.692E-10	1.012E+02	5.623E-07	0.000E+00	1.080E-01	0.003	-3.313
7	1.819E-03	3811.5	4.983E+01	2.041E-10	1.184E+02	7.499E-07	0.000E+00	1.075E-01	0.003	-2.084
8	2.195E-03	3836.9	6.014E+01	2.447E-10	1.353E+02	1.000E-06	0.000E+00	1.064E-01	0.003	-0.673
9	2.637E-03	3862.6	7.223E+01	2.919E-10	1.517E+02	1.334E-06	0.000E+00	1.051E-01	0.003	-0.458
10	3.154E-03	3888.2	8.640E+01	3.469E-10	1.680E+02	1.778E-06	0.000E+00	1.036E-01	0.003	-0.549
...										
46	1.010E+00	4980.0	2.767E+04	8.676E-08	7.602E+02	5.623E-02	0.000E+00	2.717E-01	0.004	0.010
47	1.180E+00	5035.1	3.233E+04	1.003E-07	7.784E+02	7.499E-02	0.000E+00	3.010E-01	0.005	0.009
48	1.379E+00	5099.1	3.778E+04	1.157E-07	7.968E+02	1.000E-01	0.000E+00	3.345E-01	0.006	0.017
49	1.611E+00	5174.7	4.413E+04	1.332E-07	8.155E+02	1.334E-01	0.000E+00	3.733E-01	0.005	-0.057
50	1.880E+00	5264.1	5.150E+04	1.528E-07	8.343E+02	1.778E-01	1.519E-13	4.191E-01	0.001	-0.164
51	2.190E+00	5369.8	6.001E+04	1.745E-07	8.533E+02	2.371E-01	5.415E-10	4.757E-01	-0.009	-0.265
52	2.545E+00	5496.8	6.972E+04	1.981E-07	8.724E+02	3.162E-01	5.877E-08	5.501E-01	-0.042	-0.710
53	2.940E+00	5648.2	8.055E+04	2.227E-07	8.912E+02	4.217E-01	1.649E-05	6.584E-01	-0.101	-1.298
54	3.364E+00	5831.7	9.215E+04	2.467E-07	9.092E+02	5.623E-01	7.306E-04	8.338E-01	-0.034	0.841
55	3.783E+00	6082.4	1.036E+05	2.659E-07	9.256E+02	7.499E-01	1.423E-02	1.138E+00	0.304	0.255
56	4.169E+00	6334.9	1.142E+05	2.814E-07	9.397E+02	1.000E+00	7.794E-02	1.517E+00	0.281	-0.283
57	4.534E+00	6548.1	1.242E+05	2.959E-07	9.523E+02	1.334E+00	1.581E-01	1.892E+00	0.021	-0.137
58	4.883E+00	6777.8	1.338E+05	3.079E-07	9.639E+02	1.778E+00	2.350E-01	2.413E+00	0.036	-0.003
59	5.211E+00	7034.0	1.428E+05	3.164E-07	9.744E+02	2.371E+00	3.047E-01	3.158E+00	-0.019	0.000
60	5.513E+00	7315.7	1.510E+05	3.216E-07	9.838E+02	3.162E+00	3.649E-01	4.238E+00	0.046	0.098
...										
70	7.983E+00	9722.4	2.187E+05	3.394E-07	1.060E+03	5.623E+01	9.499E-01	5.045E+00	0.019	-0.007
71	8.341E+00	9904.8	2.285E+05	3.462E-07	1.070E+03	7.499E+01	9.616E-01	4.595E+00	-0.283	0.000
72	8.744E+00	10076.2	2.395E+05	3.548E-07	1.082E+03	1.000E+02	9.674E-01	4.608E+00	0.305	0.024

3D model atmospheres of cool stars

- 1D model atmospheres standard 'work-horses' in astronomy
- High-quality observational material demands for increasingly refined models



Devision of the world: codes for hot and cool atmospheres

- Demarcation line around spectral type A ($T_{\mathrm{eff}} \approx 10,000\,\mathrm{K}$)

- Codes for cool atmospheres
  - line blanketing treated in LTE with statistical techniques
    $\rightarrow$ ODFs, opacity sampling
  - treatment of convective energy transport in the framework of mixing-length theory

- Codes for hot stellar atmospehers
  - line blanketing treated as far as possible in NLTE
  - smaller number of lines allows explicite treatment
  - convective energy transport not important
  - sometimes inclusion of a stellar wind

- Distinction between codes for hot and cool atmospheres not strict

1D atmosphere codes – adapted from Stasińska et al. 2011

For each code the name is listed, whether it employes plane-parallel (P) of spherical (S) geometry (geom.), whether the line blanketing (blank.) is treated in LTE or NLTE (with approximations "≈"), a wind is included, and the main domains of application. The domains of application are denoted by the stellar spectral type, or particular classes of objects like brown dwarfs (BD), planets (Pl), novae (N), supernovae (SN), or Wolf-Rayet (WR) stars.

Name	geo.	blank.	wind	main application
ATLAS	P	LTE	no	AFGKM
MARCS	P	LTE	no	AFGKM
MAFAGS-OS	P	LTE	no	AFGKM
TLUSTY	P	NLTE	no	OBAFGKM, BD, Pl
PHOENIX	P,S	NLTE	yes	AFGKM, N, SN, BD, Pl
Detail/Surface	P	–	no	BA
TMAP	P,S	NLTE	no	hot compact stars
PoWR	S	NLTE	yes	WR
CMFGEN	S	NLTE	yes	OBA, WR, SN
WR-basic	S	NLTE	yes	OB with dense winds, SN
FASTWIND	S	≈NLTE	yes	OBA