Spectroscopy of giants and supergiants

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Motivation – why do spectroscopy of giant stars?
Spectroscopy – state-of-the-art in modeling and observations
Simulations – predictive power of theory
Conclusions – forthcoming instruments: what can we expect with ‘giants’ like E-ELT?
• low and high-mass, 0.6 \sim M \sim 30 \, M_{\odot}

• L: 10 - 10^3 \, L_{\odot} \ldots 10^2 - 10^3 \ldots 10^4 - 10^6

wide range of ages, metallicities, and extremely luminous!

see the talks by C. Evans, B. Davies, R. Kudritzki

T_{\text{eff}} : 3500 \ldots 5500 \, K
log g : -0.5 \ldots 3.5
[Fe/H]: from -5 to +0.5
Plume – mass loss

ESO VLT

Herschel Space Observatory (observations @ 60 – 600 mikron)

Betelgeuse: the nearest Red supergiant

Imaging

e-MERLIN radio interferometry (5 cm)
Motivation

- RSG’s, RGB’s, AGBs are so bright – best tracers of chemical abundances in galaxies
  bright in the IR – AO advantage
  with E-ELT’s we can go as deep as \( \sim \) Mpc
- and we still get a lot of giants in the Milky Way (bulge, outer disk, halo, Ultra-metal-poor stars)
- probe populations of all ages: from Myr to Gyr
- astro-seismology
  CoRoT, Kepler2 missions
  very precise \( \log(g) \) and (finally!) age determinations possible
- surface chemistry very sensitive to stellar nucleosynthesis
- they are so good-looking! – resolved (Interferometry) images possible
- Spectroscopy: the spectra are so rich with chemical elements
  In combination with million datasets from ongoing and future surveys (Gaia-ESO, APOGEE), we get a complete mapping of the Galaxy and extra-galactic populations (Local Group+)
RGB spectrum
Spectra

RGB spectrum

RSG spectrum

Flux (Arbitrary Units)

Wavelength (Å)
The worst situation for spectral analysis

- not only do we need to match this complexity with the spectral models
- but also to make sure the spectral models give good answers
Atmospheres of giants

1. Molecular opacities (+ a ‘forest’ of other parasitic spectral features)
2. Asymmetric shapes with ‘hot spots’ and mass loss
3. MOLsphere, Dust
   Deviations from hydrostatic equilibrium and giant convective cells
4. Deviations from local thermodynamic equilibrium (NLTE)
5. Chromospheres
1. Molecular opacities (+ a ‘forest’ of other parasitic spectral features)
Atmospheres of giants

1. Molecular opacities (\textit{+ a ‘forest’ of other parasitic spectral features})
2. Asymmetric shapes with ‘hot spots’ and mass loss

Interferometric observations resolve structure on Betelgeuse: hot spots, ‘plumes’ and giant convective cells

Haubois et al. (2009)  
Kervella et al. (2009)
Atmospheres of giants

1. Molecular opacities (+ a ‘forest’ of
2. Asymmetric shapes with ‘hot spots
3. MOLsphere, Dust

Circumstellar dust needed to explain Infra-red radiation excess

Tsuji (2003)
Atmospheres of giants

1. Molecular opacities (plus a ‘forest’ of other parasitic spectral features)
2. Asymmetric shapes with ‘hot spots’ and mass loss
3. MOLsphere, Dust
4. Deviations from hydrostatic equilibrium and giant convective cells

Chiavassa et al. (2011)

3D radiation hydrodynamics models of surface convection are needed
(Freytag et al. 2002)

\[
\begin{align*}
\frac{\partial \ln \rho}{\partial t} & = -\mathbf{u} \cdot \nabla \ln \rho - \nabla \cdot \mathbf{u}, \\
\frac{\partial \mathbf{u}}{\partial t} & = -\mathbf{u} \cdot \nabla \mathbf{u} + \mathbf{g} - \frac{P}{\rho} \nabla \ln P + \\
\frac{\partial e}{\partial t} & = -\mathbf{u} \cdot \nabla e - \frac{P}{\rho} \nabla \cdot \mathbf{u} + Q_{\text{rad}} + Q_{\text{visc}},
\end{align*}
\]
Atmospheres of giants

1. Molecular opacities (+ a ‘forest’ of other parasitic spectral features)
2. Asymmetric shapes with ‘hot spots’ and mass loss
3. MOLsphere, Dust
4. Deviations from hydrostatic equilibrium and giant convective cells

Convective motions overshoot into the photosphere

➔ the concept of a ‘mean’ 1D hydrostatic structure becomes meaningless

Red supergiant
1. Molecular opacities (+ a ‘forest’ of other parasitic spectral features)
2. Asymmetric shapes with ‘hot spots’ and mass loss
3. MOLsphere, Dust
4. Deviations from hydrostatic equilibrium and giant convective cells

Convective motions overshoot into the photosphere
→ the concept of a ‘mean’ 1D hydrostatic structure becomes meaningless

Red giant

Kervella et al. (2009)
Atmospheres of giants
Atmospheres of giants

1. Molecular opacities (+ a ‘forest’ of other parasitic spectral features)
2. Asymmetric shapes with ‘hot spots’ and mass loss
3. MOLsphere, Dust
4. Deviations from hydrostatic equilibrium and giant convective cells

Convective motions overshoot into the photosphere

→ the concept of a ‘mean’ 1D hydrostatic structure becomes meaningless

The effect of convection on the radiation field is strongest in deep layers of the atmosphere, where the optical and UV continua form.

Chiavassa et al. (2011)
Atmospheres of giants

1. Molecular opacities (+ a ‘forest’ of other parasitic spectral features)
2. Asymmetric shapes with ‘hot spots’ and mass loss
3. MOLsphere, Dust
4. Deviations from hydrostatic equilibrium and giant convective cells
5. Deviations from local thermodynamic equilibrium (NLTE)

Surface densities in giants and RSGs are $10^{-2}$ to $10^{-4}$ that of the Sun. Collisions are too weak to establish LTE. We need consistent non-local thermodynamic equilibrium transfer models.
Kervella et al. (2009)

1. Molecular opacities (a 'forest' of other parasitic spectral features)
2. Asymmetric shapes with 'hot spots' and mass loss
3. MOLsphere ($H_2O, SiO$)
4. Deviations from hydrostatic equilibrium and giant convective cells
5. Deviations from local thermodynamic equilibrium (NLTE)

Atmospheres of giants

NLTE – LTE abundance differences are mainly a function of $T_{eff}$ and metallicity:
- small impact at $[Z] \sim 0$

Bergemann et al. 2012
NLTE – LTE abundance differences are mainly a function of $T_{\text{eff}}$ and metallicity:
- small impact at $[Z] \sim 0$
- large impact at $[Z] < 0$
NLTE: excellent fits to spectra of RSG’s in Per OB1 cluster and smaller errors in [Fe/H] compared to classical models
Models and their predictive power
Models and their predictive power

- Simulations for modern and future instruments
  ISAAC (VLT), KMOS (Keck), NIRspec, XSHOOTER – R from 1000 to 20000
  CRIRES
  R $\sim$ 100000

- OPTIMOS-EVE,
  HARMONI (E-ELT)
  R $\sim$ 500 to 20000
  YJHK bands
High-resolution

Exquisite resolution is very useful: 15 chemical elements, isotopes red giants in the H-band – CRIRES, R up to 100000
Simulations

1. S/N 100, Res = 20000
2. S/N 30, Res = 6000
3. S/N 10, Res = 3000
Y-band: S/N 100, R - 20000

T_{\text{eff}} = 4300, \log(g) = 1.5, [\text{Fe/H}] = -0.5

Y-band
- Fe I
- Cr I
- Ti I
- Ca I
- Si I
- Sr II
- S I
- Ni I
J-band: S/N 100, R - 20000

$T_{\text{eff}} = 4300$, $\log(g) = 1.5$, $[\text{Fe/H}] = -0.5$
H-band: S/N 100, R - 20000

$T_{\text{eff}} = 4300$, $\log(g) = 1.5$, $[\text{Fe/H}] = -0.5$

H-band
- $\text{K I}$
- $\text{Si I}$
- $\text{Mg I, Al I}$
- $\text{Cr I}$
- $\text{Fe I}$
- $\text{Ti I}$
- $\text{Ni I}$
- $\text{CO}$
- $\text{CN}$
- $\text{OH}$
- $\text{V I (1.67)}$
K-band: S/N 100, R - 20000

$T_{\text{eff}} = 4300$, $\log(g) = 1.5$, $[\text{Fe/H}] = -0.5$
Simulations

1. S/N 100, Res = 20000
2. S/N 30, Res = 6000
3. S/N 10, Res = 3000
Y-band: S/N 30, R - 6000

$T_{\text{eff}} = 4300$, $\log(g) = 1.5$, $[\text{Fe/H}] = -0.5$

Y-band
- Fe I
- Cr I
- Ti I
- Ca I
- Si I
- Sr II
- S I
- Ni I
J-band: S/N 30, R - 6000

$T_{\text{eff}} = 4300$, $\log(g) = 1.5$, $[\text{Fe/H}] = -0.5$
H-band: S/N 30, R - 6000

$T_{\text{eff}} = 4300, \log(g) = 1.5, [\text{Fe/H}] = -0.5$

- K I
- Si I
- Mg I, Al
- Cr I
- Fe I
- Ti I
- Ni I
- CO
- CN
- OH
- V I (1.67)
K-band: S/N 30, R - 6000

$T_{\text{eff}} = 4300$, $\log(g) = 1.5$, $[\text{Fe/H}] = -0.5$

K-band
- Mg I
- Si I
- Fe I
- Sc I
- Al I
- Na I (2.2)
- C12/C13
- HF (2.3)
Simulations

1. S/N 100, Res = 20000
2. S/N 30, Res = 6000
3. S/N 10, Res = 3000
Y-band: S/N 30, R - 3000

$T_{\text{eff}} = 4300$, $\log(g) = 1.5$, $[\text{Fe/H}] = -0.5$
J-band: S/N 30, R - 3000

$T_{\text{eff}} = 4300$, $\log(g) = 1.5$, $[\text{Fe/H}] = -0.5$

J-band
- $K$ I
- $Si$ I
- $Mg$ I
- $Cr$ I
- $Fe$ I
- $Ti$ I
- $Ca$ I
H-band: S/N 30, R - 3000

$T_{\text{eff}} = 4300$, $\log(g) = 1.5$, $[\text{Fe/H}] = -0.5$

- $K\,I$
- $Si\,I$
- $Mg\,I$, $Al$
- $Cr\,I$
- $Fe\,I$
- $Ti\,I$
- $Ni\,I$
- $CO$
- $CN$
- $OH$
- $V\,I\,(1.67)$
K-band: S/N 30, R - 3000

$T_{\text{eff}} = 4300$, $\log(g) = 1.5$, $[\text{Fe/H}] = -0.5$

- Mg I
- Si I
- Fe I
- Sc I
- Al I
- Na I (2.2)
- C12/C13
- HF (2.3)
Red supergiant: S/N 100, R - 5000

$T_{\text{eff}} = 4400$, $\log(g) = 1$, $[\text{Fe/H}] = 0.0$

J-band
- K I
- Si I
- Mg I
- Cr I
- Fe I
- Ti I
- Ca II
Metal-rich giant $[\text{Fe/H}] = 0$, S/N 100, R - 20000
Metal-poor giant [Fe/H] = -3, S/N 100, R - 20000

Metal-poor stars:
Spectroscopy at least R = 20000
Conclusions

- great progress with instrumentation and spectroscopic surveys in the Milky Way medium/high-resolution, e.g. Gaia-ESO – optical, APOGEE - IR
- State-of-the-art models: atmospheres and radiative transport
  - attained the necessary level of complexity
  - need improvements to describe features forming in the chromospheres, outflows & dynamics
- IR is tricky
  - R > 20000 is needed for metal-poor stars
  - Red Supergiants – J-band O’K for R down to 3000

For the future generation instruments, well-defined programs based on simulations and careful target selection are needed.
One of possible scenarios: RGB surface

Tsuji (2002)
AGB stars: atmospheres

Decin (2013)
Modeling complexities

1. Molecular opacities
2. Asymmetric shapes with ‘hot spots’
3. MOLsphere (H₂O, SiO)
4. Deviations from hydrostatic equilibrium and giant convective cells

The effect of convection on the radiation field is huge in the frequencies of strong molecular absorption (e.g. TiO)

Chiavassa et al. (2011)
Spectra

warm TP-AGB spectrum

RSG spectrum

Lancon & Wood (2000)