DIVISION G
COMMISSION 36

THEORY OF STELLAR ATMOSPHERES
THÉORIE DES ATMOSPHÈRES STELLAIRES

PRESIDENT	**Joachim Puls**
VICE-PRESIDENT	**Ivan Hubeny**
PAST PRESIDENT	**Martin Asplund**
ORGANIZING COMMITTEE	**France Allard, Carlos Allende Prieto, Thomas R. Ayres, Mats Carlsson, Bengt Gustafsson, Rolf-Peter Kudritzki Tatiana A. Ryabchikova**

HEXENNIAL REPORT 2009-2015

1. Introduction

Different from previous triennial reports, this report covers the activities of IAU Commission 36 'Theory of Stellar Atmospheres' over the past *six* years†, and will be the last report from the 'old' Commission 36. After the General Assembly in Honolulu (August 2015), a new Commission 'Stellar and Planetary Atmospheres' (C.G5, under Division G, 'Stars and Stellar Physics') has come into life, and will continue our work devoted to the outer envelopes of stars, as well as extend it to the atmospheres of planets (see Sect. 4).

From its establishment in 1970 on (with Commission President Richard Thomas), Commission 36 has covered the field of the *physics* of stellar atmospheres, and closely related topics. For all this time, and also during the last six years, the scientific activities in this large field have been very intense, and have led to the publication of a large number of papers, which makes a detailed report even on the last hexennium almost impossible.

We have therefore decided on a two step approach. In the first part (Sect. 5), we highlight specific contributions that directly refer to the central topic of our – now ending – Commission, namely the *theory* of stellar atmospheres. Because of the somewhat different approaches, assumptions and methods, we divide this section into the atmospheres of late-type (low and intermediate mass) stars, and of massive stars. In the second part (Sect. 6), we keep the format of the preceding reports, namely we list the areas of current research. Web links for obtaining further information are provided in Sect. 7.

At first, however, we will briefly outline the composition of the Organization Committee of Commission 36 during the triennium 2009 to 2012 in Sect. 2 (the members quoted at the beginning of this report refer to the triennium between 2012 and 2015), summarize the scientific meetings held between 2009 and 2015 that were relevant for our Commission (Sect. 3), and comment on the establishment of the new Commission C.G5 (comprising

† because of technical reasons, the report on the years 2009 to 2012 could not be delivered.

an extended scientific field compared to the 'old' one) within the re-structuring process of the IAU.

2. Presidents and OC of Commission 36 during the triennium 2009 to 2012

President: Martin Asplund; Vice-President: Joachim Puls; Past President: John D. Landstreet; Organization Committee members: Carlos Allende Prieto, Thomas R. Ayres, Svetlana V. Berdyugina, Bengt Gustafsson, Ivan Hubeny, Hans G. Ludwig, Lyudmila I. Mashonkina, Sofia Randich

3. Scientific meetings related to the interests of Commission 36

Many conferences and workshops have been held during the period covered by this report on topics related to the interests of Commission 36. The following symposia were sponsored by the IAU: IAU Symposium No. 265 *Chemical Abundances in the Universe: Connecting First Stars to Planets*; IAU Symposium No. 268 *Light Elements in the Universe*; IAU Symposium No. 272 *Active OB stars: structure, evolution, mass loss, and critical limits*; IAU Symposium No. 273 *The Physics of Sun and Star Spots*; IAU Symposium No. 279 *The Death of Massive Stars: Supernovae and Gamma-Ray Bursts*; IAU Symposium No. 282 *From Interacting Binaries to Exoplanets: Essential Modeling Tools*; IAU Symposium No. 283 *Planetary Nebulae: An Eye to the Future*; IAU Symposium No. 294 *Solar and Astrophysical Dynamos and Magnetic Activity*; IAU Symposium No. 298 *Setting the scene for Gaia and LAMOST*; IAU Symposium No. 301 *Precision Asteroseismology*; IAU Symposium No. 302 *Magnetic Fields throughout Stellar Evolution*; IAU Symposium No. 305 *Polarimetry: The Sun to Stars and Stellar Environments*; IAU Symposium No. 307 *New windows on massive stars: asteroseismology, interferometry, and spectropolarimetry.*

Our members also participated in many of the Joint Discussions and Special Sessions at the IAU XXVII General Assembly in Rio de Janeiro, August 2009 (e.g., JD4 *Progress in Understanding the Physics of Ap and Related Stars*; JD10 *3D Views on Cool Stellar Atmospheres - Theory Meets Observation*; JD11 *New Advances in Helio- and Astero-Seismology*; JD13 *Eta Carinae in the Context of the Most Massive Stars*; SpS1 *IR and Sub-mm Spectroscopy - a New Tool for Studying Stellar Evolution*; SpS7 *Young Stars, Brown Dwarfs, and Protoplanetary Disks*),
and at the IAU XXVIII General Assembly in Beijing, August 2012 (e.g., JD2 *Very massive stars in the local universe*; SpS5 *The IR view of massive stars: the main sequence and beyond*; SpS13 *High-precision tests of stellar physics from high-precision photometry*).

Meetings not organised under the auspices of the IAU also attracted interest. Among others, the following international meetings were attended by our members:

Deciphering the Universe through Spectroscopy, September 2009, Potsdam, Germany; *The 3rd Magnetism in Massive Stars (MiMeS) Workshop*, November 2009, Hawaii, USA; *Magnetic Fields: From Core Collapse to Young Stellar Objects*, May 2010, London, Ontario, Canada; *Binary Star Evolution: Mass Loss, Accretion, and Mergers*, June 2010, Mykonos, Greece; *The Multi-Wavelength View of Hot, Massive Stars, July 2010*, Liege, Belgium; *The 10th International Colloquium on Atomic Spectra and Oscillator Strengths for Astrophysical and Laboratory Plasmas*, August 2010, Berkeley, USA; *17th European White Dwarf Workshop*, August 2010, Tübingen, Germany; *The 16th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, September 2010, Seattle, USA; *Workshop on Convection in Stars*, January 2011, Johannesburg, South-Africa; *8th Serbian*

Conference on Spectral Line Shapes in Astrophysics, June 2011, Divcibare, Serbia; *Stellar Atmospheres in the Gaia Era: Quantitative Spectroscopy and Comparative Spectrum Modelling*, June 2011, Brussels, Belgium; *Four Decades of Research on Massive Stars: A Scientific Meeting in the Honour of Anthony F. J. Moffat*, July 2011, Saint-Michel-des-Saints, Canada; *The Fifth Meeting on Hot Subdwarf Stars and Related Objects*, July 2011, Stellenbosch, South Africa; *From Atoms to Stars: The Impact of Spectroscopy on Astrophysics*, July 2011, Oxford, UK; *The Mass Loss Return from Stars to Galaxies*, March 2012, Baltimore, USA; *Circumstellar Dynamics at High Resolution*, March 2012, Foz do Iguacu, Brazil *30 Doradus: The Starburst Next Door, September 2012*, Baltimore, USA; *50 Years of Brown Dwarfs: from Theoretical Prediction to Astrophysical Studies*, October 2012, Ringberg Castle, Germany; *Putting A Stars into Context: Evolution, Environment, and Related Stars*, June 2013, Moscow, Russia; *Massive Stars: From alpha to Omega*, June 2013, Rhodes, Greece; *11th International Colloquium on Atomic Spectra and Oscillator Strengths for Astrophysical and Laboratory Plasmas*, August 2013, Mons, Belgium; *400 Years of Stellar Rotation*, November 2013, Natal, Brazil; *Ionising processes in atmospheric environments of planets, Brown Dwarfs, and M-dwarfs*, January 2014, RAS, London, UK; *The 18th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, June 2014, Flagstaff, USA; *Fast outflows in massive stars: from single objects to wind-fed and colliding-wind binaries*, July 2014, Geneva, Switzerland; *X-ray Astrophysics of Hot Massive Stars*, Scientific Event E1.3, COSPAR-14, August 2014, Moscow, Russia; *Bright Emissaries: Be Stars as Messengers of Star-Disk Physics*, August 2014, London, Ontario, Canada; *Magnetism and Variability in O stars*, September 2014, Amsterdam, The Netherlands; *The Brown Dwarf to Exoplanet Connection Conference: Making sense of Atmospheres and Formation*, October 2014, Newark, Delaware, USA; *Ringberg Workshop on Spectroscopy with the Stratospheric Observatory For Infrared Astronomy*, March 2015, Ringberg Castle, Germany; *Massive Stars and the Gaia-ESO Survey*, May 2015, Brussels, Belgium; *International Workshop on Wolf-Rayet Stars*, June 2015, Potsdam, Germany; *The physics of evolved stars: A conference dedicated to the memory of Olivier Chesneau*, June 2015, Nice, France.

4. Towards a new Commission on 'Stellar and Planetary Atmospheres'

During the General Assembly (GA) in Beijing 2012, several steps had been decided upon to initiate a re-structuring process of the IAU scientific bodies. At first, new Divisions were created that came into live just after the GA (regarding Commission 36, this refers to our new parent-Division G 'Stars and Stellar Physics'). Within a second step, all old Commissions were planned to terminate with the upcoming GA in Honolulu 2015, with new Commissions to be suggested and applied for during the year 2014. To this end, a subgroup of our OC, together with other interested scientists, were installed to discuss and prepare a proposal for a new Commission related to our present subjectives. After many discussions, a final group chaired by Ivan Hubeny and co-proposers France Allard, Katia Cunha and Adam Showman submitted a proposal on the establishment of a new Commission on 'Stellar and Planetary Atmospheres' within Division G. The original proposal (including the ideas/objectives behind it) can be found at `http://www.iau.org/submissions/newcommissions/detail/81/`, where it was suggested to

"... reshape the original Commission 36, 'Theory of Stellar Atmospheres', and to extend its scope beyond the stars to atmospheres of substellar objects like Brown Dwarfs and extrasolar planets."

In brief, it was thought that such an extension is possible and *required* in the present astronomical context, since the latter objects and their atmospheres are in the focus of intense studies (now and in future), and the physics/techniques to model and study their atmospheres are quite similar to the approach performed in the investigations of stellar atmospheres. The proposers concluded that "a fruitful interaction between the stellar and planetary communities, with connections to other areas where the stellar modeling paradigm can be applied, will be mutually beneficial."

Indeed, this proposal was approved by the IAU Executive Committee (Padua, Italy, 15-17 April 2015), together with various other proposals. Subsequently, the IAU members were asked to decide whether and in which Commission they want to participate, and 207 (status July 2015) decided to become a member of the new Commission C.G5. The new Commission President is the chair of the proposers, and the co-proposers became members of the OC. Just before the GA in Honolulu, elections for the Vice-President and the remaining OC members were conducted, and the complete list for our new Commission 'Stellar and Planetary Atmospheres' reads as follows:

President: Ivan Hubeny, Vice-President: Carlos Allende Prieto, OC-members: France Allard, Katia Cunha, John D. Landstreet, Thierry Lanz, Lyudmila I. Mashonkina, Adam Showman.

We are convinced that the new Commission (which started its activities just after the GA in Honolulu) will successfully continue and extend our previous work, and that they will promote the physics and modeling of stellar and planetary atmospheres worldwide.

5. Specific contributions related to the *theory* of stellar atmospheres

Before we summarize specific contributions and achievements within our research field during the last hexennium – as outlined in the introduction, here we will concentrate on theoretical work – let us mention that during the period covered by this report, a major textbook on stellar atmospheres was written and published, by Ivan Hubeny and the late† Dimitri Mihalas (Hubeny & Mihalas 2014), who also served as a President of this Commission between 1976 to 1979. In this textbook, one can find over 1200 references, many referring to publications from the covered time period.

5.1. *Late-type stars*

1D hydrostatic atmosphere models. One-dimensional, hydrostatic atmosphere models of late-type stars continue to be a staple food in the field of stellar physics and beyond in astronomy. Such models are continuously improved, especially in terms of accuracy and completeness of input data such as opacities. In recent years, extended grids of 1D, LTE stellar atmosphere models across a wide range of stellar parameter space for AFGKM stars have been computed using the MARCS (Gustafsson *et al.* 2008; Mészáros *et al.* 2012), MAFAGS (Grupp *et al.* 2009) and PHOENIX (Husser *et al.* 2013) codes. Short & Hauschildt (2009) investigated the importance of non-LTE effects for the atmospheric structures and UV radiation fields for a few benchmark stars, concluding that shortcomings in atomic data still exist. Claret *et al.* (2012, 2013) have employed 1D PHOENIX models to calculate detailed limb-darkening coefficients for a variety of photometric systems. de Laverny *et al.* (2012) calculated detailed synthetic stellar spectra for the MARCS grid of models and for a variety of chemical compositions to be used for stellar parameter and abundance determinations, especially for the new generation of large-scale spectroscopic

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† Dimitri Mihalas, known to all of us as a world-leading expert on stellar atmospheres, radiation hydrodynamics and spectroscopy, passed away on Nov. 21, 2013. We will greatly miss him.

surveys, such as the Gaia-ESO (Gilmore *et al.* 2012) and the GALAH survey (De Silva *et al.* 2015).

Stellar winds and mass loss of red giants and AGB stars. Models of dust-driven winds of carbon stars have been computed by Mattsson *et al.* (2010), Mattsson & Höfner (2011), and Eriksson *et al.* (2014), including an investigation of the importance of grain size on the resulting wind properties. Similar modelling but for M-type asymptotic giant branch stars has been carried out by Bladh & Höfner (2012), who found that a two-stage process is required: atmospheric levitation by pulsation-induced shock waves followed by radiative acceleration on dust grains. They investigated possible dust species, ruling out most but speculated that Mg_2SiO_4 is the main actor, which was confirmed by more detailed calculations by Bladh *et al.* (2015).

3D hydrodynamical models of stellar surface convection and atmospheres. More physically motivated and realistic models of the atmospheres and surface convection of late-type stars are now possible to compute using full 3D, time-dependent, radiative-hydrodynamical simulations that self-consistently predict the crucial radiative heating/cooling and convective energy transport (e.g. Nordlund *et al.* 2009, and references therein). Recently such modelling has been extended to stars other than the Sun, including for solar-type stars (Beeck *et al.* 2013; Hayek *et al.* 2010), red giant stars (Dobrovolskas *et al.* 2015), AGB and supergiants (Chiavassa *et al.* 2011), metal-poor stars (Collet *et al.* 2011), white dwarfs (Tremblay *et al.* 2013), M dwarfs (Wende *et al.* 2009), brown dwarfs (Freytag *et al.* 2010), and Cepheids (Mundprecht *et al.* 2015). Several 3D hydrodynamics codes are available for the purpose, which have been used to compute extensive grids of realistic 3D stellar models, including STAGGER (Magic *et al.* 2013a,b), CO5BOLD (Freytag *et al.* 2012; Ludwig & Kučinskas 2012), MURAM (Vögler *et al.* 2005; Rempel *et al.* 2009b), ANTARES (Muthsam *et al.* 2010; Grimm-Strele *et al.* 2015), and the Stein & Nordlund (1998) code (Trampedach *et al.* 2013). Beeck *et al.* (2012) concluded that different codes produce very similar results for the case of the Sun. Pereira *et al.* (2013) carried out a detailed comparison of the predictions of a 3D solar model computed with the STAGGER code against an arsenal of observational diagnostics and found extremely satisfactory agreement, demonstrating that such 3D models are indeed highly realistic. Such 3D stellar models have been used among others to calculate limb-darkening (Magic *et al.* 2015a), stellar spectra (Ramírez *et al.* 2009), and stellar oscillations and asteroseismic diagnostics (Samadi *et al.* 2013a,b).

Stellar magneto-convection. Magnetic fields are ubiquitous in late-type stars such as the Sun (e.g. Stein 2012, and references therein). Fabbian *et al.* (2010) and Fabbian *et al.* (2012) calculated 3D MHD models of varying magnetic field strengths for the Sun and investigated the impact on the resulting spectral line profiles and inferred solar Fe abundance, finding significant differences compared with pure 3D hydrodynamical models. However, Moore *et al.* (2015) found that the assumed magnetic field topology is important and concluded that more realistic initial configurations result in reduced differences with previous, pure hydrodynamical modelling. Beeck *et al.* (2015a) have calculated 3D MHD models for different FGM dwarfs for a range of field strengths, discovering notable differences in the manifestation of the magnetic fields depending on the stellar parameters. Beeck *et al.* (2015b) used these 3D MHD models to investigate the impact on the predicted stellar spectra. The physics and dynamics of sunspots have been modelled by Rempel *et al.* (2009a) and Rempel (2011) by means of 3D MHD simulations, achieving impressive agreement with observations. Hotta *et al.* (2015) and Rempel (2014) have investigated the small-scale dynamo in the solar convection zone and how it generates the solar magnetic field and its various manifestations.

Calibrating the mixing length theory using 3D stellar models. One very attractive feature with realistic 3D hydrodynamic stellar models is their ability to predict the convective energy transport without invoking any free parameters such as the traditional mixing length parameters or close relative thereof required in 1D stellar atmosphere and interior models. It is thus possible to calibrate the mixing length theory using 3D models, something which has recently been carried out by Trampedach *et al.* (2014) and Magic *et al.* (2015b). They find significant variations of the mixing length parameter across the HR-diagram, in contrast to the constant value calibrated on the Sun invariably assumed in traditional 1D modelling.

Non-LTE radiative transfer. Detailed radiative transfer calculations taking into account departures from local thermodynamic equilibrium for key elements and transitions have been carried out by several groups, including by Bergemann *et al.* (2013) who investigated line formation in red supergiants. Mashonkina *et al.* (2011) and Lind *et al.* (2012) performed comprehensive non-LTE computations for Fe for late-type stars using 1D model atmospheres. Bergemann *et al.* (2012) did similar calculations for a selection of well-studied benchmark stars but employed also spatially and temporally averaged 3D models (thus reducing them to effectively 1D models but with a more realistic atmospheric stratification). Full 3D non-LTE calculations have been carried out by Amarsi *et al.* (2015), who investigated the line formation of O across a large range of stellar parameter space, finding substantial non-LTE effects at solar metallicity but surprisingly small departures at low metallicity. Steffen *et al.* (2015) have performed 3D non-LTE line formation calculations for the O I 777nm triplet in the Sun. Lind *et al.* (2013), and Sbordone *et al.* (2010) have investigated departures from LTE in 3D hydrodynamical stellar atmosphere models for Li in metal-poor stars. Hauschildt & Baron (2010), Hauschildt & Baron (2014) and Pereira & Uitenbroek (2015) have developed new and computationally efficient codes to handle 3D non-LTE radiative transfer for parallel processing (see also Sect. 5.2).

Solar chemical composition. The exact chemical make-up of the Sun continues to attract a great deal of attention. This fundamental yardstick for astronomy has undergone a drastic downward revision for the most abundant metals – C, N, O and Ne in particular – over the past 15 years. Asplund *et al.* (2009) published a comprehensive solar analysis of all spectroscopically accessible elements using a realistic 3D hydrodynamic solar atmosphere STAGGER model, non-LTE spectral line formation, updated atomic/molecular data and careful consideration of blending lines. This is the first time all elements have been analysed homogeneously and with the statistical and systematic uncertainties carefully estimated. Further details of their 3D-based solar analysis are available in Pereira *et al.* (2009), Scott *et al.* (2015b), Scott *et al.* (2015a), and Grevesse *et al.* (2015). A similar solar analysis using an independent 3D solar model computed with the CO5BOLD code but for a restricted selection of elements has been carried out by Caffau *et al.* (2009), Caffau *et al.* (2010) and Caffau *et al.* (2015); a summary of the group's findings in terms of the solar composition is available in Caffau *et al.* (2011a). Their derived C, N and O abundances are intermediate between the low values advocated by Asplund *et al.* (2009) and the canonical high values from two decades ago. Similar intermediate abundances are supported by Pinsonneault & Delahaye (2009) who assessed the available spectroscopic analysis at the time although did not carry out their own line formation calculations. Fabbian *et al.* (2010) and Moore *et al.* (2015) have investigated the influence of magnetic fields in the quiet Sun on the emergent spectral line profiles and derived abundances of Fe, concluding that the impact is very modest for the transitions typically used in solar abundance analysis.

The new solar chemical composition, especially the low C, N, O and Ne abundances found by Asplund *et al.* (2009), has caused a great deal of consternation within the helioseismology community: solar models constructed with the new solar chemical composition no longer agree with the sound speed variation with depth, He abundance in the convection zone and the depth of the convection zone inferred from solar oscillations (e.g. Serenelli *et al.* 2009; Villante *et al.* 2014). Many possible solutions to this *solar modelling problem* have been proposed over the past decade, none entirely successful to date. The suggestion that the problem arises from missing opacity in the solar interior, especially immediately below the convection zone, has recently received very convincing support from new experimental opacity measurements (Bailey *et al.* 2015). These new data imply that the predicted opacities for Fe based on state-of-the-art calculations such as OP and OPAL are wrong by 30-400%. By themselves, the new Fe opacities can explain half of the *solar modelling problem*; similar experiments for other elements and improved atomic physics calculations are urgently needed whether missing opacity is the full solution. It is important to note that this is a *stellar* physics problem rather than only facing solar physics: whatever the solution turns out to be, it will have profound implications for all of stellar physics and by inference much of astronomy.

First stars. Much work in recent years has focussed on the nature of the very first generations of stars formed after the Big Bang as inferred from the chemical compositions of extremely metal-poor stars. Detailed 3D hydrodynamical stellar atmosphere models have been calculated for a few of the most metal-poor stars discovered to date, including for SMSS J031300.36-670839.3, the current record-breaker in terms of Fe abundance (Keller *et al.* 2014): a remarkable upper limit of $10^{-7.1}$ times the solar abundance. This star however has enormous over-abundances of C and O as inferred from 3D LTE calculations of CH and OH lines (Bessell *et al.* 2015), making its overall metal content low but not particularly extreme. Instead the star with the lowest overall metallicity is SDSS J102915+172927, for which Caffau *et al.* (2011b) analysed the chemical composition using a 3D stellar atmosphere CO5BOLD model.

Molecule and dust formation in brown dwarfs and (exo-)planetary atmospheres. The low temperatures and high densities encountered in the atmospheres of brown dwarfs and exoplanets are conducive to the formation of complex molecules and eventually nucleation and condensation of various species of dust (e.g. Allard *et al.* 2012; Helling & Fomins 2013). Helling & Casewell (2014) has reviewed the literature of atmospheres of brown dwarfs, remarking that dust forms already at effective temperatures of about 2,800 K, coincidentally marking roughly the boundary between M dwarfs and brown dwarfs. Witte *et al.* (2009) performed detailed calculations for dust nucleation, condensation and evaporation and allowing for dust drift in brown dwarfs and extra-solar planets for a range of stellar parameters and chemical compositions using 1D PHOENIX models. They concluded that dust formation is ubiquitous and that the dust-to-gas ratio does not scale linearly with the object's metallicity for a given effective temperature. Freytag *et al.* (2010) have studied the role of convection, overshoot, and gravity waves for the transport of dust in M dwarf and brown dwarf atmospheres using 3D hydrodynamical models with a simplified treatment of dust formation.

5.2. *Massive stars and related objects*

Atmospheric models/spectrum synthesis for massive stars require(s) a non-LTE (NLTE) treatment, and in many cases the inclusion of a stellar wind. Przybilla (2010) summarized the construction of the underlying model atoms, and Puls (2009) reviewed various aspects of the above requirements, including a brief comparison of the most-

used model codes suited for the analysis of massive stars, namely DETAIL/SURFACE, TLUSTY/SYNSPEC (both codes: plane-parallel, hydrostatic), CMFGEN, FASTWIND, PHOENIX, PoWR, and WM-basic (latter five codes: spherical, including winds). For original references, see Puls (2009), but note that most of these codes have been updated since release, which is also true for the NLTE OB-star wind models updated by Krtička & Kubát (2009) regarding the X-ray emission from wind-embedded shocks. Overviews of specific codes can be found in Hubeny & Lanz (2011a, TLUSTY), Hubeny & Lanz (2011b, SYNSPEC), Hillier (2012, CMFGEN), Rivero González *et al.* (2012, FASTWIND) and Hamann *et al.* (2009, PoWR). Model grids for massive stars have published by Zsargo *et al.* (2013, CMFGEN) and by Todt *et al.* (2015, PoRW: WN-stars). Massey *et al.* (2013) compared the results when analyzing observed spectra by means of either CMFGEN or FASTWIND, whilst Przybilla *et al.* (2011) compared the results from ATLAS9/SYNTHE and TLUSTY/SYNSPEC vs. DETAIL/SURFACE.

Similar (NLTE-) methods as used above have been applied to model the ejecta/remnants of supernovae and corresponding emergent spectra (Noebauer *et al.* 2012; Kerzendorf & Sim 2014; Pauldrach *et al.* 2014), to calculate theoretical models/spectra of accretion disks in AGN (Hubeny *et al.* 2010), and to model the atmospheres of Brown Dwarfs and extrasolar giant planets (Hubeny 2012).

Multi-D radiative transfer. The 'general-purpose' code PHOENIX has been updated and tested for 3-D radiative transfer in spherical/cylindrical coordinate systems and an operator-splitting technique (Hauschildt & Baron 2009, 2010), including a multi-level NLTE description (Hauschildt & Baron 2014). Weber *et al.* (2013) reported on 3-D modeling of ionized gas (objective: cosmic reionization) and the 3-D, time-dependent modeling of the metal ionization in HII regions, irradiated by consistent atmospheric models of (very) massive stars. Ibgui *et al.* (2013) presented a first version of the 3-D, plane-parallel radiative transfer code IRIS.

Time-dependent radiative transfer has been implemented in the context of spectrum synthesis of supernovae (Kromer & Sim 2009; Hillier & Dessart 2012; Dessart *et al.* 2014; Dessart & Hillier 2015; Dessart *et al.* 2015).

Macroturbulence and subsurface convection. As a first hypothesis, supersonic macroturbulence (detected in the spectral lines from the majority of OB-stars) has been suggested as a collective effect from gravity mode pulsations (Aerts *et al.* 2009), and such relation has been studied by, e.g., Simón-Díaz *et al.* (2010, 2011, 2012). Macro- (and also micro-)turbulence might be also related to the presence of a subsurface convection zone due to the iron-opacity peak (Cantiello *et al.* 2009; Grassitelli *et al.* 2015). Such convection zones might be suppressed by strong magnetic fields, as indicated by absent macroturbulence in the highly magnetic star NGC 1624-2 (Sundqvist *et al.* 2013a).

Envelope inflation. Also because of the iron-opacity peak, stellar envelopes might become inflated near the Eddington-limit, which would explain the (previous) discrepancy between the radii of Wolf-Rayet stars derived either from spectroscopy or from stellar modeling (Gräfener *et al.* 2012). Such inflation has meanwhile been studied also in evolutionary models, both for massive main-sequence stars (Sanyal *et al.* 2015) and for Wolf-Rayet stars (Sanyal *et al.* 2015).

Stellar winds and outflows – stationary mass-loss. A new method to model line-driven winds, based on Monte Carlo radiation hydrodynamics, has been presented by Noebauer & Sim (2015). Curé *et al.* (2011) studied 'slow' wind solutions for A-type Supergiants, and Silaj *et al.* (2014) revisited line-driven winds in the context of Be Stars, based on such slow solutions. Müller & Vink (2014) provided solutions for the velocity field and mass-loss rates for 2-D axisymmetric outflows, whilst in a series of papers Lucy (2010a,b,

2012a) derived O-star mass fluxes (also at low metallicities) using a code for constructing moving reversing layers.

In the context of so-called weak winds, Lucy (2012b) revised a phenomenological two-component (hot and cool gas) model, where the external outflow turns out to become a decelerating, coronal wind (see also Huenemoerder *et al.* 2012 below).

In rapidly rotating stars close to critical rotation, mass and angular momentum can be lost via decretion disks (Krtička *et al.* 2011), and time-dependent models of such disks have been modeled by Kurfürst *et al.* (2014).

Stellar winds – mass-loss near the Eddington limit and Very Massive Stars (VMS), Wind models of VMS have been presented by Vink *et al.* (2011) and Pauldrach *et al.* (2012), where the former authors concentrated on optically thick and the latter on optically thin winds. Gräfener *et al.* (2011) stressed that the Eddington factor is key to understand the winds of the most massive stars, and found evidence for an Eddington-Gamma dependence of Wolf-Rayet type mass loss. The sub-photospheric layers of classical Wolf-Rayet stars were traced by Gräfener & Vink (2013), and Owocki & Shaviv (2012) provided their view on instabilities and mass loss near the Eddington Limit.

Stellar winds – bi-stability braking. A potentially decisive process for the late and post main sequence evolution of massive stars has been identified by Vink *et al.* (2010), the so-called bi-stability braking: due to the predicted increase of mass-loss over the bi-stability jump, significant angular momentum might be lost, and the steep drop in the rotation rates of B-supergiants below 22,000 K might be elegantly explained.

Stellar winds – interaction with magnetic fields. Though only present in roughly 10% of massive stars, magnetic fields need to explained†, and their interaction with line-driven winds to be (further) studied. ud-Doula *et al.* (2009) performed dynamical simulations of magnetically channelled, line-driven winds, and calculated the angular momentum loss and rotational spin-down. Sundqvist *et al.* (2012) devised a dynamical magnetosphere model for the periodic H_α-emission from the magnetic O star HD 191612, and ud-Doula *et al.* (2013) performed first 3-D MHD simulations of a massive-star magnetosphere, applying their model to the H_α-emission from Θ^1 Ori C. The radiative cooling in multi-D models of magnetically confined wind shocks was investigated by ud-Doula (2013), and a magnetic confinement versus rotation classification of massive-star magnetospheres has been presented by Petit *et al.* (2013).

Stellar winds – instabilities/wind-embedded shocks. The possibility to obtain clumping also in the inner winds of hot, massive stars (due to the presence of limb-darkening when calculating the line-force) has been studied and discussed by Sundqvist & Owocki (2013). Such early onset has been actually measured, by means of X-ray spectroscopy, in the wind of QV Nor (B0I) (Torrejón *et al.* 2015). Progress on the effects of scattering (w.r.t. the transonic solution topology and the intrinsic variability of line-driven winds) has been obtained by Sundqvist & Owocki (2015). Owocki *et al.* (2013) studied the effects of thin-shell mixing in radiative wind-shocks, and Cohen *et al.* (2014) measured the shock-heating rates in O-star winds using X-ray line spectra.

Stellar winds – X-ray and Gamma-ray emission (general, and from clumped winds in High Mass X-ray Binaries). The X-ray emission from wind-embedded shocks was studied by means of hydrodynamical simulations in NLTE wind models (Krtička *et al.* 2009), and Leutenegger *et al.* (2010) modeled the broadband X-ray absorption in massive star winds. An interesting possibility to solve the so-called weak wind problem in massive stars by

† to date, the hypothesis of fossil origin is favoured, e.g., Braithwaite 2014

means of X-ray spectroscopy has been presented by Huenemoerder *et al.* (2012), revealing a massive *hot* wind (for the example of μ Col).

Nazé *et al.* (2014) investigated general aspects of the X-ray emission from *magnetic* massive stars, whilst ud-Doula *et al.* (2014) considered the specific effects of a cooling-regulated shock retreat w.r.t. the X-ray emission from magnetically confined wind shocks.

Oskinova *et al.* (2012) highlighted the impact of wind clumping in supergiant High Mass X-ray Binaries (HMXBs) on X-ray variability and photoionization. Wind clumping also affects the variability at even higher, Gamma-ray energies, in HMXBs with jets (Owocki *et al.* 2009), and such Gamma-Ray Emission has been modeled by Owocki *et al.* (2012) for the case of the HMXB LS 5039.

Radiative transfer – wind-inhomogeneities. During the covered period, a main focus of radiative transfer in massive star atmospheres was the (phenomenological) description and implementation of wind-inhomogeneities (most likely related to the line-driven instability). Particularly, the effects from optically thick clumps leading to 'macro-clumping' and porosity in physical and velocity space have been investigated. The multi-D resonance line formation in such inhomogeneous media was studied by Sundqvist *et al.* (2010) and Šurlan *et al.* (2012), and macro-clumping/porosity was suggested as a solution for the long-standing discrepancy between H_α and P V mass loss diagnostics (Oskinova *et al.* 2007; Sundqvist *et al.* 2011; Šurlan *et al.* 2013). Sundqvist *et al.* (2014) suggested an effective-opacity formalism for the line transfer in accelerating, clumped two-component media, which is ready to be implemented in state-of-the-art, NLTE model atmosphere codes.

Radiative transfer – X-ray line diagnostics. Another focus of radiative transfer was set to X-ray line diagnostics, also here in combination with wind-inhomogeneities. Sundqvist *et al.* (2012) formulated a generalized porosity formalism for isotropic and anisotropic effective opacity (spherical vs. oblate/prolate clumps), and studied its effects on the X-ray line attenuation in clumped winds. Leutenegger *et al.* (2013) provided constraints on porosity and mass loss, from modeling of X-ray emission line profile shapes, concluding that 'X-ray mass-loss rate estimates are relatively insensitive to both optically thin and optically thick clumping'. Additionally, they compared their method with the alternative one by Oskinova *et al.* (2006).

Using various techniques (partly related to those just mentioned), the X-ray spectra of individual Galactic O-stars were analyzed, and mass-loss rates, structure and shock physics constrained (Cohen *et al.* 2010 and Hervé *et al.* 2013: ζ *Pup*; Rauw *et al.* 2015: λ *Cep*; Cohen *et al.* 2014: sample of Galactic O-stars).

Radiative transfer – The formation of specific lines affected by complex NLTE effects was studied in various publications. Rivero González *et al.* (2011) revisited the Nitrogen III emission line formation in O-stars (those classified by 'f'), and demonstrated that the emission is due to wind effects, but rather unaffected by dielectronic recombination as had been suggested previously. The formation of C III 4647-50-51 and C III 5696 in O star atmospheres, essential to derive carbon abundances, has been explained by Martins & Hillier (2012). In this context, strong constraints on the [N/C] vs. [N/O] abundance ratios (for CNO cycled material mixed into the atmosphere) that are (almost) independent on specific evolutionary scenarios have been outlined by Przybilla *et al.* (2010).

Petrov *et al.* (2014) discussed the formation and behaviour of H_α over the theoretically predicted bi-stability jump in blue supergiants, and Przybilla (2010) and Najarro *et al.* (2011) investigated the NLTE line formation in the near-IR and the L-band, respectively.

Analysis techniques. Various publications dealt with specific analysis techniques. First, we refer to problems in the application of the popular Fourier transform method to derive

rotational velocities, when analyzing slowly rotating stars (Sundqvist *et al.* 2013b) or stars with time-dependent profiles (because of pulsations, Aerts *et al.* 2014). Simón-Díaz *et al.* (2011) presented a grid-based automatic tool for the quantitative spectroscopic analysis of O-stars (IACOB-GBAT), whilst DISKSPEC (Hubeny 2013) is a new tool for analyzing the spectra of accretion disk systems. BONNSAI (Schneider *et al.* 2014) is a Bayesian tool for comparing observationally derived stellar parameters with stellar evolution models. In this context, a valuable, radius-free analogue to the conventional Hertzsprung-Russell diagram is provided by the the 'spectroscopic Hertzsprung-Russell diagram', with axes T_{eff}^4/g vs. T_{eff} (Langer & Kudritzki 2014).

6. Primary research areas 2009 - 2015

6.1. *Physical processes*

General properties. Line-blanketed, unified NLTE models of massive star atmospheres (including winds) available to the community. 3D radiative-hydrodynamical models of stellar surface convection and atmospheres for a range of temperatures, gravities and metallicities corresponding to late-type stars. Magneto-convection in stars. 1D hydrodynamical models of atmospheres and dust-driven winds of AGB stars. Dust nucleation and condensation in planetary and brown dwarf atmospheres. Continuous and atomic/molecular line opacities. Non-equilibrium spectrum formation and chemistry. Grids of synthetic fluxes and spectra. Calibrating parameterized models through physical modeling. Calibrating abundance determinations by filter photometry or low-resolution spectroscopy. Laboratory studies of laser-induced plasma to simulate physical conditions in stellar atmospheres.

Hydrodynamical processes within stellar atmospheres. Convection (granulation) in surface layers, and its effects upon emergent spectra. Interplay between convection and non-radial pulsation. Scales of surface convection in stars in different stages of evolution. Hydrodynamic simulations of entire stellar volumes. 3D convection simulations of white dwarfs. Calibration of mixing length theory of convection using 3D hydrodynamical stellar models. Effects of magnetic fields on atmospheric structure and emergent spectrum. Excitation of solar/stellar oscillations by surface convection. Sub-surface convection in massive stars. Inflation of massive star atmospheres.

Transient processes. Shocks in pulsating stars. Radiative cooling of shocked gas. Emission lines as shock-wave diagnostics. Co-rotating interaction regions in radiation driven stellar winds. Particle acceleration during flares. Interaction of jets with interstellar medium. Episodic outflows and star-disk interaction.

Magnetic phenomena. Magnetic structures in single and binary stars. Dynamo generation of magnetic fields by convection. Observational manifestation of stellar magnetic fields. Magnetic surface phenomena: sun-/starspots, bright pores, active regions, flares etc. Magnetic and acoustic heating of solar/stellar chromospheres and coronae. Generation of magnetic fields in massive stars. Discovery of strong magnetic fields in roughly 10% of massive stars. X-ray line emission from magnetically confined winds. Interaction of magnetic fields and radiation-driven winds. Effects by magnetic fields on convective structures. Exploration of the turbulent nature of the general field of the Sun. Magnetic cycles at varying activity levels. Polarized radiation, gyrosynchrotron and X-ray emission. Deriving and interpreting Zeeman-Doppler images of stellar surfaces. Hanle effect diagnostics in stellar environments.

Radiative transfer and emergent stellar spectra. Effects on atmospheric structure by deviations from local thermodynamic equilibrium (non-LTE). Multidimensional radiative transfer. 3D non-LTE spectral line formation. Radiative hydrodynamics. Origin and

transfer of polarized light. Theory of scattering of polarized light by atoms and molecules, particularly for understanding the second solar spectrum. Numerical methods in radiative transfer. Scattering mechanisms in circumstellar disks. Impact of optically thick clumps in stellar winds on line and continuum formation (UV and X-rays). Atomic and molecular opacities (line and continuous).

Spectral lines and their formation. Line formation in convective atmospheres. Explanation of classical micro-/macroturbulent velocities as convective and oscillatory Doppler shifts. Wavelength shifts and spectral line profiles as signatures of convection. Non-LTE radiative transfer. 3D LTE spectral line formation. Full 3D non-LTE radiative transfer calculations with realistic atomic models. Hydrogen lines as stellar thermometers. Fe excitation and ionization balance as temperature and gravity indicators. Automated and accurate abundance analyses for large-scale spectroscopic surveys. Detection of strong broadening of metal lines in OB supergiants, and interpretation in terms of supersonic 'macroturbulence'. Spectra of rapidly rotating stars viewed pole-on and equator-on. Non-LTE effects in permitted and forbidden lines. Explanation of N III $\lambda\lambda$ 4634-4640-4642 emission in O-stars due to wind effects. Line formation of optical C III lines in massive stars. NLTE IR-diagnostics of massive hot stars, particularly those close to the Galactic Centre. X-ray line emission from line-driven winds in massive stars. Atomic and quantum processes affecting spectral lines. Databases for spectral lines. Atlases of synthetic spectra.

Forbidden lines and maser emission. Molecules in atmospheres of cool giant stars. Effects of fluorescence. Permitted and forbidden lines from shocked atmospheres of pulsating giants. Maser and laser emission from stellar envelopes.

Chemical abundances. Precise abundance measurements in BA supergiants. N abundances for massive stars as a function of rotation, which challenge present stellar evolution models. Abundance anomalies. Solar chemical composition. 3D and/or non-LTE based stellar abundance analyses. Chemical compositions of stars from large-scale spectroscopic surveys. Neutron-capture elements in solar-type and low-metallicity stars. Li, C and O abundances in exoplanet host stars to probe planetary properties. Stellar chemical signatures of planet formation. Lithium isotopes in metal-poor stars. Nucleosynthetic signatures of the first stars. Hydrodynamical models of metal-poor stars. Depletion of light elements through convection and mixing processes: diffusion, rotation, turbulence etc. Pollution of atmospheres by interstellar dust. r- and s-process elements. Chemical stratification in stable atmospheres. Coronal versus photospheric abundances. Chemical inhomogeneities and pulsation.

Molecules. Theory of the molecular Paschen-Back effect, scattering and Hanle effect in molecular lines in the Paschen-Back regime. Molecular linelists based on realistic quantum mechanical calculations. Molecule and dust formation in brown dwarfs and planetary atmospheres. Non-equilibrium chemistry. Non-LTE radiative transfer for molecules. Molecular lines as abundance indicators in the Sun and late-type stars. Molecules to infer stellar parameters of M dwarfs.

6.2. *Stellar structure*

Structures across stellar disks. Doppler mapping of starspots. Radii and oblateness at different wavelengths for giant stars. Gravitational micro-lensing and transits to test model atmospheres. Interaction between rotation and pulsation. Doppler tomography of stellar envelopes. Limb-darkening.

Stellar coronae. Coronal heating mechanisms (quiescent and flaring). Effects of age and chemical abundance. Multicomponent structure. Coronae in also low-mass stars and brown dwarfs. Diagnostics through X-ray spectroscopy and radio emission. Stellar winds and mass loss. First Ionization Potential effect.

Dynamic outer atmospheres. Multi-component radiation and dust-driven winds. Mass loss from pulsating red giants and AGB stars. Effects of mass flows on the ionization structure. Coronal mass ejections. Instabilities in hot-star winds. X-ray emission.

Dust, grains, and shells. Dust nucleation and condensation. Interplay between convection, pulsations, dust formation and mass loss in AGB stars. Formation of stellar dust shells. Grains in the atmospheres of red giants, and in T Tauri stars.

6.3. *Different classes of objects*

Stellar parameters of massive stars. Significant downscaling of effective temperature scale of OB-stars, due to line-blanketing and mass-loss effects. Rotation rates for massive stars, as a function of metallicity. VLT-FLAMES survey of massive stars: 86 O-stars and 615 B-stars in 8 different clusters (Milky Way, LMC, SMC) observed and analyzed. VLT-FLAMES Tarantula Survey: High resolution spectroscopy and analysis of more than 1000 massive stars in the Tarantula Nebula, incl. 300 O-type stars. First explanation of Vz stars. Stellar parameters/abundances of Red Supergiants.

Stellar parameters of late-type stars. Testing different methods for stellar parameter estimations using benchmark stars with almost model-independent parameters (e.g. interferometry, parallaxes, binaries, asteroseismology). 3D/non-LTE based excitation and ionization balance of Fe and other metals to infer effective temperatures and surface gravities. H lines as stellar thermometers: effects of 3D stellar atmospheres and non-LTE line formation. Line depth ratios. Strictly differential line-by-line analysis to achieve extremely precise relative stellar parameters and abundances. Molecules as temperature and gravity indicators in giants. Wings of strong, pressure-dampened lines as gravity indicators. Colour-effective temperature calibration for broad-band and intermediate-band photometry. Infrared flux method. Automated and accurate stellar parameter estimations for large-scale spectroscopic surveys. Global spectrum fitting. Data-driven stellar parameter estimations without stellar or spectral modelling. Improved stellar parameters for metal-poor stars. Predicted micro- and macroturbulent velocities from 3D stellar surface convection models. Stellar age signatures imprinted in stellar spectra (e.g. H lines, C/N ratio).

Stellar winds and mass-loss. Inhomogeneities in stellar winds affect derived mass-loss rates. Weak-winds from late O-/early B-dwarfs, which display significantly lower mass-loss rates than theoretically expected. Self-consistent models for winds from Wolf-Rayet stars. Theoretical mass-loss rates from optically thick winds close to the Eddington limit. Empirical mass loss-metallicity relation for O-stars. Empirical mass-loss rates from X-ray line emission in wind-embedded shocks. Stellar winds at very low abundances (First Stars). Continuum driven winds for super-Eddington stars. Wind-diagnostics by linear polarization variability. Dust-driven and molecular-driven winds of red giants and AGB stars. Interplay between convection, pulsations and stellar winds. Predicted mass loss rates of late-type stars.

Pulsating stars and helio-/asteroseismology. Conflict between solar abundances inferred from helioseismology and solar spectroscopy using 3D solar atmosphere models and non-LTE line formation. Asteroseismic scaling relations to infer stellar radii, masses, gravities and ages. Excitation of solar-like oscillations in stars by stellar surface convection. Classically variable stars, and 'ordinary' solar-type ones. Evidence for opacity-driven gravity-mode oscillations in periodically variable B-type supergiants. Inverting observed pressure-mode frequencies into atmospheric and interior structure. Mass-loss mechanisms in pulsating stars. Effects of rapid rotation on pulsation. Potential relation between oscillations and 'macro-turbulence' in massive stars.

Binary stars. Atmospheric structure and magnetic dynamos in common-envelope binaries. Role of binarity on mass loss. Tidal effects. Non-LTE effects by illumination from the component. Reflection effects in close binaries. Colliding stellar winds. Prominent role of binarity in massive stars (50-70% of massive stars in binaries). Test of stellar parameters of massive and low-mass stars from eclipsing binaries.

New classes of very cool stars. Dust, clouds, weather, and chemistry in brown dwarfs (spectral types L, T, Y). Cloud clearings and hot-spots. Magnetic activity. The effective temperature scale. Molecular line and continuum opacities. Transition between extrasolar giant planets and ultracool brown dwarfs.

White dwarfs and neutron stars. Radiative transfer in magnetized white-dwarf atmospheres. Stokes-parameter imaging of white dwarfs. Molecular opacities in white dwarfs. 3D convection modelling of white dwarfs. Broad-band polarization in molecular bands in white dwarfs. Atmospheres and spectra of neutron stars. Effects of vacuum polarization and accretion around magnetized neutron stars.

Special objects. Central stars of planetary nebulae. Winds of central stars as a tool to constrain their masses. Population II and III stars of extremely low metallicity. Protostars. Accretion disks and coronal activity in young stars.

Interaction with exoplanets. Characteristics of stars hosting exoplanets. Stellar chemical signatures of planet formation. Stellar Li, C and O abundances to infer planetary properties. Effects of planets on the atmospheres of evolved red giants.

6.4. *Development of techniques*

Computational techniques. Parallel (super)computing to simulate convective surface regions, and throughout complete stars. 2- and 3-D 3D radiative magneto-hydrodynamical models of stellar surface convection and atmospheres. 3D non-LTE radiative transfer and spectrum formation. Polarized radiative transfer. NLTE unified models including winds for hot stars. Neural networks and machine-learning algorithms. Analysis of stellar spectra using genetic algorithms. Automated analysis of stellar spectra using libraries of synthetic spectra. Data-driven stellar parameter estimations without stellar or spectral models. Preparing for the widely distributed network of computational tools and shared databases being developed for the forthcoming computing infrastructure GRID.

6.5. *Applications of stellar atmospheres*

Besides their study per se, stars are being used as probes for other astrophysical problems:

Exoplanets. Variable wavelength shifts in stellar spectra serve as diagnostics for radial-velocity variations induced by orbiting exoplanets. Atmospheric modeling can indicate which spectral features are suitable as such probes, and which should be avoided due to their sensitivity to intrinsic stellar activity. Stellar granulation, oscillations and activity impacts on the radial velocity precision, specially when reaching for sub-m/s level.

Chemical evolution in the Galaxy. How accurately observations of stellar spectral features can be transformed into actual chemical abundances depends sensitively on the sophistication of the stellar model atmospheres and radiative transfer modelling for predicting the emergent stellar spectra.

Kinematics of the Galaxy. The astrometric Gaia space mission measures radial velocities and stellar parameters/abundances for huge numbers of stars. Model atmospheres are used to identify suitable spectral features for such measurements in different classes of stars and predict intrinsic convective blue-shifts.

Chemical evolution of Galaxies. Accurate measurements of metallicity gradients in various galaxies based on BA supergiants. Late-type stars as probes of stellar, galactic

and cosmic evolution. First stars and their immediate successors as relics from the first billion years after the Big Bang. Chemistry in external galaxies based on red supergiants.

Evolution of First Stars. Effects from winds may be stronger than expected, due to fast rotation, continuum driving or self-enrichment. Strong mass-loss offers possibility to avoid Pair-Instability SNe.

Distance scales. Flux-weighted gravity-luminosity relationship as a tool to derive independent, precise extragalactic distances from A-supergiants and Red Supergiants.

Galaxies and cosmology. Stars are the main observable component of galaxies, and population synthesis for galaxies utilize model atmospheres to interpret observations. Cosmological origin of the lowest-metallicity stars. Have any Pop. III star survived from redshifts > 10 to the present time? Cosmological Li problems: ^{7}Li and ^{6}Li.

7. Useful Web links

The following collection of links (in alphabetical order) provides introductions and overviews of several significant subfields of the physics of stellar atmospheres.

7.1. *Calculating atmospheric models and spectra*

ATLAS, SYNTHE, and other model grids: `<kurucz.harvard.edu>`

CCP7 - Collaborative Computational Project: `<ccp7.dur.ac.uk>`

CLOUDY - photoionization simulations: `<trac.nublado.org>`

CMFGEN - stellar atmosphere code:
   `<kookaburra.phyast.pitt.edu/hillier/web/CMFGEN.htm>`

CO5BOLD - 3D hydrodynamical models of stellar surface convection, atmospheres and spectra:
   `<http://www.astro.uu.se/~bf/co5bold_main.html>`

INSPECT - non-LTE spectral line formation for late-type stars:
   `<http://inspect-stars.com/>`

MARCS, model grids: `<marcs.astro.uu.se>`

MOOG - stellar spectrum synthesis code:
`<http://www.as.utexas.edu/~chris/moog.html>`

MULTI - non-LTE radiative transfer: `<folk.uio.no/matsc/mul22/>`

PANDORA - atmospheric models and spectra:
   `<cfa.harvard.edu/~avrett/pandora.lis.copy>`

PHOENIX - stellar and planetary atmosphere code:
   `<hs.uni-hamburg.de/EN/For/ThA/phoenix/>`

PoWR: The Potsdam Wolf-Rayet Models, grid of synthetic spectra:
   `<astro.physik.uni-potsdam.de/~wrh/PoWR/powrgrid1.html>`

RH - 1D, 2D, 3D non-LTE stellar spectrum synthesis code:
   `<http://www4.nso.edu/staff/uitenbr/rh.html>`

STAGGER - 3D hydrodynamical models of stellar surface convection, atmospheres and spectra:
   `<http://www.stagger-stars.net>`

STARLINK - theory and modeling resources:
   `<astro.gla.ac.uk/users/norman/star/sc13/sc13.htx>`

Synthetic spectra overview: `<am.ub.es/~carrasco/models/synthetic.html>`

TLUSTY/SYNSPEC - model atmospheres: `<nova.astro.umd.edu>`

Tuebingen: Stellar atmosphere code, grid of models, etc.:
   `<physik.uni-tuebingen.de/institute/astronomie-astrophysik/`
   `institut/astronomie/kontakt/mitarbeiter/thomas-rauch.html>`

WM-Basic: unified hot star model atmospheres incl. consistent wind structure:
   `<usm.uni-muenchen.de/people/adi/adi.html>`

7.2. *Research groups or individual researchers*

AIP Potsdam: Stellar convection:
   `<aip.de/de/forschung/forschungsschwerpunkt-kmf/`
   `cosmic-magnetic-fields/stellar/stellar-physics/stellar-convection>`

F. Allard: PHOENIX model atmospheres and radiative transfer:
   `<http://perso.ens-lyon.fr/france.allard/>`

M. Asplund: Stellar atmospheres and spectroscopy:
   `<http://www.mso.anu.edu.au/~martin>`

G. Basri: Brown dwarfs: `<w.astro.berkeley.edu/~basri/bdwarfs/>`

M. Bergemann: Non-LTE radiative transfer: `<http://www.mpia.de/~bergemann/>`

CO5BOLD: B. Freytag, H. Ludwig, M. Steffen *et al.*: 3D hydrodynamical models of stellar surface convection, atmospheres and spectra:
   `<http://www.astro.uu.se/~bf/co5bold_main.html>`

A. Collier Cameron: Starspots and magnetic fields on cool stars:
   `<star-www.st-and.ac.uk/~acc4/coolpages/imaging.html>`

P. Crowther: Hot Lumionous Star Research Group:
   `<pacrowther.staff.shef.ac.uk/science.html>`

J. F. Donati: Magnetic fields of non degenerate stars:
   `<ast.obs-mip.fr/users/donati/>`

D. Dravins: Stellar surface structure and more: `<astro.lu.se/~dainis/>`

D. F. Gray: Stellar rotation, magnetic cycles, velocity fields:
`<astro.uwo.ca/~dfgray/>`

P. Hauschildt: PHOENIX model atmospheres and radiative transfer:
   `<http://hobbes.hs.uni-hamburg.de/>`

C. Helling: atmospheres of brown dwarfs and (exo-)planets:
   `<https://leap2010.wp.st-andrews.ac.uk/>`

S. Höfner: dynamical atmospheres and winds of AGB stars:
   `<http://www.astro.uu.se/~hoefner/>`

M. Jardine: Stellar coronal structure:
   `<www-star.st-and.ac.uk/~mmj/Research_cool_stars.html>`

S. Jeffery: Stellar model grids, hot stars: `<star.arm.ac.uk/~csj/>`

F. Kupka: 3D stellar convection modelling, atomic data:
   `<http://www.mat.univie.ac.at/~kupka/>`

R. Kudritzki: Hot Stars and Winds, Extragalactic Stellar Astronomy:
   `<ifa.hawaii.edu/~kud/kud.html>`

K. Lind: Non-LTE radiative transfer:
`<www.astro.uu.se/~klind/index/Welcome.html>`

J.L.Linsky: Cool stars, stellar chromospheres and coronae:
   `<jilawww.colorado.edu/~jlinsky/>`

D. Montes *et al.*: Libraries of stellar spectra:
 `<pendientedemigracion.ucm.es/info/Astrof/invest/actividad/spectra.html>`

Munich Hot star group (A. Pauldrach and J.Puls), lecture notes and more:
   `<usm.uni-muenchen.de/people/adi/wind.html>`,

S. Owocki: Theory of line-driven winds, hydrodynamics, rotation, magnetic fields:
   `<bartol.udel.edu/~owocki/>`

N. Przybilla: NLTE atmospheres of massive stars, extragalactic stellar astronomy:

$<$`sternwarte.uni-erlangen.de/~przybilla/research.html`$>$ (Note: site to be moved)

R. J. Rutten: Lecture notes: Radiative transfer in stellar atmospheres and more:
$<$`staff.science.uu.nl/~rutte101/Course_notes.html`$>$

C. Sneden - MOOG stellar spectrum synthesis code:
$<$`http://www.as.utexas.edu/~chris`$>$

STAGGER: M. Asplund, R. Collet, Z. Magic, Å. Nordlund *et al.*: 3D hydro-dynamical models of stellar surface convection, atmospheres and spectra:
$<$`http://www.stagger-stars.net`$>$

P. Stee: Be-star atmospheres and circumstellar envelopes:
$<$`https://www-n.oca.eu/stee/page1/page1.html`$>$

R. F. Stein: Convection simulations & radiation hydrodynamics:
$<$`pa.msu.edu/~steinr/research.html#convection`$>$

R. Townsend: Astrophysics of massive stars:
$<$`astro.wisc.edu/~townsend/static.php?ref=research`$>$

H. Uitenbroek: Non-LTE radiative transfer: $<$`http://www4.nso.edu/staff/uitenbr/`$>$

Vienna: Stellar atmospheres and pulsating stars: $<$`univie.ac.at/asap`$>$

Joachim Puls and Martin Asplund
President and Past President of the Commission

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