BETELGEUSE WORKSHOP 2012

THE PHYSICS OF RED SUPERGIANTS

26-29 NOVEMBER, 2012

PARIS (FRANCE)

PROGRAMME BOOK

l'Observatoire de Paris

îledeFrance

Acknowledgements

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The practical organization of the workshop would not have been possible without the efficient help of the following persons:

Isabelle Aleci (Paris Observatory),

Claudine Colon (LESIA, Paris Observatory),

Cris Dupont (LESIA, Paris Observatory),

Annick Gassais (LERMA, Paris Observatory).

We are also grateful to James Lequeux and François Sèvre for kindly presenting the Cassini exhibit and the Arago's refractor at Paris Observatory.

Scientific Organizing Committee

Andrea Chiavassa	ULB, Belgium / Observatoire de la Côte d'Azur, France
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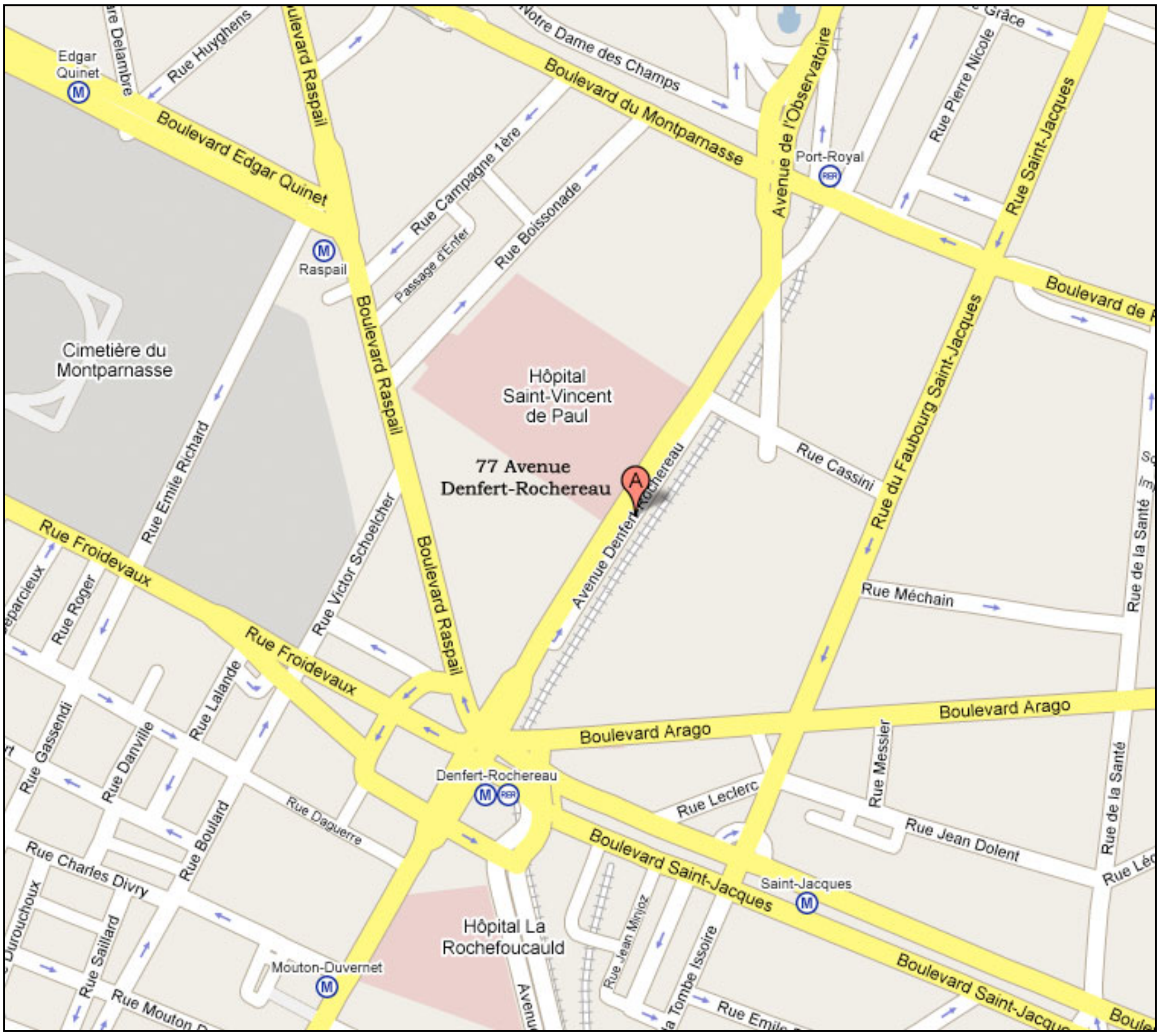
Local information

Venue

The Betelgeuse workshop will take place at

Observatoire de Paris, 77 avenue Denfert-Rochereau, 75014 Paris.

Tel: 01.40.51.22.21, Fax: 01.43.54.18.04.



Public transportation

From Roissy-Charles de Gaulle airport :

Take the RER B to Denfert-Rochereau.

From Orly airport :

Two solutions : cheaper (Bus) or faster (OrlyVal).

Take the OrlyBus up to Denfert-Rochereau or

Take the OrlyVal up to Antony then take the RER B direction Paris up to Denfert-Rochereau.

RER (fast suburban train) stations: **Port-Royal** or **Denfert-Rochereau** (also Métro station).

It is also possible to use bus lines in Paris. More information is available through the RATP web site (public transportation, available in english and other languages): http://www.ratp.fr

Meeting room

The meeting room will be the "Salle de l'Atelier", located close to the entrance of the Observatory. The registration, poster exhibition and coffee breaks will take place on the ground floor of "Building B".

Instructions for the Proceedings

The proceedings of the Betelgeuse 2012 workshop will be published in the European Astronomical Society (EAS) Publications Series:

http://www.eas-journal.org/action/displayJournal?jid=EAS

The papers will be reviewed by the Scientific Organizing Committee. The papers will be referenced in the ADS.

The authors can retrieve the package for editing their manuscript at:

ftp://ftp.edpsciences.org/pub/eas/

Name your TeX file as follows : lastname.tex, and your figures :

lastname_fig1.pdf, lastname_fig2.eps, ... etc (use only lowercase).

Please follow the editing rules of the *Astronomy & Astrophysics* Journal.

For the number of pages, we recommend the following limits:

- Invited talks : 10 pages,
- Contributed talks : 8 pages,
- Poster contributions: 6 pages,
- Discussions : 6 pages.

When ready send a tar file (with latex file and figure files plus a pdf version of your mansucript) to : betelgeuse@sciencesconf.org.

We aim at a rapid publishing of these proceedings (before summer 2013). The deadline for manuscript submission is : Jan. 31, 2013.

List of participants

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Daily schedule

The oral presentations will take place in the "Salle de l'Atelier". The coffee breaks and poster exhibition will take place on the ground floor of Building B, in front of the Salle de l'Atelier.

Monday, November 26, 2012

9:00 am - 11:00 am	Registration and poster exhibit - *Building B (ground floor)*
11:00 am - 11:10 am	Welcome address
11:10 am - 12:50 pm	**Invited introductory talks**
11:10 am - 12:00 pm	Betelgeuse - challenging our understanding for more than 2000 years - S. T. Ridgway, NOAO
12:00 pm - 12:50 pm	Past and future evolution of a massive star like Betelgeuse - G. Meynet, Observatory of Geneva University
12:50 pm - 1:00 pm	Informations from the LOC
1:00 pm - 2:00 pm	Lunch
2:00 pm - 3:30 pm	**Structure and evolution of massive stars**
2:00 pm - 3:00 pm	RSG in the perspective of stellar evolution - S. Ekstrom
3:00 pm - 3:30 pm	How the mass-loss rates of red-supergiants determine the fate of massive stars ? - C. Georgy
3:30 pm - 4:00 pm	Coffee break - *Building B (ground floor)*
4:00 pm - 5:00 pm	**Atmospheric structure and dynamics**
4:00 pm - 5:00 pm	Atmospheric structure and dynamics: the spatial and temporal domains - G. Harper
5:00 pm - 6:00 pm	poster session (brief oral presentation of posters: 5 minutes each)

Tuesday, November 27, 2012

9:15 am - 10:45 am	**Atmospheric structure and dynamics**
9:15 am - 9:45 am	The Temperatures of Red Supergiants - B. Davies
9:45 am - 10:15 am	Direct Ultraviolet Imaging of Betelgeuse - A. Dupree
10:15 am - 10:45 am	Envelope tomography of red supergiant stars - S. Lion
10:45 am - 11:05 am	Coffee break

11:05 am - 12:45 pm	**Atmospheric structure and dynamics**
11:05 am - 11:45 am	Atmospheric structures and wavelength dependent angular diameters of red supergiants - B. Arroyo-Torres
11:45 pm - 12:15 pm	NLTE effects in the atmospheres of Red Supergiants - M. Bergemann
12:15 pm - 12:45 pm	NLTE radiative transfer in Red supergiant atmospheres - J. Lambert
12:45 pm - 2:00 pm	Lunch

2:00 pm - 4:15 pm	**Atmospheric structure and dynamics**
2:00 pm - 3:00 pm	Spatially resolving the dynamics over the surface of red supergiants with the Very Large Telescope Interferometer - K. Ohnaka
3:00 pm - 3:30 pm	Turbulent Structure in the Upper Chromospheres of Cool Supergiants - E. Griffin
3:30 pm - 4:15 pm	Discussion: How does Betelgeuse fit ? - observations versus models - G. Meynet/ A. Chiavassa
4:15 pm - 5:00 pm	Coffee break and conference photo
5:00 pm - 5:30 pm	poster session

5:30 pm - 8:30 pm	**Social event (Salle Cassini)**

Wednesday, November 28, 2012

9:00 am - 10:30 am	**Atmospheric structure and dynamics**
9:00 am - 9:30 am	Global radiation hydrodynamics simulations of red supergiant and AGB stars - B. Freytag
9:30 am - 10:00 am	3D hydrodynamical simulations of red supergiants to interpret observations of stellar surfaces - A. Chiavassa
10:00 am - 10:30 am	Discussion: What have we learned and not learned from surface observations ? - A. Dupree/ P. Kervella
10:30 am - 11:00 am	Coffee break

11:00 am - 12:30 pm	**Mass loss mechanisms, dust formation chemistry**
11:00 am - 12:00 pm	The chemistry of dust formation in red supergiants - I. Cherchneff
12:00 pm - 12:30 pm	Red Supergiants, Post-Red Supergiants, and Red Transients -- the Evidence for High Mass Loss Episodes Over a Wide Range of Luminosities - R. Humphreys
12:30 pm - 2:00 pm	Lunch

2:00 pm - 4:00 pm	**Mass loss mechanisms, dust formation chemistry**
2:00 pm - 2:30 pm	Tracing the long-term mass-loss history of Betelgeuse in CO radio lines - T. Kaminski

2:30 pm - 3:00 pm	Towards a coherent view at infrared wavelengths of mass loss in Betelgeuse - P. Kervella
3:00 pm - 4:00 pm	Mass loss from Betelgeuse - where is it going? - A. Richards
4:00 pm - 4:30 pm	Coffee break

4:30 pm - 6:00 pm	**Mass loss mechanisms, dust formation chemistry**
4:30 pm - 5:00 pm	The kinematics in the large-scale environment of Betelgeuse from radio HI-line observations - T. Le Bertre
5:00 pm - 5:30 pm	The enigmatic nature of the circumstellar envelope and bow shock surrounding Betelgeuse as revealed by Herschel. Evidence of clumps, multiple arcs and a linear bar-like structure. - L. Decin
5:30 pm - 6:00 pm	Dust and gas dynamics in the bowshock of alpha-Orionis - A. van Marle

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Thursday, November 29, 2012

9:00 am - 10:30 am	**Mass loss mechanisms, dust formation chemistry**
9:00 am - 9:30 am	3D simulations of Betelgeuse's bow shock - S. Mohamed
9:30 am - 10:00 am	Models for the circumstellar medium of runaway young red supergiants: application to Betelgeuse - J. Mackey
10:00 am - 10:30 am	Discussion: Do we know what causes mass loss in Betelgeuse ? - L. Decin/ T. Le Bertre
10:30 am - 11:00 am	Coffee break

11:00 am - 1:00 pm	**Red supergiants in galaxies**
11:00 am - 12:00 pm	Red Supergiants in the Local Group - E. Levesque
12:00 pm - 12:30 pm	Betelgeuse in context of the Massive Star Population in Orion - N. Przybilla
12:30 pm - 1:00 pm	Stephenson 2, a nest of red supergiants - I. Negueruela
1:00 pm - 2:00 pm	Lunch

2:00 pm - 4:00 pm	**Red supergiants in galaxies**
2:00 pm - 2:30 pm	Red Supergiant Stars as Cosmic Abundance Probes - R. Kudritzki
2:30 pm - 3:00 pm	Discussion : Future directions - optical interferometry, ALMA, ELT - G. Perrin/ S. Ridgway
3:00 pm - 3:50 pm	Summary and recommendations - J. van Loon
3:50 pm - 4:00 pm	Final informations from the LOC

Poster Abstracts

The evolution of Red Supergiants at very low metallicity

Groh Jose [1], Meynet Georges [1], Ekström Sylvia [,2], Eggenberger Patrick [1]

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2 : Observatory of Geneva University (ObsGE)
Maillettes 51 - Sauverny 1290 Versoix
www.unige.ch/sciences/astro/

Red Supergiants (RSG) are a crucial phase in the evolution of intermediate mass stars, representing the stage where substantial amounts of mass and angular momentum are lost. We present results about the evolution of RSGs at very low metallicity (Z=0.0004) with and without rotation, using the latest version of the Geneva stellar evolution code. In particular, we discuss the lifetimes, the mass ranges for forming RSGs, the maximum luminosity of RSGs, and how these are affected by rotation.

Water vapour in the outer photospheres of giants and supergiants

Farzone Mohsen [1], Ryde Nils [1*], Harper Graham [2], Josselin Eric [3], Lambert Julien [3], Richter Matthew [4]

1 : Lund Observatory
Box 43, SE-221 00 Lund, Sweden
2 : School of Physics
Trinity College Dublin
Ireland
3 : Universite Montpellier II
Université Montpellier II - Sciences et Techniques du Languedoc
4 : Physics Dept, UC Davis
Physics Dept, UC Davis
* : Corresponding author

The outer atmospheres of M supergiants are puzzling. For example, stronger than expected water vapour features is detected at high spectral resolution at 12 microns for Betelgeuse and mu Cep (Ryde et al. 2006). These data seems to suggest a cooler than expected outer atmospheric temperature structure for these stars. In order to investigate these features further as to their origin, we have observed a set of supergiant and giant stars spanning a range of temperatures. Here, we present these new high-resolution, mid-infrared spectra observed with the TEXES spectrometer. The trends we find are discussed and different possible solutions are presented to the origin of these common features.

Long-term spectropolarimetric monitoring of the cool supergiant Betelgeuse

Bedecarrax Iker [1], Petit Pascal [1]

1 : Institut de recherche en astrophysique et planétologie (IRAP)
CNRS : UMR5277Université Paul Sabatier - Toulouse III

We report on a long-term monitoring of the cool supergiant Betelgeuse, using the NARVAL and ESPaDOnS high-resolution spectropolarimeters, respectively installed at Telescope Bernard Lyot (Pic du Midi Observatory, France) and at the Canada-France-Hawaii Telescope (Mauna Kea Observatory, Hawaii). The data set, constituted of circularly polarized (Stokes V) and intensity (Stokes I) spectra, was collected between 2010 and 2012. We investigate here the temporal evolution of magnetic field, convection and temperature at photospheric level, using simultaneous measurements of the longitudinal magnetic field component, the core emission of the Ca II infrared triplet, the line-depth ratio of selected photospheric lines and the radial velocity of the star.

Exploring the water and carbon monoxide shell around Betelgeuse with VLTI/AMBER

Montargès Miguel [1*], Kervella Pierre [1], Perrin Guy [1], Ohnaka Keiichi [,2]

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2 : Max Planck Institute for Radio Astronomy (MPIfR)
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We will present the results of the analysis of our recent interferometric observations of Betelgeuse, using the AMBER instrument of the VLTI. Using the medium spectral resolution of the instrument (R~1500) we detected the presence of the water vapor and carbon monoxide molecules in the H and K band. I will also present our data reduction procedure, that was complicated by the extreme brightness and very low fringe visibilities. By analyzing the depth of the molecular lines and the interferometric visibilities, we derived the column densities of those molecules, as well as the temperature and the size of the corresponding regions in the atmosphere of Betelgeuse (the MOLsphere) using a single shell model around the photosphere. Moreover, the analysis of the closure phase indicates strong asymmetries in those molecular lines.
We also derived the photospheric angular diameter in the continuum. Our results confirm the findings by Perrin et al. (2004) and Ohnaka et al. (2011) that the H2O and CO molecules are distributed around Betelgeuse in a MOLsphere extending to approximately 1.3 times the star's radius.

Potential of observations of the environment of Betelgeuse with the extreme-AO instrument SPHERE.

Chesneau Olivier [1]

1 : Chesneau
Observatoire de la Cote d'Azur
Laboratoire Lagrange, UMR7293, Univ. Nice Sophia-Antipolis, CNRS, Observatoire de la Cote d'Azur, 06300 Nice, France

SPHERE, the Spectro-Polarimetric High-contrast Exoplanet Research instrument for the VLT is optimized towards reaching the highest contrast in a limited field of view and at short distances from the central star, thanks to an extreme AO system. SPHERE is very well suited to study the close environment of Betelgeuse, and has a strong potential for detecting the ejection activity around this key red supergiant.

Constraints on the mass loss of Red supergiant stars

Josselin Eric [1], Mauron Nicolas, Lambert Julien [1], Ryde Nils [,2], Faure Alexandre

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Université Montpellier II - Sciences et Techniques du Languedoc
2 : Lund Observatory
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Mass loss plays a key-role in stellar evolution in general, and especially during the red supergiant phase. The prescription used for mass loss in evolutionary codes is thus particularly important to derive reliable evolutionary tracks.
We present a new analysis of recent observations and confront them to different prescriptions. We show that the de Jager law, used e.g. in the Geneva code, is consistent with mass-loss rate estimates for RSGs of the solar neighborhood. However, a dependency on metallicity has probably to be taken into account for extragalactic RSGs.
Furthermore, we present new observations (near infrared spectroscopy and millimeter interferometry) which bring new constraints on the underlying mass loss process in RSG.

The infrared view of the super star cluster NGC1705-1: a population of red supergiants

Martins Fabrice [1], Lutz Dieter, Forster-schreiber Natascha, Eisenhauer Frank

1 : LUPM
CNRS & Université Montpellier II

We present K--band integral field spectroscopy of the super star cluster in the amorphous galaxy NGC1705. We provide upper limits on the spatial extent of the cluster and analyze the K--band spectrum of the cluster. We show that it is similar to K4-5 Galactic supergiants. We constrain the cluster age from evolutionary models. We show that the Geneva and Utrecht models are very different in the red supergiant phase, leading to uncertainties of 3-7 Myr (or 20 to 50%) on the cluster age. We discuss the origin of these differences.

Spectral classification of very late luminous stars in the GAIA region.

Dorda Ricardo [1*], Negueruela Ignacio [,2]

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The GAIA spectral region is not very useful to classify very late stars, as the main atomic features are obliterated by molecular bands, mainly from TiO. The whole spectral region falls within the triple-headed infrared TiO band, and so its strength cannot be gauged, making the determination of effective temperature almost impossible. In addition, there are no MK spectral standards for late-M supergiants, because of the variability characterising stars in this evolutionary phase. To improve the situation, we have observed a large number of MK standard stars and late-M giants and supergiants with well-established spectral types in the 8000-9000A range at intermediate resolution (R~10000). We try to to find useful criteria for both temperature and luminosity and then apply these criteria to a large sample of very late luminous stars, looking for statistical trends that verify their validity.

Authors Index

Oral Presentation Abstracts

Betelgeuse - challenging our understanding for more than 2000 years

Ridgway Stephen [1]

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As a bright, colorful and variable star, Betelgeuse has attracted popular interest from the earliest times. As a prototypical evolved supergiant, it has been investigated with many photometric and spectroscopic techniques. With hundreds of focused studies, many measurements remain puzzling after decades reflection. We begin our exploration of the Betelgeuse story with an illustrated historical tour of observations and maybe some thoughts on interpretive paths.

Past and future evolution of a massive star like Betelgeuse

Meynet Georges [1]

1 : Observatory of Geneva University

We shall discuss the physics and the evolution of a typical massive star passing through an evolutionary stage similar to that of Betelgeuse. We shall present the main physical processes governing the evolution of such stars. We shall examine the various evolutionary scenarios leading to Betelgeuse and see whether it is possible from its observed characteristics to identify its most probable past evolution. We shall conclude by studying the possible future evolutions of Betelgeuse.

RSG in the perspective of stellar evolution

Ekström Sylvia [1]

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After a reminder of the key steps of massive stars evolution, we will focus on the RSG phase as we understand it from stellar models. We will present results from recent models and place Betelgeuse and similar objects at solar and other metallicities in this context.

How the mass-loss rates of red-supergiants determine the fate of massive stars ?

Georgy Cyril [1]

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In the framework of current stellar evolution models, rotation and mass loss play a essential role. The mass-loss rates are still not well constrained, either observationally, nor theoretically. Particularly, the mass-loss rates during the red-supergiant phase are uncertain, and are crucial to determine the evolution of the star through the more advanced stages of their evolution.
I will present how an increased mass-loss rate (compared to standard prescriptions) during that stage allows to improve the agreement of the theoretical stellar evolution models with respect to various observations, particularly with respect to the maximum luminosity of observed Galactic red supergiants, the maximum inferred mass of the progenitors of type II-P supernovae, and also the recent determinations of yellow supergiant as the progenitor of peculiar type II-L or II-b supernovae. I will also discuss the implications on the Wolf-Rayet stars populations.

Atmospheric structure and dynamics: the spatial and temporal domains

Harper Graham [1]

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Multi-wavelength studies of M supergiants have revealed atmospheric structure over a large range of spatial scales, and variability on multiple time scales. Focusing on the well studied Betelgeuse, these scales and their perplexing connections from the photosphere to the interstellar medium are reviewed. Of particular current interest is the dynamic origin of the ubiquitous and relatively dust-free mass loss. Is it multiple plumes of convectively driven ejecta, episodic ejection of molecular reservoirs, or a more steady and uniform flow? With powerful new facilities such as the VLT and ALMA we may begin to understand the connections and answer such puzzles, but ultimately detailed studies of a sample of M supergiants will be needed to disentangle the physics from the stars' personalities.

The Temperatures of Red Supergiants

Davies Ben [1], Kudritzki Rolf [2], Plez Bertrand [3], Bergemann Maria [4], Gazak Zach [2], Lancon Arianne [5], Trager Scott [6], Evans Chris [7], Chiavassa Andrea [8]

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We have re-appraised the temperatures of Red Supergiants (RSGs) in the Magellanic Clouds, by studying their spectral energy distributions (SEDs) from 400-2500nm using VLT+XSHOOTER, in conjunction with MARCS model atmospheres. We determine temperatures using 3 methods: from model fits to the TiO bands in the optical; from model fits to the SED using the line-free continuum in the near-infrared; and from the integrated fluxes.
We find that the temperatures from the TiO fits are systematicallylowerthat those from the other methods by several hundred Kelvin. The TiO fits also dramatically over-predict the flux in the near-IR, and imply extinctions which are anomalously low compared to neighbouring stars. In contrast, the SED temperatures provide good fits to the fluxes at all wavelengths other than the TiO bands, are in agreement with the temperatures from the flux integration method, and imply extinctions which are consistent with stars nearby.
After considering a number of ways to reconcile this discrepancy, we conclude that the TiO bands are extremely sensitive to 3-D effects (convection, granulation), which alter the temperature structure in the upper layers where TiO forms. The continuum, however, which forms at much deeper layers, is robust to such effects. We therefore conclude that RSG temperatures are much warmer than previously thought, and we discuss the implications of this result for stellar evolution and supernova progenitors.

Direct Ultraviolet Imaging of Betelgeuse

Dupree Andrea [1]

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Seven direct images of Betelgeuse (Alpha Ori, M2 Iab, HD 39801) have been obtained over a span of 4 years with the Faint Object Camera on the Hubble Space Teleseope. Images in a 300 Angstrom wide band centered at 2550 A reveal the extended continuum emission, the varying overall stellar ultraviolet flux levels, and a pattern of bright surface continuum features that changes in position and appearance.The features are sometimes unresolved (at the ~38 mas level of the FOC), yet at other times appear extended and occur at different position angles on the UV disk. Concurrent photometry and radial velocity measures support the model of a pulsating star. The position of these features near the center of the limb-darkened ultraviolet disk which is close to the polar regions as suggested by HST spectroscopy, is consistent with their production by an outwardly propagating shock wave in an atmosphere modified by rotation.

Envelope tomography of red supergiant stars

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3-D simulations suggest that the atmospheres of red supergiants are subject to large-amplitude convective motions, which are suspected to generate supersonic motions and shocks. We perform tomography of supergiant-star atmospheres, on temporal series of high-resolution HERMES spectra and 3-D synthetic snapshot spectra. We improve the tomographic technique by computing the contribution function, which is used in the construction of numerical spectral masks probing different optical depths.
Cross-correlating these masks with observed and synthetic spectra results in a complex cross-correlation function profile displaying distinct components. This allows to constrain (spatially and temporally) the propagation of convective shocks in the atmosphere, as well as velocity fields of 3-D model atmospheres.

The atmospheric structures and fundamental parameters of the red supergiants AH Sco, UY Sct, and KW Sgr

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Red supergiants (RSGs) are candidates for supernova progenitors. Hence, the determination of their fundamental parameters is of much relevance. Broadband spectrophotometric observations compared to recent model atmospheres have led to a dramatic revision of the location of RSGs in the HR diagram (Massey et al. 2006, Levesque et al. 2009). On the other hand, Perrin et al. (2004) , Ohnaka et al. (2009), and Wittkowski et al. (2012) have shown that RSGs have extended atmospheres with complex molecular shells. Thus, the determination of the fundamental parameters needs to be made with an adequate characterization and modeling of those shells.
We have carried out spectrointerferometric observations of AH Sco, UY Sct, and KW Sgr in the near-infrared bands (K2.1 and K2.3) with the VLTI/AMBER instrument with medium spectral resolution. In our visibility data, we observe the presence of molecular layers of water and CO in extended atmospheres. For a uniform disk modeling, we observe size increases in the water band centered at 1.9 micron and in the CO band at 2.3-2.5 micron, with respect to the near-continuun bandpass (2.20-2.25 micron). With our spectral resolution, we obtain diameters in the near-continuum, that are free from contamination by molecular layers. Using the PHOENIX atmospheric model, we estimate Rosseland-mean photospheric angular diameters of AH Sco, UY Sct, and KW Sgr of 6.12±1.88 mas, 5.67±1.42 mas, and 4.07±0.20 mas, respectively (preliminary values). We estimate radii and effective temperatures, and place the stars on the HR diagram.

Wavelength-dependent angular diameters and asymmetries of red giants and supergiants

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We discuss recent near-infrared spectro-interferometric observations of asymptotic giant branch (AGB) stars and of the red supergiant VY CMa obtained with the AMBER instrument at the VLT interferometer with spectral resolutions of 35 and 1500. The visibility data show significant variations as a function of wavelength that can only be described by a variation of the apparent angular size with wavelength. The visibility variations correlate with the positions of molecular bands of CO and water vapor, indicating that our data allow us to study photospheric and molecular layers at different atmospheric depths. Furthermore, the closure phase values show a significant variation as a function of wavelength as well, allowing us to study deviations from point symmetry at different atmospheric depths. Both the data of red giants and of the red supergiant VY CMa show relatively small deviations from symmetry at continuum bandpasses originating close to the stellar photosphere, and larger deviations at bandpasses of molecular layers at layers of 2-3 photospheric radii. We discuss possible shaping mechanisms thay may explain the observations, and include in particular the possibility of pulsation- and shock-induced chaotic motion in the extended atmosphere.

The Structure of the Outer Atmosphere of the Betelgeuse Proxy VV Cephei

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The long-period (20.34 yr) binary VV Cephei (M2 Iab + B0-2) is the brightest (V=4.9) M supergiant eclipsing binary in the sky. The M supergiant primary is a close spectral match to that of Betelgeuse. In the ultraviolet, the early B-type hot companion dominates the spectrum, and as the system emerges from eclipse, the line of sight to the B star probes deep into the outer atmosphere (the "chromosphere") of the M supergiant. From these observations, it should be possible to reconstruct a spatially-resolved empirical model of the outer atmosphere of an M supergiant that is a close spectral proxy of Betelgeuse. Observing time on theHubble Space Telescope(HST) and theFar Ultraviolet Spectroscopic Explorer(FUSE) was obtained by the PI (Bennett) to carry out this program. We observed VV Cep from total eclipse (1997-98) through quadrature (2002) almost until periastron (2005), at a total of 22 epochs, including 20 epochs of HST/STIS high-resolution (R~10^(5)) ultraviolet spectroscopy. We present here an analysis of the subset of the STIS observations (immediately following the egress from totality) that probed the chromosphere of VV Cephei. From these observations we have inferred the temperature, density and velocity structure of the outer atmosphere of VV Cep above the classical photosphere but below the wind acceleration region.

NLTE effects in the atmospheres of Red Supergiants

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Red supergiants with their enormous brightness at J-band are ideal probes of cosmic chemical composition. It is therefore crucial to have realistic models of radiative transfer in their atmospheres, which will permit determination of abundances accurate to 0.15 dex, the precision attainable with future telescope facilities in galaxies as distant as tens of Mpc. Here, we study the effects of non-local thermodynamic equilibrium (NLTE) on the formation of iron, titanium, and silicon lines, which dominate J-band spectra of red supergiants. It is shown that the NLTE radiative transfer models enable accurate derivation of metallicity and effective temperature in the J-band. We also discuss consequences for RSG spectrum synthesis in different spectral windows, including the heavily TiO-blanketed optical region, and atmospheric structure. We then touch upon challenges of NLTE integration with new generation of 3D hydrodynamical RSG models.

NLTE radiative transfer in Red supergiant atmospheres

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The atmospheres of red supergiant stars are cool enough to allow the formation of molecules, even polyatomic ones such as water. In return, these molecules play a potentially important role in the dynamics of these atmospheres, through their cooling capacities, and their ability to initiate mass loss by radiation pressure on them. Our knowledge of their abundance and distribution is thus a fundamental aspect of our understanding of these objects. Up to now, different observational approaches, including mid- to high resolution spectroscopy and interferometry, have led to contradictory interpretations, concerning e.g. the occurrence of the so-called "MOLspheres". However, the interpretation of these observations relies mostly on static, LTE model atmospheres and spectrum synthesis.
We present an original method to deal with NLTE radiative transfer in molecular lines. Contrary to standard iterative schemes, such as the Accelerated Lambda Iteration (ALI), this new parallel code, named MoRad, aims at solving a system of coupled Fredholm equations representing the global statistical equilibrium. This code is able to handle with the huge amount of rovibrational energy levels and transitions required to properly model their spectra.
We present its application to infrared water lines in RSG atmospheres. We show that NLTE effects account for extra absorption with respect to LTE computation. This should represent an important step toward the reconciliation of different observations.

Spatially resolving the dynamics over the surface of red supergiants with the Very Large Telescope Interferometer

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The mass-loss mechanism in red supergiants is a long-standing problem. The milliarcsecond angular resolution achieved by infrared long-baseline interferometry provides us with the only way to spatially resolve the region where the material is accelerated. We present high-spatial and high-spectral resolution observations of the 2.3 micron CO lines in the red supergiants Betelgeuse and Antares using the Very Large Telescope Interferometer (VLTI). This has enabled us to spatially resolve the gas dynamics over the stellar surface and in the outer atmosphere for the first time other than the Sun. We have detected the vigorous motions of large CO gas clumps with velocities of up to 20-30 km/s. Comparison of the CO line data taken 1 year apart shows a significant change in the dynamics of the atmosphere. In contrast to the CO line data, the continuum data reveal no or only marginal time variations, much smaller than the maximum variation predicted by the current 3-D convection simulations. Our VLTI observations suggest the following new picture: the material within ~1.5 stellar radii is strongly stirred possibly by magnetohydrodynamical processes and/or pulsation and may be violently flung out rather than spilling out in an ordered, spherical fashion as often assumed.

Turbulent Structure in the Upper Chromospheres of Cool Supergiants

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The traditional way for a model of a stellar photosphere to acknowledge the presence of the chromosphere is to ignore it. However, while the contribution of a chromosphere to the total flux may be small, it plays a vital role as the interface between the star and IS space, as it is where the stellar wind originates. The very outermost layers of a star are expected to be turbulent. Images of the solar chromosphere and corona reveal both small-scale inhomogeneities (prominences and spaces) and large-scale variability (polar plumes near sunspot minima, streamers near sunspot maxima), and something similar but more exaggerated can be expected in cool supergiants. Samplings of the high chromosphere in late-K supergiants show extreme variability in both density and velocity, and can be thought of as analogues of the solar case. Can they therefore represent how the winds from such stars are energized and propelled? Suitably illustrated with series of chromospheric-eclipse spectra of the Ca II K line in 31 Cyg, 32 Cyg and Zeta Aur, the presentation will demonstrate (a) the presence in the high chromosphere of discrete, rapidly-moving clumps of gas, (b) that structures are not stable or symmetrical, either from eclipse to eclipse or from ingress to egress in the same eclipse, (c) plenty of empty space, and (d) huge differences between one late-K supergiant and another. What information can this evidence offer as regards the outer structure and wind of Betelgeuse?

Global radiation hydrodynamics simulations of red supergiant and AGB stars

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The small-scale surface granulation on cool main-sequence stars and white dwarfs influences the overall appearance of these objects only weakly. And it is only indirectly observable by analyzing line-shapes or e.g. temporal fluctuations -- except for the Sun. On the other hand, the large-scale and high-contrast convective surface cells and accompanying sound waves on supergiants and low-gravity AGB stars have a strong impact on the outer atmospheric layers and are directly detectable by interferometric observations.
The natural complement of modern observations with their high resolution in frequency, time, and/or space are detailed numerical multi-dimensional time-dependent radiation-hydrodynamical simulations.
For local models of small patches of convective surface layers and the atmosphere of main-sequence stars, these have matured over three decades and have reached an impressive level of agreement with observations and also between different computational codes. Global simulations of the entire convective surface and atmosphere of a red supergiants are considerably more demanding and have become available only for about one decade.
It will be demonstrated what older and current versions of these models can tell us about the functioning of surface convection in a red supergiant and the interaction with its atmosphere. The route to more complete future models will be discussed, that comprise the outer atmosphere of the stars and that could explain some of the little-understood phenomena like chromosphere, molsphere, or wind-formation.

3D hydrodynamical simulations of red supergiants to interpret observations of stellar surfaces

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Red supergiant (RSG) stars are among the largest stars in the universe and the brightest in the optical and near-infrared. These stars exhibit variations in integrated brightness, surface features, and the depths, shapes, and Doppler shifts of spectral lines; as a consequence, stellar parameters and abundances are difficult to determine. Moreover, RSGs eject massive amounts of mass back to the interstellar medium with an unidentified process. The study of the dynamical convective pattern of RSGs is then crucial for the understanding of the physics of these stars that contribute extensively to the chemical enrichment of the Galaxy.
Nowadays, the development of the observational instruments is so high that became very sensitive to the details of stellar surface. The interpretation of the stellar surfaces images, the fundamental parameters, the stellar variability needs realist simulations of stellar convection.
The effects of convection and non-radial waves can be represented by numerical multi-dimensional time-dependent radiation hydrodynamics simulations with realistic input physics. Three-dimensional radiative hydrodynamics simulations of red supergiant stars are essential to a proper and quantitative analysis of these observations. I will present how these simulations have been (and will be) crucial to prepare and interpret the spectrophotometric, interferometric, astrometric, and imaging observations.

The chemistry of dust formation in red supergiants

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Red supergiants (RSGs) stars experience mass loss in their late stages of post-main sequence evolution. The mass loss rates span a wide value range, some RSGs being characterised by high episodic mass-loss events while others experience moderate-to-low mass-loss, e.g. Betelgeuse. RSGs also produce molecules and dust grains in their warm, inner wind. Unlike AGB stars, the dust does not trigger the mass-loss phenomenon in RSGs but controls the gas-phase content of the inner layers. I will discus the chemistry related to the formation of molecules and oxygen-rich dust (e.g., silica, silicates, metal oxides) in the dense inner layers of RSG winds.

Red Supergiants, Post-Red Supergiants, and Red Transients -- the Evidence for High Mass Loss Episodes Over a Wide Range of Luminosities

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The complex circumstellar environments associated with several of the most luminous cool supergiants provide evidence for episodic high mass loss events. The origin of the high mass loss is not understood but circumstantial evidence strongly suggests that large scale surface activity and magnetic fields are responsible. The newly recognized Intermediate-Luminosity Red Transients (ILRTs) are apparently stars of somewhat lower mass and luminosity experienceing short-lived eruptions. They may be red supergiants or AGB stars in transition to a warmer state. The origin of their instability is not known. I will review the observational evidence from multi-epoch imaging and spectroscopy for the high mass loss events and instabilities in these stars. New results from high-resolution AO near and mid-IR imaging of VY CMa, IRC+10420 and mu Cep will be presented.

Tracing the long-term mass-loss history of Betelgeuse in CO radio lines

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Using APEX and IRAM 30-m telescopes, we obtained maps of CO radio emission in Betelgeuse. The mapped transitions include J=1-0, 2-1, 3-2, and 6-5, and cover spatial scales of tens of arcsec. At our spatial resolutions between 8-27 arcsec, the CO emission is very inhomogeneous and shows a strong asymmetry in line profiles and in the spatial distribution of the emission. We combine these mapping data with sensitive observations at the stellar position in multiple CO and [CI] lines from Herschel, APEX, IRAM 30m, and ISO to perform radiative transfer calculations aiming to constrain the structure and the physical state of the CO envelope. The results are discussed in the context of the long-term mass-loss history of Betelgeuse.

Towards a coherent view at infrared wavelengths of mass loss in Betelgeuse

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Mass-loss of red supergiants is a significant contributor to the chemical enrichment of the interstellar medium. The violent convective motions, low surface gravity, and high brightness of these massive stars combine to trigger an intense stellar wind. As the distance from the star increases, the standard scenario is that the ejected material forms molecules, then dust particles. But this general picture is still fragmentary. The goal of our program is to assemble a better understanding of mass loss in Betelgeuse, considered as a prototype for its class, from its photosphere to the interface of its wind with the interstellar medium. Thanks to its proximity (~200 pc), it is ideally suited for such a detailed study. Over the past few years, our team obtained an extensive set of observations of Betelgeuse from high angular resolution instruments, probing a broad range of spatial scales: 1) interferometric imaging of its photosphere anc close envelope in the near- and thermal-IR domains (IOTA/IONIC, VLTI/MIDI, VLTI/AMBER, VLTI/PIONIER), 2) adaptive optics "lucky imaging" of its compact molecular envelope (VLT/NACO, 1.0-2.2 microns), and 3) diffraction-limited imaging of its dusty envelope (VLT/VISIR, 8-20 microns). From our interferometric data, we detect the presence of spots at the surface of the star, as well as the presence of the CO and H2O molecules, as well as dust particles close to the star. Within 6 Rstar, the flux distribution of the envelope is compatible with the presence of the CN molecule. At a few arcseconds from the central star, we observe a complex dusty envelope probably containing O-rich dust (e.g. silicates, alumina). We will present an overview of these recent observational results and ongoing work. They provide new hints on the physical and chemical mechanisms through which Betelgeuse interacts with its environment.

Mass loss from Betelgeuse - where is it going?

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Betelgeuse is just starting to produce a wind which is thick enough to form dust However, the grains seem to coalesce at much greater distances than those in 'dust-driven' winds from later-stage AGB and RSG stars. Is the mass loss mechanism different, and how will it evolve? We know a great deal about the kinematics of the more evolved winds, thanks to sub-AU imaging using masers, and easily-resolved CO shells, but Betelguese is a much fainter target, only imaged with great difficulty (although ALMA will change that). On the other hand, Betelgeuse was the first star other than the Sun to be imaged in detail in the radio as well as optical. Radio studies from the photosphere to the astropause will reveal:
- How is mass lost from the stellar surface?
- In what form is this returned to the ISM?
and even help to answer
- How will Betelgeuse evolve in the next few millennia?

The kinematics in the large-scale environment of Betelgeuse from radio HI-line observations

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The observations of mass losing stellar sources in the HI line at 21 cm allow us to study in details the kinematics in their large size circumstellar shells.
We will report on the results that have been obtained on Betelgeuse with the Nancay Radiotelescope (NRT) and with the Very Large Array (VLA). On the star position, we find a double-horn line-profile characteristic of a freely expanding wind at a velocity of ~14 km/s. We find also that the stellar outflow is slowed down by the pressure from the ambient medium, and forms a quasi-stationary detached shell of ~4 arcmin in diameter (0.24 pc at a distance of 200 pc). The HI line-profile from this detached shell has a width of 3 km/s, and is centered at a velocity close to the star radial velocity (Vlsr= +3 km/s). The bulk of the material detected in HI (~0.05 solar mass) has been heated at a temperature ~6000 K, and is cooling down to ~200 K. Furthermore, due to the motion relative to the local interstellar medium, the detached shell is distorted and elongated in a direction close to the space motion. Finally, HI emission, associated with the 6 arcmin radius far-infrared arc discovered by IRAS and with a newly discovered far-ultraviolet emitting arc, has been found in a velocity range (from +6 to +10 km/s) which matches that of the interstellar medium observed on the same line-of-sight.

The enigmatic nature of the circumstellar envelope and bow shock surrounding Betelgeuse as revealed by Herschel. Evidence of clumps, multiple arcs and a linear bar-like structure.

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The interaction between stellar winds and the interstellar medium (ISM) can create complex bow shocks. In this talk, we give an overview of the recent results obtained with the Herschel Space Observatory. The infrared Herschel images of the environment around Betelgeuse are spectacular, showing the occurrence of multiple arcs at 6-7' from the central target and the presence of a linear bar at 9' .The inner envelope shows clear evidence for non-homogeneous clumpy structure (beyond 15"), probably related to the giant convection cells of the outer atmosphere. The non-homogeneous distribution of the material even persists until the collision with the ISM. A strong variation in brightness of the inner clumps at a radius of 2' suggest a drastic change in mean density ~32 000 yr ago. Using hydrodynamical simulations, we try to explain the observed morphology of the bow shock around Betelgeuse

Dust and gas dynamics in the bowshock of alpha-Orionis

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We present hydrodynamical simulations of the interaction between the stellar wind of alpha-Orionis and the interstellar gas. By varying the input parameters such as mass loss rate, stellar velocity and the density of the interstellar medium we investigate how these properties influence the structure of the bowshock. In particular we focus our efforts on reproducing the multiple arc structure of the bowshock that was observed with Herschel.
Because we include the presence of dustgrains in our simulations we can predict how the results of our simulations would appear in infra-red observations. This is of great importance as it allows us to compare our results with observations from Herschel and, in the future, ALMA.

3D simulations of Betelgeuse's bow shock

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Betelgeuse, the bright, cool red supergiant in Orion, is moving supersonically relative to the local interstellar medium. The star emits a powerful stellar wind that collides with this medium, forming a cometary structure, a bow shock, pointing in the direction of motion. We present the first 3D hydrodynamic simulations of the formation and evolution of Betelgeuse's bow shock. The models include realistic low-temperature cooling and cover a range of plausible interstellar medium densities of 0.3-1.9 cm^(-3) and stellar velocities of 28-73 km/s. We show that the flow dynamics and morphology of the bow shock differ substantially because of the growth of Rayleigh-Taylor or Kelvin-Helmholtz instabilities. The former dominate the models with slow stellar velocities resulting in a clumpy bow shock substructure, whereas the latter produce a smoother, more layered substructure in the fast models. If the mass in the bow shock shell is low, as seems to be implied by the AKARI luminosities (~3x10^(-3) Msun), then Betelgeuse's bow shock is very young and is unlikely to have reached a steady state. The circular nature of the bow shock shell is consistent with this conclusion. Thus, our results suggest that Betelgeuse only entered the red supergiant phase recently.

Models for the circumstellar medium of runaway young red supergiants: application to Betelgeuse

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A significant fraction of massive stars are moving supersonically through the interstellar medium (ISM), with their stellar winds generating bow shocks. In post-main sequence evolution these stars may evolve rapidly from red to blue and vice versa on the Hertzsprung-Russell diagram, with accompanying rapid changes to their stellar winds and bow shocks. Our constant wind 3D simulations of the bow shock produced by the nearby runaway red supergiant (RSG) Betelgeuse indicate that the bow shock is very young (less than 20,000 years old), hence Betelgeuse may have only recently become a RSG. To test this possibility we calculated stellar evolution models for single stars with properties consistent with Betelgeuse. We incorporated the resulting evolving stellar wind into 2D hydrodynamic simulations to model a runaway blue supergiant (BSG) undergoing the transition to a RSG near the end of its life. The collapsing BSG wind bubble induces a bow shock-shaped inner shell which at least superficially resembles Betelgeuse's bow shock. Surrounding this is the larger-scale retreating bow shock generated by the now defunct BSG wind's interaction with the ISM. We investigate whether this outer shell could explain the bar feature located (at least in projection) just in front of Betelgeuse's bow shock.

Red Supergiants in the Local Group

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The galaxies of the Local Group span a factor of 15 in metallicity, ranging from the super-solar M31 to the Wolf-Lundmark-Melotte (WLM) galaxy, which is the lowest-metallicity (0.1x solar) Local Group galaxy currently forming stars. Studies of massive star populations across this broad range of environments have revealed important metallicity-dependent evolutionary trends, allowing us to test the accuracy of stellar evolutionary tracks at these metallicities for the first time. The RSG population is particularly valuable as a key mass-losing phase of moderately massive stars and a source of core-collapse supernova progenitors. By reviewing recent work on the RSG populations in the Local Group, we are able to quantify limits on these stars' effective temperatures and masses and probe the relationship between RSG mass loss behaviors and host environments. Extragalactic surveys of RSGs have also revealed several unusual RSGs that display signs of unusual spectral variability and dust production, traits that may potentially also correlate with the stars' host environments. I will present some of the latest work that has progressed our understanding of RSGs in the Local Group, and consider the many new questions posed by our ever-evolving picture of these stars.

Betelgeuse in context of the Massive Star Population in Orion

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The Orion OB1 association hosts several agglomerates of recent and ongoing star formation. Massive stars in different evolutionary stages are found scattered thoughout the region. Objects near the zero-age to the terminal-age main sequence are numerous, while the visual appearance is dominated by a few supergiants. We have studied the hot massive star population recently, providing a wealth of data on stellar parameters and elemental abundances. This facilitates a quantitative investigation of the massive star population with respect to stellar evolutionary and (sub)association properties based on tight observational constraints. We will discuss the sole red supergiant, Betelgeuse, in context of the blue massive star population in Orion.

Stephenson 2, a nest of red supergiants

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The open cluster Stephenson 2 contains the largest collection of red supergiants known in the Galaxy, and is likely to be the second most massive young cluster in the Milky Way. We have obtained multi-epoch intermediate resolution spectra around the CaII triplet for more than 30 red supergiants in Stephenson 2 and its surroundings. We find a clear separation between a majority of RSGs having spectral types M0-M2 and the brightest members in the NIR, which have very late spectral types and show strong evidence for heavy mass loss. The distribution of spectral types is similar to that of RSGs in NGC7419, but somewhat different from that in RSGC3. The cluster data strongly support the idea that heavy mass loss and maser emission is preferentially associated with late-M spectral types, suggesting that they represent an evolutionary phase.

Red Supergiant Stars as Cosmic Abundance Probes

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The determination of the chemical composition of galaxies is crucial for constraining the theory of galaxy formation and evolution in a dark energy and cold dark matter dominated universe. However, the standard techniques to obtain information about the chemical composition of star forming galaxies are subject to large systematic uncertainties which are poorly understood. As an alternative, we introduce a new method, which uses low resolution J-band spectroscopy of individual red supergiant stars (RSGs) in distant galaxies. Using spectra of Milky Way and Magellanic Cloud RSGs obtained with IRTF, Subaru/IRCS and VLT/XShooter and MARCS model atmospheres we have demonstrated that our analysis method allows individual metallicities to be determined with an accuracy of about 0.15 dex. The extension of the method to star forming galaxies beyond the Local Group with IR MOS devices at large telescopes such as MOSFIRE/Keck and KMOS/VLT is straightforward and preparative work is presently under way.
This new method will gain tremendous momentum with the next generation of ELTs and AO supported MOS instruments. Detailed simulations show that we can reach individual RSGs in galaxies as distant as the Coma Cluster at 100 Mpc. In addition, the potential of observing the integrated light of young Super Star Clusters (SSCs) is even larger. The J-band light of these objects is entirely dominated by RSGs as soon as the cluster age is larger than 8 Myr. This allows for the determination of accurate detailed chemical composition by simple population synthesis techniques. Because of the outstanding brightness of SSCs with the dominating contribution of many dozens of RSGs in the J-band an enormous volume of the local universe even beyond the Coma Cluster can be studied in this way.

summary and discussion

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I will attempt to summarise the new results and thoughts that were presented during this meeting, and discuss these in the light of what we try to learn about Betelgeuse and red supergiants in general. I will finish with an outlook to the future, formulating outstanding questions and possible ways of answering them, before inviting the audience to further unrestrained discussion (which I shall try to incorporate in the write-up).

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