IAUS 329: The Lives and Death-throes of Massive Stars

10th IAU Symposia on Massive Stars
Auckland, New Zealand

Talks Abstracts

November 28th to December 2nd, 2016

Contents

The mass-loss before the end: two luminous blue variables with a collimated stellar wind

Claudia Agliozzo

Departamento de Ciencias Fisicas, Universidad Andres Bello

Recently, the classical view of luminous blue variables (LBVs) as a phase of post-main sequence evolution of a single massive star has been challenged by Smith & Tombleson (2015), that proposed that LBVs are mass-gainers in binary systems with Wolf Rayet (WR) stars, which are the mass-donor. Humphreys et al. 2016 defended the accepted description of LBVs as evolved massive stars that have to lose quickly their H envelope through severe mass-loss, before to evolve as WRs. There is a growing evidence that H-poor Core Collapse-SNe progenitors consist of both binary and single stars. The mechanism that induces some LBVs to explode as Type IIn SNe is not know. The debate is very active and the mass-loss mechanism is still poorly understood. We gathered a multiwavelength dataset consisting of high-spectral resolution optical data and centimeter (ATCA) and sub-millimeter (ALMA) data of two well-known Magellanic LBVs. We found a complex mass-loss, with evidence of variability, such as have been seen previously. In addition, our data reveal signatures of collimated stellar winds. The outer nebulae are not equatorial disks as previously thought but instead they seem conical helices. We propose a new scenario for these two stars where the mass-loss geometry is influenced by an external factor rather than intrinsic asymmetries of the mass-loss. I will discuss the simplest and most convincing scenario.

The Magnetic Furnace: Intense Core Dynamos in B Stars

Kyle Augustson
CEA Service d'Astrophysique

The dynamo action achieved in the convective cores of main-sequence massive stars is explored here through 3-D global simulations of convective core dynamos operating within a young 10 Msun B-type star, using the anelastic spherical harmonic (ASH) code. These simulations capture the inner 65% of this star by radius, encompassing the convective nuclear-burning core (about 23% by radius) and a portion of the overlying radiative envelope. Eight rotation rates are considered, ranging from 0.05% to 16% of the surface breakup velocity, thereby capturing both convection barely sensing the effects of rotation to others in which the Coriolis forces are prominent. The vigorous dynamo action realized within all of these turbulent convective cores builds magnetic fields with peak strengths exceeding a megagauss, with the overall magnetic energy (ME) in the faster rotators reaching super-equipartition levels compared to the convective kinetic energy (KE). The core convection typically involves turbulent columnar velocity structures roughly aligned with the rotation axis, with magnetic fields threading through these rolls and possessing complex linkages throughout the core. The very strong fields are able to coexist with the flows without quenching them through Lorentz forces. The velocity and magnetic fields achieve such a state by being nearly co-aligned, and with peak magnetic islands being somewhat displaced from the fastest flows as the intricate evolution proceeds. As the rotation rate is increased, the primary force balance shifts from nonlinear advection balancing Lorentz forces to a magnetostrophic balance between Coriolis and Lorentz forces.

OWN, a survey of O and WR stars

Rodlofo Barba
Universidad De La Serena

Effect of a Dipole Magnetic Field on Massive Star Line-Driven Winds

Christopher Bard

NASA-GSFC/University of Wisconsin-Madison

Massive star winds greatly influence the evolution of both their host star and local environment though their mass-loss rates, but current radiative line-driven wind models do not incorporate any magnetic effects. Recent surveys of O and B stars have found that about ten percent have large-scale, organized magnetic fields. These massive-star magnetic fields, which are thousands of times stronger than the Sun's, confine most of the stellar wind and force it to co-rotate with the star in a magnetosphere. Here, I present the first study of how a stellar magnetic field affects a simple line-driven CAK wind by changing its mass-loss rate and velocity structure. We generalize the Rigid-Field Hydrodynamic equations to accommodate arbitrary magnetic field topologies, resulting in a new Arbitrary Rigid-Field Hydrodynamic (ARFHD) formalism. After undertaking a critical point calculation of the steady-state ARFHD equations with a CAK-type radiative acceleration, we determine the effects of a dipole magnetic field on the usual CAK mass-loss rate and velocity structure. Enforcing the proper optically-thin limit for the radiative line-acceleration is found to decrease both the mass-loss and wind acceleration, while rotation boosts both. Our initial results demonstrate that the effective stellar mass-loss rate, which ignores plasma that falls back onto the star but includes confined, rotationally-supported plasma, is about 65% of the non-magnetic, non-rotating CAK mass-loss rate for a star rotating at 80% of breakup, and lower for more slowly rotating stars. We define optically-thin-correction and rotation parameters to quantify these effects on the global mass-loss rate and develop scaling laws for the surface mass-flux as a function of surface colatitude. These scaling laws are found to agree with previous laws derived from magnetohydrodynamic simulations of magnetospheres. However, the dipole magnetosphere velocity structure is found to differ between individual field lines. This contradicts a central assumption of the previously-developed XADM model of X-ray emission from magnetospheres, which assumes a global beta-law velocity structure.

The evolution of red supergiants to supernovae

Emma Beasor

Astrophysics Research Institute, Liverpool John Moores University

The mass loss rates of red supergiants (RSGs) govern their evolution towards supernova and dictate the appearance of the resulting explosion. To study how mass-loss rates change with evolution we have measured the mass-loss rates and extinctions of 19 red supergiants in the young massive cluster NGC2100 in the Large Magellanic Cloud. By targeting stars in a coeval cluster we are able to study the mass-loss rate evolution whilst keeping the variables of mass and metallicity fixed. Our results indicate that there is little justification for substantially increasing the mass loss rates during the RSG phase, as has been suggested recently in order to explain the absence of high mass Type IIP supernova progenitors. We also argue that an increase in reddening towards the end of the RSG phase, as observed for the two most evolved cluster stars, may provide a solution to the red supergiant problem.

Modelling the SN and progenitors

Melina Bersten
Ialp-fcaglp, Argentina

Difference between Iib/Ib/Ic/Ic-BL

Fed Bianco
New York University

Magneto-asteroseismology of hot stars

Bram Buysschaert
Paris Observatory

Thanks to recent surveys, such as MiMeS and the BRITE spectropolarimetric survey, the sample of known magnetic hot stars keeps expanding rapidly. Studying the 10Meanwhile, dedicated space missions, e.g. CoRoT, Kepler, K2, and the BRITE constellation, provide precise photometry over long timebases. Therefore, periodic variability can be determined with high accuracy and precision for a myriad of stars. Some of this variability is caused by stellar pulsations, permitting us to determine and study the internal stellar properties via asteroseismology. An exact determination of these properties, such as chemical internal mixing, is crucial for stellar structure and evolution models. Hot stars that host both a magnetic field and pulsations can be studied in greater detail by combining spectropolarimetry and asteroseismology: this is called magneto-asteroseismology. This technique employs the effect of magnetism on pulsations or other internal properties to tighly constrain seismic models. In this talk, we will describe the principle of magneto-asteroseismology, while highlighting results of our current sample of hot magnetic pulsators. In particular, we will show how internal mixing can be constrained and the effect of magnetism on pulsation frequencies and amplitudes.

The Young and the Massive: Stars at the upper end of the Initial Mass Function

Saida Caballero-Nieves

Physics and Astronomy, UK

The question of how massive a star can be is still an open question. In this talk, we will discuss observations of the most massive stars (greater than 100 solar masses) in the local universe and how the observations fit in with theoretical predictions. In particular, the Large Magellanic Cloud plays hosts to a numerous amount of very massive stars, making it an ideal template to study the roles that environment, metallicity and multiplicity play in the formation and evolution of the most massive stars. We will discuss the work that is instrumental in laying the groundwork for interpreting future observations by James Webb of starburst regions in the high redshift universe.

The Stellar Ultrasound

Matteo Cantiello
KITP - UCSB

Internal rotation and magnetism are key ingredients that largely affect explosive stellar deaths (Supernovae and Gamma Ray Bursts) and the properties of stellar remnants (White Dwarfs, Neutron Stars and Black Holes). However, the study of these subtle internal stellar properties has been limited to very indirect proxies. In the last couple of years, exciting asteroseismic results have been obtained by the Kepler satellite. Among these results are 1) The direct measure of the degree of radial differential rotation in many evolved low-mass stars and in a few massive stars, and 2) The detection of strong ($> 10^5$ G) internal magnetic fields in thousands of red giant stars that had convective cores during their main sequence. I will discuss the impact of these important findings for our understanding of massive star evolution.

Massive infrared clusters in the Milky Way

André-Nicolas Chené
Gemini Observatory

Where and how do massive stars form? What are the details of the massive stars evolution from the main sequence to the supernova explosion? Does the Milky Way (MW) host a cluster equivalent to R136? The study of young, open clusters is a powerful way to bring new constraints to answer these questions.

Our position in the MW is both a blessing and a curse. We are nearby to many star clusters, but they are obscured by the dust that is a product of their very existence. Also, many massive young clusters are expected to be located near, or across the Galactic Center, where the dust extinction is extreme (Av ¿ 15 mag). Estimates indicate that the MW presently hosts 23000-37000 or more star clusters, but optical observations allow the discovery and the study of a mere 5% of them, and is limited to the nearest ones.

The dust can be penetrated by infrared photons, and recent infrared surveys have revitalized star cluster research: 2MASS, GLIMPSE, WISE, Vista Variables in the Va Lctea, and UKIDSS GPS. Indeed, new star clusters have been discovered, thus extending the census effort to approximately 3900-catalogued clusters.

We will review the discovery and the study of new MW massive stars and massive clusters made possible by infrared observations. We will visit the main clusters discovered in the last 10-15 years, and discuss what the studies of their mass function, composition, dynamics and fundamental parameters have taught us.

3D Hydrodynamic Simulations of the Carbon Shell in a Massive Star

Andrea Cristini

Astrophysics group, Keele university

We present the first detailed three-dimensional hydrodynamic implicit large eddy simulations (ILES) of turbulent convection for carbon burning. The simulations start with an initial radial profile mapped from a carbon burning shell within a 15 solar mass stellar evolution model. We considered 4 resolutions from 128 to 1024 radial zones. These simulations confirm that convective boundary mixing (CBM) occurs via turbulent entrainment as in the case of oxygen burning. We confirm that turbulent fluid elements impacting on the convective boundary regions distort the boundary layers and excite internal gravity waves in the surrounding stable regions. We see a reduction in the residual (numerical plus physical) dissipation of kinetic energy at the upper boundary with increasing resolution. This suggests that our highest resolution ILES are able to resolve the turbulent cascade well into the inertial range. Our resolution study shows that a radial resolution of 512 zones is sufficient to resolve the upper boundary but a resolution of roughly 1500 is needed to fully resolve the lower boundary. The width of the boundary and the entrainment rate are smaller at the bottom boundary because it is stiffer than the upper boundary. We estimate the widths of the upper and lower boundaries to be 29% and 11% of the local pressure scale heights, respectively. These widths are significantly larger than those calculated by stellar evolution models assuming strict Ledoux or Schwarzschild boundaries. The results of this and similar studies call for improved CBM prescriptions in 1D stellar evolution models.

The Tarantula as a template for extragalactic star forming regions from VLT/MUSE

Paul Crowther

Physics & Astronomy, University of Sheffield

We present an overview of Science Verification VLT/MUSE observations of NGC2070, the central ionizing nebula of 30 Doradus. Integral field spectroscopy permits a complete census of all massive stars within the central 2x2 arcmin of NGC 2070, corresponding to 30x30 pc at the distance to the LMC, together with gas kinematics of this region. We emphasise the contribution of individual massive stars to the integrated optical spectrum from this region in the context of extragalactic star forming regions. Indeed, blue and yellow Wolf-Rayet bumps arise primarily from classical WR stars in R140 rather than the more numerous H-rich WN stars in R136. We also present an integrated far-UV spectrum of NGC 2070 obtained via our census, exploiting LMC templates of O-type, B supergiant and WR stars appropriate to this region, especially relevant for rest frame UV studies of extragalactic s.f. regions.

Eta Carinae A: a star with a hole

Augusto Damineli
IAG - USP

After 20 years of intense observational efforts and 3D hydro simulations, we were able to draw a robust scenario for the binary system in eta Carinae, including the orbital elements and the wind-wind collision. Using reflected light in the Homunculus walls it was possible to map latitude dependent emission from the central star and in particular the position of the secondary star at periastron. Although the system is eclipsing, this is not the cause of the 5.54-yr period low excitation events. Around periastron, the hot secondary star plunges inside the dense inner wind of the primary causing the absorption of the UV photons, shutting down of the high excitation lines formed in the fossil wind-wind collision walls and in the Weight blobs. The impressive growth of (the normally absent) HeII4686A line at the same time when the other high excitation lines were fading, looks a paradox. The observed emission demands 100Lsun to be emitted in the UV shorter than the He+ ionisation threshold (54 eV). The source of these photons is the shocked wind of the primary star and the dense reservoir of He+ is the sub-photospheric layers of etaA. It is the first time in Astronomy we see a hole drew into the outer layers of a star, which temporarily exposes the sub photosphere to the outside space.

Red Supergiants as Cosmic Abundance Probes

Benjamin Davies
Liverpool JMU

Over the past 6 years we have been establishing a novel method for determining chemical abundances from only moderate resolution near-IR spectroscopy of Red Supergiants (RSGs), the brightest stars at infrared wavelengths. We show that we can now routinely perform stellar abundance analysis at distances of 4Mpc, and around 10x this distance for young RSG-dominated clusters. This is a substantial volume of the local Universe, containing hundreds of star-forming galaxies, and we are now determining accurate metallicities and abundance gradients for a substantial sample of galaxies. Ultimately we will provide a robust measurement of the mass-metallicity relation at low redshift, free of the systematic errors that plague HII-region-based work.

A Candidate Red Supergiant X-ray Binary in M31

Trevor Dorn-Wallenstein

Astronomy Department - University of Washington

We have recently identified a candidate for what may be the first high-mass X-ray binary (HMXB) with a red supergiant (RSG) donor star. While much work has gone into the study of HMXBs with main sequence companions, HMXBs with evolved companions are relatively rare and thus poorly understood. Systems with RSG donor stars are particularly compelling: they represent an important evolutionary phase for massive binary systems, the large diffuse envelopes of RSGs offer the possibility of studying exotic accretion rates not usually found in HMXBs (which typically accrete via a rarefied stellar wind), and they are excellent candidates for studying both common envelope systems with a compact primary and possible proto-Thorne-Zytkow objects (cool massive stars with an embedded neutron star core). We present the results from a spectrophotometric study of the donor star in question, previously identified as a 12 solar mass RSG in M31, and discuss its membership in M31, its physical properties, and evidence for a compact companion.

Probing the Extremes of Pre-SN Mass Loss with the PanSTARRS1 Medium-Deep Survey

Maria R. Drout
Carnegie Observatories

A non-negligible fraction of massive stars undergo enhanced (possibly violent/eruptive) mass-loss in the final decades before core collapse. Theoretical models of such mass-loss are challenging and observational probes are necessary to help constrain the full diversity of pre-SN mass-loss (e.g. density profile, physical extent), the mechanism by which this mass is ejected, and the progenitors of various sub-classes of events. In this talk I will present new results from PS1 observations of super-luminous Type IIn SN (SLSN-II). In particular, I will highlight new constraints on the progenitors of SLSN-II based on a joint analysis of their explosion/CSM properties and host galaxy environments.

BH+BH merger rates from massive overcontact binaries

Lise du Buisson
University of Oxford

We have just seen the first detection of gravitational waves from GW150914, a BH+BH binary merger of roughly 29 and 36 solar masses, respectively, which merged around 1.3 billion years ago. Massive overcontact binaries (MOBs) consist of stars that remain chemically homogenous due to their tight orbits and tidally induced high spins and can, at low metallicities, produce BH+BH pairs that merge within a Hubble time. These MOBs then typically produce BH+BH systems with masses in the ranges 25 - 60 and ¿ 130 solar masses (with PISNe produced in between) and mass ratios close to one, remarkably like the detection mentioned above. It has been suggested that these systems can be prime candidates for detection by gravitational wave experiments. In my talk I will present a Monte-Carlo simulation which uses results from galaxy formation, cosmology, general relativity and the MOB stellar evolution route in order to predict not only the BH+BH merger rate, but also the properties of this specific population. Results from cosmological N-body simulations provide us with the distribution of metallicities and star formation throughout the history of the universe. In my talk, I will explain how to use these to simulate MOBs with the correct distribution of ages and metallicities and how I follow their fate with predictions from Marchant et al. (2016). Using aLIGO detection probabilities (De Mink & Mandel, 2016), I further estimate the aLIGO BH+BH merger detection rate.

New Insights into the Puzzling P-Cygni Profiles of Massive Magnetic Stars

Christiana Erba
Department of Physics and Astronomy, University of Delaware

Magnetic massive stars comprise approximately 10% of the total massive-star population, presenting a new species in the wider massive star zoology. Unlike their non-magnetic counterparts, modern spectropolarimetry has shown these stars to host strong, stable, large-scale, often nearly dipolar magnetic fields of 1 kG or more. Such strong global magnetic fields trap outflowing stellar wind material, inducing regions of shock-heated, X-ray-emitting gas. For the pre-shocked material, P-Cygni line profiles provide a powerful probative tool for examining the effects of magnetic channeling on such wind outflows. In stark contrast to the strong line saturation observed in non-magnetic O-stars, recent HST UV spectra of NGC 1624-2 the most magnetic O-type star observed to date show atypically unsaturated P-Cygni profiles in the CIV and NV resonance lines, as well as a distinct dependence on rotational phase. Our initial investigation focused on the role of X-rays in reducing ion fractions, but showed opposite trends for the two lines; it was thus unable to fully explain the unsaturation in both lines. This poster examines the further effect of non-radial, magnetically-channeled wind outflow on line formation, using a Sobolev Exact Integration (SEI) approach to synthesize P-Cygni lines for direct comparison with HST UV spectra of NGC 1624-2. Our study thus provides a first step toward a broader understanding of how strong magnetic fields affect the stellar wind outflow of this and other magnetic massive stars.

Investigating the Magnetospheres of Rapidly Rotating B-type Stars

Corinne Fletcher

Physics and Space Science, Florida Institute of Technology

The Magnetism in Massive Stars (MiMeS) project has found that 10% of OB-type stars contain strong (mostly dipolar) magnetic fields (kG). The prominent idea describing the interaction between the stellar winds and the magnetic field is the magnetically confined wind shock (MCWS) model. In this model, the stellar wind plasma is forced to move along the closed field loops of the magnetic field, colliding at the magnetic equator, and creating a shock. As the shocked material cools radiatively it will emit X-rays. Therefore, X-ray spectroscopy is a key tool in detecting the wind material confined by the magnetic fields of these stars. Some B-type stars are found to have very short rotational periods. The effects of the rapid rotation on the X-ray production within the magnetosphere have yet to be explored in detail. The added centrifugal force is predicted to cause faster wind outflows along the field lines, which leads to higher shock temperatures and harder X-rays. However, this is not observed in all rapidly rotating magnetic B-type stars. In order to address this from a theoretical point of view, we use the X-ray Analytical Dynamical Magnetosphere (XADM) model, developed for slow rotators with an implementation of rapid rotational physics. Using X-ray spectroscopy from ESAs XMM-Newton space telescope, we observed 5 rapidly rotating B-types stars to add to the previous list of observations. Comparing the observed X-ray luminosity and hardness ratio to that predicted by the XADM allows us to determine the role the added centrifugal force plays in the magnetic field and mass loss of these stars.

Progenitors of core-collapse supernovae

Morgan Fraser

Institute of Astronomy, Cambridge

Massive stars are expected to end their lives as luminous core-collapse supernovae. But while a growing sample of core-collapse supernovae have been matched to their stellar progenitors through serendipitous archival imaging, there now exist multiple lines of evidence that there is a systematic deficit of higher mass supernova progenitors. An exciting possibility is that some of the most massive supernova progenitors collapse to form black holes without an accompanying bright optical transient. I will review the observational case for these failed supernovae, and discuss ongoing efforts to find such vanishing massive stars.

Asteroseismology of massive stars

Jim Fuller
California Institute of Technology

The basic principles of asteroseismic techniques applied to massive stars will first be explained for a non-expert audience and it will be addressed which stellar interior physics can be tested from studying their stellar oscillations. Afterwards, an overview of the main achievements over the last decade will be presented by means of several relevant case studies, especially in the framework of past and ongoing space missions. It will also be illustrated how asteroseismoloy and spectropolarimetry can be combined to probe magnetic hot stars. The review will end with a discussion on the current challenges and future prospects.

Winds of low metallicity OB stars

Miriam Garcia & Artemio Herrero
Instituto De Astrofisica De Canarias

Evolution models of red supergiants

Cyril Georgy
Genenva University

Taking the Measure of Massive Stars and their Environments with the CHARA Array Long-baseline Interferometer

Douglas Gies

CHARA, Physics & Astronomy, Georgia State Univ.

Most massive stars are so distant that (with the exception of some red supergiants) their angular diameters are too small for direct resolution. However, the observational situation is now much more favourable for progress, thanks to the new opportunities available with optical/IR long-baseline interferometry. The Georgia State University Center for High Angular Resolution Astronomy (CHARA) Array at Mount Wilson Observatory is a six-telescope instrument with a maximum baseline of 330 meters, which is capable of resolving stellar disks with diameters as small as 0.2 milliarcsec. At this level of angular resolution, the distant stars are no longer out of range, and many kinds of investigations are possible. Here we summarize a number of ongoing studies involving angular diameter measurements and effective temperature estimates for OB stars, binary and multiple stars (focusing on the sigma Orionis system), and outflows in Luminous Blue Variables.

The Elusive Population of Massive Binary Star Products: the far UV Spectra of Stripped Stars

Ylva Louise Linsdotter Goetberg

Anton Pannekoek Institute for Astronomy, University of Amsterdam

Young massive stars are very frequently found in close binary systems, implying that the majority of massive stars interact with a companion during their lives. This raises two questions: How do we identify binary products and why do they appear to be so rare?

Models predict that Roche lobe overflow strips the hydrogen rich envelope of the primary star, exposing its hot helium core. These long-lasting, post-interaction systems are of wide astrophysical interest as (1) direct progenitors of Ib/c supernovae, as (2) unconventional sources of UV radiation and for (3) their capability of calibrating models and thus the theory of binary interaction. Surprisingly, very few stars stripped through binary interaction have been identified observationally - a clear contradiction with theoretical predictions.

We have conducted an extensive computational study using the binary evolutionary code MESA and the radiative transfer code CMFGEN to provide grids of tailor-made atmosphere models of stripped stars. We compute the contribution of stripped stars to the emitted radiation of stellar populations with focus in particular on their high UV-flux. We also propose several concrete observing strategies to systematically search for this elusive population.

Clumping in stellar winds and interiors

Götz Gräfener

University of Bonn

The uncertain clumping properties pose a major problem for thequantitative analysis and the modelling of hot star winds. New resultssuggest that also the outer envelopes of massive stars may be affectedby clumping, with important consequences for their observable radiiand ionising properties. In this talk I will discuss how clumping isincorporated in stellar interior and wind/atmosphere models, howcurrent theoretical results compare with observations, and what we canlearn from a combination of stellar interior models and winds.

Spectroscopic evolution of supernova progenitors

Jose Groh
Trinity College Dublin

The metallicity dependence of WR winds

Rainer Hainich
University of Potsdam

Wolf-Rayet stars are the most advanced stage in the evolution of massive stars. The strong feedback provided by these objects and their subsequent SN explosions is decisive for a variety of astrophysical topics such as the cosmic matter cycle. Consequently, understanding the properties of WR stars and their evolution is indispensable. A crucial but still not well known quantity determining the evolution of WR stars is their mass-loss rate. Since the mass loss is predicted to increase with metallicity, the feedback provided by these objects and their spectral appearance are expected to be a function of the metal content of their host galaxy. This has severe implication for the role of massive stars in general and the exploration of low metallicity environments in particular. Hitherto, the metallicity dependence of WR star winds is not well studied. In this talk, we present the results from our comprehensive spectral analyses of WR stars in environments of different metallicities, ranging from slightly super-solar to SMC-like metallicities. Based on these studies, we derived the first empirical mass-loss metallicity relation for WN stars. We will discuss this relation and its implication for the evolution of WR stars as well as its broader consequences.

Origin of Extremely Hard X-ray Emission from Eta Carinae and Its Connection to Gamma-rays

Kenji Hamaguchi

CRESST NASA/GSFC & UMBC

Massive binary systems drive high energy activities via collisions of their winds (wind-wind collisions: WWC). With typical wind speeds of ¿ 1000 km s-1, the collisional shock thermalizes plasma up to several tens of millions of Kelvin and radiates soft thermal X-rays. This collision is also suspected to accelerate a small portion of particles to the GeV energy range, whose non-thermal radiation could be seen in the extremely hard X-ray (¿ 10 keV) and/or gamma-ray bands. The supermassive binary system, Eta Carinae, emits soft thermal X-rays through this activity, which varies with its 5.5 years binary orbital cycle. It is also the only WWC system for which extremely hard X-ray and GeV gamma-ray emission has been reported based upon observations with INTEGRAL, Suzaku and Fermi observatories. However, the source identification and emission mechanism are controversial due to limitations in positional determination and quality of the spectra.

The NuSTAR observatory, with ¡ 1 imaging capability, is ideal for measurements in the extremely hard X-ray band. NuSTAR performed multiple observations of eta Carinae near its periastron in 2014; two observations were simultaneous with XMM-Newton observations. NuSTAR clearly detected kT $\sim$ 6 keV thermal X-ray emission from Eta Carinae extending over 10 keV, but it did not confirm emission in the extremely hard X-ray band as reported with INTEGRAL and Suzaku. NuSTAR performed another joint observation with XMM-Newton in 2015 (orbital phase $\sim$ 0.2), which showed a significantly flatter spectrum above $\sim$ 17 keV than the observations in 2014. The observed flux is only slightly lower than that measured with INTEGRAL and Suzaku, suggesting that the extremely hard X-ray component emerged after periastron. This excess component is located within ¡ 10 from the WWC thermal X-ray source, suggesting an association with the central binary system. This flux varies differently from both soft thermal X-rays, which decline abruptly for a month around periastron, and GeV gamma-rays, which changes little across periastron. This perhaps suggests that the extremely hard X-ray component originates from a different emission mechanism or process from the soft X-ray and GeV gamma-ray emission components. We will also present the result of a deep NuSTAR observation planned this year.

Massive stars in advanced evolutionary stages, and the potential progenitors of GW150914

Wolf-Rainer Hamann

Universitt Potsdam

The recent discovery of a gravitational wave from the merging of two black holes of about 30 solar masses each in a low metallicity environment challenges our incomplete understanding of massive stars and their evolution. Critical ingredients comprise mass-loss, rotation, internal mixing, and mass transfer in close binary systems. The imperfect knowledge of these factors implies large uncertainties for models of stellar populations and their feedback. In this talk I will summarize our empirical studies of Wolf-Rayet populations at different metallicities by means of modern non-LTE stellar atmosphere models, and confront these results with the predictions of stellar evolution models. We discuss the spectroscopic signatures of potential GW progenitor systems, as predicted by different binary evolution scenarios, and consider if such objects are observable or even already known.

Quantitative spectroscopy of supernovae

John Hillier
University A

"Current deep, high cadence, untargeted surveys of the sky are revealing the great diversity of core-collapse supernovae of all types. These massive star explosions, understood to follow the gravitational collapse ouillierf the progenitor iron core, produce two distinct types of supernova with a comparable rate. Type II supernovae stem from the explosion of H-rich supergiant stars, while Type Ib/c supernovae stem from the explosion of H-poor and more compact progenitor stars.

For the most nearby SNe II, progenitor identification is sometimes possible. However, in general, all our inferrences on such explosions rely on the analysis of the supernova radiation. This will be even more true for the forthcoming deep surveys of the transient sky (e.g., with the Large Synoptic Survey Telescope). Understanding massive star explosions therefore requires detailed radiative transfer tools to connect progenitor/explosion and supernova observables.

In this talk, I will review the basic properties of core-collapse supernova ejecta and their observed properties. I will then describe the various methods used to model supernova radiation, and focus in particular on two approaches. The first is a local approach that treats the photospheric regions and assumes steady state. The second is a global approach that treats the entire ejecta in a time dependent way. This allows for the accurate computation of the evolution of the escaping radiation, providing multi-band light curves and spectra.

I will show the results from recent studies obtained with the code CMFGEN to emphasize the importance of line blanketing, non-LTE effects, time dependence, and non-thermal processes. I will also summarize the inferrences based on such studies concerning the explosion mechanism and progenitors of core-collapse supernovae."

Reconstructing the Scene: New Views of Supernovae and Progenitors from the SNSPOL Project

Jennifer L. Hoffman

Physics & Astronomy, University of Denver

Because polarization encodes geometrical information about unresolved scattering regions, it provides a unique tool for analyzing the 3-D structures of supernovae and their surroundings. Supernovae of all types exhibit time-dependent spectropolarimetric signatures produced primarily by electron scattering. These signatures reveal physical phenomena such as complex velocity structures, changing illumination patterns, and asymmetric morphologies within the ejecta and surrounding material. Interpreting changes in polarization over time yields unprecedentedly detailed information about supernovae, their progenitors, and their evolution.

Begun in 2012, the SNSPOL project continues to amass the largest database of time-dependent spectropolarimetric data on supernovae of all types. I present an overview of the project and its recent results combining time-series observations with interpretive radiative transfer models. This two-pronged technique allows us to constrain explosion mechanisms, understand the physical processes that shape SN ejecta, uncover new relationships among SN types, and probe the properties of progenitor winds and circumstellar material.

Common envelope: progress and transients

Natalia Ivanova
Physics, University of Alberta

Common-envelope events are fate-defining episodes in the lives of massive close binary systems. During a common envelope event, two stars temporarily orbit within a shared envelope, and the episode ends with an exciting outburst, leaving behind either a significantly shrunk binary, or a single merged star. These episodes are believed to be vital for the formation of a wide range of extremely important astrophysical objects, including X-ray binaries, close double-neutron stars, the potential progenitors of Type Ia supernovae and gamma-ray bursts, and double black holes that could produce gravitational waves. I will review the common envelope physics, and will report the recent progress that was made by the inclusion of recombination physics, as well as new perspectives that opened up by observations of a new class of astronomical transients, Luminous Red Novae.

44Ti and 56Ni Production and Distribution in a Cassiopeia A like 3D Supernova Model

Hans-Thomas Janka

Max Planck Institute for Astrophysics

The spatial and velocity distributions of nuclear species synthesized in the innermost regions of core-collapse supernovae (SNe) can yield important clues about explosion asymmetries and the operation of the still disputed explosion mechanism. Recent observations of radioactive 44Ti with high-energy satellite telescopes (NuSTAR, INTEGRAL) have measured gamma-ray line details, which provide direct evidence of large-scale explosion asymmetries in Supernova 1987A, and in Cassiopeia A (Cas A) even by mapping of the spatial brightness distribution (NuSTAR). Here, we discuss three-dimensional (3D) simulations of neutrino-driven explosions which can explain basic properties of the production and anisotropic ejection of radioactive nuclei in these stellar explosions.

3D Radiation Magnetohydrodynamic Simulations of Massive Star Envelopes at the Iron Opacity Peak

Yan-Fei Jiang

Smithsonian Astrophysical Observatory

I will describe a set of three-dimensional radiation (magneto-) hydrodynamic simulations of the structure and dynamics of the radiation dominated envelopes of massive stars at the location of the iron opacity peak. One-dimensional hydrostatic calculations predict an unstable density inversion at this location, whereas our simulations reveal a complex interplay of convective and radiative transport whose behavior depends on the ratio of the photon diffusion time to the dynamical time. Our simulations provide the first numerical calibration of mixing length theory in the radiation dominated regime. When diffusion time is shorter than the dynamic time scale, the envelopes show large amplitude oscillations and density fluctuations that allow photons to preferentially diffuse out through low-density regions. Magnetic field enhances the advective energy transport through magnetic buoyancy and increases the density fluctuation as well as the porosity effect. The simulations show that the turbulent velocity field may affect the broadening of spectral lines and therefore stellar rotation measurements in massive stars, while the time variable outer atmosphere could lead to variations in their mass loss and stellar radius.

Massive binary stars

Stephen Justham

University of the Chinese Academy of Sciences & NAOC

The evolution of magnetic hot massive stars: implementation of the quantitative influence of surface magnetic fields in modern models of stellar evolution

Zsolt Keszthelyi

Royal Military College of Canada / Queen's University

Strong, large-scale fossil magnetic fields are observed at the surfaces of a fraction of massive OB stars. These magnetic fields play a significant role in the surface angular momentum evolution of these stars by confining and channeling their radiatively-driven winds. The wind confining and channeling effects of magnetic fields are clearly evidenced by the slow surface rotation and non-spherical, rigidly rotating winds of known magnetic hot stars.

The two major consequences of surface magnetic fields on the evolution of massive stars are due to rotational braking and mass-loss quenching. We are performing 1D stellar evolution model calculations including these effects from the ZAMS to the post-main sequence phases. We take into account the evolution of the (assumed dipolar) surface magnetic field as implied by flux conservation, and the dependence of mass-loss and rotational spindown as parametrized by the magnetic confinement parameter (ud Doula et al. 2008, 2009).

Our first results imply that massive stars possessing strong surface magnetic fields will lose much less mass during their main sequence evolution than equivalent non-magnetic stars. Ultimately, this has consequences for their final masses in the pre-supernova stages. In particular, we find that magnetic stars with initial mass greater than 40 solar masses in a Galactic metallicity environment may potentially provide a pathway to the formation of massive stellar mass black holes. Such black holes were recently detected by the LIGO team, and associated with the evolution of (non-magnetic) massive stars in a low metallicity environment. Our results also predict that the hot supergiant descendants of magnetic main sequence OB stars should have very weak surface magnetic fields, typically of order 1-10 G.

Studying Stellar Winds in Massive X-ray Binaries

Peter Kretschmar
European Space Astronomy Centre (ESA/ESAC), Science Operations Department

Strong winds from massive stars are a topic of interest to a wide range of astrophysical fields. In High-Mass X-ray Binaries the presence of an accreting compact object on the one side allows to infer wind parameters from studies of the varying properties of the emitted X-rays; but on the other side the accretors gravity and ionizing radiation can strongly influence the wind flow. Based on a collaborative effort of astronomers both from the stellar wind and the X-ray community, this presentation attempts to review our current state of knowledge and indicate avenues for future progress.

The II Zw 40 Supernebula: 30 Doradus on Steroids

Claus Leitherer

Space Telescope Science Institute

We obtained HST COS G140L spectroscopy of the enigmatic nearby blue compact dwarf galaxy II Zw 40. The galaxy hosts a nuclear super star cluster with a luminosity 10 times that of 30 Doradus, the most powerful giant HII region in the Local Group. The super star cluster has been suggested to be the ionizing source of a "supernebula" detected via its free-free radiation in the radio. The physical conditions, however, are much more complex, as demonstrated by the detection of the nebular He II and the mid-infrared line of [O IV] 25.9. These lines are unlikely to be related to hot stars and require a different powering source. II Zw 40 shares many similarities with the related blue compact dwarfs NGC 5253 and Henize 2-10. However, II Zw 40's UV spectrum is unique in terms of the exceptional strength of He II 1640, O III 1663 and CIII 1909. The spectrum bears a striking resemblance to the young high-z galaxy BX 418. We determined reddening, age, and the stellar initial mass function and perform a comparison with the local benchmark 30 Doradus. Photoionization modeling is used to determine the origin of the nebular lines as due to stellar ionization, shocks, or powering by a black hole.

Conference Summary

Emily Levesque
University Of Washington

Gaia and spectroscopic surveys of O stars: the solar neighborhood in 6-D

Jesús Maíz Apellániz

Centro de Astrobiologa

We will present the results of combining the Tycho-Gaia Astrometric Solution (TGAS), the Galactic O-Star Spectroscopic Survey (GOSSS), and four high-resolution multi-epoch optical spectroscopic surveys (OWN, IACOB, CAF-BEANS, and NoMaDS). GOSSS provides the selection of a magnitude-complete sample of 400 O stars in the solar neighborhood; TGAS (available in the northern summer of 2016) provides precise positions, parallaxes, and proper motions; and the high-resolution surveys provide precise radial velocities (with multi-epoch measurements of spectroscopic binaries) and stellar parameters. Therefore, for the first time we will have an accurate and complete knowledge of the spatial distribution of the O-type stellar population in the solar neighborhood. We will discuss the implications on the Galactic rotation curve, the location and dynamical effect of nearby spiral arms, the distances to known clusters and associations, the height scale for massive stars, and the spatial distribution of dust.

Hα imaging for BeXBs in the Small Magellanic Cloud

Grigoris Maravelias
Astronomical Institute, Czech Academy of Sciences

High-Mass X-ray Binaries consist of an early-type (OB) massive star and a compact object (neutron star or black hole), which accretes matter from the massive star either through strong stellar winds and/or Roche-lobe overflow in supergiant systems or through an equatorial decretion disk in, non-supergiant, OBe stars (Be X-ray Binaries;BeXBs). Due to these disks the BeXBs display strong Balmer line emission in their optical spectra. At the same time they are among the brightest sources when observed with narrow-band α imaging. The Small Magellanic Cloud (SMC) hosts a large number of BeXBs (almost 100) and offers a unique laboratory to examine these sources with a homogenous and consistent approach. Driven by this, we performed an H survey of the SMC (covering both the Bar and the Wing regions) using wide-field cameras (WFI at the MPG/ESO 2m, and MOSAIC at the CTIO/Blanco 4m telescopes). We obtained broad-band R and narrow-band Hα photometry, and identified 10000 H emission sources down to a sensitivity limit of 18.7 mag (equivalent to B8 type Main Sequence stars). We find that OBe stars (the parent population of BeXBs) are 13% of the total OB star population in the SMC down to 18.7 mag, and by investigating this fraction as a function of the brightness of the stars we deduce that Hα excess peaks at spectral range O9-B2. Using the most up-to-date numbers of BeXBs in the SMC we find their fraction with respect to the OBe stars to be in the range $0.5 - 1.4 \times 10^{-3}$ BeXB/OBe, a direct measurement of the formation rate of BeXBs in the SMC.

The Red Supergiant Content of the Local Group

Philip Massey
Lowell Observatory

Red supergiants (RSGs) are evolved from OB stars with initial masses of 30Mo or less, and represent an important phase in the lives of massive stars. They contribute a significant amount of dust to the interstellar environment, and the lower-mass RSGs (18Mo and below) are believed to be the immediate precursors to type II-P and II-L (or even II-n?) supernovae, leaving behind neutron star or black hole remnants. If a massive RSG loses enough mass, it will likely evolve back to the blue side of the HRD, possibly even becoming a Wolf-Rayet star. We have completed surveys for RSGs in many of the nearby galaxies of the Local Group, including the SMC, LMC, WLM, M31, and M33, eliminating foreground stars. We have then determined spectral types, and used model atmosphere fits to measure effective temperatures and determine reddenings and bolometric luminosities. We have thus identified samples of many hundreds of RSGs, and determined their physical properties; we will compare these to what stellar evolutionary models predict.

An extremely energetic supernova in the nucleus of a merging system of galaxies

Seppo Mattila

Department of Physics & Astronomy, University of Turku

In luminous and ultraluminous infrared galaxies (U/LIRGs), the infall of gas into the central regions strongly enhances the star formation rate (SFR), especially within the extremely dense, nuclear (¡ 500 pc) regions, which have also very large amounts of interstellar dust. Within these regions SFRs of several tens to hundreds of solar masses per year correspond to core-collapse supernova (SN) rates up to 1-2 SNe every year per galaxy. Our combined high angular resolution infrared (IR) and radio observations revealed an extremely energetic transient buried deep in the nucleus of the nearby LIRG Arp 299 hosting one of the most prolific supernova factories in the local Universe. We discuss three plausible scenarios for this extraordinary object: an AGN-driven event, a tidal disruption event (TDE), and a super-luminous supernova (SLSN). Our extensive multi-wavelength observations show that this transient rivaling the most energetic known stellar explosions is most likely explained by a SLSN that occurred within the dense and dusty nuclear environment. There, most of its kinetic energy was initially converted into ultraviolet and optical radiation by interaction with the dense environment, and then absorbed and re-radiated at infrared wavelengths by large amounts of dust within the nuclear regions. The object radiated more than 10^{52} ergs over a timespan of about 10 yr. Such energetic transients, if ubiquitous in the dense nuclear regions of starburst galaxies, will provide an additional energetic input that must be accounted for in models of galaxy feedback and evolution.

Helium stars: Towards an understanding of Wolf-Rayet evolution

Liam McClelland

University of Auckland, Department of Physics

Recent observational modelling of the atmospheres of hydrogen-free Wolf-Rayet stars have indicated that their stellar surfaces are cooler than those predicted by the latest stellar evolution models. We have created a large grid of pure helium star models to investigate the dependence of the surface temperatures on factors such as the rate of mass loss and the amount of clumping in the outer convection zone. Upon comparing our results with Galactic and LMC WR observations, we find that the outer convection zones should be clumped and that the mass-loss rates need to be slightly reduced. We discuss the implications of these findings in terms of the detectability of Type Ibc supernovae progenitors,and in terms of rewriting the Conti scenario.

Overview of Recent developments in stellar theory and supernovae

Georges Meynet
University of Geneva

The quest for blue supergiants: Binary merger models for the evolution of the progenitor of SN 1987A

Athira Menon
Department of Physics and Astronomy, Monash University

The discovery of SN 1987A in the Large Magellanic Cloud (LMC) and its B3 Ia supergiant progenitor, Sk –69 °202, indicated that not all progenitors of Type II supernovae are red supergiants. A triple-ring nebula, ejected by the progenitor at least 20,000 yr before explosion, was also detected and found to be enhanced in helium, nitrogen and possibly s-process elements. The structure of the nebula strongly implied that the origin of Sk –69 °202 may lie in the merger of a binary system. Eleven other supernovae with the same dome-shaped light curve as SN 1987A have been recorded implying that they also had blue supergiant progenitors. Our main aim in this work is to produce models that match the observed characteristics of Sk –69 °202, based on the binary merger scenario proposed by Podsiadlowski 1992. For this purpose, we build the first ever set of Type II SNe progenitor models from mergers of massive binary systems. Using the 1D stellar evolution code KEPLER, we effectively merge a red supergiant star (primary) and a main sequence star (secondary) and follow its evolution until the core-collapse stage. Our grid of initial parameters comprise of various primary and secondary masses and merging parameters. The majority of our pre-supernova models are compact, hot blue supergiants ($T_{\rm eff} > 12,000$K and $30 - 70\mathrm{R}_\odot$). Of these, ten models successfully match the properties of Sk –69 °202. The main parameter found to affect the end state of a post-merger star is its core mass to envelope mass ratio – large envelope masses for a given core mass favour hot, compact progenitors. Red supergiants are scarce within the initial parameter space of our simulations, leading us to conclude that this binary merger scenario is highly favourable to produce blue supergiants.

Core-collapse SNe modelling - how many ways can you explode a star?

Bemhard Muller

Queen's University Belfast

Core-collapse supernovae, the violent deaths of massive stars, are among the most spectacular phenomena in astrophysics: Supernovae can only outshine their host galaxy for weeks; they are laboratories for the behaviour of matter at extreme densities; and they also play a central role for the chemical evolution of galaxies, e.g. as the dominant producers of oxygen and many other elements. Yet the mechanism by which massive stars explode has eluded us for decades. As I shall explain in this talk, this is about to change: Recent first-principle 3D simulations of these events have finally been able to demonstrate that the most popular explosion scenario, the so-called neutrino-driven mechanism, is viable. Including the initial seed asymmetries in the progenitors from convective shell burning could further help to produce even more robust supernova explosion models. Distilling the physical essence of modern 3D supernova simulations into semi-analytic models also allows us to predict the properties of supernova explosions and compact remnants across the whole range of stellar initial masses in reasonable agreement with observations.

The Spatial Distribution of Massive Stars and Stellar Evolution

Jeremiah Murphy

Physics, Florida State University

We propose that the spatial distribution of O stars encodes information about their evolution, in particular their binary evolution. Smith & Tombleson 2015 noted that Luminous Blue Variables are very far away from other massive O stars, and they suggested that LBVs, as a class, are highly associated with binary evolution, kicks, and mass gainers. We have attempted to model the spatial distribution of O stars and LBVs hoping to provide theoretical constraints on the Smith & Tombleson 2015 observation. In just modeling the distribution of O stars, we are able to reproduce the average separation among O stars, but it is much more difficult to model the variance in separations with simple models. This implies that something is missing in these simple models and that we can learn about stellar evolution from the spatial distribution of O stars. In addition, we crudely model the spatial distribution of LBVs, and we find two models that are consistent with the very large separations between LBVs and other O stars. In model one, LBVs are mass gainers in binary evolution and receive, on average, 200 km/s kick when the primary star explodes, and in model two, LBVs are the product of mergers, in which the merger is triggered by the post main sequence evolution of at least a 17 solar mass star.

The Massive stellar population at the Galactic Center

Francisco Najarro
Centro de Astrobiologa CSIC

We present results from our ongoing infrared spectroscopic studies of the massive stellar content at the Center of the Milky Way. This region hosts a large number of apparently isolated massive stars as well as three of the most massive resolved young clusters in the Local Group. Our survey seeks to infer the presence of a possible top-heavy recent star formation history and to test massive star formation channels : clusters vs isolation.

X-ray lightcurves of colliding-wind binaries

Yaël Nazé
FNRS/University of Liege

Massive binaries harbour two supersonic stellar winds doomed to collide, which may generate high energy emission. In the few systems where this is the case, monitoring the X-ray emission provide crucial information on the wind and binary properties (such as relative wind strengths, wind densities, or binary geometries). In this contribution, the results obtained with Swift and XMM observatories will be examined, emphasizing the unique constraints provided by such data.

Massive stars in Galactic clusters

Ignacio Negureruela
Universidad De Alicante

The Evolutionary Status of WN3/O3 Wolf-Rayet Stars

Kathryn Neugent
Lowell Observatory / Northern Arizona University

We recently began a multi-year search for Wolf-Rayet (WR) stars in the Magellanic Clouds. As of the end of year three we've found 14 new WRs in the Large Magellanic Cloud (LMC), eleven of which (so 10% of WRs in the LMC) appear to belong to an entirely new class of WRs. While one might naively classify these stars as WN3+O3V binaries, such a pairing is unlikely given their faint visual magnitudes. Spectral modeling suggests effective temperatures and bolometric luminosities similar to those of other early-type LMC WNs but with mass-loss rates that are three to five times lower than expected. Additionally, they still retain a significant amount of hydrogen, while also having nitrogen at its CNO-equilibrium value (10-12x enhanced). These stars have physical parameters similar to SMC-WR 1, which Martins et al. (2013) suggests is indicative of chemically homogeneous evolution. If true, these WN3/O3Vs become Type Ib/Ic supernovae and may produce long soft gamma ray bursts. We will compare the WN3/O3s to other hydrogen-rich WRs and discuss the possibility that these stars have chemically evolved homogeneously.

High accuracy quantitative spectroscopy in the Galaxy

Maria-Fernanda Nieva
University Of Innsbruck

Radiation Hydrodynamics of Type I Superluminous Supernovae: Constraints on Progenitors and Explosion Mechanisms

Kenichi Nomoto

Kavli IPMU, University of Tokyo

The physical origin of Type-I (hydrogen-less) superluminous supernovae (SLSNe-I), whose luminosities are 10 to 500 times higher than normal core-collapse supernovae, remains still unknown. Thanks to their brightness, SLSNe-I would be useful probes of distant Universe. For the power source of the light curves of SLSNe-I, radioactive-decays, magnetars, and circumstellar interactions have been proposed, although no definitive conclusions have been reached yet. Since most of light curve studies have been based on simplified semi-analytic models, we have constructed multi-color light curve models by means of detailed radiation hydrodynamical calculations for various mass of stars including very massive ones and large amount of mass loss. We compare the rising time, peak luminosity, width, and decline rate of the model light curves with observations of SLSNe-I and obtain constraints on their progenitors and explosion mechanisms. We particularly pay attention to the recently reported double peaks of the light curves. We discuss how to discriminate three models, relevant models parameters, their evolutionary origins, and implications for the early evolution of the Universe.

Resolving the mass loss from red supergiants by high angular resolution

Keiichi Ohnaka

Universidad Católica del Norte, Chile

The intensive mass loss in the red supergiant (RSG) phase is important for understanding not only the final fate of massive stars but also the chemical enrichment of galaxies. Despite such importance, the mass-loss mechanism in RSGs is one of the long-standing problems in stellar astrophysics. We even do not know the driving force of the mass loss, and at the moment, there are no satisfactory theoretical models for the RSG mass loss. To solve this problem, observations of the wind acceleration zone within 10 stellar radii are of utmost importance. Unfortunately, the angular size of this innermost key region is too small to resolve by conventional imaging. However, recent years have seen amazing progress in high spatial resolution observations. Milliarcsecond-resolution achieved by infrared long-baseline interferometry provides us with a unique opportunity to spatially resolve not only the complex inhomogeneities in the photosphere and the extended outer atmosphere but also the velocity field in unprecedented detail, just like observations of the Sun. The advent of the Atacama Large Millimeter Array (ALMA) and extreme adaptive optics also opens new possibilities to image the gas and dust environment in the immediate vicinity of the star. I will review recent results of high spatial resolution observations of red supergiants and related objects.

The evolution of magnetic fields in hot stars

Mary Elizabeth Oksala
Department of Physics, California Lutheran University

Over the last decade, tremendous strides have been achieved in our understanding of magnetism in main sequence hot stars, in particular the statistical occurrence of their surface magnetism has been established (10%) and the field origin is now understood to be fossil. However, fundamental questions remain: how do these fossil fields evolve during the post-main sequence phases, and how do they influence the evolution of hot stars from the main sequence to their ultimate demise?Filling the void of known magnetic evolved hot (OBA) stars, studying the evolution of their fossil magnetic fields along stellar evolution, and understanding the impact of these fields on the angular momentum, mass-loss, rotation, and evolution of the star itself, is crucial to answering these questions, with far reaching consequences, in particular for the properties of the precursors of supernovae explosions and stellar remnants.In the framework of the BRITE spectropolarimetric survey, we have discovered the first few magnetic hot supergiants. Their longitudinal surface magnetic field is very weak but their configuration resembles the ones of main sequence hot stars. In this talk I will present these first observational results and propose to interpret them at first order in the context of magnetic flux conservation as the radius of the star expands with evolution. I will then also consider the impact of stellar structure changes along evolution.

X-ray diagnostics of massive star winds

Lidia Oskinova
University of Potsdam

Nearly all types of massive stars with radiatively driven stellar winds are X-ray sources that can be observed with the presently operating powerful X-ray telescopes. In this talk I will address recent advances in our understanding of stellar winds obtained from X-ray data. Measurements of clumping properties, mass-loss rates, and wind velocities from analyses of high-resolution X-ray spectra will be presented. All sufficiently studied O stars display variable X-ray emission that might be related to corotating interaction regions in their winds. I will discuss our new joint UV (HST) and X-ray (XMM-Newton) observations that for the first time provided a real-time multiwavelength view on the development of structures in the wind of an O-type star. These new results may overturn the accepted paradigm on X-ray production in massive-star winds. First results of our large XMM-Newton observational program to study early B-stars, the most common type of massive stars in the Galaxy, will also be presented. Furthermore, I will discuss new insights on the winds of Wolf-Rayet stars obtained from high-resolution X-ray spectroscopy. Finally, it will be shown that X-ray observations of massive stars in the Magellanic Clouds provide important constraints on winds at low metallicites and on the final stages in the evolution of massive binaries.

The Most Massive Heartbeat : Finding the Pulse of Iota Orionis

Herbert Pablo

Department of Physics, University of Montreal

Heartbeat stars are a class of close binaries with high eccentricities leading to strong tidal forces around periastron. This results in strong changes in amplitude due to ellipsoidal variations as well as the ringing of tidally induced oscillations in the star. While the light curves are spectacular in their abnormality, their true beauty comes from the ability to derive the orbital inclinations and by extension masses- for stars with clear pulsations. This peculiar effect was theorized more than 20 years ago, but had not been observed until the onset of the Kepler spacecraft. However, the heartbeat stars found with Kepler are mostly medium mass likely due to selection effects as there were very few B stars and no O stars in the original field. The lack of massive stars in general, and particularly O stars, for these spaced-based photometric missions has been a significant problem, with a total of 6 O stars in CoRoT and less than 30 in the MOST archive. While the K2 mission may change this, it has limitations on observation length (60 days) which make observations of massive stars, which have longer timescale variations, more difficult. Recently, this has been ameliorated by the launch of the BRITE-constellation, a network of nanosatellites which observe in 2 colors the brightest, and often most intrinsically luminous, stars in the sky. In its very first observation field, BRITE has discovered the most massive binary with a heartbeat : Iota Orionis. In addition to this milestone, Iota Orionis becomes the only O star to show tidally induced pulsations, and the only pulsating O star known for which the masses can be found empirically. Using 3 and 6 months of continuous data spaced a year apart, we will discuss the full binary modeling of this star including the determination of masses. Moreover, we will highlight the asteroseismic impact of this system has on our knowledge of massive star structure and evolution.

Binary Evolution and the Final Fate of Massive Stars

Philipp Podsiadlowski
Oxford University

Binary interactions do not only affect the envelope structure of massive supernova progenitors, thereby determining the appearance of the resulting supernova, but also the final fate of the core, specifically whether the core collapses to a neutron star or black hole or produces a gamma-ray burst or other exotic event. In this talk I will summarize how various binary interactions (mass loss, accretion, mergers, tidal interactions) affect the final fate of stars and its potential implications for a variety of "normal" and exotic supernova events, including supernovae with a circumstellar medium ("LBV supernovae"), superluminous supernovae, gamma-ray burst sources, pair-instability supernovae and aLIGO gravitational-waves sources.

Progenitors of the black-hole binary mergers detected by LIGO

Konstantin Postnov

Sternberg Astronomical Institute

Unveiling the formation of stellar-mass black-holes through the study of black-hole X-ray binaries

Serena Repetto

Technion, Israel

The formation of stellar-mass black holes (BHs) is still very uncertain. Two main uncertainties are the amount of mass ejected in the supernova (SN) event (if any) and the magnitude of the natal kick (NK) the BH receives at birth (if any). Measuring these two quantities gives clues into the SN engine as well as the physical mechanism which drives the NK, whether it is an ejecta-driven NK, or a neutrino-driven NK. We study the evolution and kinematics of X-ray binaries hosting a BH (BH-XRBs) in order to shed light on how BHs are formed. This is motivated by the fact that the orbital parameters, peculiar velocities and Galactic position of BH-XRBs directly follow from their evolutionary history, and are affected in particular by the conditions at the moment of BH formation. We use two different but complementary approaches: i) the study of the evolutionary history of single BH-XRBs; ii) the study of the population of BH-XRBs as a whole. The former approach relies on tracking backwards in time the binary evolution of a subset of BH-XRBs (those ones with a short orbital period) until the BH was formed and adding the information on the Galactic kinematics of the sources. We find three possible scenarios for the birth of the BH. Two of these scenarios have been discussed previously in the literature: either the BH does not receive any NK, or it receives an neutron-star (NS) like NK. The new scenario that we suggest, is a BH having formed with an NK and zero baryonic mass ejection, i.e formed in the *dark*. The second approach relies on building synthetic populations of BH-XRBs with different assumptions of the BH formation, following their binary evolution, and integrating their orbits in the most updated model for the Galactic potential. We find that a population model in which at least some BHs receive a (relatively) high NK (~ 100 km/s) fits the observed BH-XRBs best. An application to the population of NS-XRBs will also be discussed.

Re-examining the upper mass limit of stars using an isolated 140 Msun twin of R136's WNh5 core stars

Maria del Mar Rubio

Centros de Astrobiologa (CSIC-INTA)

Recent studies of WNh stars at the cores of young massive clusters have challenged the previously accepted upper stellar mass limit (150 M), suggesting some of these objects may have initial masses as high as 300 M . VFTS 682 has been recently identified as a WNh5 very massive star, 29 pc away from the core of the R136 cluster in the LMC. Because of its apparent isolated location, VFTS 682 can be used as a test-case avoiding the crowding issues that may affect stellar analyses at the cluster-center. We investigated the possible existence of observed stars above 150 M by i) analyzing VFTS 682 and the most massive members of R136 and ii) studying uncertainties in their measured magnitudes due to the crowding. Our spectroscopic analysis reveals that the most massive members of R136 and VFTS 682 are basically twins and our K-band photometric study of R136s core stars indicate higher uncertainties than previous studies; moreover, for the most massive stars in the cluster, R136a1 and a2, we found previous magnitudes were overestimated by at least 0.4 mag. As such, luminosities and masses of these stars have to be significantly scaled down, which then also lowers the hitherto observed upper mass limit of stars.

Modeling the Chandra observations of the Galactic Center

Christopher Russell
NASA Goddard Space Flight Center

Properties of the O dwarf population in 30 Doradus

Carolina Sabín-Sanjulián
Universidad de La Serena

The O dwarf phase of massive stars offers us a good opportunity to investigate the properties and evolution of these extreme objects. This phase, where massive stars spend most of their lives, represents a direct link between the first stages of formation and the advanced phases of their evolution. Here we present a study of a statistically significant sample of O dwarf stars within the same star-forming region, aiming at clarifying some long-standing unsolved questions regarding the early phases in the evolution of massive stars.

We perform a quantitative spectroscopic analysis of 105 presumably single O dwarf stars in 30 Doradus, the largest H II region in the Local Group, located within the Large Magellanic Cloud. We have used mid-to-high resolution multi-epoch optical spectroscopic data obtained within the VLT-FLAMES Tarantula Survey. We determine stellar and wind parameters by means of IACOB-GBAT, an automatic method based on a large grid of FASTWIND models and developed for the analysis of optical spectra of O-type stars. We also benefit from the Bayesian tool BONNSAI to estimate evolutionary masses.

We provide a spectral calibration for the effective temperature of O dwarf stars in the LMC. We also discuss the evolutionary state of our stars, paying special attention to the fastest rotators of the sample. We also discuss the mass discrepancy problem and possible explanations for this phenomenon in our particular case. Finally, the wind properties of the sample are investigated.

Multiplicity of massive stars

Hugues Sana
Instituut voor Sterrenkunde, Belgium

Massive stars like company. In this talk, I will provide an overview of progresses made over the last 5 years in characterizing the multiplicity properties of massive stars. I will highlights striking results from a number of medium- and large-surveys. These results, put together, provide new insights, on the intrinsic multiplicity properties of main sequence massive stars and on the initial conditions for their future evolution. The same quantities do also provide interesting constraints on the outcome of the massive star formation process. I will finish this talk by reviewing some open questions and future perspectives offered by new and upcoming instrumentation.

Recent advances in NLTE stellar atmosphere models

Andreas Sander
Inst. for Physics & Astronomy, University of Potsdam

In the last decades, stellar atmosphere models have become a key tool in understanding massive stars. Applied for spectroscopic analysis, these models provide quantitative information on stellar wind properties as well as fundamental stellar parameters.

The intricate non-LTE conditions in stellar winds dictate the development of adequate sophisticated model atmosphere codes. The increase in both, the computational power and our understanding of physical processes in stellar atmospheres, ensured a rapid growth of complexity in the models. As a result, modern model codes can tackle a wide range of astrophysical situations and problems.

In this review I will briefly address the fundamentals of stellar atmosphere modeling as well as discuss the power and limitations of modern models. The current stage of clumped and line-blanketed model atmospheres will be discussed, and the advantages and caveats of the different current approaches will be compared.

Finally, the path for the next generation of stellar atmosphere models will be outlined. Apart from discussing multi-dimensional approaches, I will emphasize on the coupling of hydrodynamics with a sophisticated treatment of the radiative transfer. Such self-consistent models will, likely, be the next generation of atmosphere models, that will eventually allow for realistic predictions of mass-loss rates and other wind properties, thus overcoming the limitation of Monte-Carlo or CAK-like approximations. This next generation of models with their predictive power will open new doors for our understanding of the various facets of massive star physics, evolution, and death.

X-ray Emission from Massive Stars at the Core of Very Young Clusters

Norbert S. Schulz

Massachusetts Institute of Technology

Most cores of very young stellar clusters contain one or more massive stars at various evolutionary stages. In many cases we can now spatially resolve these stars in X-rays with Chandra and measure detailed spectral properties with the high resolution transmission grating spectrometer. Observations of the Orion Nebula Cluster, Trumpler 37, NGC 2362, RCW38, NGC 3603 and many others provide the most comprehensive database to study stellar wind properties of these massive cluster stars in X-rays. We resolve X-ray line profiles of a variety of shapes and emission measures which in combination with the availability of more sophiaticated X-ray wind models result in a wide range of stellar wind parameters, such a terminal velocities, optical depth, wind penetration, temperatures, emission power and abundances. Determinations of the He-like ion line ratios place the onset of the X-ray emission at various distances from the photosphere ranging from only fractions to hundreds of stellar radii. In some cases we infer abundance anomalies that might relate to the evelotionary state of the stars. In this presentation we review these observations and results and discuss them in the context of stellar winds and possible evolutionary implications.

A high-contrast imaging survey of nearby red supergiants

Peter Scicluna
Institute of Astronomy and Astrophysics, Academia Sinica

Mass-loss in cool supergiants remains poorly understood, but is one of the key elements in their evolution towards exploding as supernovae. Some show evidence of asymmetric mass loss, discrete mass-ejections and outbursts, with seemingly little to distinguish them from more quiescent cases. To explore the prevalence of discrete ejections and companions we have conducted a high-constrast survey using near-infrared imaging and optical polarimetric imaging of nearby southern and equatorial red supergiants, using the extreme adaptive optics instrument SPHERE, which was designed to image planets around nearby stars. I will present the initial results of this survey, including the detection of large (500nm) dust grains in the ejecta of VY CMa and a candidate dusty torus aligned with the maser ring of VX Sgr. These will be compared with observations of circumstellar material at other wavelengths. I will briefly speculate on the consequences for our understanding of mass loss in these extreme stars.

Rotation, Evolution, Magnetic Fields, and Emission: Results from the First Population Study of Magnetic Early B-type Stars

Matthew Shultz

Uppsala University, Department of Astronomy & Space Physics

About 10% of early-type stars host large-scale, organized magnetic fields which confine their radiative winds, leading to rapid rotational braking and, in some cases, optical emission lines. Amongst magnetic B-type stars, this emission is thought to originate in Centrifugal Magnetospheres (CMs), structures arising due to the combined effects of magnetic wind confinement and centrifugal support of the co-rotating plasma. A large fraction of the known magnetic B-type stars are recent magnetic detections with poorly constrained magnetic and rotational properties, leading to ambiguity about the conditions under which CMs become optically thick. I present the results of the first population study of magnetic early B-type stars, based upon the large databases of high-resolution spectropolarimetry assembled by the Magnetism in Massive Stars (MiMeS) and Binarity and Magnetic Interactions in various classes of Stars (BinaMIcS) large programs. These data enabled rotational periods and dipolar oblique rotator models to be determined for the majority of the sample stars. This has clarified the evolutionary, magnetic, and rotational properties of stars with and without emission, which turn out to be without exception strongly magnetized rapid rotators in the early stages of their main-sequence lifetimes. Surface magnetic field strengths appear to decline over time in a fashion compatible with magnetic flux conservation. These results also enable a direct comparison between spindown timescales and ages inferred from evolutionary models, with possible implications for the pre-main sequence properties of magnetic, massive stars, as well as for the mass-loss rates of B-type stars in general. Finally, an examination of the spectroscopic properties of the emission-line stars in the context of their magnetospheric and rotational parameters provides evidence that mass-balance within CMs is not governed by stochastic breakout events, but most likely occurs via an as-yet unidentified leakage mechanism.

Multi Epoch views of massive stars

Sergio Simon-Diaz
Instituto de Astrofísica de Canarias, Spain

The beginning of the 21st century has witnessed the compilation of several high quality spectroscopic surveys of massive OB stars. The scientific exploitation of this unique observational material, in combination with the imminent information provided by the Gaia mission will, without any doubt, quantitatively change our view of the properties and evolution of massive stars. Some of these surveys include multi-epoch observations scheduled with different time-resolution. In this talk I will benefit from the spectroscopic observations gathered by the IACOB project (Simón-Díaz et al. 2015, http://www.iac.es/proyecto/iacob/) to present an illustrative summary of the spectroscopic variability phenomena which are commonly detected in the O and B star domain. I will also highlight the importance of complementing the empirical information provided by the spectroscopic analysis of single-epoch observations of large samples of O- and B- type stars with the compilation and analysis of specifically designed time-resolved observations.

Challenges to stellar evolution from LBVs, SN Impostors, and Supernovae with Dense CSM

Nathan Smith

Steward Observatory, University of Arizona

I will discuss luminous blue variables (LBVs) and their connections to extragalactic transients and supernova (SN) explosions, as well as the challenges they pose for our understanding of massive star evolution in general. Their role in single-star evolution as transition objects between H and He burning appears to be invalid, and some massive LBVs appear to be exploding as SNe. This makes it challenging to understand what LBVs are, and also poses fundamental challenges to models of single-star evolution. I will report new results from spectroscopic and photometric monitoring of the light echoes of Eta Carinae for the past several years, and will discuss critical clues they provide for understanding the physics of this classic LBV giant eruption and connections to recent spectroscopic studies SN impostors. All proposed physical models, including stellar merger events, still have severe short-comings and open questions in trying to accound for LBV eruptions. I will also discuss the basic nature of LBVs and the viability of LBVs as progenitors of Type IIn supernovae, considering the environments of LBVs and SNe IIn, combined with the properties of their CSM, explosion parmeters, and direct progenitor detections.

The Very Massive Star Content of the Nuclear Star Clusters in NGC 5253

Linda Smith

Space Telescope Science Institute

The blue compact dwarf galaxy NGC 5253 hosts a very young starburst containing twin nuclear star clusters, separated by 5 pc. One cluster coincides with the peak of the H-alpha emission in NGC 5253 and the other with an ultracompact H II region (Turner et al. 2000). In a recent paper, Calzetti et al. (2015) find that the two clusters have an age of 1 Myr, in contradiction to the age of 3-5 Myr inferred from the presence of Wolf-Rayet spectral features. We use HST UV and ground-based optical spectroscopy to show that the cluster stellar features arise from very massive stars (VMS), with masses greater than 100 $M_{\odot}$, at an age of 1-2 Myr. We discuss the implications of this for stellar feedback and show that the very high ionizing flux can only be explained if VMS are present in the NGC 5253 clusters. We further discuss our findings in the context of VMS in young massive clusters contributing to He II 1640 emission in high redshift galaxies, and emphasize that population synthesis models with upper mass cut-offs greater than 100 $M_{\odot}$ are crucial for future studies of young massive clusters.

What Distant Galaxies can tell us about Massive Stars

Elizabeth Stanway
Department of Physics, University of Warwick

The galaxies observed in the distant Universe, and the local galaxies studied as their analogues, are selected to be ultraviolet luminous and intensely star-forming. While the stellar populations of these galaxies are unresolved, ruling out the study of individual massive stars, their integrated spectra provide a detailed window into the bulk properties of their stars. Given that the majority of work on distant galaxies is done in the rest-frame ultraviolet (redshifted into the optical), these spectra are dominated by the youngest stellar population and the massive stars which contribute the bulk of its light. As a result both individual and stacked spectra of young galaxies, including Lyman break galaxies and their analogues, show signs of Wolf-Rayet and other massive stellar features. Galaxies in the distant Universe thus provide laboratories in which to identify the presence and effects of massive stars at a range of formation metallicities, together with their contribution to galactic scale winds and the resultant quenching of star formation, while those few which are also identified as gamma-ray burst hosts provide evidence for the eventual demise of these stars and the effect of that demise on their hosts.

Low Frequency Radio Observations of Massive Stars

Ian Stevens

School of Physics and Astronomy, University of Birmingham

The low frequency portion (¡1 GHz) of the radio spectrum is very poorly explored for massive stars. However, this frequency regime contains evidence of some important physical processes in the stellar wind, both emission processes associated with shock acceleration and also absorption processes (such as free-free emission or Razin absorption).

In this talk I will review recent observations of a series of massive stars. This will include both Wolf-Rayet and O-type stars and both single stars and colliding wind binaries. The data is taken primarily with the GMRT array in India and I will also present some high resolution e-Merlin observations of colliding wind systems. I will discuss some of the physical insights into the wind physics that result from these observations and some basic constraints on wind magnetic field strengths.

I shall also look ahead to what is possible with the both the current radio arrays that are in the process of being upgraded, as well as the very exciting possibilities afforded by the upcoming Square Kilometer Array (SKA).

SN 2015bh: an LBV becomes NGC 2770s forth SN... or not?

Christina Thöne
IAA - CSIC

Massive stars in the final phases of their lives are rather unstable and frequently expel large amounts of material. Some of these eruptions can be almost as bright as a core-collapse SN interacting with the previously ejected gas and therefore resemble Type IIn SNe. An interesting example was SN 2009ip that had shown variations in brightness years before its possible core-collapse. Here we present SN 2015bh in NGC 2770 that shows striking similarities to SN 2009ip. It experienced frequent, short-term variabilities for at least 21 years before a smaller "precursor" in Feb-May 2015 and the "main event" or possible final explosion in May 2015 where it reached an absolute magnitude of -17.5. Its spectra are consistent with an LBV in outburst before May 2015 and a 1998S-type IIn during the main event showing a double P-Cygni profile reminiscent of the complex line profiles exhibited by SN 2009ip. Both SN 2009ip and 2015bh during the entire span of pre-explosion observations were always situated red wards of LBVs in outburst in the HR diagram in a region usually occupied by YHGs or Eta Carinae during its great eruption but at lower luminosity. Another SN impostor with very similar behaviour is SN 2000ch which could experience a similar fate in the near (or far) future. Whether SN 2009ip or SN 2015bh did survive the following "main event" can currently not be answered securely, SN 2009ip, however, has now been found at levels lower than pre-explosion observations in 1999. The two events might be a rare new class of event showing Eta-Car type eruptions for many years before a hyper-eruption of a final core-collapse. If the star survives this event it is undoubtedly altered, and we suggest that these "zombie stars" could be LBVs evolving into a Wolf Rayet star over a very short timescale of only a few years. SN 2015bh was the already (possible) 4th SN in NGC 2770, a MW-type spiral galaxy that has hosted 3 Ib SNe in the past. We will also show some results on the host of SN 2015bh and its peculiarities using various 3D spectroscopic techniques.

Extragalatic Supergiants

Miguel A. Urbaneja
University of Innsbruck

The VLT-FLAMES Tarantula Survey

Jorick Vink
Armagh Observatory and Planetarium

Magnetic fields in massive stars

Gregg Wade

Department of Physics, Royal Military College of Canada

Magnetic fields are directly observable only at the surfaces of stars, and while surface magnetic fields have important consequences for the evolution of OB stars (see Z. Keszthelyi's presentation), interior fields are in principle even more significant. For example, modern models of massive star evolution including interior magnetic field prescriptions find that fields dominate the angular momentum transport. Such models differ fundamentally from non-magnetic models, and are characterized by rigidly-rotating envelopes and strong core-envelope coupling. These affects have fundamental consequences for predicted surface rotation rates and chemical abundances, and ultimately HR diagram positions and evolutionary pathways.

In this presentation we report first results of an effort to employ new and existing observational results to constrain the influence of interior magnetic fields on the internal structure and evolution of hot stars. We adopt two approaches. First, we examine the physical properties of stars with radiative envelopes and detected surface magnetism (in part a legacy of the MiMeS and BoB large surveys), comparing with the properties of their non-magnetic peers, searching for differences attributable to their (interior, fossil) magnetic fields. Second, we examine the larger population of (apparently) non-magnetic hot stars, searching for mass- and rotation-dependent behaviour as predicted by radiative envelope shear and turbulent dynamo models.

Emission-line diagnostics of Nearby HII Regions including Supernova host

Lin Xiao

Department of Physics, University of Auckland

The formation and evolution of massive stars impact most observable properties of the HII regions. Their stellar ages, metallicities, and supernova explosions are the principal sources of feedback that ultimately control the local properties of HII regions. In oder to model their physical properties theoretically, we combine the results of the Binary Population and Spectral Synthesis (BPASS) code with the photoionisation code Cloudy to reproduce the observed emissions.We explore a variety of emission-line diagnostics of these star-forming HII regions and examine the effects of metallicity variations and duplicity on the nebula emission-lines. We are then able to compare their properties with stellar populations and provide new constraints on supernova progenitors. We find that only models including massive star binaries can successfully match all The formation and evolution of massive stars impact most observable properties of the HII regions. Their stellar ages, metallicities, and supernova explosions are the principal sources of feedback that ultimately control the local properties of HII regions. In oder to model their physical properties theoretically, we combine the results of the Binary Population and Spectral Synthesis (BPASS) code with the photoionisation code Cloudy to reproduce the observed emissions.We explore a variety of emission-line diagnostics of these star-forming HII regions and examine the effects of metallicity variations and duplicity on the nebula emission-lines. We are then able to compare their properties with stellar populations and provide new constraints on supernova progenitors. We find that only models including massive star binaries can successfully match all the observational constraints and explain the environment dependencies of supernova progenitor. We also discuss what is different about the binary populations that provides their unique ionization spectra.the observational constraints and explain the environment dependencies of supernova progenitor. We also discuss what is different about the binary populations that provides their unique ionization spectra.

Very Massive Stars at Different Metallicities

Norhasliza Yusof
Department of Physics, University of Malaya

In the work, we will present the evolution of Very Massive Stars (M¿100 Mo) at different metallicities (Z=0.001 to Z=0.02). This includes the general properties, impact on the chemical abundances due to the rotational impact, dependence on metallicities and mass loss of very massive stars. Very massive stars has very large convective core during the main sequence thus their evolution are not affected strongly by rotational mixing but more by the mass loss due to strong stellar winds. In this presentation, we will also present pair instability supernovae modelled with our VMS progenitor models and compare them to super-luminous supernovae.

Author Index