International Workshop on Wolf-Rayet Stars

Abstracts

1 *Opening*

General overview of Wolf-Rayet stars

Anthony F.J. Moffat
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— Review Talk —

Although we all use Wolf-Rayet to refer to specific groups of stars, Wolf-Rayet is really an astrophysical phenomenon of fast-moving, hot plasma. However, practicality demands that we follow trends by referring to three groups: cWR, "classical" He-burning descendants of massive O stars; WNh, the most massive and luminous hydrogen-rich main-sequence stars with strong winds; and [WR],the central stars of some 15% of Planetary Nebulae. Wolf-Rayet stars are the epitome of relatively stable stars with the highest mass-loss rates. It behooves us to understand the why, what and how of this circumstance, along with its manyfold and fascinating consequences.

2 *WR surveys*

Wolf-Rayet content of the Milky Way

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— Review Talk —

I will review techniques used to detect Wolf-Rayet (WR) stars in the Galaxy via their characteristic emission line spectra and dense ionized stellar winds. The advent of efficient large format IR detectors has allowed Galactic plane surveys to be conducted (notably GLIMPSE, WISE), which in turn have led to an increase in the known Milky Way WR content from 298 less than a decade ago (van der Hucht 2001, 2006) to 638 in Dec 2014. The observed subtype distribution is assessed, with an estimate of the global content made following Rosslowe & Crowther (2015).

Finding Wolf-Rayet Stars In the Milky Way - Input to Star Formation and Stellar Evolution Studies

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The total population of Wolf-Rayet (WR) stars in the Galaxy is predicted by models to be as many as ∼6000 stars, and yet the number of catalogued WR stars as a result of optical surveys was far lower than this (∼200) at the turn of this century. When beginning our WR searches using infrared techniques it was not clear whether WR number predictions were too optimistic or whether there was more hidden behind interstellar and circumstellar extinction. During the last decade we pioneered a technique of exploiting the near- and mid-infrared continuum colours for individual point sources provided by large-format surveys of the Galaxy, including 2MASS and Spitzer/GLIMPSE, to pierce through the dust and reveal newly discovered WR stars throughout the Galactic Plane. The key item to the colour discrimination is via the characteristic infrared spectral index produced by the strong winds of the WR stars, combined with dust extinction, which place WR stars in a relatively depopulated area of infrared colour-colour diagrams. The use of the Spitzer/GLIMPSE 8μm and, more recently, WISE 22μm fluxes together with cross-referencing with X-ray measurements in selected Galactic regions have enabled improved candidate lists that increased our confirmation success rate, achieved via follow-up infrared and optical spectroscopy. To date a total of 102 new WR stars have been found with many more candidates still available for follow-up. This constitutes an addition of 16% to the current inventory of 636 galactic WR stars. In this talk we review our methods and provide some new results and a preliminary review of their stellar and interstellar medium environments. We provide a roadmap for the future of this search, including statistical modelling and what we can add to star formation and high mass star evolution studies.

Near-IR and Optical Survey of O2If* and OIf*/WN stars in the Periphery of four Galactic Massive Star Forming Regions

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In this contribution I will present the main results of an optical and near-IR spectroscopic survey aimed to confirm the O2If* and OIf*/WN nature of a sample of massive star candidates, using MagE and OSIRIS at Clay and SOAR. The main goal here was to obtain (when posible) optical and near-IR spectra of a sample of about 10 newly discovered Galactic O2If* and O2If*/WN6 stars, whose discovery was made from the use of near-IR color-magnitude selection criteria combined with J-, H- and K-band OSIRIS low to medium S/N ratio spectra, taken by us in previous exploratory runs at SOAR. Few more than 10 members of such stars are known in the Galaxy, some of them belonging to massive binary systems. Therefore, this study contributes to improve the number of known O2If* stars in the Galaxy, as well as almost doubling the known galactic sample of extreme objects of the rare OIf*/WN type.

Wolf-Rayet Stars in the Local Group

Philip Massey[1]

[1] Lowell Observatory

— Review Talk —

The galaxies of the Local Group can act as our astrophysical laboratories for testing massive star star evolution models as a function of metallicity. Recent surveys have identified and characterized WR stars in the nearby spiral galaxies M31 and M33, and on-going work is identifying new WRs in the Magellanic Clouds. I'll discuss what these new data are telling us, and what the implications may be.

Statistics and Characterization of Wolf-Rayet stars in M81 Young Star Clusters

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We here investigate a sample of young star clusters (YSCs) with Wolf-Rayet (W-R) features discovered in the relatively nearby spiral galaxy M81 by analysing long-slit and Multi-Object Spectroscopy (MOS) spectra, obtained using the 10-m Gran Telescopio Canarias (GTC). Broad emission lines of He (He II λ4686), C (C III/C IV λ4650, CIV λ5808), and N (N III λ4640) from W-R stars are detected in the integrated spectra of the star clusters. Hubble Space Telescope (HST) images reveal the spatial localization, morphology and environments of the star clusters hosting the W-R stars. We present the statistics and characterization of the W-R stars found. We perform a detailed fitting of the nebular and broad emission lines within the Blue Bump and the Red Bump and quantify the number of W-Rs in each YSC. We obtain at least one Nitrogen-type (WN) and one Carbon-type (WC) W-R star in each YSC. We estimate the O star populations and N(WR)/N(O) for each star cluster. Finally, we discuss the implications of our results.

Finding new Wolf-Rayet-Stars in the Magellanic Clouds

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A complete census of massive, evolved stars in a galaxy is a key ingredient for testing stellar evolution models. However as the evolution of stars is also strongly dependent on their metallicity, it is inevitable to have this kind of data for a variety of galaxies with different metallicities. Between 2009 and 2011, we conducted the Magellanic Clouds Massive Stars and Feedback Survey (MSCF); a spatially complete, multi-epoch, broad- and narrow-band optical imaging survey of the Large and Small Magellanic Clouds. With the inclusion of shallow images, we are able to give a practically complete photometric catalog of stars between $B \approx 8$ and $B \approx 19$ mag.

These observations were extended with additional photometric data from UV to IR (e.g. from GALEX, 2MASS and Spitzer) in order to sample a large portion of the spectral energy distribution of the brightest stars ($B < 16$ mag) in the Magellanic Clouds. Using this data, were are able to train a machine learning algorithm that gives us a good estimate of the spectral type of tens of thousands of stars.

This method can be applied to the search for Wolf-Rayet-Stars to obtain a sample of candidates for follow-up observations. As this approach can in principle be adopted for any resolved galaxies, as long as sufficient photometric data is available, it can form an effective alternative method to the classical strategies (eg. He II filter imaging).

The presented method can therefore help to sample the stellar populations in nearby galaxies and to complete a census of massive evolved stars.

Luminous Wolf-Rayet stars at very low metallicity

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Evolution of massive stars is one of the key input parameters for the understanding of formation and evolution of galaxies. These stars provide the ionizing and mechanical feedback into the ISM of their host galaxy and its circumgalactic environment. While these processes are hard to study directly during the epoch of galaxy formation and early evolution, we can use proxies at low redshift, which resemble in many ways the early universe objects. These are the strongly starforming dwarf galaxies with very low metallicity. Using HST and high resolution ground-based imaging it is possible to study massive stars several nearby such galaxies on a star by star basis. Recent progress in stellar evolution models of massive rotating single stars and the evolution of binary stars predict a bewildering zoo of different evolutionary paths for massive stars, which require observational tests especially at very low metallicities, which can be performed with these data. In this contribution we will analyze the stellar content of the upper Hertzsprung-Russell diagrams of 4 dwarf galaxies with metallicities between $\sim 1/5$ and $\sim 1/40$ of solar. The population of luminous Wolf-Rayet stars and other hot luminous evolved stars in the program galaxies was extracted by excess emission in the HeII 4686Å line images and by HST UV-optical color magnitude diagrams together with astro-informatics methods. The combination of classic narrow-band selection with astro-informatics methods using the full UV and optical/NIR SED of the individual stars yields large and complete samples with solid type classification without requiring detailed spectroscopy of the full sample. Comparison to evolutionary tracks with rotation and with effects from binaries will provide estimates for the evolutionary state of the stars and especially the Wolf-Rayet stars and luminous O-type supergiants. Trends in the relative numbers of Wolf-Rayet stars and their luminosities and colors with metallicity, environment, and burst age are analyzed.

WRs in metal-poor galaxies unveiled from integral field spectroscopy

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We are performing a program to investigate a sample of metal-poor Wolf-Rayet (WR) galaxies using integral field spectroscopy (IFS). Since evolutionary models for single (rotating/no-rotating) massive stars predict very few, if any, WRs in low metallicity (Z) environments, the study of metal-poor WR galaxies is crucial to test such models at low-Z. IFS has allowed us to study the spatial correlation between WRs and the surrounding nebular properties, i.e., a spatially resolved view of the feedback from WRs in our galaxy sample. We will show how using IFS one can locate and find WR stars where previous non IFS observations have failed. In this contribution we highlight our recent results from the first IFS study of Mrk178, the closest metal-poor WR galaxy, and of IZw18, the most metal-poor star-forming galaxy known in the local Universe. Our IFS data have revealed for the first time the entire region of the nebular HeII4686 emission and the total HeII-ionizing photon flux in IZw18 and in Mrk178. In the context of the radiative feedback from WRs, we discuss the formation of nebular HeII lines in low-Z galaxies which is still an open issue. Finally, the role of aperture effects on the detection and measurements of WR spectral features in galaxies will be addressed.

WR Stars in Integrated Light Studies of Galaxies

Claus Leitherer[1]
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— Review Talk —

Spectral signatures of Wolf-Rayet stars are routinely observed in star-forming galaxies at redshifts up to 5 with spectrographs on 8 – 10-m class telescopes. While the overall spectra are well understood and have been successfully modeled using empirical and theoretical libraries, some challenges remain. I will present case studies of selected local Wolf-Rayet galaxies as well as an overview of the properties of galaxies with WR features at high redshift. I will identify shortcomings of model atmospheres and evolution models and point out future directions.

A 2D view of Wolf Rayet Galaxies

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The main objective of this work is to do a comprehensive study of the Wolf-Rayet (WR) population, supernovae remnants (SNRs) and the properties of the ionized gas (metallicity, temperature, ionizing sources, etc) for a sample of nearby WR galaxies. We will use optical integral field spectroscopy in combination with multi-wavelength data, specially radio observations using Giant Metrewave Radio Telescope (GMRT). Combining optical integral field unit and radio data, we will be able to locate the WR stars and SNRs across the WR galaxies, and to study the spatial correlation between them, and the ionized gas properties. This study will shed light on the massive star formation and its feedback, and will help us to better understand distant star-forming galaxies.

3 WR spectroscopy and polarimetry

Spectrum formation in Wolf-Rayet stars

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— Review Talk —

We highlight the basic physics that allows fundamental parameters, such as the effective temperature, luminosity, abundances, and mass-loss-rate, of Wolf-Rayet (W-R) stars to be determined. Since the temperature deduced from the spectrum of a W-R star is an ionization temperature, a detailed discussion of the ionization structure of W-R winds, and how it is set, will be given. We will also provide an overview of line and continuum formation in W-R stars. Mechanisms that contribute to the strength of different emission lines, such as collisional excitation, radiative recombination, dielectronic recombination, and continuum fluorescence, will also be discussed.

Worldwide Amateur Observations - A Future of Massive Star Research

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For some years, spectroscopic measurements of massive stars in the amateur domain fullfill professional requirements. Various groups in the north and in the south have been established running successfull professional-amateur (ProAm) campaigns, e.g., WR, O and B type stars. Today high quality results (echelle and standard) are regularly delivered and published. Long-term observations from night to night of the order of months to years open a new oportunity for massive star research. We will introduce recent and ongoing campaigns (e.g. η Car, ζ Pup, WR 134), show respective results and present the vast amount of data in respective data bases.

The Results of the ProAm 2013 Wolf-Rayet Campaign

E. J. Aldoretta[1], N. St-Louis[1]
[1] Université de Montréal

Since their discovery, Wolf-Rayet stars have been studied using various methods in order to understand the many physical phenomena taking place in their dense outflows. In the case of variability that is not strictly periodic or for epoch-dependant changes, the challenge is to observe for sufficiently long periods of time and with a high enough time sampling to be able to grasp what is the underlying phenomena taking place.

During the summer of 2013, professional and amateur astronomers around the world contributed to a 3-month long campaign, mainly in spectroscopy but also in photometry and polarimetry, to observe the first 3 Wolf-Rayet stars discovered: WR134, 135 and 137. Each of these stars are interesting in their own way, showing a variety of stellar wind structures. The spectroscopic data from this campaign has been reduced and analyzed for WR134 in order to better understand its behavior and long-term periodicity in the context of CIRs in the wind. I will be presenting the results of this spectroscopic data.

Studying large and small scale wind asymmetries from spectroscopy and polarimetry

N. St-Louis[1]
[1] Université de Montréal, Canada

— Review Talk —

The winds of Wolf-Rayet stars are known to show small but also large scale structures. There are many observational signatures of these departures from a uniform and spherically symmetric outflow. I will present results from polarimetric and spectroscopic observations of Wolf-Rayet stars that reveal large-scale asymmetries and discuss what can be learned about the structure of these winds and about the the physical mechanism responsible for generating them.

Structure and fate of binary WR stars: Clues from spectropolarimetry

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Recent results from population studies indicate that most massive stars occur in binary systems; at least 75% will be affected by a companion during the course of their evolution. Given these statistics, we cannot afford to neglect binaries when considering the role of Wolf-Rayet stars in producing supernovae and gamma-ray bursts. I will discuss how linear polarization in the emission lines of close WR binaries allows us to probe the structures of these systems' winds and wind interaction regions. In particular, tracking line polarization over the course of a binary's cycle reveals the location and extent of line-scattering regions in the system. This makes it possible to map the complex morphologies of the wind collisions, shocks, and other mass loss and mass transfer structures that shape its subsequent evolution. Observing line polarization variations with orbital phase in these binaries also enables us to distinguish polarimetric signatures arising in the interaction zone between and near the stars from those produced far away from the orbital plane. The constant polarization in the far-scattering lines traces the degree of asphericity of the WR wind. Thus, these lines may form the basis for a "binary line-effect method" to detect rapidly rotating WR stars (and hence GRB progenitor candidates) in binary systems. I will demonstrate both these techniques using HPOL spectropolarimetric observations of the bright, eclipsing WR+O binary V444 Cygni.

4 WR spectral analysis, parameters, and wind theory

Wind models and spectral analyses

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— Review Talk —

The emission-line dominated spectra of Wolf-Rayet stars are formed in expanding layers of their atmosphere, i.e. in their strong stellar wind. Adequate modeling of such spectra has to face a couple of difficulties. Because of the supersonic motion, the radiative transfer is preferrably formulated in the co-moving frame. The strong deviations from local thermodynamical equilibrium (LTE) require to solve the equations of statistical equilibrium for the population numbers, accounting for many hundred atomic energy levels and thousands of line transitions. Moreover, millions of lines from iron-group elements must be taken into account for their blanketing effect. A couple of simplifications are introduced in order to make this problem tractable, including spherical symmetry and stationarity. The velocity field in the wind is usually specified by an analytical law, but a few pilote calculations exist with consistently solved hydrodynamic equations. Approximations have been introduced for dealing with wind inhomogeneities. A specific Wolf-Rayet model atmosphere is described by its chemical composition and its fundamental parameters: luminosity L, mass-loss rate $\dot{M}$, and effective temperature. The latter is related via the Stefan-Boltzmann relation to the "stellar radius", which can be defined in different ways. Most of the emission lines are fed by recombination cascades. For the normalized line spectrum, this leads to a certain degeneracy in the parameter space.

Model atmospheres of the described kind can reproduce the observed WR spectra satisfyingly, and have been widely applied for corresponding spectral analyses. WN stars have helium-dominated atmospheres with enhanced traces of nitrogen. A rest of hydrogen is found mainly in WN stars of late subtype (WNL), while the early subtypes (WNE) are in general hydrogen-free. WC and WO winds are composed mainly of helium, carbon and oygen. Empirical Hertzsprung-Russell-Diagrams have been constructed for the WR populations in the Galaxy and the Magellanic Clouds, and form the basis for discussing the late stages of massive-star evolution.

Improving distances to Galactic Wolf-Rayet stars

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The absolute magnitude of Wolf-Rayet (WR) stars be estimated to be between $M_v = -3$ mag for earlier subtypes and $M_v = -6$ mag for late subtypes, or $M_v = -7$ mag for WNH stars (Crowther 2007). But for accurate determination of the luminosity (and the mass) of WR stars, a precise determination to their distance and extinction is necessary. Before GAIA improves HIPPARCOS survey, direct determination of the distance via parallax is only possible for γ Vel, but the analysis of the cluster or association to which WR stars are associated can give distances with a 50% to a 10% accuracy. The list of clusters, associations and clusters/association candidates has grown significantly in the last decade with the numerous deep, high resolution surveys of the Galaxy. In this work, we revisit the fundamental parameters of known clusters with WR stars, and we present the analysis of clusters that are the best candidates for being the origin of known WR stars. All our work is based on the catalogs from the VVV (from the VISTA telescope) and the UKIDS (from the UKIRT telescope) near infrared surveys. Finally, the relations between the fundamental parameters of clusters with WR stars are explored.

The Discovery and Physical Parameterization of a New Type of Wolf-Rayet Star

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[1] Lowell Observatory; [2] Las Campanas Observatory; [3] University of Pittsburgh

Spurred on by our surprising discovery of a WO star in the LMC's Lucke-Hodge 41 region, we recently began a survey of WR stars in the Magellanic Clouds. In the first year we covered ~15% of each cloud and discovered 9 new WR stars. We've now covered ~50% of each Cloud and have a whole new list of candidates. At this meeting we'll bring you up to date on the exciting new results of our survey's second year. However, the most exciting outcome of our survey is not the number of new WRs we've found, but the unique characteristics of our discoveries. Five (and possibly six) of our new WRs appear to belong to an entirely new class of WRs. While one might naively classify these stars as WN3+O3V, such a paring is unlikely. First, O3V stars are quite rare since they are the hottest and most luminous of the dwarfs. Second, the absolute visual magnitudes of our newly discovered stars are faint, with M_Vs ~ -3. Third, these stars do not exhibit radial velocity variations as expected

in a binary system, though we are in the process of gathering more data for confirmation. Finally, from an evolutionary point of view, a WN3+O3V simply does not make sense: a massive star evolves out of the O3V phase in around a million years but it takes several million years to form a WR star. Preliminary modeling done using CMFGEN on the optical data suggests that (despite the faint visual magnitudes) the bolometric luminosities of these stars are normal for early-type WNs. Additionally. these stars appear to be evolved, with significantly enriched N and He. Their effective temperatures are also normal for early-type WNs. What is unusual about these stars is that they have a surprisingly small mass-loss rate compared to other early-type WNs. How these stars got to be the way they are (single star evolution? binary evolution?) remains an open question. For now, we are designating this class as WN3/O3, in analogy to the late-type WN "slash" stars. By the time of the conference we expect to have refined the modeling using our soon-to-be-obtained HST UV data to see if these results still hold.

Physical properties of Wolf-Rayet stars in Westerlund 1

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The Westerlund 1 (Wd1) cluster hosts one of the richest and most varied collections of massive stars in the Galaxy (Clark et al 2005). The dynamical youth of the cluster and the absence of ongoing star formation indicates a coeval population. As such, the simultaneous presence of both late-type supergiants and Wolf-Rayet stars has defied explanation in the context of single-star evolution (e.g. Crowther et al. 2006). This population of massive stars offers a robust test for evolutionary models accounting for a variety of physical effects, from fast rotation to binary interaction. We present an optical to near-IR (VLT & NTT) spectroscopic analysis of 22 WR stars in Wd 1 carried out using the CMFGEN model atmosphere code. In obtaining luminosities, we account for any known binary companions and the hot circumstellar dust surrounding some WC stars, unveiling the true nature of the WR components. We discuss the extent to which obtained WR parameters may be reconciled with the predictions of single and binary evolutionary models, and how the cluster age inferred from WR stars compares to that implied by other types of star, e.g., pre-main sequence, OB supergiants, etc. We also compare the physical, chemical and wind properties of the Wd1 WR population with those in the Galactic field (Hamann et al. 2006).

Wolf-Rayet stars on the verge to explode: the properties of the WO stars

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The nature of the enigmatic oxygen-sequence Wolf-Rayet (WO) stars have long been under debate. With only nine members currently known, the WO stars are the rarest type of Wolf-Rayet (WR) stars, and are usually interpreted as being in a very short evolutionary state after the WC stage. In this talk I will present the results of the most detailed quantitative analysis of the (apparently) single WO stars to date. All stars are extremely hot, with stellar temperatures ranging from 150 kK up to 210 kK. Their helium surface abundances are typically between $20 - 30\%$, but is as low as 14% for one star.
I compare the obtained stellar properties to dedicated evolutionary models, and show that

the WO stars must be in a post-core helium burning state to explain their observed stellar temperatures, luminosities and surface abundances. Their progenitors have an estimated initial mass between $40 - 60\,M_{\odot}$. The stars will explode within a few thousand years, likely as a type Ic supernova.

The WR population in the Galactic Center

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Hosting three of the most massive, WR rich resolved young clusters in the Local Group as well as a large number of apparently isolated massive stars, the Galactic Center constitutes a test bed for studying the star formation history of the region, testing a possible top-heavy scenario and addressing massive star formation (clusters vs isolation) in a such a dense and harsh environment. We present results from our ongoing infrared spectroscopic studies of WRs and other massive stars at the Center of the Milky Way.

The WN population in the Magellanic Clouds

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Detailed and comprehensive studies of Wolf-Rayet stars of the nitrogen sequence (WN) in the Small Magellanic Cloud (SMC) and the Large Magellanic Cloud (LMC) are presented, using optical spectra as well as UV spectra if available. We derived the fundamental stellar and wind parameters for more than 100 massive stars, encompassing almost the whole WN population in the Magellanic Clouds (MCs). The observations are fitted with synthetic spectra, using the Potsdam Wolf-Rayet model atmosphere code (PoWR). For this purpose, large grids of line-blanket models for different hydrogen abundances have been calculated, covering a wide range of stellar temperatures and mass-loss rates. Since the samples are nearly complete, we can perform a statistical study of the WN properties in the MCs without selection bias. Current stellar evolution tracks, even when accounting for rotationally induced mixing, still partly fail to reproduce the observed ranges of luminosities and initial masses. To investigate the impact of the low LMC metallicity and the even lower SMC metallicity, we compare our new results to our previous analysis of the Galactic WN population.

Accurate parameters of massive eclipsing binaries in the Danks clusters

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We present results from our near-infrared spectroscopy with VLT/ISAAC of four, massive eclipsing binary systems in the young, heavily reddened, massive Danks clusters. We derive accurate fundamental parameters and the distance to these massive systems, which comprise

of OIf+, WR and O-type stars. Our goal is to increase the sample of well-studied WR stars and constrain their physics by comparison with evolutionary models.

Time dependent modeling of line profile variability due to clumping

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It is observationally established that winds of Wolf Rayet stars have highly variable characteristics. The variability evident in the winds is believed to be caused by structures on a broad range of spatial scales. Here we present a new version of our 3-D Monte Carlo radiative transfer code for clumped hot-star winds using the ray-tracing method. The time dependent simulations of line profile variability due to different distributions and properties of clumps in the wind will be presented.

Evolution of Wolf-Rayet spectra

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Wolf-Rayet stars are important sources for the enrichment of the ISM with nuclear processed elements, UV photons and momentum. They are descendants of high-mass stars for which short lifetimes and transition times can challenge the spectral classification of the stars in their different evolutionary phases. The expanded stellar atmospheres of Wolf-Rayet stars can show spectra which seem inconsistent with the anticipated underlying evolution phase, e.g., late hydrogen-burning WN stars and Of/WN transition stars.
I will present a sequence of synthetic spectra of the Potsdam Wolf-Rayet models based on the latest Geneva stellar evolution models. This will visualize the changes in stellar spectra over a full stellar lifetime. Direct comparison with observed stellar spectra, as well as the evolution of diagnostic line ratios will allow to connect stellar classification and evolution phase much better.

The true origin of Wolf-Rayet stars

J. S. Vink[1],
[1] Armagh Observatory

— Review Talk —

Wolf-Rayet mass-loss rates are key ingredients for massive star evolution, as they determine the final black hole masses. I review the theory and mass-loss rates of both (i) young very massive WNh stars, as well as (ii) the more evolved classical WR stars as a function of the stellar parameters, including the luminosity and the Eddington factor.

Hydrodynamic modelling of massive star atmospheres

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Stellar atmosphere codes are a powerful tool to obtain the stellar and wind parameters of massive stars. While they sufficiently reproduce the observed spectral appearance, they often lack a certain level of consitency as they cannot provide the amount of acceleration that would be required to actually drive the predicted wind. To overcome this gap, a new branch of the Potsdam Wolf-Rayet model atmosphere (PoWR) code, where we solve the hydrodynamic equation consistently throughout the stellar atmosphere, thus forcing the provided acceleration and the predicted wind to be consistent by adjusting the mass-loss rate and the velocity law. We show the impact of hydrodynamically consistent modelling in comparison to conventional models and discuss the obtained velocity fields and their impact on the observed spectral lines.

Magnetospheres of massive stars

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We study the interaction of line-driven winds from massive stars with the magnetic field rooted in these stars by carrying out numerical simulations using the Nirvana MHD code in 2D in spherical polar coordinates. The code's adaptive mesh refinement feature allows high spatial resolution across the whole simulation box. We study both O and Wolf-Rayet stars for a range of magnetic field strengths from weak to strong as measured by the confinement parameter. For weak fields our simulations show that the initially dipolar field opens up far away from the star and a thin disk-like structure forms in the equatorial plane of the magnetic field. For stronger fields the disk is disrupted close to the stellar surface and closed field lines persist at low latitudes. For very strong fields a pronounced magnetosphere forms where the gas is forced to move along the field lines and eventually falls back to the stellar surface.

5 η*Car, LBVs*

Eta Carinae: Many Advances, but Even More Puzzles

T. R. Gull [1]
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— Review Talk —

Over the past few decades, we have learned much about the massive binary, Eta Carinae. Yet our understanding of what caused the two historical massive ejections in the nineteenth century and even its present state is still limited. Between 10 to 40 M_o were ejected in the Great Eruption of the 1840s, yet today a massive binary with massive winds still exists. Did just one of the stars eject all of this mass? Was this a stellar merger? What happened in the 1890s? Do we understand the current binary state? Can we predict the future evolution of this system? Space observations have provided new insights on the atomic and molecular

abundances of the ejecta: 1) Nitrogen is overabundant compared to carbon and oxygen. 2) In addition to the usual atomic and ionic species, strontium, scandium and vanadium – never seen previously in the interstellar space – are strongly present. 3) Herschel instruments detect many molecules with an overabundance of nitrogen-bearing species. Both ^{12}C- and ^{13}C-bearing molecules are seen in an abundance ratio of 4, consistent with the ejecting star(s) exceeding 60 M_o. We now have much more detailed knowledge of the spatial structures: 1) Molecular hydrogen mapping demonstrated point-symmetry of structures in the Homunculus bipolar lobes and wing-like protrubances. 2) [Fe II] mapping of the Little Homunculus indicates similar asymmetries. 3) Multiple line-of sight, velocity components may provide a history of changing primary wind velocity. Space and ground-based observations, coupled with 3D modeling, provide new insights on the interacting winds: 1) X-ray flux monitoring and spectroscopy at critical phases show considerable similarities from cycle to cycle. 2) Intensive monitoring of He II and He I profiles show repeatable behavior. 3) High spatial- and spectral-resolution of [Fe III] and [Fe II] mappings across the most recent 5.5 cycle provide detailed information on the spatially-resolved ionization structures of the winds. 4) The observations guide 3D hydrodynamic/radiative transfer models and have led to greatly improved boundaries on the interacting winds. 5) 3D prints, derived from the hydrodynamic models, have provided much new insight on the interacting wind structures including apparent tubules caused by transitions between adiabatic to radiative conditions.

Measuring the Dust Properties of the High Mass Ejecta from η Carinae

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The luminous, massive binary system η Carinae is both one of the nearest and most unstable objects in a class of evolved massive stars, near the end of its lifetime that will culminate in a Type I supernova. Similar luminous objects in other galaxies undergoing pre-SN outbursts, often identified initially as new SN events, are called “SN imposters” or “η Car” analogs due to their similar energy expenditures and light curve properties without destroying the central source. The most obvious characteristic of η Car which sets it off from these other events, however, is the enormous amount of mass ejected, forming a nebula of extremely high dust mass. Little dust production has been observed in these extra-galactic events so far, while the outburst in 1843 that produced the well-known Homunculus nebula contains some 15 to 40 M$\odot$ in warm (170 K) and cool (90-110 K) dust and associated gas, according to mid-infrared spectroscopy from the Infrared Space Observatory (Morris et al. Nature 1999). However the spatial distribution and extinction properties of the dust have been poorly known, in part because difficulties to map the nebula at IR wavelengths at extreme brightnesses. These are crucial to understanding the mass loss history, and as constraints on the latest 3D hydrodynamical + radiative transfer simulations of the Homunculus nebula. We will review the ISO observations and what constraints they provided (in view of final bright source calibrations), new dust chemistry models, and our new observations from the Herschel Space Observatory which allow us to asses variability of the IR SED, and which fill in key regions between the ISO data and recent sub-mm observations with the Atacama Large Millimeter Array. We will also show new mid-infrared imaging planned withe FORCAST instrument on-board SOFIA (if they have been obtained by the time of this conference). Together these give new insights on the formation, unique chemistry, and distribution of the dust produced since the 1840's, and possibly in a previous and even more massive outburst indicated by published sub-mm observations.

X-ray Monitoring of η Car, 1992-2014

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Eta Carinae is the nearest example of a supermassive, superluminous, unstable star. Mass loss from the system is critical in shaping its circumstellar medium and in determining its ultimate fate. Eta Car currently loses mass via a dense, slow stellar wind and possesses one of the largest mass loss rates known. It is prone to episodes of extreme mass ejection via eruptions from some as-yet unspecified cause; the best examples of this are the large-scale eruptions which occurred in the mid-19th century, and then again about 50 years later. Eta Car is a colliding wind binary in which strong variations in X-ray emission and in other wavebands are driven by the violent collision of the wind of Eta Car and the fast, less dense wind of an otherwise hidden companion star. X-ray variations are the simplest diagnostic we have to study the wind-wind collision and allow us to measure the state of the stellar mass loss from both stars. We present the X-ray lightcurve over the last 20 years from ROSAT observations and monitoring with the Rossi X-ray Timing Explorer and the X-ray Telescope on the Swift satellite. We compare and contrast the behavior of the X-ray emission from the system over that timespan, including surprising variations during the 2014 X-ray minimum.

Extremely Hard X-ray Emission from η Carinae observed with *XMM-Newton* and *NuSTAR* around Periastron in 2014.5

K. Hamaguchi[1,2], M. F. Corcoran[1,3], and the Eta Carinae team

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The super massive colliding wind binary system, η Carinae, experienced another periastron passage in the summer of 2014. We monitored this event using the multiple X-ray observatories, *Chandra*, *XMM-Newton*, *NuSTAR*, *Suzaku* and *Swift*. With a high eccentricity of its 5.5 year orbit, X-ray emission from the wind-wind collision (WWC) increases strongly toward periastron but then drops sharply by more than two orders of magnitude in two weeks around periastron due probably to an eclipse and an intrinsic activity decline of the WWC plasma. In this observing campaign, *XMM-Newton* and *NuSTAR* coordinated two simultaneous observations around the X-ray flux maximum on June 6 and just before the flux minimum on July 28. These two observations captured η Carinae with X-ray focusing telescopes in the extreme hard X-ray band above 10 keV for the first time. During the first observation, *XMM-Newton* and *NuSTAR* detected stable X-ray emission from the central binary system between 1−40 keV. A fit of a 1-temperature bremsstrahlung model to the high energy slope in the *NuSTAR* spectrum derives an electron temperature of ∼6 keV,

which is significantly higher than an ionization temperature at ∼4.5 keV, measured from the Fe K emission lines resolved in the *XMM-Newton* spectrum. This result suggests the presence of very hot plasma and/or X-ray reflection at surrounding cold material. During the second observation, the X-ray flux between 5−10 keV declined steadily by a factor of ∼2 in a day, while the other energy bands were rather stable. This variation may be explained by an increase of the line of sight absorption to emission from the plasma component that dominates above 5 keV. *NuSTAR* did not detect, in either observation, the very hard non-thermal component that dominated emission above 25 keV seen in earlier *INTEGRAL* and *Suzaku* observations. We discuss the plasma condition and the wind structure of η Carinae around periastron, and the nature of the non-thermal component.

3D Hydrodynamical and Radiative Transfer Modeling of η Carinae's Colliding Winds

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We present the results of full 3D hydrodynamical and radiative transfer simulations of the colliding stellar winds in the massive binary system η Carinae. We accomplish this by applying the SimpleX algorithm for 3D radiative transfer on an unstructured Voronoi-Delaunay grid to recent 3D smoothed particle hydrodynamics (SPH) simulations of the binary colliding winds. We use SimpleX to obtain detailed ionization fractions of hydrogen and helium, in 3D, at the resolution of the original SPH simulations. We investigate several computational domain sizes and Luminous Blue Variable (LBV) primary star mass-loss rates. We show how the SimpleX simulations can be used to generate synthetic spectral data cubes for comparison to data obtained with the Hubble Space Telescope (HST)/Space Telescope Imaging Spectrograph as part of a multi-cycle program to map changes in η Carinae's spatially-extended interacting wind structures across one binary cycle. Comparison of the HST observations to the SimpleX models can help lead to more accurate constraints on the orbital, stellar, and wind parameters of the η Carinae system, such as the LBV primary's mass-loss rate and the companion star's temperature and luminosity. We furthermore present new methods of visualizing and interacting with output from complex 3D numerical simulations, including 3D interactive graphics and 3D printing. While we initially focus specifically on η Car, the numerical methods employed can be applied to numerous other colliding wind (WR 140, WR 137, WR 19) and dusty 'pinwheel' (WR 104, WR 98a) binary systems. Coupled with 3D hydrodynamical simulations, SimpleX simulations have the potential to help determine the regions where dust can form and survive in these unique objects.

Family ties of WR to LBV nebulae yielding clues for stellar evolution

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Luminous Blue Variables (LBVs) are stars is a transitional phase massive stars may enter while evolving from main-sequence to Wolf-Rayet stars. The to LBVs intrinsic photometric variability is based on the modulation of the stellar spectrum. Within a few years the spectrum shifts from OB to AF type and back. During their cool phase LBVs are close to the Humphreys-Davidson (equivalent to Eddington/Omega-Gamma) limit. LBVs have a rather high mass loss rate, with stellar winds that are fast in the hot and slower in the cool phase of a LBV. These alternating wind velocities lead to the formation of LBV nebulae by wind wind interactions. A nebula can also be formed in a spontaneous giant eruption in which larger amounts of mass being ejected. LBV nebulae are generally small ($< 5\,\mathrm{pc}$) mainly gaseous circumstellar nebulae, with a rather larger fraction of LBV nebulae being bipolar. After the LBV phase the star will turn into a Wolf-Rayet star, but note that not all WR stars need to have passed the LBV phase. Some follow from the RSG and the most massive directly from the MS phase. In general WRs have a large mass loss and really fast stellar winds. The WR wind may interact with winds of earlier phases (MS, RSG) to form WR nebulae. As for WR with LBV progenitors the scenario might be different, here no older wind is present but a LBV nebula ! The nature of WR nebulae are therefore manifold and in particular the connection (or family ties) of WR to LBV nebulae is important to understand the transition between these two phases, the evolution of massive stars, their winds, wind-wind and wind-nebula interactions. Looking at the similarities and differences of LBV and WR nebula, figuring what is a genuine LBV and WR nebula are the basic question addressed in the analysis presented here.

HD 5980: A unique laboratory for understanding massive binary stars

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HD 5980 is a quadruple system containing at least 3 very massive and luminous stars. It's location in the Small Magellanic Cloud make it ideal for studying the structure and evolutionary processes in such stars in low-metallicity environments. The most prominent members of the HD 5980 system are the two eclipsing stars, denoted Star A and Star B, both of which currently are believed to possess a Wolf-Rayet type spectrum. Star A became the dominant contributor to the spectrum after it erupted in 1994 in what appears to have been a Luminous Blue Variable instability event. It's properties suggest that it may be following a quasi-homogeneous chemical evolutionary track, with important consequences for the final product of its evolution. Furthermore, the varying wind structure of Star A as it went through the LBV phase into the WNE phase provides a unique laboratory for studying the effects of wind-wind interactions. The five decades of spectroscopic and photometric observations of this system are a wealth of information that is just beginning to be exploited. In this proposed presentation, I will review the known properties of HD 5980, describe its current (2014) spectroscopic properties, and describe the great potential that this systems provides for understanding massive star evolution in binary systems.

6 *Structure & Evolution of WR stars*

The importance of getting the single-star physics correct in binary evolution.

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— Review Talk —

The fact that binary stars are important for modelling massive stars and Wolf-Rayet populations cannot be disputed. However the importance of the "single-star" physics used in the stellar models is just as vital. I will outline which features of Wolf-Rayet models that are dependent on binary interactions and which are dependent on the single-star physics. The single-star physics I will consider are the mass-loss rates and the metallcity dependence within the stellar evolution code. I will also discuss some of the useful comparisons possible with population synthesis that constrain the binary and single-star physics such as the relative rates of different types of supernovae and observations of Wolf-Rayet stellar populations from those in our Galaxy to galaxies at the edge of the observable Universe.

Physics of massive stars relevant for the modeling of Wolf-Rayet populations

G. Meynet[1]
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— Review Talk —

Key physical ingredients of massive stars are mass losses, convection and mixing in radiative zones. These effects are important both in the frame of single and close binary evolution. In this talk, I shall review the different approaches for modeling convection (Ledoux or Schwarzshild criterion, overshooting) and for modeling the mixing in radiative zones induced by rotation with and without a magnetic field. After a brief recall of the physical arguments supporting these different approaches, I shall discuss possible impacts on the properties of the Wolf-Rayet stars. If time permits, some considerations about the impact of mass loss rates especially during the red supergiant phase, as well as the impact of tidal interactions in close binary systems will be made.

WR stars from fast rotating massive stars at low metallicity

D. Szécsi[1], N. Langer[1]
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Massive stellar evolution is essentially different at low metallicity than at solar composition. Fast rotating stars at low metallicity may undergo chemically homogeneous evolution and become hydrogen burning WR stars of spectroscopic class WNh or WN. Some of these objects are predicted to evolve to long gamma-ray bursts in the collapsar scenario. To clarify the conditions for their existence, we need to study their evolutionary behaviour from the theoretical point of view. We computed stellar evolutionary model sequences with a composition suitable for the WR-galaxy I Zwicky 18 (Z_{IZw18} ∼1/50 $Z_\odot$). From the 320 tracks

computed in the mass range of 10-300 $M_{\odot}$, 125 tracks evolve chemically homogeneously and become WR stars. This large set of tracks allow us to investigate in detail the chemically homogeneous evolution that leads to fast rotating WR stars. We present the evolutionary behaviour of these tracks in the main sequence and beyond, we analyse the consequences of the WR mass loss for the stellar structure, and we predict their final fates as long gamma-ray bursts or pair instability supernovae. Furthermore, we compare our I Zw 18 tracks to previously calculated WR tracks of different initial composition and discuss the conditions needed for chemically homogeneous evolution.

The impact of rotation on WR spectra

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There are various indications that rapidly rotating WR stars should exist. Unfortunately, due to their expanding atmospheres, rotational velocities of WR stars are very difficult to measure. Recently observed spectra of several WNE stars reveal peculiarly broad and round emission lines, so far not reproduced by the standard assumptions of non-LTE model atmospheres. In my talk, I will discuss the conditions under which rotation could help to reproduce the peculiar spectra, and explore whether the implications of such models (large co-rotation radii, strong magnetic fields) are consistent with modern observations.

Helium stars: Towards an understanding of Wolf-Rayet evolution

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There are outstanding problems in trying to reproduce the observed nature of Wolf-Rayet stars from theoretical stellar models. We have investigated the effects of uncertainties, such as composition and mass-loss rates, on the evolution and structure of Wolf-Rayet stars and their lower mass brethren. We find that the normal Conti scenario needs to be altered—with different WR types being due to different initial masses as well as different stages of evolution of the WR stars.

Observational diagnostic of the unstable envelopes of Wolf-Rayet stars

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The envelopes of stars near the Eddington limit are known to be prone to various instabilities. We investigate the partly convective envelopes of massive helium stars, where the instability to convection is due to the opacity peak associated with the partial ionization of the iron-group elements and where the envelope in some cases is unstable against pulsations. We determine the physical parameters and especially the average velocities of the convective

blobs in the convective regions. Then we estimate the amplitude of the turbulent velocities at the base of the wind which can potentially lead to the formation of small scale structures, as observed in the winds of Wolf-Rayet stars. Our solar metallicity Wolf-Rayet models in the range $2 - 17\,M_\odot$ are computed with the Bonn stellar evolution code. The properties of convection in the envelope of these stars are computed adopting the Mixing Length Theory and the OPAL opacities. Mass-loss by stellar winds is also applied and can play a crucial role for pulsating inflated envelopes.
Our results show the occurrence of sub-surface convective regions in all the studied models. Small surface velocity amplitude are found for models with masses below $10\,M_\odot$. For models with $M \geq 10\,M_\odot$, the surface velocity amplitudes are of the order of 10 km/s. Moreover we find the occurrence of pulsations in the mass range $9 \ldots 14\,M_\odot$, as well as a stabilizing effect of mass-loss for the most massive models. Our study can relate the surface velocity fluctuations to the formation of clumping in the inner part of the wind as a function of the mass-luminosity ratio in WR stars. We predict this to become significant for WR stars with masses above $10\,M_\odot$. We compare our models with observations of spectral variability in single WR stars that are of the WNE-type, and we find a similar trend as in our predictions.

Examining Wolf Rayet Light Curve Variability with MOST

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Photometric variability in Wolf-Rayet (WR) stars is not a new phenomenon, but much like in their O-star progenitors, the source of this variation is still unknown. Indeed, the situation is much more complicated for WR stars as explanations of O star variability are much harder to apply to their denser windier cousins. Arguments have been made for spots (and their possible relation to CIRs), clumps, pulsations (p-mode, g-mode, and strange), as well as binary interactions to explain this variability in WR stars. Just as in other types of stars, there may be a variety of phenomena responsible. However, it is reasonable to suggest that their is a main cause or source for this variation in the majority of WR stars. With the advent of the *MOST* satellite we have been afforded our first real chance to answer this question. In total there have been 12 WR stars which have been observed. While this is hardly a robust or unbiased sample, it should be indicative of the variation expected in these stars. Instead of looking at each star on a case by case basis, as has been done previously, we will treat them as a group. In this way, we are able to study similarities in the parameters that describe this variability, such as amplitude and period. We will discuss these similarities and differences in an attempt to derive their root cause.

How new limits on convection remove old limits on evolution

Irit Idan[1], Nir Joseph Shaviv[2], Tomer Shacham[2]

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We study evolution of very massive stars, and find that in the radiative outer layers, convection couples to inhomogeneity triggered by the high luminosity. This coupling induces various pulsations - of radius, luminosity, and mass loss. We further show the dynamic nature

given to the boundary conditions at the surface of the star, which turns out to solve the Mixing-Length-Theory-related convergence problem of high mass stelar evolution codes.

Are Wolf-Rayet envelopes inflated?

G. Gräfener[1],
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The effective temperatures of many WR stars are much cooler than predicted by stellar structure/evolution models. In many cases the discrepancy reaches a factor three, corresponding to a radius discrepancy of an order of magnitude. Currently it is controversially discussed whether this 'WR radius problem' is caused by the extension of the optically thick winds of WR stars, or by a theoretically predicted inflation of their sub-surface layers. The latter possibility has consequences for the mass loss of WR stars, its dependence on metallicity, and the origin of wind-clumping and pulsations. Furthermore, the inflation effect may be related to the radius variability of Luminous Blue Variables, and may affect the properties of direct supernova progenitors. To nail down the question whether the inflation effect occurs in nature, we focus here on the observational determination of WR radii and effective temperatures and discuss the involved uncertainties.

Inflated envelopes of Wolf-Rayet stars leading to extended supernova shock breakout signals

D. Sanyal[1], T. M. Moriya[1], L. Grassitelli[1] & N. Langer[1]
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Models of massive Wolf-Rayet stars which reach the Eddington limit in their interior exhibit the phenomenon of 'envelope inflation' whereby the star develops a pronounced core-envelope structure. This results in an extended, extremely dilute and radiation-pressure dominated envelope. If the inflated envelopes are not removed by the strong winds, they might significantly affect the properties of the pre-supernova progenitors like radii, effective temperatures, etc. Although these peculiar structures were proposed in the literature around thirty years ago, they have been explored rather recently, e.g. to address the so-called Wolf-Rayet radii problem. We will provide a general overview of the physics of inflated envelopes in the context of Wolf-Rayet stars and discuss their consequences for Type Ib/c supernovae. We show that these structures may be responsible for the long rise times of shock breakout signals of hydrogen-free supernovae. In this scenario, the rise times of the shock breakout signals are dominated by the diffusion time in the inflated envelope rather than by the light-crossing time of the progenitors. Our inflated Wolf-Rayet star models whose radii are of the order of $\sim R_{\odot}$ can thus produce shock breakout signals longer than ~ 100 sec and serves as a natural explanation to the puzzlingly long shock breakout signal observed in Type Ib SN 2008D.

Massive close binaries in general, WR binaries in particular

D. Vanbeveren
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— Review Talk —

We review some milestones in the research of massive close binaries with special emphasis on WR binaries. We first focus on the previous millenium starting from the late sixties, early seventies. We then discuss some important new massive binary results that were published in the present millenium.

Wolf-Rayet runaways: the search for WR+cc binaries

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Current Wolf-Rayet (WR) evolution theories agree that WR stars originate from O-type main sequence stars. Thus, we expect a commonplace O+O binary system to evolve into an O+cc (compact companion) and eventually to a WR+cc system. Yet, while the number of known O + cc (which are among the MXRBs = massive X-ray binaries) is significant, the number of detected WR+cc systems is much lower than predicted, especially knowing that most O stars are found in O+O systems. In fact, to date there is only a single confirmed WR+cc binary: Cyg X-3. Considering that the supernova explosion of the compact companion (original primary) may cause such binaries to separate in most cases and be ejected from the Galactic plane ($z = 0$), we limit our search for surviving WR+cc candidates among the runaways. Among the most extreme cases ($z > 600$ pc), WR 148 (WN8) and WR 71 (WN6) are the only two WR runaways indicated with a possible binary status. WR 148 is already a clear and confirmed single-line binary, where the secondary has been previously narrowed down to be either a B2-4III-V star or a black hole (BH). However, a BH is less favoured due to lack of accretion X-rays like in Cyg X-3. In the case of WR 71, the presence of a companion is subject to debate. We are currently examining large amounts of high-precision spectroscopic and photometric data in an attempt to reveal the true status and its implication for these two key objects.

Wolf-Rayet stars as an evolved stage of stellar life

C. Georgy[1]
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Wolf-Rayet stars, as an evolved stage of massive stars life, are an important test to check the stellar models, and to improve our understanding of the physics of stellar interiors. The recent surveys searching for Wolf-Rayet stars in our Galaxy or in the nearby Universe, by investigating different metallicity environments, provide new constraints on massive stars modelling, and can also highlight the role of binary evolution. In this talk, I will present the Wolf-Rayet populations predicted by the new grids of single stars model computed with the Geneva stellar evolution code at 3 different metallicities (MW, LMC and SMC), and highlight the effects of metallicity on the evolution of massive stars. In this context, I will also show the crucial role played by rotation and mass loss, and more particularly how the

uncertainties in the mass-loss rates of red-supergiants can affect the predictions of Wolf-Rayet populations. Finally, I will compare our results with the observed number ratio of WC/WN at different metallicities.

Ages and masses of LEGUS young massive clusters obtained with different stellar evolution tracks and atmospheres

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Young massive clusters (YMCs) are dense aggregates of stars that are young ≤ 100 Myr, massive $\geq 10^4$ $M_\odot$, and considered fundamental building blocks of galaxies. Constraining their extinction-corrected ages and masses is essential for investigating star formation and its relation with galaxy environment, from individual clusters to kpc-size structures. The Legacy ExtraGalactic Ultraviolet Survey (LEGUS) used the Wide Field Camera 3 aboard the Hubble Space Telescope to collect five-band photometry in NUV to I-band filters F275W, F336W, F438W, F555W, and F814W, at high angular resolution (~ 0.07"), for tens of thousands of star clusters in 50 nearby (≤ 12 Mpc) galaxies. By comparing LEGUS observations with computed SEDs, we obtain metallicities, reddenings, ages, and masses for a sub-sample of LEGUS YMCs. Our aims are to i) determine if the above cluster properties are well constrained by models that use different stellar evolution tracks and atmospheres, and ii) quantify uncertainties in cluster properties due to differences in models. We include stellar and nebular contributions do the SED. For the stellar component, we try models based on old and newer Wolf-Rayet atmospheres, and where massive stars evolve as non-rotating, rotating, or close-binary systems. We present results for a well-sampled initial mass function.

The end stages of massive star evolution: WN and WO stars as SN Ibc progenitors from stellar evolution models

J. H. Groh[1]

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The morphological appearance of massive stars across their post-Main Sequence evolution and before the SN event is very uncertain, both from a theoretical and observational perspective. In this talk, I will present coupled stellar evolution and atmospheric modeling of stars done with the Geneva and CMFGEN codes, for initial masses between 9 and 120 Msun. We are able to predict the observables such as the high-resolution spectrum and broadband photometry. I will discuss how the spectrum of a massive star changes across its evolution and before death, with focus on the WR stage. Our models indicate that single stars with initial masses larges than 30 Msun end their lives as WR stars. Depending on rotation, the spectrum of the star can either be that of a WN or WO subtype at the pre-SN stage. Our models allow, for the first time, direct comparison between predictions from stellar evolution models and observations of SN progenitors. I will discuss how our models compare with progenitor observations and with recent early-time spectroscopy of SNe.

The Eddington limit and Wolf-Rayet stars

N. Langer[1], D. Sanyal[1], L. Grassitelli[1]
[1] Bonn University

We show that while the Eddington limit is reached at about $10^6\,M_\odot$ when the opacity is only due to electron scattering, it comes down to about $30\,M_\odot$ in realistic models at solar metallicity. However, the Eddington limit is generally not reached at the stellar surface, but inside the stellar envelope, with drastic consequence for the stellar structure. We discuss how this changes the stellar observables, which we outline for OB stars, and for Wolf-Rayet stars of different the types.

Wolf-Rayet stars as supernova progenitors

Luc Dessart[1]
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— Review Talk —

Wolf-Rayet stars are considered the progenitors of core-collapse supernovae (SNe) of type IIb, Ib, and Ic. While such massive stars eventually form an iron core that collapses, it is today unclear what fraction of these objects actually explode, and if they do, what remnant star they leave behind. The current consensus is that binary-star evolution of moderate mass massive stars is the favoured channel to produce the low-mass ejecta typically associated with observed SNe Ib/c. In this talk, I will review the basic hydrodynamical features of successful core collapse supernova explosions and describe results for explosions of "bare" helium cores relevant to SNe IIb/Ib/Ic, resulting from both single-star and binary-star evolution. I will then describe the radiative properties (light curves and spectra) of the resulting supernovae as simulated with CMFGEN, and confront to observations. These simulations help us understand the differences between SNe Ib and Ic (i.e., presence or absence of HeI lines in optical spectra), and assess the importance of mass-transfer in close binaries to produce low-mass pre-SN progenitors. I will then wrap-up by discussing the connection between WR star explosions and super-luminous SNe. Although very rare, these enigmatic explosions are sometimes seen in association with a GRB (e.g., SN 1998bw), or suggestive of a magnetar-power source (e.g., SN 2005ap), or interaction with a He-rich circum-stellar medium (e.g., SN 2006jc).

7 *WR-type central stars of PNe*

Wolf-Rayet centrals stars of planetary nebulae

H. Todt[1], W.-R. Hamann[1]
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— Review Talk —

A significant number of the central stars of planetary nebulae (CSPNe) are hydrogen-deficient, showing a chemical composition of helium, carbon, and oxygen. Most of them exhibit Wolf-Rayet-like emission line spectra, similar to those of the massive WC Pop I stars, and are therefore classified as of spectral type [WC]. In the last years, CSPNe of other

Wolf-Rayet spectral subtypes have been identified, namely PB 8, which is of spectral type [WN/C], and IC 4663 and Abell 48, which are of spectral type [WN]. We review spectral analyses of Wolf-Rayet type central stars of different evolutionary stages and discuss the results in the context of stellar evolution. Especially we consider the question of a common evolutionary channel for [WC] stars. The constraints on the formation of [WN] or [WC/N] subtype stars will also be addressed.

The role of binarity in Wolf-Rayet central stars of planetary nebulae

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Around 45 post-common-envelope close binary central stars of planetary nebulae (CSPNe) are now known. The majority contain main sequence or white dwarf (WD) companions, however there is a conspicuous absence of Wolf-Rayet ([WR]) components with only two discovered so far. The available observations suggest WD companions are the most likely companion type to appear in [WR] binaries. Such systems are best found with radial velocity monitoring surveys and could not have generally been detected in the mostly photometric monitoring campaigns for close binary CSPNe. I will give an overview of our current knowledge about binarity in CSPNe with an emphasis on new observations of [WR] CSPNe. Implications for various formation scenarios for [WR] CSPNe will be discussed with a focus on possible explanations for the He-rich [WN] CSPNe whose formation remains an open question.

X-ray emission from planetary nebulae and their central stars

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The fast stellar wind emanating from the central stars of planetary nebulae can produce diffuse X-ray emission inside a hot bubble, but also in shocks embedded within the stellar wind. The properties of the stellar wind (mass-loss rate, terminal velocity, and chemical abundances) determine the production of hot gas in planetary nebula. I review here the different X-ray properties of planetary nebulae for H-rich and [WR] types of central stars.

8 WR colliding winds, dust

Dust synthesis in carbon-rich Wolf-Rayet colliding winds

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— Review Talk —

Infrared photometry provided the first evidence for the formation of dust in some evolved, carbon-rich Wolf-Rayet stars. These stars are often part of binary systems where the interaction with the stellar companion triggers colliding winds regions, which are characterised by shock heating and X-ray emission. Despite the harsh gas conditions in the shock-compressed wind, dust formation proceeds, probably in the wake of the compression shock, where the post-shock gas temperature is sufficiently low. We present new modelling efforts on dust synthesis in WC colliding winds. The wind interaction region is modelled by using 3D Smoothed Particle Hydrodynamics to derive the gas physical conditions in the dust production zone. An exhaustive chemical description of the shocked gas that includes the formation of both molecules and carbon dust is used, based on the latest laboratory studies of fullerene synthesis. The description of carbon dust condensation includes the formation of small carbon chains, rings, and cages as nucleation agents, and coalescence and coagulation of these clusters is followed to form carbon grains. Grain size distributions and final masses are derived for the conditions pertaining to the colliding wind region of typical WC binaries, and compared to available observational data.

The Colliding-wind WC9+OB binary WR 65 and dust formation by WR stars

P. M. Williams[1], K. A. van der Hucht[2]

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Observations of the WC9+OB system WR 65 in the infrared show variations of its dust emission consistent with a period near 4.9 yr, suggesting formation in a CWB having an elliptical orbit. If, as occurs in systems like WR 140 and WR 19, maximum dust emission coincides with periastron passage at orbital phase zero, the times of X-ray maximum count and minimum extinction to the hard component measured by Oskinova & Hamann fall at phases 0.4–0.5, when the separation of the WC9 and OB stars is greatest. The spectrum and radio emission by WR 65 are discussed in the context of this model. We consider WR 65 in the context of of the 8–10 WC+OB stars showing variable dust emission and a comparable number of WC8–9 stars whose infrared photometric histories spanning 15+ years suggest that they make dust at constant rates in a search for clues to this still enigmatic process.

3D Modelling of dust formation in colliding-wind binary WR98a including dust dynamics and radiative transfer

T. Hendrix[1], R. Keppens[1]
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We present the results of our efforts to model the observations of the persistent (yet possibly variable) formation of dust in the binary system WR98a, which displays a clear spiral morphology in observations at 2.2μm. To do so, we have performed full 3D hydrodynamics simulation of the binary system using the dust+gas module of the `MPI-AMRVAC` code, resolving the inner wind acceleration zone as well as distances up to 100 times the binary separation. In these simulations we include important physics such radiative cooling, dust formation and size dependent dust dynamics. By coupling the `MPI-AMRVAC` with the dust radiative transfer code `SKIRT` , we produce synthetic observations of dust formed in our hydrodynamical simulations which we can directly compare to observations in the infrared.

Shaping the Outflows of Wolf-Rayet Stars

S. Mohamed[1] et al.
[1] South African Astronomical Observatory

— Review Talk —

Wolf-Rayet (WR) stars lose copious amounts of mass, momentum and mechanical energy through powerful, dense stellar winds. The interaction of these outflows with their surroundings results in highly structured and complex circumstellar environments, often featuring knots, arcs, shells and spirals. Recent improvements in computational power and techniques have led to the development of detailed, multi-dimensional simulations that have given new insight into the origin of these structures, and better understanding of the physical mechanisms driving their formation. In this talk, I will review three of the main mechanisms that shape the outflows of WR stars:
- interaction with the interstellar medium (ISM), i.e., **wind-ISM interactions**;
- interaction with a stellar wind, either from a previous phase of evolution (e.g., the slower red supergiant winds) or the wind from a companion star, i.e., **wind-wind interactions**;
- and interaction with a companion star that has a weak or insignificant outflow (e.g., a compact companion such as a neutron star or black hole), i.e., **wind-companion interactions**.
I will also highlight the broader implications and impact of these morphological studies for related WR phenomena, e.g, for X-ray binaries and Gamma-ray bursts.

Magnetic fields, non-thermal radiation and particle acceleration in colliding winds of WR-O stars

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Non-thermal emission has been detected in WR-stars for many years at long wavelengths spectral range, in general attributed to synchrotron emission. Two key ingredients are needed to explain such emissions, namely magnetic fields and relativistic particles. Particles can be accelerated to relativistic speeds by Fermi processes at strong shocks. Therefore, strong synchrotron emission is usually attributed to WR binarity. The magnetic field may also be amplified at shocks, however the actual picture of the magnetic field geometry, intensity, and its role on the acceleration of particles at WR binary systems is still unclear. In this work we discuss the recent developments in MHD modelling of wind-wind collision regions by means of numerical simulations, and the coupled particle acceleration processes related.

9 X-rays and WR stars

X-ray emission of WR stars

L. M. Oskinova[1],

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— Review Talk —

I will briefly summarize our knowledge of X-ray emission from Wolf-Rayet stars of different types. At present we don't fully understand how and why WR stars produce X-ray radiation. The same time, we can use their X-ray emission as a sensitive probe of stellar wind structure and dynamics. I will discuss how X-ray spectroscopy can be used to constrain stellar wind parameters such as mass loss rate, wind velocity field and clumping properties.

High Resolution X-Ray Spectra of WR 6

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WR 6 is a putatively single WN4 star, and is relatively bright ($V = 6.9$), and as such, it is an ideal case for studying the wind mechanisms in these extremely luminous stars. WR 6 shows variability consistent in period ($P = 3.765$ days), but variable in phase and amplitude. XMM/Newton observations have indicated that X-ray emission occurs far out in the wind. To obtain higher resolution, and also at higher energy (above 1 keV), we have observed WR 6 with the Chandra High Energy Transmission Grating Spectrometer for 450 ks. We have resolved emission lines of S, Si, Mg, Ne, and Fe, which all show a sawtooth profile, characteristic of a uniformly expanding shell. Sharp blue edges gives a robust maximal expansion velocities which are on average about 2000 km/s, somewhat larger than the 1700 km/s value derived from UV lines. The He-like lines all indicate that X-ray emitting plasmas are far from the photosphere — even at the higher energies where opacity is lowest — as was also the case for the longer wavelength lines observed with XMM-Newton/RGS. The star was also variable in X-rays and in simultaneous optical photometry obtained with aspect camera. We will present detailed models of the WR 6 wind incorporating X-ray, UV, and optical data.

Studies of WR+O colliding-wind binaries

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Massive stars (O and their descendants WR stars) are very important objects that play a major role in the evolution of galaxies. Despite this importance, several aspects of their live remain poorly known. Two of the main parameters that govern their evolution, the mass and the mass-loss rate, are still poorly determined from the observational point of view. Only binary systems could provide well constrained masses and colliding wind binaries could bring some constraints on the mass-loss rate. In this framework, we present detailed studies of basic observational data obtained with the XMM-Newton facility combined with ground-based observations for a few WR+O binaries with possible colliding winds.

Hydrodynamic and Radiative Transfer Modeling of X-ray Emission from WRs in Binary & Higher-order Systems

C. M. P. Russell[1], M. F. Corcoran[1,2], S. P. Owocki[3], J. Cuadra[4], A. M. T. Pollock[5], T. R. Kallman[1]

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When located in multiple-star systems, the strong winds of WR stars lead to wind-wind collisions that produce thermal X-ray emission detected by a multitude of X-ray observatories. To interpret these observations, we perform 3D hydrodynamic simulations of interacting binary systems, such as the WC+O binary WR 140, and higher order systems, such as the Galactic center where 30 WR stars orbit the central super-massive black hole, and then synthesize the model X-ray emission by solving the formal solution to radiative transfer. For WR 140, the model reproduces the *RXTE* observations over $\sim 95\%$ of the orbit, with the divergence coming in the depth of the drop in X-ray flux associated with periastron passage. The *RXTE* hardness ratio is matched well throughout the orbit, as well the, e.g., *XMM-Newton* and *Suzaku* spectra taken outside the X-ray minimum. The model also does a good job reproducing the shape of the line profiles seen in *Chandra* observations. For the Galactic center, the diffuse X-ray emission of the central $r = 5$pc observed by the 3Ms *Chandra* X-ray Visionary Project is well reproduced by the model, except for point-like sources coming from, e.g., the IRS 13 cluster. This suggests a downward revision of the wind strengths (either in mass loss rate or terminal velocity) of the 2 WR stars in IRS 13. This presentation will compare the model results to observations with an emphasis on what we can learn about the WR stars in these systems.

The 3XMM-DR4 catalogue of Wolf-Rayet stars

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[1] Observatoire Astronomique de Strasbourg

We present a X-ray catalogue of Wolf-Rayet stars built cross-correlating the version available as in March 2014 of the Galactic Wolf-Rayet Catalogue maintained by P. A. Crowther with the 3XMM-Newton enhanced catalogue. The enhanced catalogue is a multi-wavelength catalogue created as part of the ARCHES project. Sources in different catalogues (from X-ray to infrared) are cross-correlated based on their positions and using a statistical method based on local space densities, each possible match provides us with the probability of association. Among others, the catalogue provides us with spectral energy distributions and finding charts for all possible matches. We here present X-ray properties with special emphasis on the hard X-ray emission found among a subset of these Wolf-Rayet stars.

Unexpected consequences of Kepler's laws in WR 25

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In binary systems, Kepler's laws provide a secure temporal and geometrical framework for analysis and interpretation of measurements. Application to X-ray observations of the well-known system WR 25 during its 208-day orbit lead to conclusions that are difficult to reconcile with conventional thinking. There are two X-ray eclipses, first one by the wind and then one by the star itself. The wind eclipse suggests an orbital inclination of 54° and a mass-loss rate far too small by more than an order of magnitude. Ingress of the stellar eclipse takes about 4 days and implies a firm lower limit to the stellar radius of only 6 $R_\odot$ although a firm value must await detailed morphology of the X-ray source. The X-ray source is detached from the Wolf-Rayet stellar surface but lies closer than it should.

10 WR nebulae

Wolf-Rayet nebulae and the wind–interstellar medium interaction

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— Review Talk —

I review our current understanding of the interaction between a Wolf-Rayet star's fast wind and the surrounding medium, and discuss to what extent the predictions of numerical simulations coincide with multiwavelength observations of Wolf-Rayet nebulae. Through a series of examples, I endeavour to show the effect of changing the input physics on the results of the numerical simulations. Finally, I discuss how numerical simulations together with multiwavelength observations of these objects allow us to unpick the previous mass-loss history of massive stars.

A consistent spectral model of WR 136 and its associated bubble NGC 6888

J. Reyes-Pérez[1], C. Morisset[1], M. Peña[1]
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The main aim of this work is to test the possibility of modelling simultaneously the stellar and nebular spectra of a WR star and its nebula. We want to test whether the stellar model found to provide an optimal description of the stellar observations is able to satisfactorily ionize the nebula and reproduce the nebular observations. In this way we tried to succesfully construct a coherent stellar and nebular model that reproduces observations of the ring nebula NGC 6888 and its central star. This allowed us to determine, in a consistent way, all the physical parameters of both the star and the nebula, including chemical abundances and distance. The procedure was first to compute an atmosphere model by using the code CMFGEN. All the observational material available (far and near UV and optical spectra) were used to constrain such a model. We found that even when luminosity and the mass-loss rate were well constrained, the stellar temperature T_* at τ=20, can be in a range between 70 000 and 110 000 K. These different models reproduce fairly well the stellar continuum and many of the spectral features. This degeneracy in atmosphere models is due by our misunderstanding of the velocity structure in the inner regions of the stellar wind. A photoionization model for the nebula NGC 6888, computed with the pyCloudy code, was built to test the different stellar models. When using the nebula as an additional restriction we find that the stellar models with $T_* \sim 70\ 000$ K represent the best solution for both, the star and the nebula. Results from the photoionization model show that the observed N/O trend found in different regions of NGC 6888 can be reproduced even if we consider a chemically homogeneous nebula. Our work shows the importance of calculating coherent models including stellar and nebular constraints.

Ring Nebulae: Tracers of the CNO Nucleosynthesis in Wolf-Rayet Stars

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Ring nebulae are interstellar bubbles of ionized gas that have swept-up the surrounding interstellar medium after the mass loss episodes experienced by their massive progenitors, especially during the Wolf-Rayet phase. The presence of stellar ejecta in ring nebulae allows us to better understand the nucleosynthesis of massive stars and the effects of the H-burning reactions on the elements involved in the CNO cycle. A detailed analysis of the chemical composition and abundance ratios of these elements provides us valuable information to constrain stellar evolution models of massive stars and the evolutive scenario of the stellar progenitors. Within this framework, we will present results from new spectroscopic data in the optical range of the Galactic ring nebulae NGC6888, G2.4+1.4, RCW58 and NGC7635 based on very deep observations obtained with the 10m GTC telescope and the 6.5m Clay telescope. In comparison with previous studies, these new observations have allowed us to derive physical conditions and chemical abundances with great accuracy in different zones of the nebulae. Therefore, we have been able to detect and localize areas of shocked gas, and investigate the presence of chemical inhomogeneities in these objects. Additionally, we will present the first determinations of C abundances in these ring nebulae based on the faint recombination line C II 4267 Å as well as their implications when comparing with the

predictions of stellar evolution models. These crucial results represent the first constrains on C abundances, providing long-awaited information on the action of the CNO cycle that controls the nucleosynthesis processes in massive stars.

Ionization-Gasdynamics Modelling, and X-ray Spectral Calculations, of Wind-Bubbles around Wolf-Rayet Stars

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Using a code that employs a self-consistent method for computing the effects of photo-ionization on circumstellar gas dynamics, we model the formation of wind-driven nebulae around massive Wolf-Rayet (W-R) stars. Our algorithm incorporates a simplified model of the photo-ionization source, computes the fractional ionization of hydrogen due to the photo-ionizing flux and recombination, and determines self-consistently the energy balance due to ionization, photo-heating and radiative cooling. We take into account changes in stellar properties and mass-loss over the star's evolution. Our multi-dimensional simulations clearly reveal the presence of strong ionization front instabilities. Using various X-ray emission models, and abundances consistent with those derived for W-R nebulae, we compute the X-ray flux and spectra from our wind bubble models. We show the evolution of the X-ray spectral features with time over the evolution of the star, taking the absorption of the X-rays by the ionized bubble into account. Our simulated X-ray spectra compare reasonably well with observed spectra of Wolf-Rayet bubbles. They suggest that X-ray nebulae around massive stars may not be easily detectable, consistent with observations.

Diffuse X-ray emission within Wolf-Rayer nebulae

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We present high-quality X-ray observations of the diffuse X-ray emission from Wolf-Rayet (WR) nebulae. There are only 5 WR nebulae observed with the current generation of X-ray satellites, and only three of them have been reported to harbor diffuse X-ray emission, that is, S 308, NGC 2359, and NGC 6888 around WR 6, WR 7, and WR 136. Here, we discuss the results from our recently acquired *XMM-Newton* observations of NGC 6888 and NGC 3199 and put them in context with previous results.

The Importance of Wolf-Rayet Ionization and Feedback on Super Star Cluster Evolution

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The feedback from massive stars is extremely important to super star cluster (SSC) evolution and the timescales on which it occurs. SSCs form embedded in thick material, and eventually, the cluster is cleared out and revealed at optical wavelengths. However, this transition is not well understood, particularly which physical processes are essential and how they couple to the surrounding material. We are investigating this critical SSC evolutionary transition with a multi-wavelength observational campaign. Although previously thought to appear after the cluster has fully removed embedding material, SSCs host large populations of Wolf-Rayet stars that provide ionization and mechanical feedback that we hypothesize is the tipping point in the combined feedback processes that drive a SSC to emerge. Utilizing optical spectra obtained with the 4m Telescope at Kitt Peak National Observatory and the 6.5m MMT and archival data from *Hubble*, *Spitzer*, and *Herschel Space Telescopes*, we have compiled a sample of embedded SSCs that are likely undergoing this short-lived evolutionary phase and in which we confirm the presence of Wolf-Rayet stars. We determine the massive star populations, study the physical environments such as metallicity and age, and compare the sample to predictions as well as observations of SSCs in other evolutionary phases. The ionizing radiation is clearly extreme throughout the sample – observed optical ionized line ratios of Hα, Hβ, [NII], and [OIII] show that these sources border the theoretical and empirical limits produced by star formation alone.

The Wolf-Rayet Star Population and ISM Interaction in Nearby Starbursts

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The interaction between massive star formation and gas is a key ingredient in galaxy evolution. Given the level of observational detail currently achievable in nearby starbursts, they constitute ideal laboratories to study interaction process that contribute to global evolution in all types of galaxies. Wolf Rayet stars, as an observational marker of high mass star formation, play a pivotal role and their winds can strongly influence the surrounding gas. VLT imaging spectroscopy of two nearby (D<4 Mpc) starbursts, both of which show multiple regions with WR stars, are presented. The relation between the WR content and the physical and chemical properties of the surrounding ionized gas will be explored.

11 Posters

P Cygni and its Observations at the Abastumani Observatory

S. Beradze[1], N. Kochiashvili[1], R. Natsvlishvili[1], I. Kochiashvili[1], E. Janiashvili[1], T. Urushadze[1], M. Vardosanidze[1]

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We found original observations by E.Kharadze and N.Magalashvili of *P Cygni* in the archives of the Abastumani observatory. These observations were carried out during 1951-1983 period. Initially they used 29 *Cygni* as comparison star and all observations of *P Cygni* were processed using this star. On the basis of their calculations, authors decided that *P Cygni* may be a $W\ UMa$ type binary with orbital period of 0.500565, but this hypothesis was not confirmed. The observations of only 1951-1955 yy have been published in the Bulletin of the Abastumani Astrophysical Observatory. There is a whole observational data not only of *P Cygni* and 29 *Cygni* but in great majority of cases also those of 36 *Cygni* in the archives. So we recalculated all data (where it was possible) using 36 *Cygni* as comparison star. We are presenting plots of UBV light curves of the variable and also observations made by V.Nikonov in Abastumani during 1935-1937.

Stellar parameters from photometric data for fainter and more distant WR stars

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Spectroscopic data are essential to study the physical properties and stellar winds of massive stars in detail. With decreasing signal to noise ratio the uncertainties of the derived parameters increases and spectroscopic observations are limit to objects in the Milky Way or to nearby galaxies in our local group. The situation will change when the new class of extremely large telescopes are built. However already today, a probable solution could be to derive stellar parameters from the spectral energy distribution based on photometric data. In addition the large data sets of current all sky survey in the optical and near-infrared can be harvest to study a larger number of massive stars over a wider metallicity range. By applying the filter system to theoretical spectra compute with state of the art stellar atmosphere codes and in combination with the latest stellar evolutionary models there is great potential to estimate effective temperatures, luminosities, mass-loss rates, type of beta-velocity law, helium abundances and reddening parameters for WR stars only using photometric data.

The Distribution of WR Stars in M101

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The short lives of massive stars mean they don't have time to move far from their natal environment. The location of massive stars has been used to probe properties of stellar evolution, such as metallicity, as well as to investigate the massive star–supernova connection. Here we present an enviromental study of Wolf-Rayet stars in M101 including their distribution as a function of radius and fractional flux. Comparisons are made to predictions of stellar evolutionary models as well as to observations of core-collapse supernovae.

Formation of the infalling Galactic Centre cloud G2 by collision of stellar winds

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A gas clump has been recently discovered on its way to be tidally disrupted by the Galactic centre massive black hole, Sgr A*. The region around the black hole is populated by a large number of Wolf-Rayet stars, which produce strong outflows. Here, we show that gas clumps such as the one observed could have originated from the collision of stellar winds via Non-linear Thin-Shell Instability. Our instability analysis is based on a simple semi-analytical model and 1D hydrodynamical simulations of colliding stellar winds, in particular the time-scales for clump growth, their sizes and masses. Also, at the moment we are studying this problem using RAMSES (AMR hydrodynamical code) in order to perform more realistic analysis of the system. Our results show that the collision of slow stellar winds (~ 500 km s^{-1}) from stars at short separations ($\sim 10^{-3}$pc) is a process that indeed originates clumps on the required time-scales. These clumps have masses about 0.1 Earth masses, consistent with the observed value. However, these events would be rare and not as common as seen in numerical SPH simulations.

Analysis of the variable Wolf-Rayet star WR6 with CMFGEN.

Alex C. Gormaz-Matamala[1,2] et al.

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HD50896 (WR6) is a variable Wolf-Rayet star with a period of $P = 3.766$ days and it has been one of the most studied stars within its type. Since this one was one of the first variable WR with a stellar wind structure (CIR) confirmed, we think its study opens windows for a better understanding about the stellar winds of WR stars. Using IUE ultraviolet data and ESPaDOnS optical spectra of WR6, we determine new values for the parameters of its stellar wind: temperature, mass loss rate, terminal velocity, beta factor and abundances, contrasting them with the values given by other authors. Also, we search variations on the stellar wind parameters during the different phases of rotation where the star was observed. We use the radiative transfer code CMFGEN for creating the synthetic model spectra, using them for comparing with our observations and modifying after the studied parameters. Our work gives new stellar wind parameters for WR6, being $T_* = 73[kK]$, $\dot{M} = 2.7 \times 10^{-5}$ and $v_\infty = 1700[km/s]$ the most important ones. We also can give a value for the turbulent velocity of $150[km/s]$, which is a little smaller than the common used ($\sim 10\%$ of the terminal velocity). Also, we include variations in the stellar wind temperature, mass loss rate and f-factor found at the different phases. We discuss the link between the different values for parameters found in the wind with the already known atmospheric structure of WR6: which role may play its Co-Rotating Interaction Region in these variations.

Inversion of X-ray Flux Profiles for Hot Bubbles to Infer Radial Emissivities

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Massive stars drive winds into interstellar environments that lead to shocks and hot gas bubbles. A number of papers have presented simulations for the evolution of such bubbles and their physical properties as functions of radius in 1D spherical models. This contribution highlights the idea that under such conditions, assuming the emission is (a) optically thin and (b) unabsorbed at the source, the relationshp between the X-ray flux profile and the radius-dependent X-ray emissivity takes the form of Abel's equation. This equation has an analytic solution for the inverseion, which yields the run of emissivity with radius. Indeed, the inversion does not require monotonicity of the emissivity, and so the method offers the promise of rigorously confronting simulations with observations (for suitable signal-to-noise data). However, the inversion is "ill-posed" in this case, and regularization will be needed in applications to imaging data.

New Galactic Wolf-Rayet Stars

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Over the course of 6 months in 2013, we observed nearly 400 Wolf-Rayet candidates in the Galactic plane. Spectra were taken on the SMARTS 1.3m telescope at CTIO, using Université de Montréal's SIMON NIR spectrograph. Results from this dataset will be presented, including the identification of an estimated 100 new Galactic WR stars.

New Photometric Observations of P Cygni

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We are presenting results of new photometric observations of P Cygni made during the observing run of 2014. These observations were held using 48 cm Cassegrain telescope of the Abastumani Astrophysical Observatory, Georgia. Some interesting behaviors of B,V,R,I light curves are given. We have new results about the periodicity of variations of the star, which were made on the base of analysis the total photometric data of the Abastumani observatory (U,B,V filters) from 1937 up to 1983 and the ones of 2014.

Modeling of spectral variability of Romano's star

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We present results of investigation of spectral variability of one of the most interesting massive stars, V532, or Romano's star, located in the M33 galaxy. Brightness of the star changes together with its spectral class, which varies from WN11 to WN8. Using CMF-GEN code we estimated parameters of stellar atmosphere and found that during last ten years bolometric luminosity of the star changes synchronously with stellar magnitude. Our calculations argue in favor of the hypothesis of a post-LBV status of V532.

Wolf-Rayet in moderately massive young clusters

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Wolf-Rayet stars are expected mainly into massive stellar clusters. According to Weidner et al. (2013), an 80 $M_\odot$ star should be found in 10^4 $M_\odot$ clusters. In this poster I will present two young clusters discovered by two different groups (the Star Clusters group at Universidad de Valparaiso and the Masgomas group from IAC, Spain) with a moderate total mass (i.e. $\sim 10^3$ $M_\odot$). Each of these young clusters have a spectroscopically identified main sequence population, together with a confirmed Wolf-Rayet star (one WN8-9 and one WN6). The presence of very massive stars in moderately massive clusters challenges the "most massive star-cluster total mass" relation, and extreme star loss is needed to explain the mass difference.

Numerical model of the NGC6888: thermal X-ray emission

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Runaway stars with velocities supersonic ≥ 20 Km s^{-1} relative to the ISM to form a bow shock in the direction of its motion. The bow shocks, arc-like shape, can be detected in the optical, infrared, radio and X-ray wavebands. A prototype of an runaway stars is Wolf-Rayet star HD192163 associated with nebula ngc6888, this nebula show limb-brightened surface brightness profiles as opposed to the center-filled appearance expected in analitic models. The numerical simulation (we have carried out the 3D numerical simulations with the adaptive grid code Yguazú-a) shows that this is due to motion of the star and the interaction of winds its evolutionary stages —as red giant and wolf-rayet—.

The Launching and Structure of Wolf-Rayet Winds

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Observations indicate that Wolf-Rayet stars have extended optically-thick winds. An understanding of the wind's structure is crucial to measuring basic stellar characteristics that would otherwise be obscured (e.g. hydrostatic radius, rotation, etc.) and constraining stellar evolutionary models. In this work, we present a suite of optically-thick, steady, transonic

wind solutions that continuously extend from the stellar interior. We find these solutions are extended by several hydrostatic stellar radii, much like the solutions for envelope inflation, but only for a strict range of mass loss rates. In addition, this work is of particular interest for envelope inflation, radiative instabilities (eg. clumping), and the initial acceleration of Wolf-Rayet winds.

The Wolf-Rayet stars WR 102ka and WR 102c and their isolation

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We will discuss two Wolf-Rayet stars in the Galactic Center region using observations in the infrared obtained with VLT SINFONI. Our analysis confirms that one of our targets, the WNL-type star WR 102ka, is one of the most luninous stars of the Milky Way. It was found to be relatively isolated. In a projected distance of about 1 pc around it no other massive stars (i.e. spectral type O or B) were found, challenging the models of clustered massive-star formation. Another target of our observations, the WNE-type WR 102c, is located on the far outskirts of the Quintuplet cluster. We find that this star is surrounded by its own, very small cluster. Our results show this small cluster has a different age than Quintuplet. We analysed the spectrum of WR 102c by means of non-LTE models (PoWR) and derived its stellar and wind parameters. Its present-day mass is about $M = 20\,M_\odot$ and the initial mass was about 40 solar masses. This demonstrates the importance of Wolf-Rayet stars for providing input of mass and energy to their environment, like the Central Molecular Zone in this case.

The Swift monitoring of the colliding wind binary WR 21a

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The X-ray observations of the colliding wind binary WR 21a is reported. WR 21a is one of the X-ray brightest colliding wind binaries (e =0.64, $P_{\rm orb}$ =31.673 d). These masses are estimated to be $M_{\rm WR} > 87$ solar masses (one of the most massive stars) and $M_{\rm O} > 53$ solar masses. The first monitoring performed by Swift/XRT in order to reveal the phase-locked variation. Our observations cover 21 different epochs from 2013 October 1 to 2014 June 25 for a total exposure of about 94 ks. The X-ray spectra were well-fitted with single-absorbed component at kT ~2–4 keV, which are compatible with the thermal shocked plasma. The absorption-corrected X-ray luminosity in the 0.5–10 keV band varies from 2e33 to 1e34 ergs s^{-1}. It is found for the first time that the luminosity varies roughly in inverse proportion to the separation of the two stars before the X-ray maximum but later drops rapidly toward periastron. In this paper, we will discuss the interpretations of this X-ray variations.

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