The Wolf-Rayet phenomenon in the Universe

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INVITED SPEAKERS

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CONTRIBUTING TALKS
(ABSTRACTS)

**Monday 19th

WR stars - Structure and winds (22 contributions)

1) Evolution of massive stars adopting new self-consistent wind models

A. Gormaz-Matamala

Mass loss due to radiatively line-driven winds is crucial to understand the evolution of massive stars. Recent studies calculating self-consistent solutions for the winds of massive stars have predicted lower values for mass-loss rate (i.e., weaker winds) than the values commonly implemented in evolution models.

Here, we summarize the most important results for the evolution of stars with $M_\text{zams}~\ge~25\,M_\odot$ from Gormaz-Matamala et al. (2022b,2023a), together with analyze the respective implications. The decrease in the value for mass-loss rates strongly affects the tracks of the most massive models. Weaker winds allow the star to retain more mass, but also more angular momentum. As a consequence, weaker wind models rotate faster and show a less efficient mixing in their inner stellar structure at a given age. Particularly this last aspect closely agrees with diagnostics on rotational velocities, found by recent surveys of O-type stars in the Milky Way.

Hence we discuss the implications for the features of the WR stage, given the previous evolution during the main sequence stage. Additionally, we predict higher masses for the remnants of massive stars coming from the population synthesis code \textsc{StarTrack}, adopting both our new weaker winds at the main sequence (optically thin) and the updated hydrodynamically consistent (optically winds) for WR stars from Sander \& Vink (2020). We expect in the near future to fully combine the recipes for the mass loss rates at both wind regimes, in order to appropriately reproduce the total evolution of massive stars at different sets of mass, rotation and metallicities.

2) The fundamentals of the WR phenomenon

J. Vink

Many astronomers still associate WR stars with evolved massive stars. While in many cases this turns out to be true, this is actually more by coincidence than by design. In order to properly understand the emission line WR phenomenon, we need to consider radiation-driven wind physics. Over the last decade we have argued on the basis of Monte Carlo models, empirical, and analytical considerations that it is the proximity to the Eddington limit that is the key parameter. I discuss the physics of the transition mass-loss point where optically thin winds turn into optically winds thick winds with vigorous multi-line scattering. This regime is shown to coincide with the range where the He II lines turn into emission. I finally discuss the transition mass-loss point for various hydrogen (H) rich and H-poor regimes and metallicities including binary stripped stars, before ending with a cosmological outlook relevant for JWST.

3) Mass loss implementation of Very massive stars

G. N. Sabhahit

Very massive stars (VMS) up to 200-300 Msun have been found to exist in the Local Universe. The spectral appearance of these VMSs closely resemble those of emission-line dominated Wolf-Rayet (WR) stars of the nitrogen sequence (WN), but with hydrogen (H) making them likely still core-H burning objects. The strong emission lines of these WNh stars are suggestive of strong stellar winds capable of substantially affecting the final fates of these stars. We use the Potsdam Wolf-Rayet (PoWR) stellar atmosphere code to run hydro-dynamical simulations of hydrogen-rich VMS winds and study their mass-loss properties in close proximity to the Eddington limit. Informed by these hydro-models, we implement a mass loss recipe in the 1D stellar evolution code MESA, specifically tailored to study the evolution of VMSs. Above an initial mass of 200 Msun, VMSs undergo chemically homogeneous evolution throughout their MS, with mass loss being the single-most important process deciding their end fates. Our VMS models drop in luminosity and evolve vertically downwards in the Hertzsprung-Russel (HR) diagram at nearly constant temperatures. This distinct behavior of a drop in luminosity is shown to self-regulate the temperatures, keeping it nearly constant during the evolution and might naturally explain the small temperature range of observed WNh stars in young clusters of our Galaxy and the Large Magellanic Cloud.

4) Evolution of classical Wolf-Rayet stars: winds, nucleosynthesis, and consequences for the black hole mass spectrum

E. Higgins

The Wolf-Rayet (WR) stage strongly influences the final progenitor mass of black holes (BHs) due to their strong outflows which are heavily dependent on metallicity (Z), with implications for the upper mass limit of black holes and (pulsational) pair instability supernovae (PPISNe). We provide a direct comparison of the new hydrodynamically-consistent wind prescription from Sander & Vink (2020) for classical WRs with two frequently used wind recipes in stellar evolution and population synthesis modelling, at five metallicities (from solar down to just 2% solar). Results show that if the upper BH mass limit is set by WR mass loss then only one of our tested wind prescriptions is capable of producing a convergence on the upper black hole mass (~30Msun). However, we also find that if the limit is not set by winds then the initial mass and the PPI are responsible for the range of black hole masses observed at various Z. We show that the Z cut off for producing PPISNe changes with each wind recipe, having major consequences for observations of both heavy black holes and PPISNe across galaxies of varying Z. We also explore the chemical tracers of WR subtypes with a large nuclear network comprising 92 isotopes. We find that Neon and Magnesium isotopes, alongside CNO abundances, may provide key insights into the evolutionary paths of WN, WC, and WO stars towards their relevant fates.

5) Impact of mass loss on the formation, structure and evolution of Wolf-Rayet stars

J. Josiek

Stellar winds are one of the most important drivers of massive star evolution, and they are at the origin of the Wolf-Rayet (WR) phenomenon in the universe. Despite its significance, mass loss remains a major source of uncertainty in stellar models, and understanding its role in stellar evolution and its effects on observable phenomena is therefore crucial. In this study, we focus on mass loss during the main sequence of massive stars and its impact on the evolution and structure of stars in the WR phase. Using the Geneva stellar evolution code (GENEC), we computed grids of single, non-rotating stellar models with initial masses between 20 and 120 solar masses, at solar and LMC metallicity, using two different prescriptions for main-sequence mass loss and two different prescriptions for the red supergiant (RSG) phase. Our numerical predictions provide detailed insights into the structure and evolution of massive stars, and we compare the results from the different prescriptions to infer the role of mass loss. We find that main sequence winds can significantly shape the structure of evolved stars, including WR stars, despite being much weaker than winds experienced in later evolutionary phases. Moreover, the mass limits of WR-type stars can be shifted significantly depending on the chosen mass loss rates, both during the main sequence and the RSG phase. We discuss the implications of these results, as well as their limitations, within the broader context of stellar evolution modeling and observation.

6) Origin of structure formation in the envelopes and winds of Wolf-Rayet stars

C. Van der Sijpt

The spectra of classical Wolf-Rayet (WR) stars show broad and variable emission lines, suggesting a structured and turbulent wind outflow. Recent 2D and 3D radiation-hydrodynamical (RHD) simulations of WR stars (Moens et. al., 2022), covering the deep sub-surface layers of the star up to the outer parts of the wind, indeed show such turbulent outflows. However, the origin of these large structures remains unclear. In this talk, we investigate the physical origin of the structures found in the envelopes and winds of WR stars. A short wavelength WKB linear analysis (Blaes & Socrates, 2003) shows that convective and strange mode instabilities can be driven by the so-called iron opacity bump in the sub-surface layers of the star. We discuss to what extent these instabilities are able to produce the observed structures or whether the origin of structure formation may be better explained by a ‘failed’ radiation-driven wind outflow. In such a ‘failed’ wind scenario, accelerating gas crashes into slower, decelerating gas, causing the structure to break up and form clumps.

7) Feasibility of Wolf-Rayet formation in single stars using line-driven winds

O. Verhamme

To form single Wolf-Rayet stars, the envelope must be ejected efficiently by stellar winds. In evolutionary models this mass loss is modelled with the use of a mass loss prescription based on input stellar parameters (mass, luminosity, effective temperature, etc.). The most used prescription for massive stars shows a bi-stability jump at around 25000K. Stars cooler than this temperature have mass loss rates up to an order of magnitude higher than those hotter, for the same luminosity. However, a new prescription for O and B type stars, based on fully dynamically consistent steady-state 1D models (Björklund et al. 2022), does not show such a bi-stability jump. Using the Björklund prescription, it is no longer possible to form a single evolved Wolf-Rayet star as the mass loss rate is too low to expel the envelope.

To probe the potential existence of the bi-stability jump empirically, we can use spectroscopy. Previous observationally-driven studies only considered optical spectral lines, requiring ad-hoc assumed values of wind clumping. With the X-Shooter ULLYSES collaboration, we now have access to high resolution UV and optical spectra for a range of B-star supergiants across the bi-stability jump.

Combining optical and UV spectra allows us to, for the first time in this regime, determine the clumping and mass loss rate for each star simultaneously, thus giving a better handle on the bi-stability jump problem.

We obtain stellar and wind parameters through spectral fitting, using the 1D spectral synthesis code FASTWIND. We automatise the fitting procedure using genetic algorithm Kiwi-GA. This method optimizes the search for the model with the lowest possible reduced $\chi2$ value. In my talk, I will show the results of this method on a sample of 22 Large Magellanic Cloud B-supergiants focusing the discussion on whether there is any empirical evidence for a bi-stability jump in mass loss rate or not and on how these new empirical mass loss rates relate to the needed mass loss rates to form single Wolf-Rayet stars.

8) Constraints on the mass of Wolf-Rayet stars by hydrodynamically consistent atmosphere modelling

R. Lefever

The importance of a correct understanding of Wolf-Rayet (WR) stars can hardly be overstated. They serve as key contributors to local interstellar medium enrichment and powerful ionizing sources, strongly influencing their host galaxies at comparatively short timescales. Also directly preceding supernovae and the resulting neutron stars and stellar-mass black holes, understanding WR stars is paramount. Yet, the stellar mass of these objects, one of its fundamental parameters, is still ill-understood. While WR-star masses are traditionally inferred from luminosities, this approach typically gives large uncertainties. Using orbital constraints from binary systems is currently the only reliable way to get an accurate estimate of WR-star masses.

In this talk, we will present an alternative method. Based on spectral analysis using hydrodynamically consistent modelling of the usually optically thick WR-star winds, we can ultimately constrain the mass of a WR star without the need for a clearly detectable companion. For apparently single WR stars, we will show spectral fitting to observations, providing the first inherent mass estimates that do not require any assumptions on stellar structure. Additionally, we apply our method to WR-star binaries such as WR 140. By comparing the derived mass estimates to the orbital masses, we can get a benchmark for the stellar mass and identify remaining uncertainties and caveats for this new spectroscopic mass estimate. Combining our insights with stellar structure considerations, the masses derived from dynamically-consistent spectral modelling finally give us new, interesting insights on the evolutionary stage of WR stars, in particular for isolated WRs.

9) Formation of WNh-type Wolf-Rayet stars in massive binary systems

K. Sen

Most Wolf-Rayet stars are hydrogen-poor and burn helium in their cores. However, the evolutionary status of the hydrogen-rich so-called WNh stars is yet unclear. While the most luminous WNh stars may correspond to the most massive single main sequence stars, we show that at least some of them may be binary products. We investigate detailed evolutionary models of very massive binaries (35...90 Msun) which undergo mass transfer during hydrogen burning. Envelope stripping due to Roche lobe overflow increases the luminosity-to-mass ratio of the mass donors. This brings some of them so close to their Eddington limit that they may develop Wolf-Rayet-type winds, at luminosities where single stars would merely appear as O stars. We estimate the wind optical depth parameter of such models and find them to agree with the corresponding values of observed WNh stars, derived in the same way. Due to their large convective core mass, we find that many donors remain more massive and more luminous than their companions, such that their binary status may be hard to detect observationally. We argue that massive WNh binaries may be the key to understanding the evolution of very massive binaries towards observable gravitational wave sources.

10) The origin for WNL stars: impact on ionizing photon budgets

A. Roy

Even though fewer in number compared to their low-mass cousins, massive stars are primary sources of mechanical luminosity, chemical yields, and ionizing photons. Therefore, understanding the massive stars' structure and evolution is crucial to obtain a comprehensive picture of the chemical and ionization evolution of galaxies over cosmic time. The evolutionary paths taken by very massive stars, M > 60MSun, remain substantially uncertain: they begin their lives as main sequence O stars, but, depending on their masses, rotation rates, and metallicities, can then pass through a wide range of evolutionary states, yielding an equally broad set of possible surface compositions and spectral classifications. The surface enrichment of He and N is quite common in rotating WNL stars, but several observations show WNL-like surface elemental abundances in slow rotators. This puzzled astronomers for almost two decades. Previous findings hypothesized that an exotic scenario of stellar spin-down needs to be invoked in order to explain the origin of these slow rotators that have unusually high surface enrichments. Contrary to this hypothesis, I will present a different origin mechanism for WNL stars that these metal-rich slow rotators reveal the products of nucleosynthesis on their surfaces because even modest amounts of mass loss expose their "fossil"-convective cores: regions that are no longer convective, but which were part of the convective core at an early stage in the star's evolution. This mechanism provides a natural explanation for the origin of metal-rich ([Fe/H] ≥ -1.0) slowly rotating WNL stars without any need for exotic spin-downs. I will also discuss the stellar atmosphere modeling for a representative star from the model grid, properly accounting for He and N enhancements, and show that the resulting spectrum provides an excellent match to observed WNL stars that strongly suggests the above mentioned physical mechanisms being the ultimate cause for the origin of WNL stars. I will further discuss the impact of these stars on determining the ionizing photon budgets. Moreover, the origin of nebular HeII in star-forming galaxies is an unsolved problem. Can HeII photon budgets from these stars be an important avenue to explain this as well?

<u>**Tuesday 20th</u>

11) The EWOCS view of the unique population of Wolf-Rayet stars in Westerlund 1 (Remote**)**

K. Anastasopoulou

We present the first results of the EWOCS (Extended Westerlund One Chandra Survey) program on the Wolf-Rayet (WR) population in Westerlund 1. This massive star cluster is the best laboratory to study the WR phase, since it is the closest massive star cluster to the Sun, and it contains an impressive large sample of coeval massive stars including one of the largest population (24) of WR stars. With this very deep Chandra survey (1Ms) we are able to unravel the X-ray properties of the entire WR population, extract spectral information for almost all of them, and retrieve insights on their X-ray production mechanism. We discuss these results in the context of different spectral subtypes of WR stars, as well as binarity, since the majority of them show clear signs of very hot plasma which could be attributed to a colliding-wind region of a binary system.

12) The first magnetic Wolf-Rayet star (Remote**)**

by Tomer Shenar

The mysterious "quasi Wolf-Rayet (qWR)" binary HD 45166 has been the subject of dozens of studies for over a century. It was proposed to consist of a 4Msun helium star with a Wolf-Rayet spectrum orbiting a B7 V star on a 1.6d period, making it the only intermediate-mass helium star known in the Galaxy. The properties of this binary are fully at odds with our understanding of wind-launching physics and binary evolution. I will present new spectropolarimetric data obtained with the ESPaDOnS instrument in February 2022. These data reveal unmistakably the presence of a powerful magnetic field (45kG) in the Wolf-Rayet component, making it the first magnetic Wolf-Rayet star and the most heavily magnetized super-Chandrasekhar mass object ever found. Previous derivations of the mass-loss rate of this object are thus obsolete. Long-term spectroscopic monitoring further implies that the true orbital period is of the order of 20 years, and not 1.6d, yielding a mass of ~1.5-2.5Msun for the Wolf-Rayet component. I will highlight the implications of this object on our understanding of binary evolution and mergers, and conclude with a few ideas regarding the formation of such a unique object and other related objects in our Galaxy.

13) Investigation of a hidden WC9-type WR star: [KSF2015] 1381-19L

S. Kar & R. Das

We report the first multi-wavelength study of the faint and least studied Wolf Rayet (WR) star: [KSF2015] 1381-19L of WC9-type which is found to be located in the inner dust obscured region of the Milky Way galaxy at a distance of 4kpc. A detailed characterisation of the stellar atmosphere is performed using CMFGEN by fitting the spectral emission lines present in the optical (5000-9000 Angstroms) and near-IR (H & Ks bands) spectral data. From the best fitting spectroscopic model, stellar physical parameters such as effective temperature, mass, luminosity, wind velocity structure, mass loss rate etc. as well as chemical abundances of various elements such as Helium, Carbon, Oxygen, etc are estimated. Further, the object's photometric spectral energy distribution (SED) data is fitted with the model SED and corresponding photometric quantities such as absolute magnitude, extinction parameters ($E(B-V) = 2.7$) for $R(V)=3.1$, along the line of sight are derived. Based on our study, we also predict that this WR star may belong to a dust producing WC9-type star (WC9d).

14) Simultaneous spectroscopic and photometric observations of WR6 to constrain the origin of its elusive epoch-dependent variability

N. St-Louis

Radiatively driven winds, particularly those of Wolf-Rayet (WR) stars are well-known to be highly structured on a small scale, which has important consequences on their evolution and their ultimate fate. Some WR stars are also thought to harbor large-scale structures in their winds that cause epoch-dependent periodic variability in photometry, spectroscopy and polarimetry. The physical mechanism at the origin of these structures still needs to be identified as it is hidden by their optically thick winds. However, they are thought to take the shape of Corotating Interaction regions (CIRs), spiral-like structures that form in the wind as outflows of different velocities and densities collide as the star rotates. WR6 is the brightest and most well-known WR star to show periodic but epoch-dependent changes. Some authors claim that these changes occur because this star is in fact a triple system consisting of a WR star and two lower-mass companions, rather than resulting from a structured wind.

In this talk, I will present the analysis of a series of spectroscopic observations of WR6 obtained by four amateur astronomers over a continuous 2-week period in the wavelength range of the well-isolated HeII5411 emission line. These have been obtained simultaneously with an optical light-curve from the Brite-Constellation nanosatellites over a contiguous period of 160 days. The nature of the spectroscopic variability leads to a particular configuration of the CIR (location, density contrast, opening angle), which must also lead to the observed light-curve. The same can be said about a possible binary origin. The combined diagnostic of the spectroscopic and light variability is a powerful constraint to help discriminate between these two models.

15) Linear spectropolarimetric variations across spectral lines of EZ Cma as a tracer of large-scale structure in its wind

L. Fabiani

Two types of structures can be found in the winds of Wolf-Rayet (WR) stars: clumps on a small scale and CIRs (Corotating Interaction Regions) that form large and coherent structures. EZ Cma (WR6) is a bright WR star known for displaying strong epoch- dependent variations with a period of 3.76 days. As these variations are stable on a timescale of a few weeks and then change in nature, the scenario that is favored by many is that it is a consequence of the presence of CIRs in its wind.

In this work, we use linear polarimetry to probe the wind of this star for additional evidence of the presence of these CIRs. I will present the analysis of 2 sets of 4 consecutive nights of high-resolution spectro-polarimetric observations of EZ Cma obtained with the ESPaDOnS (Echelle Spectro-Polarimetric Device for the Observations of Stars) spectropolarimeter on the Canada-France-Hawaii Telescope (CFHT) in January 2009 and February 2010.

For both datasets, we find strong linear polarization variations across several HeII lines as well as for lines of other ions such as HeI, CIV, NIV and NV. The general orientation of the excursions in the QU plane caused by these changes varies from night to night. For HeII lines in particular, the polarization variations trace loops in the QU plane that appear to be restricted to the blue side of the line. The variations on the red side seem to be mostly linear in the QU plane. The loops on the blue side of the line are traced either in the clockwise and anticlockwise direction from one night to another.

Variations across spectral lines indicate the presence of some sort of asymmetry in the wind, possibly a CIR. Our data indicate that the changes are due in part to dilution of continuum polarization by unpolarized line flux (i.e. the line effect) but not entirely because the amount of depolarization is clearly not proportional to the line intensity. Some polarization of line photons and/or occultation effects are necessary to explain these complex variations.

16) New empirical mass-loss rates and wind properties of massive stars at low metallicity

C. Hawcroft

Hot, massive stars are known to host unstable, radiation-driven outflowing winds, giving rise to dense clumps of material which severely affect the diagnostic techniques used to derive wind properties of massive stars. As progenitors of the envelope-stripped Wolf-Rayet stars, it is imperative that these effects are considered in order to determine the true mass-loss rates and therefore constrain Wolf-Rayet formation scenarios. Most of the current diagnostic models account for wind inhomogeneities by assuming a one-component medium consisting of optically thin clumps, and maintaining a smooth velocity-field. However, this neglects important light-leakage effects through porous channels in-between the clumps. We have recently incorporated these light-leakage effects into our stellar atmosphere modelling code FASTWIND, and here we will present quantitative mass-loss results from a combined Ultraviolet-Optical wind analysis of 40 O-stars across the Galaxy, LMC and SMC. Using a genetic-algorithm fitting-approach, we investigate the impact the wind physics has on derived stellar and wind parameters, and how this depends on metallicity and spectral type. These results also provide an excellent base to expand upon with upcoming large surveys, such as XShootU which will provide optical data to complement the (HST-)ULLYSES UV survey for a sample of 250 OB stars at low metallicity. By applying the method presented here to such a sample we will be able to establish trends between wind properties and fundamental stellar parameters on an unprecedented scale. As the ULLYSES UV spectra are already available, we will also present results for terminal wind speeds measured from saturated P-Cygni UV line profiles. These results, when combined with previous studies on Galactic samples, allow us to obtain new empirical estimates of the metallicity dependence of terminal wind speeds.

17) A study of wind clumps in WR40 from broadband photometric and linear photopolarimetric variations

R. Ignace

Stars of the WN8 subtype are among the most variable of Wolf-Rayet (WR) stars. We summarize an in-depth study of the optically brightest WN8 star WR 40 using a mixture of broadband photometric and (linear) polarimetric data. Four months of contiguous photometry of WR 40 was obtained with the BRIght Target Explorer (BRITE) nanosatellite mission in the red band. We successfully modeled the visible light variations in terms of a large number of independent, stochastic wind clumps using on temporal functions that are combined in the context of a time-averaged spherically-symmetric wind. The model was expanded to interpret ground-based broad-band optical photometric and (linear) polarimetric light curves. While BRITE provided a unique high-cadence photometric dataset, the ground-based study provided a unique near-simultaneous dataset of photometric and polarimetric variations. Our modeling approach was able to account for the observed absence of correlation between photometric and polarimetric variations, the ratio of standard deviations for photometric and polarimetric variability, and the ratio of the average intrinsic polarization relative to its standard deviation. In particular, it became clear that clumps must emit abundant unpolarised radiation in addition to scattering light from elsewhere in the wind.

18) First effects from 3D models on observations of Wolf-Rayet stars

D. Debnath & L. Poniatowski

For a long time, observations of Wolf-Rayet (WR) stars have suggested highly structured and turbulent winds that obscure the hydrostatic layers of these stars. However, accounting for the effects of multidimensionality and time-dependence on spectrum-formation is a highly challenging problem. As such, spectral analyses of WR stars still rely on 1D codes using highly uncertain 1D parametrizations of 3D WR winds (e.g., an ad-hoc 'clumping factor'). Recent developments in 3D time-dependent radiation hydrodynamical (RHD) modeling of WR outflows allow us to examine these parametrizations. Thus far, more often than not, we find that typical assumptions in 1D codes are quite different from what 3D simulations suggest. This inconsistency suggests a need to adequately account for multidimensional effects for analyzing WR stars.

In this work, we compute synthetic observables directly from 3D models for the first time. Our study focuses on two observational features; the shapes and variability of spectral lines and stochastic photometric variability. We find strong and broad emission spectral lines with substructures whose variation overall follows a generally observed trend. Furthermore, we qualitatively reproduce observed light curves with stochastic variations with amplitudes matching those in actual observations.

We discuss future potential improvements in the modeling of WR stars and their observed radiation and also outline possible weaknesses and routes toward improving our new as well as the conventional modeling approach.

19) Modeling the Effects of Corotating Interaction Regions in the Winds of Wolf-Rayet Stars using Multi-D Radiative Hydrodynamics Simulation

G. Lenoir-Craig

Understanding the winds of Wolf-Rayet (WR) stars is important for the general evolution of massive stars but also because of their strong impact on the chemical and dynamical evolution of galaxies. Corotating Interaction Regions (CIRs) are thought to be ubiquitous in radiatively-driven O star winds but should also be present in WR stars although they could be more difficult to observe in view of their optically-thick winds. In this talk, I will present 2-D and 3-D radiative hydrodynamical simulations of the optically thick radiatively driven winds of a rotating star that includes a spot on the stellar surface that leads to the generation of a CIR. I explore the parameter space of CIRs in WR winds and derive observables such as photometric and polarimetric light-curves. Our simulations are conducted using the MPI-AMRVAC hydro code with a hybrid opacity recipe. We aim to compare our simulation results with actual photometric and polarimetric observations of WR stars, to detect and characterize the potential CIRs present in their winds.

20) Charting new pathways to form WR stars at low metallicities

D. Pauli

So far the evolution of the secondary components in post-interaction massive binaries is poorly studied. It is largely believed that the secondaries are similar to the primaries at the moment of their evolution when initiating mass-transfer on the compact object. I calculated a small grid of binary evolutionary models to model in detail the evolution of both, the primary and the secondary. In this talk I will show that primaries as well as secondaries which did not accrete a significant amount of material do form WR stars with temperatures of 100kK. On the other hand, the secondaries which did accrete a significant amount of material produce cooler WR stars with temperatures of only 50kK. I will highlight how observations could help to distinguish among different evolutionary paths using as an example a WR star in the SMC. I will briefly discuss how these new results influence our understanding of binary evolution at low metallicity, stellar feedback, and, hence, galaxy formation and evolution.

21) Monte Carlo Radiative Transfer modeling of light and polarization curves from Corotating Interaction Regions in massive star winds

R. Sincennes

The strong winds of Wolf-Rayet stars are known to be structured on small and large scales with a significant impact on mass-loss rate estimates and angular momentum transfer. In this talk, I will present results from my work on using a Monte Carlo Radiative Transfer (MCRT) code (from J. Bjorkman) to produce a model of the resulting light and polarization curves arising from the presence in the wind of Corotating Interaction Regions (CIR). These large-scale structures are thought to arise through the interaction of winds with different speeds and densities due to a perturbation on the stellar surface (e.g. a spot). To do so, we include in an otherwise spherical wind a single spiral-shaped density enhancement together with an associated spot on the stellar surface to mimic the presence of a CIR. We then calculate the resulting light and polarization from electron scattering as a function of the rotational phase. We explored the parameter space of this simplified model, and I will describe the effects on the light and polarization curves of varying the various parameters of the model such as the density contrast in the CIR compared to the general wind, the opening angle of the CIR and its location on the star, the general optical depth of the wind (i.e., mass-loss rate), the spot intensity contrast and the viewing configuration.

**Wednesday 21st

WR in binaries (4 contributing talks)

1) Stripped stars at low metallicity (**Remote**)

V. Ramachandran

Standard binary evolutionary models predict a significant population of hot and compact core helium-burning stars that lost their hydrogen-rich envelope after mass transfer via Roche-lobe overflow. However, there is a scarcity of observations of such stripped stars in the intermediate mass regime (~1.5 − 8 Msol) between low-mass subdwarfs and classical WR stars. This intermediate-mass regime gets even wider at lower metallicity (~17 Msol at SMC metallicity). Interestingly, a significant fraction of these stars may only get partially stripped, especially at low metallicity, retaining a significant amount of hydrogen envelope on their surfaces. In this talk I present detection of partially stripped stars in a binary with a Be-type companion located in the SMC using detailed spectroscopic analysis. I will discuss their fundamental parameters, wind, abundances and ionizing fluxes. Based on our evolutionary models, they represent so-far missing stage in the formation pathway of Be X-ray binaries and double neutron star mergers.

2) WR 137: Moving towards a more complete understanding of its orbit and dust production (**Remote**)

N. Richardson

WR 137 (HD 192641) was one of the first three Wolf-Rayet stars discovered and is a most unusual binary. The primary WR star is a WC7pd star with a companion O9Ve star. The orbital period is roughly 13 years with dust production observed near periastron despite a rather low eccentricity. The long period and relative proximity (2 kpc) and brightness have allowed for some unique findings about this system in recent years which I will review in this talk. The companion star was found to possess a very stable decretion disk for its early spectral type, which could impact how the dust forms near periastron. After the recent periastron, the system was resolved with long-baseline infrared interferometry with the CHARA Array. Subsequent observations have confirmed the orbital motion of the two stars, and a preliminary visual orbit will be presented. Lastly, the system was observed in the 5-8 μm region with low-resolution spectroscopy and the SOFIA telescope in its last year of observation. With these spectra, our group has shown that there is an emission line associated with unidentified infrared (UIR) features, strengthening as the dust outburst was beginning over the course of the year.

3) New core-eclipsing multiple systems with WR stars

A.-N. Chené

We have discovered three new multiple systems with Wolf-Rayet (WR) stars that display a double eclipse. One is a triple system with a WN star and an inner core-eclipsing O+OB binary. The other two are binaries: one is a WC+O system, and the other consists of two He-core burning WN stars, which is unprecedented! These systems are relatively faint in the V band, and thus have never been monitored in spectroscopy using 2m to 4m telescopes. It was only through queue programs that take advantage of poor weather on larger telescopes that we were able to efficiently reveal their true nature. Want to know which WR stars these are? Make sure to attend this talk to find out!

The double eclipsing nature of truly core-eclipsing binaries offers a unique opportunity to directly measure the masses of their components by simple, least model-dependent Keplerian orbit. Reliable determinations of WR star masses are of high value for constraining and validating evolutionary models. During our talk, we will present our preliminary results using photometric and spectroscopic analysis of the systems, including a model of the wind-wind collision zone emission when present.

4) New progresses on the spectroscopic orbital solution of the colliding-wind binary WR25

E. Gosset

After improving the SB1 orbital solution for the Wolf-Rayet component of the WN6ha+O colliding-wind binary WR25, we present a detailed search for spectral traces of the companion and introduce the first SB2 orbital solution for this massive binary. A tentative disentangling of the two spectra will be presented and the classification of both objects will be reassessed. The compatibility of the newly determined orbit with other data such as those coming from the X-ray domain is discussed.

WR nebulae (6 contributing talks)

1) Wolf-Rayet nebulae (and supernova remnants) in Local Group galaxies as seen by SITELLE

L. Drissen

SITELLE is an imaging Fourier transform spectrometer installed at the Canada-France-Hawaii telescope (CFHT), able to reconstruct the spectrum of every light source within its 11 arcmin field of view in filter-selected bands of the visible (350-900 nm). Its spectral resolution can be adjusted up to R = 10 000 and the spatial resolution is seeing-limited and sampled at 0.32 arcsec/pixel. I will present the results of a survey targeting Wolf-Rayet nebulae and, accessorily, their neighboring supernova remnants in Local Group galaxies as part of the SIGNALS Large Program: spatially resolved line ratios and kinematics of WR nebulae provide information on their ionizing stars and mass loss history.

**Thursday 22st

2) Thor's Helmet, the Wolf-Rayet Windblown Bubble Nebula Seen by SITELLE
C. Dumontier

The NGC 2359 Wolf-Rayet nebula has been observed with SITELLE, an imaging Fourier transform spectrometer on the Canada-France-Hawaii Telescope (CFHT). These data provide crucial information on the kinematics, the morphology and the electron density and temperature of the entire nebula. These physical parameters help us better understand the striking difference between the two macrostructures that compose this nebula, namely the arc-shaped component and the spherical WR bubble. The former has a lower temperature (~10 kK), is in a lower ionization state ([N Ⅱ], [S Ⅱ], [O Ⅱ]) and has a low velocity dispersion, and the latter which is closer to the central WR star, is in a higher ionization state ([OⅢ], [NeⅢ]), has a higher temperature (≳ 11 kK) and a greater velocity dispersion. Additional spectra from Gemini's GMOS-S spectrograph in longslit mode allow us to measure the electron density in the WR bubble using the [Cl Ⅲ] doublet in a filament where no [S Ⅱ] lines were detected.

3) The Wolf-Rayet bubble NGC 6888 seen by SITELLE
M. Ruest

The Wolf-Rayet star WR 136 (WN6) is surrounded by NGC 6888, a wind-blown bubble resulting from the interaction of the current fast WR wind with material previously ejected during a red supergiant or LBV phase. We present hyperspectral data cubes of NGC 6888 obtained with the imaging Fourier transform spectrometer SITELLE (at the Canada-France-Hawaii Telescope) covering most of the nebula with a spectral resolution of 1500 - 3000, allowing an unprecedented spatially resolved determination of the electron temperature and density, as well as abundances and kinematics. A 3D rendering of the nebula from these data reveals a very inhomogeneous and asymmetric structure.

4) Tracing the origins of the Wolf-Rayet bubble NGC6888 with IR observations
G. Rubio

We present the analysis of IR observations to study the distribution of dust in the Wolf-Rayet nebula NGC 6888. The unprecedented view of the IR observations from WISE, Spitzer and Herschel helped us construct a clean spectral energy distribution, free of contamination from material along the line of sight, to model the properties of the dust in NGC 6888. We used the photionization code Cloudy to model the dust and gas in the presence of WR136 (the progenitor star) to produce the most accurate model of NGC 6888. The estimated gas and dust masses estimates help us trace the stellar origin of this iconic WR nebula.

5) M 1-67 and RCW 58: Dust properties around late WNh stars as fingerprint of the stellar evolution

P. Jiménez-Hernández

The presence of Hydrogen in its spectrum has allowed WNh Wolf-Rayet (WR) stars to be considered as an intermediate stage between an O-type star and the RSG/LBV stage. On the other hand, some late-type WNh stars are surrounded by clumpy or irregular ejecta nebulae, suggesting a violent mass-loss episode as their origin. The properties of the nebular material can be used to infer their loss-mass history of the late stages of their evolution. We used archive photometric observations from WISE, Spitzer and Herschel to construct the spectral energy distributions (SED) of M 1-67 and RCW 58, which surround WN8h stars. Modelling with Cloudy shows that in both nebulae the infrared SED and photoionized gas properties can be reproduced by a dusty shell consisting of two populations of grains and with a high dust-to-gas mass ratio. The large grain size in both nebulae, as large as 0.9 microns, and the nebular material distribution suggest a common eruptive dust-formation history for the two objects. The Common Envelope (CE) evolution can result in the ejection of the CE and a tighter binary. Our results indicate that WR 40 and WR 124 have gone through and RSG stage and later evolved within a CE. That is, we suggest that the WN8h stars are products of the evolution of a binary.

6) A comprehensive hydrodynamical study of SB DEM L50: understanding off-centre SNe and soft X-ray luminosity

R. Orozco

Hydrodynamical models of superbubbles (SB) carved in the ISM by the winds and supernovae (SNe) of OB stars in associations provide insights about the interplay between massive-star feedback and the ambient medium. Models that assume a constant density medium and central SN explosions fail to reproduce the soft X-ray luminosity observed in some SBs. Off-center SNe are known to enhance soft X-ray emission in SB. We generate SB models that include the different evolutionary stages of massive stars (MS, LBV, WR, and SN), with the main goal of producing a model that naturally forms off-center SNe and can reproduce the observed soft X-ray emission of SB DEM L50 in the LMC. This object has panchromatic observations that allowed us to perform a comprehensive comparison between DEM L50 observed properties and the properties predicted by our models. We explore different initial ambient conditions where the SB forms and confront our models against archival, radio, optical, and X-ray observations of LMC's SB, DEM L50. We find that a configuration where DEM L50 forms at the edge of a filament reproduces the observed soft X-ray luminosity, optical morphology, shell velocity, and swept-up mass of neutral gas. This configuration is supported by IR observations of the LMC. Finally, we show that an off-center SN can explain the observed soft X-ray luminosity of DEM L50, and the resulting luminosity is consistent with plasma in non-equilibrium ionization.

[WR]-type stars & planetary nebulae (3 contributing talks)

1) Spectral analyses of Wolf-Rayet-type central stars of planetary nebulae

H. Todt

Most Wolf-Rayet-type stars are descendants of massive OB stars. However, also low-mass stars, like our Sun, can turn into Wolf-Rayet-type stars at the end of their life, when they become central stars of planetary nebulae. We have performed quantitative spectral analyses of WR-type central stars together with their planetary nebulae to constrain and understand their formation and evolution. While most of the known WR-type central stars have a WC-type spectrum, some also have WN, WN/WC, or Of/WN spectra, often with abundance patterns that are different from those of the massive WR-type stars. We will present the results obtained so far and compare them with predictions from stellar evolution models for hydrogen-deficient central stars.

2) Planetary nebulae with [WO]-type central stars

J.A. Toalá

Planetary Nebulae (PNe) represent a scaled-down version of Wolf-Rayet (WR) nebulae. They are also formed by the wind-wind interaction scenario, but after the evolution of Solar-like stars. About 10% of PNe harbor H-deficient [WR]-type central stars which share very similar characteristics as those of their massive WO siblings. In this talk, I will review our results on deep characterisations of selected PNe with [WO]-type central stars. I will place into context what we can learn from [WO] stars in comparison with the less numerous massive WO.

3) Study of J040901 newly discovered [WR] star

O. Maryeva

Discovery of every new WR star is a rare event, especially if the discovery is based on spectral observations in optical range. Star J040901 was found a few years ago as WR star in LAMOST spectral survey by machine learning methods. We were interested that different researchers based on different methods classify this object in different ways – ranging from RR Lyr variable to nitrogen rich WR – and we began our study. We analyzed the spatial location of the star in the Galaxy and its location in color-magnitude diagram and concluded what J040901 is low luminosity object with WR phenomen, i.e. [WR] – central star of planetary nebulae. Using new and archival photometric data we detected irregular variability in both scales: intra-night (amplitude ~0.1 mag) and long-time (amplitude ~0.8 mag). Comparison of spectrum obtained in 2022 with one in 2014 also shows evidence of spectral variability. Numerical modeling gives luminosity of star L*=1000Lsun and effective temperature Teff=50,000K.

**Friday 23rd

WR stars in other galaxies (5 contributing talks)

1) The Missing Wolf-Rayets of the Andromeda Galaxy, M31 (REMOTE)

P. Massey

Knowledge of the evolved massive star content of nearby galaxies provides a powerful tool for diagnosing the successes and failures of modern evolution theory. In a recent study, we compared the relative number of red supergiants and WR stars as a function of metallicity in the SMC, LMC, M33, and M31. The results were in excellent agreement for the predictions of the BPASS and Geneva models, requiring either an intermediate binary fraction of about 50% or an intermediate initial rotation. (The effects of rotation and binarity are hard to distinguish.) The exception was the data for M31, whose RSG/WR ratio was surprisingly large for its supra-solar metallicity. The data would match the models only if the binary fraction was essentially zero in M31, or if the OB progenitors were born with essentially no rotation. Neither seemed a likely explanation. We therefore began a pilot project to re-examine the issue of completeness of our past WR survey of M31. We obtained improved imaging data with the 4.3-meter Lowell Discovery Telescope that allowed us to identify 30 new candidates in three carefully chosen fields. Followup spectroscopy has now been obtained with Binospec on the 6.5-meter MMT, confirming 19 of these as newly found WR stars. In this talk we will discuss the implications for our knowledge of the WR content of M31, and address if our similar survey of M33 could be similarly affected. (Spoiler: no, we don't think so.)

2) The role of Wolf-Rayet stars, X-ray sources and shocks in the ionization of He+ in HII regions of the Cartwheel galaxy

D. Mayya

Detection of HeII4686 nebular recombination line in the spectra of star-forming galaxies indicates the presence of sources of hard ultraviolet radiation in them. Wolf-Rayet stars, hard X-ray binaries and radiative shocks are thought to be the sources providing the required hard radiation. Discerning which of these sources is the primary source of hard radiation has been a challenge, given that a typical star-forming galaxy is expected to harbor all these sources. HeII4686-emitting HII regions are much simpler systems where the problem of ionization of He+ can be addressed. We use the MUSE dataset to explore this problem using the HII regions in the metal-poor collisional ring galaxy Cartwheel. The Cartwheel is known to harbor a rich population of Ultra-Luminous X-ray (ULX) sources, which offers an opportunity to evaluate the effectiveness of X-rays in ionizing He+. The HeII4686 nebular line is detected in 32 HII regions, ten of which coincide with the position of an ULX source. However, nebular lines sensitive to the nature of ionizing sources do not show characteristics of ionization by X-rays in none of these ten ULX sources. On the other hand, 27 of the 32 HeII4686-emitting HII regions harbor star clusters in their WR phase, suggesting WR stars as the most likely suppliers of hard photons. The Blue bump (BB), the characteristic feature of the WR stars, however, is not detected in any of the spectra. We demonstrate that this non-detection is due to the relatively low equivalent width (EW) of the BB in metal-poor SSPs, in spite of containing sufficient number of WR stars to reproduce the observed strength of the HeII4686 line at the Cartwheel metallicity of Z = 0.004. We find evidence for shock ionization in two of the five remaining HeII4686-emitting HII regions.

3) A search for stars with CII emission in the Large Magellanic Cloud

N. Morrell

Inspired by the serendipitous discovery by Margon et al. of a [WC11] star in the Large Magellanic Cloud (LMC) during an unrelated survey, which might be an indication of the existence of a significant but unrecognized population of these objects, we decided to carry on a search for other such stars in the whole LMC. The [WC11] spectral class represents the coolest stars in the low-mass Wolf-Rayet sequence, and a sub-sample of the planetary nebulae central stars. These stars are known to display strong CII emission lines. The technique used was differential imaging through interference filters centered at the CII 7231,7236 doublet and its nearby continuum, in order to detect CII emitters. In this presentation we will briefly describe the survey and summarize its principal results, which include the identification of two new [WC11] stars in the LMC, plus five stars of earlier [WC] classes, and other interesting emission-line objects. Comparison of the relative intensities of the CII 7231,7236 doublet components in the observed sample of [WC] stars, also provided a way to differentiate among the possible origin of the CII emission, as being generated in a surrounding nebula or in a dense stellar wind. We hope that our results will be helpful for those attempting detailed modeling of this rare class of evolved stars.

4) Feedback and physical parameters of the massive stars and their environments in N11, the 2nd brightest region of the LMC

V. M. A. Gómez-González

Massive stars play a dominant role in the ionizing and mechanical feedback within star-forming regions. Lower-than-solar metallicity local environments are key to understanding the physical processes of young and hot massive stars, as well as feedback mechanisms that occurred in earlier stages of the Universe. The Large Magellanic Cloud (LMC) is one of our best local laboratories to study individual massive stars and their environment, given its relatively nearby distance, low metallicity, and low reddening. N11 is the second-brightest OB association in the LMC, after 30 Dor. Previous studies suggest sequential star formation from the central nebular cavity of N11, LH9 with a central Wolf-Rayet system, to the star-forming complexes surrounding it (N11B). We present an analysis of a sample of massive stars located in N11B and LH9, obtained from the Hubble UV Legacy Library of Young Stars as Essential Standards program. We used multiwavelength spectra from the ultraviolet and optical obtained from HST (COS and STIS) and VLT (X-shooter). We fitted the spectra of our stars using state-of-the-art NLTE PoWR atmosphere models to determine their main stellar parameters, winds, chemical abundances and ionizing feedback. This information is crucial for establishing the feedback of massive stars and investigating the ecology of this environment.

5) Looking for nebular He II emission south of the multiple-massive star system, HD 5980

A. Sixtos

The nebular He II λ1640 emission line is observed in star-forming galaxies out to large distances and can be used to constrain the properties of sources of He+-ionizing photons. For this purpose, it is crucial to understand which are the main stellar sources of these photons. In some nearby metal-poor starburst galaxies, nebular He II λ4686 (optical equivalent) is accompanied by a broad underlying component, which is generally attributed to formation in the winds of classical (He-burning) Wolf–Rayet stars, primarily of the WN subtype. In such cases, the origin of the nebular component has been proposed to be the escape of He+-ionizing photons from the winds of the WN stars, at least partially. We use archival long-slit observations obtained with Focal Reducer Low Dispersion Spectrograph (FORS1) on the Very Large Telescope to look for nebular He II λ4686 emission south of the WN6h + WN6-7 close binary in HD 5980. We only find broad He II λ4686 emission, as far as ~7.6 pc from the binary. A comparison with observations obtained with Space Telescope Imaging Spectrograph (STIS) on the Hubble Space Telescope, at a similar orbital phase, shows that the FORS1 broad He II emission is likely contamination from the multiple-star system HD 5980. We use models to show that no significant He+-ionizing flux is expected from the WN stars in HD 5980 and that when similar stars are present in a coeval stellar population, the O stars can be far greater emitters of He+-ionizing radiation.

6) The role played by Very Massive and WR stars in population synthesis models
G. Bruzual

Observational evidence favours the presence of Very Massive Stars (VMS) and WR stars in very young (a few Myr) regions of active star formation in external galaxies. The derivation of the physical properties of these stellar populations requires adequate treatment of these stars in population synthesis models. In this talk I will summarize recent advances in the field and show results for both single and binary star populations.

**Posters

1) Near-IR spectral analysis of young WR-harboring open clusters and their evolutionary implications.
A. Legault

The investigation of young open clusters containing Wolf-Rayet stars allows us to test massive star evolution theories. It is therefore important to carry out an in-depth study of each of those clusters, especially those with a lower total mass. In this poster we present a preliminary analysis of near-IR spectra of OB-star members of the WR-harboring clusters VVVCL36, 41 and 99, each of which only has a total mass of a few thousand solar masses. We use the PoWR stellar atmosphere grid of synthesized spectra to fit line profiles and determine the effective temperatures, surface gravities and luminosities of cluster members. We also determine the radial and rotational velocities using the goodness-of-fit and Fourier transform methods. We present and discuss the best-fit evolutionary tracks for our observations using the single star (with and without rotation) Geneva models and the BPASS binary evolution code.

2) A consistent photoionization model of the Wolf-Rayet planetary nebula NGC 1501 and its mixing layer
G. Rubio

Theory predicts that the temperature of the X-ray-emitting gas (~10^6 K) detected from planetary nebulae (PNe) is a consequence of mixing or thermal conduction when in contact with the ionized outer rim (~10^4 K). Gas at intermediate temperatures (~10^5 K) can be used to study the physics of the production of X-ray-emitting gas, via C IV, N V and O VI ions. Here we model the stellar atmosphere of the CSPN of NGC 1501 to demonstrate that even this hot H-deficient

[WO4]-type star cannot produce these emission lines by photoionization. We use the detection of the C IV lines to assess the physical properties of the mixing region in this PNe in comparison with its X-ray-emitting gas, rendering NGC 1501 only the second PNe with such characterization. We extend our predictions to the hottest [WO1] and cooler [WC5] spectral types and demonstrate that most energetic photons are absorbed in the dense winds of [WR] CSPN and highly ionized species can be used to study the physics behind the production of hot bubbles in PNe. We found that the UV observations of NGC 2452, NGC 6751 and NGC 6905 are consistent with the presence of mixing layers and hot bubbles, providing excellent candidates for future X-ray observations.

3) Nature of Wolf-Rayet Bubbles: Interstellar or Circumstellar

P.-S. Ou

Bubbles around Wolf-Rayet (WR) stars originate from two distinct physical processes: interstellar bubbles are generated by the stellar winds of main-sequence O stars sweeping up the interstellar medium; circumstellar bubbles are produced by the winds of Wolf-Rayet stars sweeping up the circumstellar medium (i.e. ejected stellar material). To understand the differences in the physical structures of these two kinds of bubbles, we have collected samples of WR ring nebulae in the Milky Way Galaxy and in the Large Magellanic Cloud (LMC). For the Galactic WR ring nebulae, we have investigated their morphology, radii, and nebular masses, and compared these features with the classification based on chemical abundances. We have identified the morphological characteristics that can distinguish between interstellar and circumstellar bubbles. These results have been further applied to the classification of WR bubbles in the LMC. Additionally, we have investigated the spectral types of the central WR stars and stellar environments of interstellar and circumstellar bubbles, and discussed their implications for stellar evolution toward the WR phase.

4) Simulations of Stellar Mass Loss and the Formation of Interstellar and Circumstellar Bubbles

P.-S. Ou

Massive stars can lose large fractions of mass through stellar winds. These materials form circumstellar medium (CSM) and generate interstellar and circumstellar bubbles. In this work, we systematically study stellar mass loss and formation of bubbles from the main sequence to the Wolf-Rayet (WR) phase. First we use the MESA code to produce a grid of ~2000 stellar models with various initial masses and metallicities. From these models, we calculate the total mass loss and energy feedback during the stellar lifetimes. The mass-loss rates and wind velocities as functions of time are obtained from the stellar models, and then imported into the radiation hydrodynamic simulations with the RAMSES code. Using these realistic mass-loss rates, we build up models of wind-blown bubbles. We analyze the structures of interstellar and circumstellar bubbles around WR stars and compare them with the bubbles observed in the Milky Way Galaxy and the Large Magellanic Cloud.

5) The morpho-kinematic structure of the Thor's Helmet Nebula
G. Ramos-Larios

We present a morpho-kinematic study of the Wolf-Rayet (WR) nebula NGC 2359 around WR7. Multi-epoch high-dispersion spectra were obtained with the Manchester Echelle Spectrometer (MES) mounted on the 2 m telescope of San Pedro Mártir (SPM, Mexico) which are interpreted by means of the software SHAPE. Our model helps us peer into the structure of this WR nebula.

6) Oxygen abundance of gamma Vel from far-infrared Herschel/PACS observations
P. Crowther

We present an analysis of far-IR Herschel/PACS spectroscopy of the [OIII] 88 micron fine-structure line in gamma Vel (WC8+O), using two complementary techniques (analytical approach of Barlow et al. plus model atmosphere CMFGEN spectral fits) to determine its oxygen abundance. Oxygen abundances from UV/optical lines are severely hindered by the dominant carbon line spectrum in WC stars. Fine-structure lines permit more straightforward abundance determinations, despite their low critical densities, corresponding several hundred thousand stellar radii in the case of [OIII] 88 micron for gamma Vel. We also provide updated neon abundances of gamma Vel from ISO/SWS spectroscopy. Comparisons with BPASS predictions for a several ^12C(alpha,gamma)^16O reaction rates are provided, from which Kunz et al. results are favored over NACRE (Angulo et al.)

7) What have we learned on WR124 and its iconic nebula M1-67?
J.A. Toalá

WR124 and its iconic nebula (M1-67) have been the subjects of many studies throughout the decades and we are just getting close to understanding this system. In this poster we present the recent findings on the possible binarity of WR124 and the implications for the formation of M1-67 formation. We scrutinized WR124 and M1-67 under X-ray, optical and IR observations.

8) Near-IR spectral analysis of young WR-harboring open clusters and their evolutionary implications.

A. Legault

The investigation of young open clusters containing Wolf-Rayet stars allows us to test massive star evolution theories. It is therefore important to carry out an in-depth study of each of those clusters, especially those with a lower total mass. In this poster we present a preliminary analysis of near-IR spectra of OB-star members of the WR-harboring clusters VVVCL36, 41 and 99, each of which only has a total mass of a few thousand solar masses. We use the PoWR stellar atmosphere grid of synthesized spectra to fit line profiles and determine the effective temperatures, surface gravities and luminosities of cluster members. We also determine the radial and rotational velocities using the goodness-of-fit and Fourier transform methods. We present and discuss the best-fit evolutionary tracks for our observations using the single star (with and without rotation) Geneva models and the BPASS binary evolution code.

9) Shielded from the wind: photoevaporating neutral globules around WR124

R. Reyes

The circumstellar nebula M1-67 around the Wolf-Rayet star WR~124 contains hundreds of small neutral globules, as revealed by recent JWST images. However, despite the powerful stellar wind from the star, the globules do not interact directly with the wind. Instead, they are hydrodynamically shielded by a transonic warm ionized flow away from their surfaces that is induced by the Lyman continuum radiation of the star. This inwardly directed photoevaporation flow shocks against the outflowing stellar wind to form dense hemispherical ionized shells that are a few times larger than the globules and which contribute a significant fraction of the recombination line luminosity of the nebula. We analyze archival HST Halpha images of the nebula in order to study the balance between the ram pressure of the stellar wind and the internal pressure due to the photoevaporative flows. By considering a steady state hydrodynamic model for these interactions, we obtain physical parameters of the collision shells and de-project the spatial distribution of globules, finding that the majority are concentrated in a narrow range of radii: 0.5 +/- 0.1 pc from the star.

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