Contents

Part I.

Talks

1. Session I: Monday morning

1.1. Stellar evolution

The impact of reduced mass-loss rates on the evolution of massive stars

Hirschi R.[1]
[1]*Lennard-Jones Laboratories, Keele University*

After an Introduction on the evolution of massive stars, we will discuss the impact of reduced mass loss rates for solar metallicity star Then we will present our very low metallicity models and underline the strong impact mass loss may have on the evolution of the first stellar generations. Finally, we will describe the importance of mass loss in the context of gamma-ray burst progenitors.

1.2. Spectroscopy and mass-loss diagnostic: observations

Observational overview of clumping in hot stellar winds

Moffat A.F.J.[1]
[1]*Département de physique, Université de Montréal*

In the old days (pre ∼1990) hot stellar winds were assumed to be smooth, which made life fairly easy and bothered no one. Then after suspicious behaviour had been revealed e.g. stochastic temporal variability in broadband polarimetry of single hot stars, it took the emerging CCD technology developed in the preceding decades (∼1970-80's) to reveal that these winds were far from smooth. It was mainly high S/N temporal spectroscopy of strong optical recombination emission lines in WR, and also a few OB and other stars with strong hot winds, that indicated all hot stellar winds to likely be pervaded by thousands of multiscale (compressible supersonic turbulent?) structures, whose driver was probably some kind of radiative instability. Quantitative estimates of clumping-reduced mass-loss rates came from various fronts, mainly dependent directly on density (e.g. electron-scattering wings of emission lines, UV spectroscopy of weak resonance lines, and binary-star properties including orbital-period changes, electron-scattering, and X-ray fluxes from colliding winds) rather than the more common, easier-to-obtain density-squared diagnostics (e.g. f-f emission in the IR/radio and recombination lines). Many big questions still remain, such as: What do the clumps really look like? Do clumping properties change as one recedes from the mother star? Is clumping universal? Does the relative clumping correction depend on $\dot{M}$ itself?

Revised mass-loss rates for O stars from FUV resonance lines

Fullerton A.W.[1]
[1] *Space Telescope Science Institute*

The P V $\lambda\lambda$1118, 1128 resonance doublet is now recognized to be a key diagnostic of O-star winds because it side-steps the traditional problems associated with determining mass-loss rates from UV resonance lines. Consequently, the large discrepancies between mass-loss rates determined from P V and mass-loss rates determined from "density squared" emission processes pose a significant challenge to the "standard model" of hot-star winds. The purpose of this presentation is to discuss critically the assumptions and uncertainties that underpin this discrepancy and its interpretation. The disparate measurements can be reconciled if the winds of O-type stars are strongly clumped on small spatial scales, which in turn implies that mass-loss rates based on Hα or radio emission are too large, possibly by an order of magnitude, and that predictions of the ionization equilibrium based on the "standard model" are unlikely to be correct.

Independent reasons to favor low mass-loss rates for O stars

Smith N.[1]
[1] *University of California, Berkeley*

I will discuss observational evidence, independent of the spectral analysis of stellar winds themselves, which suggests that mass-loss rates for O stars are lower than previously thought, and more in line with recent lower values of $\dot{M}$ found for highly clumped winds. I think these independent constraints are a very important part of the picture. These include the large observed mass-loss rates in LBV eruptions, the large masses of evolved massive stars and WNL stars measured in binary systems, the properties of WR stars in lower metallicity environments, observed rotation rates of massive stars at different metallicity, and other clues. I will also touch upon some far-reaching consequences for the evolution of massive stars at a range of metallicity, including Population III stars, if the line-driven wind mass-loss rates at the present epoch really are low.

Clumping in O-type supergiants

Bouret J.-C.[1], Lanz T., Hillier D.J., Foellmi C.
[1]*Laboratoire d'Astrophysique de Marseille*

We have analyzed the spectra of Galactic O supergiants, from FUV to optical. The spectra have been modeled using the NLTE wind code CMFGEN. We have derived the stellar and wind parameters and the surface composition of the stars. The surface of the five stars have a composition typical of evolved O supergiant (nitrogen-rich, carbon and oxygen-poor). For all stars, we have found that clumped wind models match well lines from different species spanning a wavelength range from FUV to optical, and remain consistent with Hα data. In particular, we have achieved an excellent match of the P v resonance doublet, N iv λ1718 Å, indicating that our physical description of clumping is adequate. We show that the success of the clumped wind models in matching these lines results from increased recombination in the clumps, hence from a better description of the wind ionization structure. We also achieve a very good match of He ii λ4686 Å (especially the electron scattering wings) with these clumped models. We find that the wind of these stars is highly clumped, as expressed by very small volume filling factors and that clumping starts deep in the wind, just above the sonic point. The most crucial consequence of our analysis is that the mass loss rates of O stars need to be revised downward significantly, **by a factor of 3 and more**. We emphasize that very small mass loss rates are similarly obtained for a few O-type dwarfs that we also analysed (10 Lac among others). These lower mass loss rates will affect substantially the evolution of massive stars. Accounting for wind clumping is essential when determining the wind properties of O stars. Our study therefore calls for a fundamental revision in our understanding of mass loss and of O-type star stellar winds.

Clumping in O-star winds

Puls J.[1]**, Hanson M., Markova N., Najarro F.**
[1] *Universitätssternwarte München*

We summarize the present status quo of empirical knowledge regarding the amount of clumping and its radial stratification in O-star winds, by comparing theoretical relations for unclumped wind-models and mass-loss rates derived from a variety of diagnostics. Special emphasis will be given to measurements relying on the IR and radio-excess, and on the analysis of new L-Band observations performed with the VLT (ISAAC) and the IRTF (SpeX).

Do Clumping Corrections Increase with Decreasing Mass-Loss?

St-Louis N.[1]**, Moffat A.F.J**
[1]*Département de physique, Université de Montréal*

We will compare density-dependant mass-loss rate determination techniques such as linear polarisation variability in a binary system with density-squared mass-loss rate determination techniques such as Hα line fits for O binaries. Our goal is to test the recently claimed clumping correction factors for the mass-loss rates of O stars which are much higher ($\sim 10 - 100$) than the correction factors required for the denser WR-winds (~ 3).

2. Session II: Monday afternoon

2.1. Spectroscopy and mass-loss diagnostic: observations (continued)

Tracking the clumping in OB stars from UV to radio

Najarro F.[1]

[1] *Instituto de Estructura de la Materia, CSIC, Madrid*

We review different line and continua diagnostics from the UV to radio which can be used to simmultaneously constrain the clumping structure throughout the stellar wind of massive OB stars.

The effect of clumping on predictions of the mass-loss rate of early-type stars

de Koter A.[1]**, Muijres L.**
[1]*Astronomical Institute "Anton Pannekoek", University of Amsterdam*

We will compare empirical mass loss rates determined in the context of the FLAMES Large Program on Massive Stars, with predictions of mass loss rates. We find that if clumping does not affect the rate of mass loss that can be driven by line radiation pressure empirical mass loss determinations are higher than predicted rates, implying a clumping factor of about four. We address the potential impact of clumping on the mass loss driving mechanism in OB-type stars.

Clumping in the winds of OB supergiants

Kraus M.[1], Krtička J., Kubát J.
[1]*Astronomical Institute Ondrejov*

We study the influence of wind clumping on the free-free and free-bound continuum emission of OB supergiants, selected from a sample of Magellanic Cloud objects. Various clumping formalisms provided in the literature are tested, and the differences in the emerging spectral energy distributions of our target stars are discussed.

Wind inhomogeneities in low-Z environment: observations

Marchenko S.V.[1]

[1]*Department of Physics and Astronomy, Western Kentucky University*

We discuss the results of time-resolved spectroscopy of three presumably single Population I Wolf-Rayet stars in the Small Magellanic Cloud, where the ambient metallicity is $\sim 1/5 Z_{\odot}$. We were able to detect and follow numerous small-scale wind-embedded inhomogeneities in all observed stars. The general properties of the moving features, such as their velocity dispersions, emissivities and average accelerations, closely match the corresponding characteristics of small-scale inhomogeneities in the winds of Galactic Wolf-Rayet stars.

Mass-loss rate and clumping in LBV stars: the impact of time-dependent effects

Groh J.H.[1], Hillier D.J., Damineli A.
[1]*Max-Planck-Institut für Radioastronomie, Bonn*

In order to analyze the complex winds of massive stars major improvements, such as the inclusion of wind clumping and a consistent treatment of line blanketing, have been incorporated into radiative transfer codes during the last decade. However, a steady state outflow is still assumed. While this is probably valid for Wolf-Rayet and O-type stars, it is invalid for LBV stars. LBVs are characterized by strong photometric and spectroscopic variability on timescales from days to decades, arising from changes in stellar and wind parameters. In this talk I present a newly-developed method to include the effects of time variability in the radiative transfer code CMFGEN. I will show how time-dependent effects significantly change the velocity law and density structure of the wind, affecting the derivation of the mass-loss rate, volume filling factor, wind terminal velocity, and luminosity. The results of this work are directly applicable to all active LBVs in the Galaxy and in the LMC, such as AG Car, HR Car, S Dor and R 127, and could result in a revision of stellar and wind parameters. I present the mass-loss rate evolution of AG Car during the last 20 years, highlighting the need for time-dependent models to correctly interpret the evolution of LBVs.

Structure in the fast winds of PN central stars

Prinja R.[1]**, Massa D., Hodges S., Fullerton A.**
[1]*University College London*

We report on results from recent FUSE and high spectral resolution optical studies of structure and variability in the fast winds of young, H-rich, PN central stars (CSPNe). The data sample characteristic time-scales from several hours to the mooted rotation rates ($\sim$ day). The targets monitored are members of the poorly understood ZZ Lep class, which are also semi-periodic photometric variables. The time-series data provide new perspectives on the inhomogeneous and structured nature of the CSPN fast winds, which can lead to non-symmetric outflows, imply downward revisions in mass-loss estimates and complicate interactions with the surrounding nebula. The results have a potential impact on the role of fast winds in shaping the nebula and the origin of X-ray emission within PNe. The diagnostics provide comparisons – on different scale settings – to the structured line-driven outflows of massive stars.

Clumping in the winds of O-type CSPNs

Urbaneja M.A.[1], Kudritzki R.-P., Puls J.
[1] *University of Hawai'i Institute for Astronomy*

Recent studies of massive O-type stars present clear evidences of inhomogeneous and clumped winds. O-type CSPNs are in some ways the low mass - low luminosity analogue of those massive stars. In this contribution, we will present preliminary results of our on-going multi-wavelength (FUV, UV and optical) study of the winds of Galactic CSPNs, presenting a novel method to estimate wind clumping factors from the relative strengths of two optical lines, Hα and He II 4686.

3. Session III: Tuesday morning

3.1. Spectral modeling

Spectrum formation in clumpy stellar winds

Hamann W.-R.[1]
[1] *Universität Potsdam*

Modeling expanding atmospheres is a difficult task because of the extreme non-LTE situation, the need to account for complex model atoms, especially for the iron-group elements with their millions of lines, and because of the supersonic expansion. Adequate codes have been developed successfully e.g. by the Munich group (Puls, Pauldrach), Hillier (CMFGEN) and in Potsdam (PoWR). While early work was based on the assumption of a smooth and homogeneous spherical stellar wind, the need to account for clumping became obvious about ten years ago. A relatively simple first-order clumping correction was readily implemented into the model codes. However, it's simplifying assumptions are severe. Only one, uniform density is assumed within each clump, and the clumps are taken to be optically thin at any frequencies. We discuss the consequences of these approximations and the approaches to a more realistic treatment of wind clumping. First results have been obtained from a statistical treatment of optically thick clumps.

The "porosity effect" on continuum opacity was shown to facilitate the emergence of X-rays. When clumps are optically thick at line frequencies, strong spectral features become generally weaker. This holds also for resonance lines. The recently reported discrepancy between the Hα line and the P V resonance doublet in O star spectra can be perfectly reconciled without a further reduction of the mass-loss rate and correspondingly stronger clumping

Modeling Line Variability in Hot Star Spectra with 3D Radiative Transfer

Lobel A.[1]

[1]*Royal Observatory of Belgium*

We perform three-dimensional radiative transfer calculations with the Wind3D code to model the detailed variability of UV spectral lines formed in the winds of massive hot stars.

We investigate the detailed time-evolution of Discrete Absorption Components (DACs) and rotational modulations in the P Cygni profiles of Si IV resonance lines by calculating the 3D transfer through hydrodynamic models of the stellar wind that incorporate large-scale coherent density- and velocity-structures. We discuss how various physical properties of these wind structures, or Corotating Interaction Regions (CIRs), can be constrained with detailed fits to observed dynamic spectra or to the individual evolution of DACs and modulations in the line profiles.

The hydrodynamic models with large-scale wind structures are computed with the Zeus code and input for Wind3D. We demonstrate important effects of the hydrodynamic input parameters (i.e. spot-intensity, -size, and -velocity) on the wind structures that determine the detailed morphology of the DACs and of the modulations (i.e. shape and flux changes) computed with 3D transfer.

We find that the range of hydrodynamic input parameters to model the DACs is well constrained, while the parameters required to match the modulations quantitatively considerably differ. It signals that both types of line variability result from substantially different large-scale hydrodynamic structures in winds of massive hot stars.

Monte-Carlo radiative transfer through porous media

Townsend R.[1]
[1]*Bartol Research Institute, University of Delaware*

A porous medium is a special case of a clumped medium, in which the variance in photon mean free paths is large. During their random walk through a porous medium, photons sample pathways with both long and short mean free paths. The long pathways can be thought of as “autobahns”, allowing the radiation to travel large physical distances without interacting with the medium. A consequence is that the radiative force on a porous medium is expected to be smaller than in the homogeneous case. In this talk, I will present new Monte-Carlo simulations of these effects, and discuss their relevance to mass loss from stars near and above the Eddington limit.

Mid-IR observations of WR stars, and the connection with wind clumping

Schnurr O.[1]**, Crowther P.**
[1] *University of Sheffield*

New Spitzer/IRS spectroscopy of Galactic WC stars provides a multitude of mid-IR recombination lines, which together with UV/optical spectral lines probe wind clumping across a range of physical radii. Preliminary multi-wavelength non-LTE studies are presented, in which clumping is sensitive to the mid-IR continuum (forming beyond the UV/optical continuum), for an adopted velocity structure. In addition, the presence of fine-structure lines - [NeIII] at 15.5 micron and [NeII] at 12.8 micron allowing measurements of Ne contents. Such lines are formed in the outer stellar wind, permitting us to test whether clumping factors differs from the inner wind, assuming Ne abundances predicted by nuclear-reaction rates.

On the influence of clumping on O star spectra

Hillier D.J.[1]
[1] *University of Pittsburgh*

3.2. Hydrodynamic modeling (stationary)

The effects of clumping on the dynamics of Wolf-Rayet winds

Gräfener G.[1]

[1]*Department of Physics, University of Potsdam*

We investigate the effects of wind clumping on the dynamics of Wolf-Rayet winds, by means of the Potsdam Wolf-Rayet (PoWR) hydrodynamic atmosphere models. Wind clumping generally enhances the radiative acceleration within hot star winds. We examine the reasons for this effect and show that the resulting wind structure depends critically on the assumed radial dependence of the clumping factor $D(r)$. The observed terminal wind velocities for WR stars imply that $D(r)$ increases to very large values in the outer part of the wind, in agreement with the assumption of detached expanding shells.

4. Session IV: Tuesday afternoon

4.1. Hydrodynamic modeling (stationary) (continued)

Mass loss predictions

Vink J.[1]

[1]*Lennard-Jones Laboratories, Keele University*

I will present the results of Monte Carlo wind predictions and critically compare these mass-loss rates to observations over a range of effective temperatures. Both theoretical and empirical rates generally rely on the assumption of sphericity and homogeneity. I will also discuss the role of linear polarimetry to measure wind asymmetries and present recent results on a range of supergiants. I will discuss whether reported discrepancies may be related to rotation and wind clumping.

The influence of clumping on predicted O star wind parameters

Krtička J.[1], **Kubát J.**, **Puls J.**
[1]*Masaryk University Brno*

We study the influence of clumping on the predicted wind structure of O-type stars. For this purpose we artificially include clumping into our stationary wind models. When the clumps are assumed to be optically thin, the radiative line force is increased compared to corresponding unclumped models, with a similar effect on either the mass-loss rate or the terminal velocity. Allowing the clumps to become optically thick, on the other hand, may decrease the radiative force alternatively

4.2. Hydrodynamic modeling (time-dependent)

Hydrodynamic simulations of instability-generated clumps in hot-star winds

Feldmeier A.[1]

[1] *Universität Potsdam*

The talk will cover (i) numerical techniques applied in time-dependent hydrodynamic simulations of radiation-driven winds, most notably the treatment of line scattering, including a short-characteristics method for 2-d simulations, and radiative transfer in presence of multiple scattering locations, (ii) the cross-relations of the line-driven instability, radiative-acoustic waves, wind solution topology and velocity kinks, i.e. weak discontinuities in the wind velocity law that propagate at shock speeds, and (iii) the relation between hydrodynamic simulations, X-ray line diagnostics, and heuristic wind models with clumps of prespecified shape, orientation, and distribution function.

Dynamical Origin of Wind Structure

Owocki S.[1]
[1]*Bartol Research Institute*

I will review the various dynamical processes involved in generating wind structure, with particular attention to its expected spatial scale. While intrinsic instabilities in line-driving seem likely to result in relatively small-scale structure, various other mechanisms – e.g. pulsation, magnetic fields, surface variations on rotating star, and perhaps even stagnation of an overloaded outflow – seem capable of generating moderate to large scale structure that approaches or even exceeds a stellar radius. I will also discuss the importance of structure scale in setting its likely observational consequences and signatures.

Hot-Star wind variability due to magnetic field

ud-Doula A.[1]
[1]*Bartol Research Institute*

In this talk I will discuss how magnetic fields can modulate hot-star winds and create moderate to large scale structures. Recent observations show that magnetic fields do exist in massive stars and this raises the possibility that the magnetic fields play an active role in modulating their winds.

Clumping in the outer winds of hot stars

Runacres M.C.[1]

[1] *Department of Industrial Sciences and Technology, Erasmushogeschool Brussel*

We present models of the 1D evolution of instability-generated structure in the winds of hot stars out to distances of more than a thousand stellar radii. The consequences of these models for the derived thermal and non-thermal radio emission are discussed, and compared with observations.

5. Session V: Wednesday morning

5.1. Magnetic fields

Hot Star Magnetic Fields

Ignace R.[1]

[1]*East Tennessee State University*

It used to be the case that magnetic fields could be playfully invoked to account for any number of observational anomalies observed in stars. However, in recent years observers have valiantly accumulated a respectable database of substantially sub-kilogauss magnetic detections and upper limits among hot, massive stars. Theory is fast on the heels of these observational developments, with relatively recent models addressing the generation of magnetic fields in massive stars, the consequences of such fields for stellar evolution, and their influence for stellar wind flow and observables (e.g., in terms of time variable phenomena). After outlining the state of the field in relation to these topics, I will focus the remaining discussion on models for circumstellar envelopes with magnetic fields. I will describe methods for modeling the Zeeman effect in line profiles of circumstellar origin, and I will describe example applications.

The impact of large and small scale magnetic fields on the winds of massive stars

Schnerr R.S.[1]**, Owocki S.P., ud-Doula A., Henrichs H.F., Townsend R.H.D.**

[1]*Astronomical Institute of the University of Amsterdam*

From the variability observed in UV wind-lines it is clear that the winds of massive stars are not smooth. Magnetic fields are a likely cause of such variability. We will present results of numerical simulations of the impact of magnetic fields on the stellar wind, and observational constraints on the strength and structure of these fields in massive stars.

5.2. Variability

The effects of clumping on wind line variability

Massa D.[1]
[1]*SGT, Inc., NASA/GSFC*

I will review the effects of large scale clumping on the observed properties of wind lines in general, and on uncoupled doublets in particular. By uncoupled doublets, I mean doublets in stars whose winds have terminal velocities which are less than half of the velocity separation of the doublet components. Such doublets are not radiatively coupled. They are extremely important because the ratio of their optical depths at every velocity should equal the ratio of their oscillator strengths (typically 2 to 1) in smooth winds. However, in clumped (or porous) winds, this ratio can lie anywhere between unity and the ratio of the oscillator strengths, and can change as a function of velocity and time, depending on the fraction of the stellar disk that is covered by material moving at a particular velocity at a given moment. Using these insights, I will present the results of SEI modeling of a sample of stars with uncoupled doublets and a time series for such a star.

Corotating Interaction Regions and Clumping

Blomme R.[1]
[1]*Royal Observatory of Belgium*

Considerable observational evidence exists for the presence of clumping in hot-star stellar winds. Habitually, this clumping is assumed to be small-scale, stochastic structure, probably related to the instability of the radiative driving mechanism.

Other observations, however, provide clear evidence for large-scale, coherent structures moving through the wind. One can therefore ask how much of the observed evidence for clumping could be explained by these large-scale structures, which are assumed to be Corotating Interaction Regions (CIRs).

To explore this, we used the Zeus hydrodynamical code to calculate CIRs. These CIRs are caused by "spots" on the stellar surface. By varying the parameters of the spots, we tried to quantitatively fit the observed Discrete Absorption Components (DACs) and rotational modulations seen in ultraviolet spectral lines (see companion talk by A. Lobel). The derived density contrasts can then be compared to those required from observations of clumping. Temperatures can be compared with those required for the emission of X-rays.

Hα Line Profile Variability in the B8Ia-Type Supergiant Rigel (β Ori)

Morrison N.D.[1], Rother S.J., Kurschat J.

[1]*Ritter Astrophysical Research Center, University of Toledo*

Hα observations of Rigel obtained on more than 150 nights during the observing seasons of 1996-1997 through 2004-2005 with the 1-meter telescope and échelle spectrograph ($R = 26,000$) of Ritter Observatory are surveyed. The line profiles are classified in terms of morphology. About 1/3 of them are of P Cygni type, about 15% inverse P Cygni, about 20% double-peaked, about 1/3 pure absorption, and a few are single emission lines. Transformation of the profile from one type to another occurs in as little as a day but more typically takes a few days. High-velocity absorption events are rare, irregularly occurring, and usually characterized by lower velocities and weaker absorption than those reported by Kaufer et al. (1996). As the absorption events come into an end, the emission typically returns with an inverse P Cygni profile.

A progress report on time-series analysis of these data will be presented.

Research and operations at Ritter Observatory are supported by NSF-PREST grant AST-0440784.

Reference: Kaufer, A., Stahl, O., Wolf, B., Gäng, Th., Gummersbach, C.A., Jankovics, I., Kovács, J., Mandel, H., Peitz, J., Rivinius, Th., and Szeifert, Th. 1996, A&A, 314, 599

Wind variabilities and asymmetries in Luminous Blue Variables

Szeifert Th.[1]
[1]*ESO Chile*

Luminous Blue Variables show strong changes in their stellar wind on time scales of typically years to decades when they expand and contract radially at approximately constant luminosity. Superimposed to this characteristic variability they show variability on shorter time scales. I will show long-term time series of high resolution spectra which we have collected in the past 20 years for many of the well known LBVs together with time series of daily (AG Car, HD 160529), to weekly sampling (HR Car, R40, R71, R110, R127, S Dor) collected over time windows of a few months. Wind variability is seen on short and intermediate time scales with the line profiles changing from P Cygni to inverse P Cygni and double peeked profiles sometimes for the same star and spectral line. On longer time scales the ionisation levels for all chemical elements change drastically due to the strong change of the temperature on the stellar surface. While on the long term the characteristic radial changes may have impact on the over all mass loss rates, the variabilities and asymmetries on short and intermediate time scales may cause false estimates of the mass loss rates when confronting models with the observed line profiles.

Rapidly Accelerating Clumps in the Wind of the Weak-Line WN3ha stars WR3

Chené A.-N.[1], Moffat, A.F.J.
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Wind inhomogeneities are manifested by subpeaks on the broad emission lines that propagate with time towards the line edges. This is due to excess recombination-line radiation from dense clumps radially accelerating outwards from the central star. Analysis of the kinematics of the inhomogeneities allows one to constrain the wind expansion law $v(r)$. By assuming the velocity law of WR winds to be a β-law of the form $v(r) = v_\infty\,(1-(R_*/r))^\beta$, previous works have already determined a velocity law for winds of several WR stars. For all observed stars (about a dozen), the value of β was constrained between 3 and 20, implying that the wind structures of WR stars are slow compared to O stars. However, in all observed WR stars, the lines available for analysis probe mostly the outer layers of the winds, where accelerations are relatively weak and timescales for the subpeak motion are long ($\sim$ 10 hours).
The wind of WR3, a WN3 type star, is particularly rapid, hot and optically thin. Most of the spectral lines of WR3 are narrow and triangular, indicating that they are formed in regions close to the hydrostatic surface of the star, where the acceleration is strongest. Data from many observatories have already been obtained and show that subpeaks appear, move towards the line edges and disappear on the He IIλ4686 emission line in timescales of 2-3 hours. The β value determined for WR3 is between 0.8 and 2.0, depending on the assumed stellar radius. For comparison purposes, the motion of clumps in the thicker winds of WR2 (WN2) and WR152(WN3) will also be discussed.

6. Session VI: Thursday morning

6.1. Colliding winds

X-ray eclipse estimates of mass-loss rates in the Wolf-Rayet binary systems WR140, WR25 and WR11

Pollock A.M.T.[1]

[1]*European Space Agency XMM-Newton SOC*

In the distant Wolf-Rayet binary systems WR140 and WR25, of periods 2900 and 208 days respectively, deep X-ray eclipses are observed during the few weeks when the Wolf-Rayet star is in front. Because the soft X-ray absorption, whose physics is apparently well understood, is caused by the bulk cool material of the Wolf-Rayet wind, the depth and shape of the eclipses provide straightforward estimates of both orbital geometry and mass-loss rates. In γ Velorum (WR11), whose 80-day period is independently very well-defined, high absorption is observed throughout the orbit and this requires some care in disentangling the contributions of the two companion stars.

Eta Carinae: viewed from multiple vantage points

Gull T.R.[1]
[1] *Goddard Space Flight Center*

The central source of Eta Carinae and its ejecta is a massive binary system buried within a massive interacting wind structure which envelops the two stars. However the hot, less massive companion blows a small cavity in the very massive primary wind, plus ionizes a portion of the massive wind just beyond the wind-wind boundary.

We gain insight on this complex structure by examining the spatially- resolved STIS spectra of the central source (0.1") with the wind structure which extends out to nearly an arcsecond (2300 AU) and the wind-blown boundaries, plus the ejecta of the Little Homunculus. Moreover, the spatially resolved VLT/UVES stellar spectrum (one arcsecond) and spatially sampled spectra across the foreground lobe of the Homunculus provide us vantage points from different angles relative to line of sight.

Examples of wind line profiles of Fe II, and the highly excited [Fe III], [Ne III], [Ar III] and [S III], plus other lines will be presented.

On irregular line profiles in the optical spectrum of Eta Carinae

Nielsen K.E.[1]
[1]*Catholic University of America*

The optical spectrum of Eta Carinae (η Car) is prominent in H I, He I and Fe II wind lines, all of which vary both in absorption and emission with phase. The phase dependance is a consequence of the interaction between the two objects in the η Car binary (η Car A & B). The binary system is enshrouded by ejecta from previous mass ejection events and consequently, η Car B is not directly observable. We have traced the He I lines over η Car's spectroscopic period, using *HST*/STIS data obtained with medium spectral ($\sim$8000) but high angular ($\sim 0.''15$) resolving power, and created a radial velocity curve for the system. The He I lines are formed in the core of the system ($<0.''1$), and appear to be a composite of multiple features formed in spatially separated regions. The sources of their irregular line profiles are still not fully understood, but can be attributed to emission/absorption near the wind-wind interface and/or a direct consequence of the η Car A's, massive, clumpy wind.

I will discuss the spectral variability, the narrow emission structure of the He I lines and how clumpiness of the winds may impede the construction of the reliable radial velocity curve, necessary for characterizations of especially η Car B.

Wind relicts: clumps, inhomogeneities and outflows in LBV nebulae

Weis K.[1]
[1]*Astronomisches Institut, Ruhr-Universität Bochum*

The most massive stars are those with the shortest but most active life. One group of massive stars, the Luminous Blue Variables (LBVs), of which only a few objects are known, is in particular of interest, concerning the stability of stars. They have a high mass loss rate and are close to being instable. The question for their stability became even more pronounced as rotation was recognized as an important factor in stellar evolution of these stars. Through massive stellar winds, wind-wind interaction, and sometimes giant eruptions, LBV nebulae are formed. Various aspects of the evolution in the LBV phase appear to image themselves in a large diversity of morphological and kinematical structures like clumps, shells, edges, and outflows in these nebulae. This leads to clues about the properties of various wind phases (also from the pre-LBV phase), stellar rotation, density changes in the ISM, and possible binary nature of the LBVs. This will be briefly addressed here as results of the nebular analysis.

6.2. High energy radiation

Using gamma-rays to probe the clumped structure of stellar winds

Romero G.E.[1], Owocki S.P., Araudo A.T., Benaglia P.
[1]*IAR/University of La Plata*

Gamma-rays can be produced by the interaction of a relativistic jet and the matter of the stellar wind in the subclass of massive X-ray binaries known as "microquasars". The relativistic jet produced by the accretion interacts with cold protons from the stellar wind, producing pions that then quickly decay into gamma-rays. Since the resulting gamma-ray emissivity depends on the target density, the detection of rapid variability in microquasars with GLAST and the new generation Cherenkov imaging arrays could be used to probe the clumping structure of the stellar wind in a variety of conditions. This talk will present the basic scenario for gamma-ray production in high-mass microquasars, with emphasis on defining potential targets for observations, and on outlining the constraints on wind clumping that can be extracted from them.

Westerlund 2 at VHE gamma-ray energies and implications for the inferred energetics

Reimer O.[1], Aharonian F., Hinton J., Hofmann W., Hoppe S., Raue M., Reimer A.
[1]*HEPL/KIPAC, Stanford University*

The H.E.S.S. collaboration recently reported the discovery of VHE gamma-ray emission coincident with the young stellar cluster Westerlund 2. This system is known to host a population of hot, massive stars, and, most particularly, the WR binary WR 20a. Particle acceleration to TeV energies in Westerlund 2 can be accomplished through several alternative emission scenarios. Here we discuss energetic constraints based on the available kinetic energy in the system, the actual mass loss rates of respective cluster members, and implied gamma-ray production efficiencies from processes like IC or neutral pion decay. From the inferred gamma-ray luminosity in the order of 10^{35} erg/s, implications for the efficiency for converting kinetic energy into non-thermal processes associated with stellar winds in the Westerlund 2 system will be discussed under consideration of either presence or absence of wind clumping effects.

Clumping effects on non-thermal particle spectra in massive star systems

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Observational evidence exists that winds of massive stars are clumped. Many massive star systems are known as non-thermal particle production sites, as indicated by their synchrotron emission in the radio band. As a consequence they are also considered as candidate sites for non- thermal high-energy photon production up to gamma-ray energies. Indeed, recent observational support comes from the detection of TeV-photons from the young stellar cluster Westerlund 2. Individual massive stellar binaries are expected to be probed at GeV energies by the upcoming GLAST mission. The present work considers the effects of wind clumpiness on the expected emitting relativistic particle spectrum in colliding wind systems, built up from the pool of thermal wind particles through diffusive particle acceleration, and taking into account inverse Compton and synchrotron losses. A comparison to the homogeneous wind case is provided

New obscured and transient HMXB systems discovered by INTEGRAL unveil clumpy stellar winds

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INTEGRAL tripled the number of super-giant High Mass X-ray Binaries known in the Galaxy. Many of the new systems are either strongly absorbed or transient when accreting dense clumps of stellar wind. The high-energy lightcurves trace the accretion rate and the stellar wind conditions encountered by the compact objects. I will review those systems and elaborate on the constraints obtained on stellar winds and on the possible very high energy signature of wind clumps

7. Session VII: Thursday afternoon

7.1. X-rays

X-raying clumped stellar winds

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X-ray emission from massive stars provides an excellent diagnostic of stellar winds. From analysis of new observations it becomes increasingly clear that X-ray emission can be understood only by addressing the general properties of stellar winds such as their clumping and mass-loss. In turn, analysis of X-ray spectra allows to gain deep insight in stellar wind dynamics and deduce properties of stellar wind inhomogeneities. I will review the latest X-ray observations and show that porous wind models are required to interpret high-resolution X-ray spectra of relatively normal single massive stars. In massive binaries, significant X-ray emission can be generated in a wind-wind collision zone. The resulting X-ray spectrum and orbital variations of the X-ray flux provide an independent tool to study clumped stellar winds. In high-mass X-ray binaries (HMXBs) the accretion rate is highly sensitive to the wind dynamics. Moreover, the strong source of continuum X-ray radiation located deep in the stellar wind illuminates surrounding material and thus provides information about wind conditions. X-ray spectra of HMXBs indicate that clumps of cool and dense material are present in their stellar winds. However, despite recent success in developing X-ray diagnostics of stellar winds, key questions regarding X-ray generation and transport in hot-star winds remain largely unanswered

The quantitative analysis of x-ray emission line profiles: constraining mass-loss rates, wind opacity, and porosity

Cohen D.[1]**, Leutenegger M.A., Owocki S.P., ud-Doula A.**
[1]*Swarthmore College*

We present quantitative statistical fits to observed x-ray emission line profiles, in order to constrain the relative contributions of reduced wind optical depth and porosity to the only slightly asymmetric profiles of normal O stars. We show that for most O stars, the profiles are consistent with shock emission distributed throughout the stellar wind above roughly 1.5 stellar radii, as long as the overall continuum optical depth of the wind is reduced by up to a factor of ten compared to the values consistent with literature mass-loss rates and atomic opacities. We show that while porosity can qualitatively reproduce the observed profiles, the fits are significantly poorer than those achieved with a smooth wind and reduced mass-loss rates and/or reduced atomic opacities. Furthermore, for porous models to even approximately fit the data, the porosity length - or inter-clump spacing - must be unrealistically large. We also emphasize the importance of accurate and detailed continuum opacity modeling of the bulk, unshocked stellar wind in interpreting the results of the data fitting.

Evidence for the importance of resonance scattering in X-ray emission line profiles of the O star ζ Puppis

Leutenegger M.A.[1], Owocki S.P., Kahn S.M., Paerels F.B.S.
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We fit the Doppler profiles of the He-like triplet complexes of O VII and N VI in the X-ray spectrum of the O star ζ Pup, using XMM-*Newton* RGS data collected over $\sim$ 400 ks of exposure. We find that they cannot be well fit if the resonance and intercombination lines are constrained to have the same profile shape. However, a significantly better fit is achieved with a model incorporating the effects of resonance scattering, which causes the resonance line to become more symmetric than the intercombination line for a given characteristic continuum optical depth τ_*. We discuss the plausibility of this hypothesis, as well as its significance for our understanding of Doppler profiles of X-ray emission lines in O stars.

X-rays formed in the bow-shocks around clumps in Winds

Cassinelli J.[1]**, Ignace R., Cho J., Murphy N.**
[1] *University of Wisconsin-Madison*

The interaction of a wind from a hot star with a clump in the wind gives rise to a bow-shock. We have run Cho's hydrodynamical code to calculate the shock interaction of a flow with a rigid sphere. After allowing the numerics to reach a steady state, we have found the temperature and density structure of the shock interaction region. The temperature at the apex of the shock is given by the classic planar shock formula $T = 14\,\mathrm{MK}[v_{\mathrm{rel}}/1000\,\mathrm{km/s}]$ while off to the wings a power law differential emission measure is found: $dEM/dT \propto T^{-4/3}$. We introduce a useful analytic expression called the "on the shock approximation" that we have used to derive X-ray line profiles. These are compared with Chandra observations of OB stars which show general properties that are difficult to understand.

Evidence for clumping in wind-accreting X-ray sources

Kaper L.[1]

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In high-mass X-ray binaries X-rays are produced by accretion of matter onto a compact object, a neutron star or a black hole. The matter is transferred to the compact object either through the stellar wind of the OB companion, or by Roche-lobe overflow. In wind-fed systems the X-ray luminosity $L_X \propto \rho v^{-3}$, with ρ the wind density at the orbit of the X-ray source and v the relative velocity of the wind material with respect to the X-ray source. Therefore, the X-ray source acts as a probe of fundamental stellar wind parameters. The observed X-ray flux of these systems is strongly variable, including X-ray flares lasting hours to days and "dips" during which the X-ray production is strongly reduced. Although the interaction between the X-ray source and the stellar wind prohibits a direct comparison with single OB stars, wind-accreting X-ray sources provide the opportunity to measure the density and velocity structure of OB star winds. Wind clumping may very well be the explanation of the observed X-ray variability.

8. Session VIII: Friday morning

8.1. Future observations

New Frontiers for Hot Star Winds: Imaging and Spectroscopy with the James Webb Space Telescope

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The James Webb Space Telescope (JWST) is a large, infrared-optimized space telescope scheduled for launch in 2013. JWST will find the first stars and galaxies that formed in the early universe, connecting the Big Bang to our own Milky Way galaxy. JWST will peer through dusty clouds to see stars forming planetary systems, connecting the Milky Way to our own Solar System. JWST's instruments are designed to work primarily in the infrared range of $1 - 28\mu$m, with some capability in the visible range. JWST will have a large mirror, 6.5 meters in diameter, and will be diffraction-limited at 2 microns (0.1 arcsec resolution). JWST will be placed in an L2 orbit about 1.5 million km from the Earth. The instruments will provide imaging, coronography, and multi-object and integral-field spectroscopy across the full $1 - 28\mu$m wavelength range. The breakthrough capabilities of JWST will enable new studies of hot star winds from the Milky Way to the early universe.

8.2. Discussion and Conference Summary

Part II.

Posters

Modelling the Polarimetric Variability of Hot Stars' Winds

Davies B.[1],Vink J.S., Oudmaijer R.D., Crowther P.A., Figer D.F.
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Many hot stars exhibit polarimetric variability, thought to arise from clumping low in the wind. Here we investigate the wind properties required to reproduce this variability using analytic models. The results suggest that the winds must be highly structured, consisting of a large number of optically-thin clumps; while we find that the overall level of polarization should scale with mass-loss rate – consistent with the correlation between the strength of line-emission and level of intrinsic polarization. The models also predict that the polarization should be variable on very short timescales, which we will show is supported by the results of a recent polarimetric monitoring campaign

Evidence for clumping in phase-resolved FUV spectra of colliding wind binaries

Iping R.C.[1], Sonneborn G., Bouret J.-C.
[1] *CUA & NASA's Goddard Space Flight Center*

Phase-locked wind variability and wind-wind collision effects in massive binaries is investigated. Variations as traced by changes in terminal velocity and optical depth of the large number of wind diagnostics in the Far Ultraviolet Spectroscopic Explorer (FUSE) spectral range (O VI, S VI, C III, N III, S III, IV, & VI, P V, Si IV) is determined. S IV, S VI, Si IV and P V lines are important and unique probes of O star winds and clumping verses wind-wind collision effects is investigated.

Moving absorption bumps in the spectra of Be stars

Kubát J.[1], **Saad S.M.**
[1]*Astronomical Institute Ondrejov*

Several Be binaries exhibit an absorption feature moving across the blue wing of hydrogen emission lines towards the line center. This feature is demonstrated for the case of two bright Be stars, κ Dra and 4 Her. It is not clear what is the reason for this travelling feature.

Radiative Transfer in Accretion Disk Winds of Cataclysmic Variables - A 3-D Monte Carlo Approach

Kusterer D.-J.[1], Nagel Th., Feldmeier A., Werner K.
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Mass accretion onto compact objects through accretion disks is a common phenomenon in the universe. It is seen in all energy domains from active galactic nuclei through cataclysmic variables (CVs) to young stellar objects. Because CVs are fairly easy to observe, they provide an ideal opportunity to study accretion disks in great detail and thus help us to understand accretion also in other energy ranges. Mass accretion in these objects is often accompanied by mass outflow from the disks. This accretion disk wind, at least in CVs, is thought to be radiatively driven, similar to O star winds. A 3-D Monte Carlo radiative transfer code for accretion disk winds of CVs is presented in this poster. First a hydrodynamical accretion disk wind model based on the CAK wind theory is introduced and compared to kinematical wind models. Then it is shown that typical signatures of outflows as they are found in observations are reproduced by the Monte Carlo simulation. Thereby the importance of disk outflow in a CV's outburst phase is manifested. Mass loss rates in the wind can be also determined.

A Comparison of mass-loss rates from UV/Optical and Radio diagnostics

Liermann A.[1], **Hamann W.-R.**
[1] *Universität Potsdam*

The mass-loss rates and other parameters for a large sample of Galactic WN stars have been revised by Hamann et al. (2006), using the most up-to date Potsdam Wolf-Rayet (PoWR) model atmospheres. For a sub-sample of these stars there exist measurements of their radio free-free emission. After harmonizing the adopted distance and terminal wind velocities, we compare the mass-loss rates obtained from the two diagnostics. The differences are discussed as a possible consequence of different clumping contrast in the line-forming and radio-emitting regions.

Multi temperature fitting to X-ray spectra of hot stars

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Early-type hot stars (O-, B- and WR-stars) are characterized by a strong stellar wind, due to their radiation field, in combination with a resonance line-driven mechanism. Turbulences and collisions in the wind are responsible for strong X-ray radiation. Over the last year we have studied the RGS-spectra of ζ Orionis, an O9.7 Ib supergiant. This has resulted in several proceedings on a new paradigm in which is assumed that the plasma is in non-equilibrium and cool, and that protons are the dominant mechanism (Pollock and Raassen), without describing the line fluxes in the spectrum.

To describe the observed fluxes I have modelled the spectrum by means of a Collisional Ionisation Equilibrium model. Three temperatures in the range from 0.06 to .6 keV have been determined. Based on the ratios of the forbidden and the intercombination lines in He-like ions (N VI, O VII, Ne IX, and Mg XI), that are sensitive to collisions as well as to the UV-radiation from the star, the plasma of these ions could be located relative to the stellar surface. The resulting distances are 6-44 R_* for N VI, 11-14 R_* for O VII, 3-6.6 R_* for Ne IX, 2.7-8.4 R_* for Mg XI

Observations of δ Ori have been made with LETGS aboard CHANDRA. Due to its proximity (and therefore lower absorption) δ Ori is brighter in X-ray than other O-stars. Especially the long wavelength range and the lines of low stages of ionization are of interest to establish the presence of cooler plasma.

[1] Pollock, A.M.T., & Raassen, A.J.J., 2006, Proceedings of the "The X-ray Universe 2005", 26-30 September 2005, El Escorial, Madrid, Spain. Ed. by A. Wilson. ESA SP-604, Volume 1, Noordwijk: ESA Publications Division, ISBN 92-9092-915-4, p. 101 - 102

3D numerical model for a superbubble : simulated thermal X-ray emission

Reyes-Iturbide J.[1]**, Velazquez P.F., Rosado M., Esquivel A., Gonzalez R.**
[1]*Instituto de Astronomia, Universidad Nacional Autonoma de Mexico*

We present 3D numerical simulations of a superbubble generated by the interaction of multiple stellar winds with an inhomogeneous surrounding interstellar medium (ISM). The simulations were carried out with the adaptive grid code Yguazu-a. We studied how inhomogeneities in the ISM affects the evolution, morphology and emission of the superbubble. In order to do a more direct comparison with observations, synthetic X-ray emission maps were generated from numerical results, employing the database CHIANTI, finding which parameters are important to describe superbubbles.

Clumping in [WC]-type Central Stars from electron-scattering line wings

Todt H.[1], **Hamann W.-R., Gräfener G.**
[1] *Universität Potsdam*

The degree of stellar-wind clumping can be estimated from a detailed fit of strong emission lines together with their electron-scattering wings. This method has been applied to a couple of massive Wolf-Rayet stars in the past. Similarly dense stellar winds are also found among low-mass stars: a significant number of central stars of planetary nebulae (CSPN) are classified as [WC] type, showing strong mass-loss and a hydrogen-deficient composition. We try constrain the clump density contrast (or volume filling factor) in these [WC]-type winds from the electron-scattering line wings and compare with the wind clumping in massive WC stars

Simulation of decoupling effect in two-component stellar wind

Votruba V.[1]**, Feldmeier A., Kubát J.**
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We developed hydrodynamical code for simulation of two-component stellar wind, composed from passive plasma and absorbing ions. Radiative force acting on absorbing ions only while passive plasma is driven by dynamical friction. We applied this code on low-dense wind , where decoupling effect was predicted. As a result we received decoupled stellar wind, with runaway effect.

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