THE HOT STAR NEWSLETTER

An electronic publication dedicated to A, B, O, Of, LBV and Wolf-Rayet stars
and related phenomena in galaxies

No. 37 February 1998

editor: Philippe Eenens http://www.astro.ugto.mx/~eenens/hot/

eenens@carina.astro.ugto.mx http://www.star.ucl.ac.uk/~hsn/index.html

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Accepted Papers

The WC10 Central Stars CPD–56°8032 and He 2–113: III. Wind Electron Temperature and Abundances

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We present a direct spectroscopic measurement of the wind electron temperatures and a determination of the stellar wind abundances of the WC10 central stars of planetary nebulae CPD–56°8032 and He 2–113, for which high resolution (0.15 Å) UCLES echelle spectra have been obtained using the 3.9 m AAT.

The intensities of dielectronic recombination lines, originating from auto–ionising resonance states situated in the $C^{2+} + e^{-}$ continuum, are sensitive to the electron temperature through the populations of these states which are close to their LTE values. The high resolution spectra allow the intensities of fine–structure components of the dielectronic multiplets to be measured. New atomic data for the autoionization and radiative transition probabilities of the resonance states are presented and used to derive wind electron temperatures in the two stars of 21 300 K for CPD–56°8023 and 16 400 K for He 2–113. One of the dielectronic lines is shown to have an autoionization width in agreement with the theoretical predictions. Wind abundances of carbon with respect to helium are determined from bound–bound recombination lines and are found to be C/He=0.44 for CPD–56°8023 and C/He=0.29 for He 2–113 (by number). The oxygen abundances are determined to be O/He=0.24 (by number) for CPD–56°8023 and 0.26 for He 2–113.

The effect of optical depth on the temperature and abundance determinations is investigated by means of a Sobolev escape probability model. We conclude that the optically thicker recombination lines can still be used for abundance determinations provided their upper levels are far from LTE.

Accepted by Monthly Notices of the RAS
Preprints from orsola@astro.phys.ethz.ch

CCD images and longslit spectroscopy of the ring nebula around θ Mus

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We present the first digital CCD images and longslit spectroscopy of the optical ring nebula around the Wolf-Rayet star θ Mus . The CCD images obtained through narrow band filters centered at [O III] and H_α, show that the nebula has a filamentary structure, similar to supernova remnants, mainly seen in [O III]. A spatial detachment between [O III] and H_α images suggests excitation stratification, or multiple rings. An analysis of the physical conditions in the nebula was performed by means of longslit CCD spectra. The spectral images show that the nebula is of low density and medium excitation. By means of quotients of recombination and collisional spectral line fluxes we determine that the principal excitation mechanism is photoionization. We have determined the electronic temperature and density, and chemical abundances for the Oxygen at different sites within the nebula. Nebular chemical abundances are found to be similar with the Galactic ISM, indicating that the nebula is mainly composed by swept up material.

Accepted by Monthly Notices of The Royal Astronomical Society
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Hubble Space Telescope Detection of Optical Companions of WR 86, WR 146 and WR 147: Wind Collision Model Confirmed

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Hubble Space Telescope (HST) WFPC2 images of the radio-binary Wolf-Rayet stars WR 146 and WR 147, as well as the 0.2" visual binary WR 86, resolve each of them into two very close optical components. The colors of these optical pairs are similar, indicating that they are likely to be physically bound WR+OB systems at the same distance. Comparison of the locations of the optical components

of WR 146 and WR 147 with high resolution radio maps strikingly demonstrates that the nonthermal radio components arise between the optical binary components, closer to the OB component than the WR. This is as expected if the nonthermal radio emission results from the collision of the stellar winds of the binary components seen in the HST images.

The similar magnitudes and colors determined for the components of WR 86 from our HST images, combined with an analysis of the unresolved, combined WC7+OB optical spectrum, indicates an absolute magnitude for the WC7 component of about $M_V \sim$ -5.

Accepted by The Astronomical Journal
Preprints from wallace@stsci.edu

The spin-up of contracting red supergiants

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We report on a mechanism which may lead to a spin-up of the surface of a rotating single star leaving the Hayashi line, which is much stronger than the spin-up expected from the mere contraction of the star.

By analyzing rigidly rotating, convective stellar envelopes, we qualitatively work out the mechanism through which these envelopes may be spun up or down by mass loss through their lower or upper boundary, respectively. We find that the first case describes the situation in retreating convective envelopes, which tend to retain most of the angular momentum while becoming less massive, thereby increasing the specific angular momentum in the convection zone and thus in the layers close to the stellar surface. We explore the spin-up mechanism quantitatively in a stellar evolution calculation of a rotating $12\,M_\odot$ star, which is found to be spun up to critical rotation after leaving the red supergiant branch.

We discuss implications of this spin-up for the circumstellar matter around several types of stars, i.e., post-AGB stars, B[e] stars, pre-main sequence stars, and, in particular, the progenitor of Supernova 1987A.

Accepted by Astronomy and Astrophysics
Preprints from ahg@mpa-garching.mpg.de
or on the web at http://www.mpa-garching.mpg.de/Stars/Preprints/7414.ps.gz

Clumping-corrected mass-loss rates of Wolf-Rayet stars

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Mass-loss rates of Galactic Wolf–Rayet stars have been determined from their radio emission power and spectral index ($\alpha = d\ln f_\nu / d\ln\nu$), accounting for the clumped structure and (potential) variable ionization in their outer winds. The average spectral index between mm- and cm- wavelengths is ∼0.77 for WN stars and ∼0.75 for WC stars, in contrast with ∼0.58 expected for smooth winds. The observed wavelength dependence of α can be explained using clumped wind models in some cases, with shocks (at 30–100 stellar radii) producing a higher ionization zone in the outer wind.

We obtain an empirical formula relating mass-loss with observed optical emission line equivalent widths, with application to stars without measured radio fluxes. Clumping-corrected mass-loss rates are generally lower than those obtained by current smooth wind models. Specifically we find for WN stars log $\dot{M}$(clumpy)–log $\dot{M}$(smooth)=−0.19 (σ=0.28) and log $\dot{M}$(clumpy)–log $\dot{M}$(smooth)=−0.62 (σ=0.19) for WC stars. New mass-loss rate estimates agree very well with (clumping independent) determinations of WR components in binary systems.

Accepted by Astronomy & Astrophysics
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A dedicated photometric system for the classification of Wolf-Rayet stars

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We present here tests of a five-filter photometric system aimed at WR classification. In addition to the well-known easy separation between the WN and WC spectral types, these tests indicate interesting potentialities in the discrimination of subgroups among the WN and the WC which look well related to the classical subtypes. The proposed combinations of filters (or derived ones) bear enough discriminating power to satisfy some evolutionary studies in crowded fields where spectroscopic follow-up is not possible.

Accepted by Astronomy & Astrophysics Suppl.
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or on the web at `http://vela.astro.ulg.ac.be/preprint/`

Submitted Papers

Line-Driven Stellar Winds: The Dynamical Role of Diffuse-Radiation Gradients and Limitations to the Sobolev Approach

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Line-driven stellar winds from hot, luminous OB stars have been most extensively modelled as smooth, *steady-state*, supersonic outflows for which a local, *Sobolev* line-transfer treatment is used to compute the line-driving force. In this paper we apply a recently developed, nonlocal *Escape-Integral-Source-Function* (EISF) method for computing the line-force toward *time-dependent* simulations. In accord with previous linear perturbation analyses, the initially most unstable flow fluctuations in numerical simulations here exhibit an *outward* phase propagation characterized by a *positive* correlation between velocity and density variations. However, such outward -mode waves quickly saturate by self-shadowing effects at a relatively low amplitude. Thus, much as in previous instability simulations, the nonlinear wind structure is still dominated by *reverse* shocks that arise from the somewhat slower (but less easily saturated) growth of *inward* mode waves with an *anti*-correlated velocity-density structure.

An unexpected result involves the important role that the diffuse, scattered radiation field – ignored in a Sobolev approach – plays in the dynamics around the wind sonic point. In particular, we find that the strong asymmetry in the forward and backward escapeprobabilities near the sonic point induces a marked depression in the scattering source function in this region. The resulting *inwardly* directed diffuse line-force can significantly alter the mean wind conditions inferred from *steady* wind models using the conventional Sobolev approach. We discuss the implications of these results, and consider in particular why these effects have been overlooked in previous wind analyses.

Submitted to Ap.J.
Preprints from owocki@bartol.udel.edu
or by anonymous ftp to ftp.bartol.udel.edu/owocki/eisf2_pp.uue

A Long Period Spectroscopic Binary in the O-Star Multiple System HD 193322

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We present radial velocity measurements and a single-lined spectroscopic orbit for the bright O-type star, HD 193322 A, which we show to be a 311 d binary system that has a distant third companion (detected by speckle interferometry) in a 31 y orbit. We suggest that the speckle companion appears in the spectrum as a broad-lined component of early B-type (and is possibly a rapidly rotating Be star). We also present a spectrum of the visual companion, HD 193322 B, which appears to be an unresolved, double-lined spectroscopic binary. Thus, HD 193322, the central object in the open cluster Collinder 419, is a multiple system that contains at least 5 stars (possibly 7 if the C and D components are physical). Such systems may play a key role in the dynamical ejection of runaway stars from young clusters.

Submitted to PASP
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or by anonymous ftp to chara.gsu.edu/Gies/McKibben.ps.gz

Theses

Hot-Star Winds: Mass Loss and Structure

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In this work we investigate whether the infrared and radio continua of hot stars are compatible with a smooth wind. We have gathered from the literature all infrared, millimetre and radio continuum observations for a sample of 18 OB stars. These observations are supplemented with UBV data.

We have developed a spherically symmetric stellar wind code that self-consistently solves the equations of radiative transfer and statistical equilibrium for a mixture of H and He. A Hubeny model photosphere provides the input of radiation at the base of the wind. The density and velocity are given by the force multiplier formalism, with empirical force multiplier parameters. We call this the smooth wind model.

We compare the continuum observations with the results of our stellar wind model. The significance of discrepancies between theory and observations is judged on the basis of the following criteria: there should be more than one discrepancy (as a single discrepancy could in principle be due to an observational mismeasurement) and the discrepancies should be large to the scatter on the observations. For four stars from our sample (HD 66811, HD 38771, HD 36486 and HD 30614) the far infrared ($\geq 20\mu$m) fluxes are significantly underestimated by the theoretical model. This points to an additional emission mechanism, not present in the smooth wind model. For the other stars from our sample, there is insufficient observational evidence to confirm – or exclude – the presence of such additional emission. Hence, the fact that we find evidence for additional emission in 4 out of 18 stars, should not be interpreted in a statistical sense.

In the light of other observational evidence, we consider wind structure to be the most plausible source of additional continuum radiation. A structured wind will have a stronger infrared and radio continuum, due to the density-squared dependence of the free-free and bound-free emission. Other explanations, such as a more gradual acceleration of the stellar wind (i.e. a larger value of β) are shown to be inadequate.

It is useful to distinguish between two kinds of structure. The influence of *stochastic* structure has already been studied, i.a. by Lamers & Waters. In this work we study larger, *localised* structure in the form of complete or partial shells. By fitting the models to the observations we estimate the position and the strength of the shells. Due to the integrated nature of the infrared continuum radiation, one cannot differentiate between a shell and a co-rotating interaction region on the basis of these observations alone.

The presence of wind structure could considerably lower radio mass loss rates, if this structure persists into the radio formation region. We give a first estimate of the effect of structure on radio mass loss rates and outline how we will derive a more precise estimate.

This PhD thesis was presented at the Vrije Universiteit Brussel, 28 November 1997, under the direction of Prof. W. van Rensbergen and Dr. R. Blomme

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Cool Wolf-Rayet Central Stars and their Planetary Nebulae

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The research presented in this thesis is concerned with the properties of Wolf–Rayet (WR) central stars and their planetary nebulae (PNe). The analysis was carried out on high (R=30 000) and intermediate (R=5 000) resolution optical and UV spectra of a sample of WR central stars and their PNe. The emphasis has been the determination of consistent stellar and nebular results via the use of a range of empirical and theoretical methods.

The definition of a robust classification system for central stars with WC spectra was proposed, consistent with the scheme of Smith et al. (1990, ApJ 358, 229) designed for massive WC stars. Our WC classification criteria have been thoroughly compared with past schemes and, in particular, WO and WCE classifications have been unified.

Nebular and stellar parameters and distances of the [WC10] central stars CPD–56°8032, He 2–113, M 4–18 and of the peculiar [WC9] SwSt 1 were determined. Distances were given a special consideration since they are the key to determining the range of luminosities of WR central stars. For instance, the difficulty in reconciling distances, luminosities and PNs characteristics for the spectroscopic twin [WC10] central stars He 2–113 and M 4–18, indicates the possibility of a slower evolution for M 4–18; this demonstrates that two identical WR central stars might follow different evolutionary paths.

¿From nebular analysis it has emerged that the most likely origin of the broad pedestal observed at the base of the Balmer profiles of CPD–56°8032, He 2–113 and M 4–18 is nebular rather than stellar emission as had been proposed by Leuenhagen et al. (1996, AA 312, 167). This reinstates WC central stars within their former hydrogen–free status so that the overlap between hydrogen–rich and hydrogen–poor central stars sequences is no longer obvious. Extremely high nebular C/H number ratios have been derived for CPD–56°8032 and He 2–113. Carbon enrichment can be expected in a variety if situations, however nebular C/H number ratios for M 4–18 and SwSt 1 are much lower showing that a high C/H ratio is not a prerogative of WR central stars. If carbon enrichment of the PN is at the hand of the stellar wind, the size and characteristics of the PN and the central star might explain the lack of carbon enrichment. Nebular parameters and abundances can be reproduced by photoionization modeling for the PNe of M 4-18 and SwSt 1 using WR model atmospheres, while modeling of CPD–56°8032 and He 2–113 was hampered by dust-gas competition in the ionized regions and no clear results could be obtained.

HST images, presented here for the first time, revealed that CPD–56°8032, He 2–113 and SwSt 1 are irregular and compact, while the PN of M 4-18 has a more developed morphology and, with a lower electron density than either of the other three, is certainly older, despite its spectrum being almost identical to that of He 2–113. No halo or second larger shell, which might reveal an association with the *born–again* scenario (Iben et al. 1983, ApJ 264, 605) is observed in these images.

Stellar recombination line analysis and non–LTE WR wind modeling (Hillier 1990, AA 231, 111) were used to determine stellar wind abundances and wind parameters. The use of dielectronic recombination lines was used for the determination of the wind electron temperature in the C II line forming region of 5 [WCL] stars (17 000 to 20 000 K). By comparison with the electron temperatures predicted by the wind models, this constitutes the first confirmation of the assumption of radiative equilibrium in the winds of WR stars. Optical depth effects on C II bound–bound recombination lines were shown *not* to preclude their use for abundance determination.

It is argued that evidence is accumulating towards the fact that there are different evolutionary sequence for all post–AGB WC central stars of PN, in the sense that it does not appear that the [WC] stars are *either all* post–AGB *or all* created though a *born–again* scenario.

Thesis done under the direction of M.J. Barlow and P.J. Storey at University College London
and accepted in October 1997

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