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Accepted Papers

Chandra Observations of Associates of η Car: II. Spectra

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The low resolution X-ray spectra around η Car covering Tr 16 and part of Tr 14 have been extracted from a Chandra CCD ACIS image. Various analysis techniques have been applied to the spectra based on their count rates. The spectra with the greatest number of counts (HD 93162 = WR 25, HD 93129AB, and HD 93250) have been fit with a wind model, which uses several components with different temperatures and depths in the wind. Weaker spectra have been fit with Raymond-Smith models. The weakest spectra are simply inter-compared with strong spectra. In general, fits produce reasonable parameters based on knowledge of the extinction from optical studies and on the range of temperatures for high and low mass stars. Direct comparisons of spectra confirm the consistency of the fitting results and also hardness ratios for cases of unusually large extinction in the clusters. The spectra of the low mass stars are harder than the more massive stars. Stars in the sequence evolving from the main sequence (HD 93250) through the system containing the O supergiant (HD 93129AB) and then through the Wolf-Rayet stage (HD93162), presumably ending in the extreme example of η Car, share the property of being unusually luminous and hard in X-rays. For these X-ray luminous stars, their high mass and evolutionary status (from the very last stages of the main sequence and beyond) is the common feature. Their binary status is mixed, and magnetic status is still uncertain.

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NGC 604, the Scaled OB Association (SOBA) Prototype. I: Spatial Distribution of the Different Gas Phases and Attenuation by Dust

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We have analyzed HST and ground-based data to characterize the different gas phases and their interaction with the Massive Young Cluster in NGC 604, a Giant H II Region in M33. The warm ionized gas is made out of two components: a high-excitation, high-surface brightness H II surface located at the faces of the molecular clouds directly exposed to the ionizing radiation of the central Scaled OB Association; and a low-excitation, low-surface brightness halo that extends to much larger distances from the ionizing stars. The cavities created by the winds and SN explosions are filled with X-ray-emitting coronal gas. The nebular lines emitted by the warm gas experience a variable attenuation as a consequence of the dust distribution, which is patchy in the plane of the sky and with clouds interspersed among emission-line sources in the same line of sight. The optical depth at Hα as measured from the ratio of the thermal radio continuum to Hα shows a very good correlation with the total CO ($1 \rightarrow 0$) column, indicating that most of the dust resides in the cold molecular phase. The optical depth at Hα as measured from the ratio of Hα to Hβ also correlates with the CO emission but not as strongly as in the previous case. We analyze the difference between those two measurements and we find that $\leq 11\%$ of the H II gas is hidden behind large-optical-depth molecular clouds; we pinpoint the positions in NGC 604 where that hidden gas is located. We detect two candidate compact H II regions embedded inside the molecular cloud; both are within short distance of WR/Of stars and one of them is located within 16 pc of a RSG. We estimate the age of the main stellar generation in NGC 604 to be ≈ 3 Ma from the ionization structure of the H II region, a value consistent with previous age measurements. The size of the main cavity is smaller than the one predicted by extrapolating from single-star wind-blown bubbles; possible explanations for this effect are presented.

To appear in the September 2004 issue of AJ

Preprints from `astro-ph/0406130` *with a ludicrous resolution for the figures or on the web at* `http://www.stsci.edu/~jmaiz` *at full resolution.*

Waiting in the Wings: Reflected X-ray Emission from the Homunculus Nebula

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We report the first detection of X-ray emission associated with the Homunculus Nebula which surrounds the supermassive star η Carinae. The emission is characterized by a temperature in excess of 100 MK, and is consistent with scattering of the time-delayed X-ray flux associated with the star. The nebular emission is bright in the northwestern lobe and near the central regions of the Homunculus, and fainter in the southeastern lobe. We also report the detection of an unusually broad Fe K fluorescent line, which may indicate fluorescent scattering off the wind of a companion star or some other high velocity outflow. The X-ray Homunculus is the nearest member of the small class of Galactic X-ray reflection nebulae, and the only one in which both the emitting and reflecting sources are distinguishable.

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or on the web at `http://xxx.lanl.gov/pdf/astro-ph/0406180`

3D hydrodynamical simulations of corotating interaction regions in rotating line-driven stellar winds

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I present radiation hydrodynamics simulations of rotating line-driven O-star winds subject to surface variations taking the shape of localized bright Gaussian spots. Following the original work of Cranmer & Owocki, I investigate the influence on resulting corotating interaction regions (CIRs) of 1) extending the simulation domain from 2D (equatorial plane) to 3D (octant of a sphere) and 2) explicitly account for the lateral components of the radiative acceleration, computed using a multiple-ray quadrature of the visible stellar disk at all wind locations. I identify the wind spin down effect of Gayley & Owocki, present in unperturbed rotating hot star winds. In 2D simulations, the perturbed azimuthal component of the radiative acceleration does not change the gross properties of CIRs. However, the resulting perturbed azimuthal velocity extrema are enhanced by a factor of 50 compared to unperturbed models, so that its magnitude is now a few times greater than the adopted isothermal sound speed. This lateral broadening of wind material at the vertical of a spot leads to an overall weakening of the CIR compression compared to Cranmer & Owocki. In 3D, the extra dimension weakens further the

CIR compression and associated velocity kink compared to equivalent 2D simulations. 3D simulations confirm the assumption of Cranmer & Owocki that the angular extent of a surface spot influence is similar in the azimuthal and latitudinal directions. 3D simulations for off-equatorial spots reveal the presence of CIRs advecting out along a fixed latitude, i.e. centred on the spot latitude and contained within a conic shell whose latitudinal thickness is of the order of the full-width-half-maximum of the Gaussian spot. Thus, the CIR properties are essentially independent of the latitude of base perturbations. These results suggest that the key properties of a line-driven wind subject to base brightness variations are well described by considering only the perturbation on the radial radiative acceleration, with, for a Gaussian spot, an angular modulation solely dependent on the distance to the spot location, irrespective of the latitudinal or azimuthal direction. Following the technique of Cranmer & Owocki, I have performed spectroscopic line synthesis computations based on 2D hydrodynamical inputs obtained using the multi-ray computation of the multi-component perturbed radiative acceleration or its perturbed radial component. For both P-Cygni and emission line profiles, the differences in hydrodynamical inputs have unnoticeable effects on profile shapes. The method developed in Cranmer & Owocki is therefore adequate for extensive investigations of the large-amplitude long-term line profile variability identified in many O-star spectra.

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Hydrogen in the atmosphere of the evolved WN3 Wolf-Rayet star WR3: defying an evolutionary paradigm?

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WR3 is the brightest very-early type WN star in the sky. Based on several years of time-resolved spectroscopy and precision photometry on various timescales, we deduce that WR3 is most likely a single, weak-lined star of type WN3ha (contrary to its current calalogue-type of WN3 + O4), with H-lines occurring both in emission and absorption in its wind. This conclusion is confirmed and strengthened via detailed modeling of the spectrum of WR3. Given the similarity of WR3 with numerous H-rich WNE stars in the LMC and especially the SMC, and its location towards the metal-deficient exterior of the Galaxy, we conclude that rotationally-induced meridional circulation probably led to the apparently unusual formation of this hot Galactic WN star with enhanced hydrogen. Though

we cannot completely rule out the possibility of a binary with a low orbital inclination and/or long period, we regard this latter possibility as highly unlikely.

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or on the web at http://gemini.tccw.wku.edu:8080/∼sergey/WR3/WR3.ps

The Double-Lined Spectrum of LBV 1806−20

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Despite much theoretical and observational progress, there is no known firm upper limit to the masses of stars. Our understanding of the interplay between the immense radiation pressure produced by massive stars in formation and the opacity of infalling material is subject to theoretical uncertainties, and many observational claims of "the most massive star" have failed the singularity test. LBV 1806−20 is a particularly luminous object, L∼10^6 $L_\odot$, for which some have claimed very high mass estimates ($M_{\rm initial}$>200 $M_\odot$), based, in part, on its similarity to the Pistol Star. We present high-resolution near-infrared spectroscopy of LBV 1806−20, showing that it is possibly a binary system with components separated in velocity by ∼70 km s^{-1}. If correct, then this system is not the most massive star known, yet it is a massive binary system. We argue that a binary, or merged, system is more consistent with the ages of nearby stars in theLBV 1806−20 cluster. In addition, we find that the velocity of $V_{\rm LSR}$=36 km s^{-1} is consistent with a distance of 11.8 kpc, a luminosity of $10^{6.3}$ $L_\odot$, and a system mass of ∼130 $M_\odot$.

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A 2dF survey of the Small Magellanic Cloud

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We present a catalogue of new spectral types for hot, luminous stars in the Small Magellanic Cloud. The catalogue contains 4161 objects, giving an order of magnitude increase in the number of SMC stars with published spectroscopic classifications. The targets are primarily B- and A-type stars (2862 and 853 objects respectively), with 1 Wolf-Rayet, 139 O-type, and 306 FG stars, sampling the main sequence to ∼mid-B. The selection and classification criteria are described, and objects of particular interest are discussed, including UV-selected targets from the Ultraviolet Imaging Telescope (UIT) experiment, Be and B[e] stars, 'anomalous A supergiants', and composite-spectrum systems. We examine the incidence of Balmer-line emission, and the relationship between Hγ equivalent width and absolute magnitude for BA stars.

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Non-LTE Line-Formation for Hydrogen Revisited

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We discuss aspects of non-LTE line formation for hydrogen in early-type stars. We evaluate the effect of variations in the electron-impact excitation cross sections in model atoms of differing complexity by comparison with observation. While the Balmer lines are basically unaffected by the choice of atomic data, the Paschen, Brackett and Pfund series members allow us to discriminate between the different models. Non-LTE calculations based on the widely-used approximation formulae of Mihalas, Heasley & Auer and of Johnson fail to simultaneously reproduce the optical and IR spectra over the entire parameter range. The use of data from *ab-initio* calculations up to principal quantum number $n \leq 7$ largely solves the problem. We recommend a reference model using the available data. This model is of general interest because of the ubiquity of the hydrogen spectrum.

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Preprints available on the web: `http://arxiv.org/abs/astro-ph/0406458`

The influence of rotation in radiation driven wind from hot stars: New solutions and disk formation in Be stars

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The theory of radiation driven wind including stellar rotation is re-examined. After a suitable change of variables, a new equation for the mass loss rate is derived analytically. The solution of this equation remains within 1% confidence when compared with numerical solutions. Also, a non-linear equation for the position of the critical (singular) point is obtained. This equation shows the existence of an additional critical point, besides the standard m–CAK critical point. For a stellar rotation velocity larger than $\sim 0.7 - 0.8\ V_{breakup}$, there exists only one critical point, located away from the star's surface. Numerical solutions crossing through this new critical point, are attained. In these cases, the wind has a very low terminal velocity and therefore a higher density wind. Disk formation in Be stars is discussed in the frame of this new line driven stellar wind solution.

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η Carinae: the 1998 brightening and the smearing-out effect

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A comparison of broad-band photometry of the Homunculus (ground-based data) and of broad-band and narrow-band photometry of the central region (HST-based) from 1997 to 2003 reveals that, apart from the brightening in 1998, the Homunculus as well as the central star varied in a very similar way. This excludes smearing-out effects as an explanation for the difference between the brightening of the central region and that of the Homunculus during 1998. A plausible reason for the homologous light behaviour is enhanced extinction decrease in the line-of-sight to the central region during a global brightening occurring after the 1998.0 spectroscopic event. ¿From 1998 to 2004 there is indeed a brightness excess of $\sim 0\overset{\mathrm{m}}{.}3$ between the Homunculus and the extrapolated secular brightening. We also illustrate that ground-based aperture photometry of the Homunculus is a reliable diagnostic tool for studying the variability of the central star.

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Metallicity in the Galactic Center: The Arches cluster

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We present a quantitative spectral analysis of five very massive stars in the Arches cluster, located near the Galactic center, to determine stellar parameters, stellar wind properties and, most importantly, metallicity content. The analysis uses a new technique, presented here for the first time, and uses line-blanketed NLTE wind/atmosphere models fit to high-resolution near-infrared spectra of late-type nitrogen-rich Wolf-Rayet stars and OfI$^+$ stars in the cluster. It relies on the fact that massive stars reach a maximum nitrogen abundance that is related to initial metallicity when they are in the WNL phase. We determine the present-day nitrogen abundance of the WNL stars in the Arches cluster to be 1.6% (mass fraction) and constrain the stellar metallicity in the cluster to be solar. This result is invariant to assumptions about the mass-luminosity relationship, the mass-loss rates, and rotation speeds. In addition, from this analysis, we find the age of the Arches cluster to be 2-2.5 *Myr*, assuming coeval formation.

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or on the web at http://arxiv.org/abs/astro-ph/0407188

Stellar evolution with rotation XII: Pre–supernova models

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We describe the latest developments of the Geneva stellar evolution code in order to model the pre-supernova evolution of rotating massive stars. Rotating and non-rotating stellar models at solar metallicity with masses equal to 12, 15, 20, 25, 40 and 60 solar masses were computed from the ZAMS until the end of the core silicon burning phase. We took into account meridional circulation, secular shear instabilities, horizontal turbulence and dynamical shear instabilities. Most of the differences between the pre-supernova structures obtained from rotating and non-rotating stellar models have their origin in the effects of rotation during the core hydrogen and helium burning phases. The effects of rotation on pre-supernova models are significant between 15 and 30 solar masses. Indeed, rotation increases the core sizes (and the yields) by a factor ~ 1.5. Above 20 solar masses, rotation may change the colour of the supernova progenitors (blue instead of red supergiant) and the supernova type (Ib instead of II). Rotation affects the lower mass limits for radiative core carbon burning, for iron core collapse and for black hole formation. For Wolf-Rayet stars (M ¿ 30 solar masses), the pre-supernova structures are mostly affected by the intensities of the stellar winds and less by rotational mixing. Finally, the core of our rotating WR stars contain enough angular momentum to produce GRBs.

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A search for late-type supergiants in the inner regions of the Milky Way

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We present the results of a narrow-band infrared imaging survey of a narrow strip ($12'$ wide) around the galactic equator between 6° and 21° of galactic longitude aimed at detecting field stars with strong CO absorption, mainly late-type giants and supergiants. Our observations include follow-up low resolution spectroscopy ($R = 980$) of 191 selected candidates in the H and K bands. Most of these objects have photometric and spectroscopic characteristics consistent with them being red giants, and some display broad, strong absorption wings due to water vapor absorption between the H and K bands. We also identify in our sample 18 good supergiant candidates characterized by their lack of noticeable water absorption, strong CO bands in the H and K windows, and HK_S photometry suggestive of high intrinsic luminosity and extinctions reaching up to $A_V \simeq 40$ mag. Another 9 additional candidates share the same features except for weak H_2O absorption, which is also observed among some M supergiants in the solar neighbourhood. Interesting differences are noticed when comparing our stars to a local sample of late-type giants and supergiants, as well as to a sample of red giants in globular clusters of moderately subsolar metallicity and to a sample of bulge stars. A large fraction of the stars in our sample have CaI and NaI features markedly stronger than those typical in the local reference sample (both giants and supergiants), whereas the equivalent widths of the CO bands are similar or

weaker. In this regard, our stars in the inner Milky Way disk display differences very similar to those identified by other authors between cool giants and supergiants near the galactic center and their counterparts in the solar neighbourhood. We propose that the systematic spectroscopic differences of our inner Galaxy stars are due to their higher metallicities that cause deeper mixing in their mantles, resulting in lower surface abundances of C and O and higher abundances of CN, which contribute to the strength of the CaI and NaI features at low resolution. Our results stress the limitations of using local stars as templates for the study of composite cool stellar populations such as central starbursts in galaxies.

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Spitzer-IRS Spectroscopy of the Prototype Wolf-Rayet Star EZ CMa (HD 50896)

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We present mid-infrared *Spitzer*-IRS spectroscopy of the prototype WN star EZ CMa (HD 50896, WN4b). Numerous stellar wind lines of He II are revealed, plus fine-structure lines of [Ne III] 15.5μm and [O IV] 25.9μm. We carry out a spectroscopic analysis of HD 50896 allowing for line blanketing and clumping, which is compared to the mid-IR observations. We make use of these stellar properties to accurately derive Ne/He=1.2–1.8$\times10^{-4}$ and O/He=4.2–4.8$\times10^{-5}$ by number, for the first time in an early WN star. In addition, we obtain N/C$\sim$40 and N/O$\sim$50 by number, values in perfect agreement with current predictions for rotating massive stars at the end of interior hydrogen burning.

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Preprints on the web at `http://ssc.spitzer.caltech.edu/pubs/apjss/morris1.pdf`

Terminal Velocities of Luminous, Early-Type Stars in the Small Magellanic Cloud

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Ultraviolet spectra from the Space Telescope Imaging Spectrograph (STIS) are used to determine terminal velocities for 11 O and B-type giants and supergiants in the Small Magellanic Cloud (SMC) from the Si IV and C IV resonance lines. Using archival data from observations with the Goddard High-Resolution Spectrograph and the *International Ultraviolet Explorer* telescope, terminal velocities are obtained for a further five B-type supergiants. We discuss the metallicity dependence of stellar terminal velocities for supergiants, finding no evidence for a significant scaling between Galactic and

SMC metallicities for $T_{eff} < 30{,}000$ K, consistent with the predictions of radiation driven wind theory. A comparison of the v_∞/v_{esc} ratio between the SMC and Galactic samples, while consistent with the above statement, emphasizes that the uncertainties in the distances to galactic OB-type stars are a serious obstacle to a detailed comparison with theory. For the SMC sample there is considerable scatter in v_∞/v_{esc} at a given effective temperature, perhaps indicative of uncertainties in stellar masses.

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Submitted Papers

High Resolution X-ray Spectra of the Brightest OB Stars in the Cygnus OB2 Association

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The Cygnus OB2 Association contains some of the most luminous OB stars in our Galaxy and the brightest of which are also among the most luminous in X-rays. We obtained a *Chandra* High Energy Transmission Grating Spectrometer (HETGS) observation centered on Cyg OB2 No. 8a, the most luminous X-ray source in the Association. Although our analysis will focus on the X-ray properties of Cyg OB2 No. 8a, we also present limited analyses of three other OB stars (Cyg OB2 Nos. 5, 9, and 12). Applying standard diagnostic techniques as used in previous studies of early-type stars (e.g., Waldron & Cassinelli 2001), we find that the X-ray properties of Cyg OB2 No. 8a are very similar to those of other OB stars that have been observed using high-resolution X-ray spectroscopy. From analyses of the He-like ion fir emission lines (Mg XI, Si XIII, S XV, and Ar XVII), we derive radial distances of the He-like line emission sources and find that the higher energy ions have their lines form closer to the stellar surface than those of lower ion states. Also these fir-inferred radii are found to be consistent with their corresponding X-ray continuum optical depth unity radii. Both of these findings are in agreement with previous O-star studies, and again suggests that anomalously strong shocks or high temperature zones may be present near the base of the wind. The observed X-ray emission line widths ($HWHM \sim 1000\ kms^{-1}$) are also compatible with the observations of other O-star supergiants. Since Cyg OB2 No. 8a is similar in spectral type to ζ Pup (the only O-star which clearly shows asymmetric X-ray emission line profiles with large blue-shifts), we expected to see similar emission line characteristics. Contrary to other O-star results, the emission lines of Cyg OB2 No. 8a show a large range in line centroid shifts ($\sim$ -800 to +250 kms^{-1}). However, we argue that most of the largest shifts may be unreliable, and the resultant range in shifts is much less than those observed in ζ Pup. Although there is one exception, the H-like Mg XII line which shows a blue-shift of -550 kms^{-1}, there are problems associated with trying to understand the nature of this isolated large blue-shifted line. To address the degree of asymmetry in these line profiles, we present Gaussian best-fit line profile model spectra from ζ Pup to illustrate the expected asymmetry signature in the χ^2 residuals. Comparisons of the Cyg OB2 No. 8a best-fit line profile residuals with those of ζ Pup

suggest that there are no indications of any statistical significant asymmetries in these line profiles. Both the line shift characteristics and lack of line asymmetries are very puzzling results. Given the very high mass loss rate of Cyg OB2 No. 8a (approximately five times larger than previous *Chandra* observed O supergiants), the emission lines from this star should display a significant level of line asymmetry and blue-shifts as compared to other OB stars. We also discuss the implications of our results in light of the fact that Cyg OB2 No. 8a is a member of a rather tight stellar cluster, and shocks could arise at interfaces with the winds of these other stars.

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A Rigidly Rotating Magnetosphere Model for Circumstellar Emission from Magnetic OB Stars

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We present a semi-analytical approach for modeling circumstellar emission from rotating hot stars with a strong dipole magnetic field tilted at an arbitrary angle to the rotation axis. By assuming the rigid-field limit in which material driven (e.g., in a wind outflow) from the star is forced to remain in strict rigid-body co-rotation, we are able to solve for the effective centrifugal-plus-gravitational potential along each field line, and thereby identify the location of potential minima where material is prone to accumulate. Applying basic scalings for the surface mass flux of a radiatively driven stellar wind, we calculate the circumstellar density distribution that obtains once ejected plasma settles into hydrostatic stratification along field lines. The resulting accumulation surface resembles a rigidly rotating, warped disk, tilted such that its average surface normal lies between the rotation and magnetic axes. Using a simple model of the plasma opacity and emissivity, we calculate formal solutions of the equation of radiative transfer, and thereby obtain time-resolved synthetic emission-line spectra for the disk. Initial comparisons show an encouraging level of correspondence with the observed rotational phase variations of Balmer-line emission profiles from magnetic Bp stars like sigma Ori E.

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Grids of model spectra for WN stars, ready for use

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Grids of model atmospheres for Wolf-Rayet stars of the nitrogen sequence (WN subclass) are presented. The calculations account for the expansion of the atmosphere, non-LTE, clumping, and line blanketing from iron-group elements. Observed spectra of single Galactic WN stars can in general be reproduced consistently by this generation of models. The parameters of the presented model grids cover the whole relevant range of stellar temperatures and mass-loss rates. We point out that there is a degeneracy of

parameters for very thick winds; their spectra tend to depend only on the ratio $L/\dot{M}^{4/3}$. Abundances of the calculated grids are for Galactic WN stars without hydrogen and with 20% hydrogen (by mass), respectively. Model spectra and fluxes are available via internet (http://www.astro.physik.uni-potsdam.de/PoWR.html).

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Jobs

Two Tenure-Track Positions
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Attention: Sylvia Diez, Academic Secretary

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