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Accepted Papers

The WO Stars III. The planetary nebula NGC 5189 and its O VI sequence nucleus

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Long slit blue and red spectra of the planetary nebula NGC 5189 (PK 307 -3°1) with its O VI sequence central object were obtained with the ESO 1.52 m telescope, in order to establish criteria that allow the discrimination between the high mass WO stars and lower mass objects having similar spectral features. The NGC 5189 stellar nucleus shows a very high ionization spectrum with emission features of He II, C IV, and O V. N V should also be weakly present. The line width suggests a maximum wind velocity of 2800 km s^{-1}. Long slit spectra on various positions across the nebula were used to study the physical structure of NGC 5189. From the [S II] 671.7/673.2 nm line ratio we find that the electron density varies from 200 to 900 cm^{-3}. The ionization, as described by the He^{++}/He^{+} ratio, largely changes from one region to another, reaching a maximum of 2.5 in a low density region 20

arcsec E of the central star, and a minimum in the regions more distant from the star. NGC 5189 appears nitrogen enriched by about a factor 5 with respect to the cosmic value, while the helium abundance is normal. The chemical composition appears homogeneous throughout the nebula. We thus conclude that, in addition to the wind velocity, the chemical composition and homogeneity of the nebulae can be used to discriminate between high mass WO stars and "O VI sequence" PNN's.

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Cyg X-3: Evidence for a Black Hole

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We have observed time-variations in the profiles of several infrared emission lines from the X-ray binary, Cyg X-3, which is believed to consist of a Wolf-Rayet star and a compact object. We conclude that the variations are due to the orbital motion of the Wolf-Rayet star and derive a mass function for Cyg X-3 of 2.3 $M_\odot$. Assuming reasonable values for the mass of the Wolf-Rayet star and the inclination of the system, we obtain a range of masses 7-40 $M_\odot$ for the compact object, with a most likely value of 17 $M_\odot$. This strongly suggests that the compact component of Cyg X-3 is a black hole.

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The Nebula around HD168625: Morphology, Dynamics and Physical Properties

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We present a new set of medium resolution spectra and high resolution coronographic images of the nebula around the galactic Luminous Blue Variable (LBV) candidate HD 168625. The observations were carried out at the WHT and INT (La Palma) in June 1994 and October 1995, and at the ESO/NTT (La Silla) in May 1995. We find that between May and October 1995, HD168625 has dimmed by $\simeq$ 0.3 magnitudes and its temperature has diminished from 15000 K to 12000 K.
With the coronograph, we clearly resolve the structure in the circumstellar nebula. We find that the nebula has a complex morphology, which includes an inner elliptical shell (12" $\times$ 16" in size), and fainter filaments forming two outer loops in the northern and southern regions, suggesting an overall bipolar structure. The nebula is clearly associated with the star, on the basis of evidence from dynamical and chemical considerations. The nebular dynamics show a shell expanding at $\simeq$ 40 km/s, centered on the star, and the N enrichment detected suggests that the nebula is formed by material ejected by the star. We also find that the nebular parameters are very similar to those found in most

nebulae around LBVs: although the mass of the ionized gas of 0.5 $M_\odot$ (from the integrated Hα flux) is somewhat small, the temperature (an upper limit of 7000 K) and the electron density (average 1000 cm^{-3}) are fairly typical. Given the position of HD168625 in the HR diagram (at the lower end of the LBV strip, in close proximity to HR Carinae), we conclude that although HD168625 has not displayed LBV type variations in the past few decades, it has certainly undergone a LBV type outburst $\simeq 10^3$ years ago. In addition, the observed nebular bipolar morphology strengthens the suggestion (1995) that all LBV type nebulae are shaped by the same mechanism, involving a wind interacting with a density contrast.

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O Stars in Transition. II. Fundamental Properties and Evolutionary Status of Ofpe/WN9 Stars from *HST* Ultraviolet Observations

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We present new *HST/FOS* ultraviolet spectroscopic observations of seven LMC Ofpe/WN9 stars. We find that Ofpe/WN9 stars have slow winds with terminal velocities of about 400 km s^{-1} and high mass-loss rates of the order of 2 - 5 x 10^{-5} $M_\odot$/yr. Ofpe/WN9 stellar temperatures and radii are in the range 30,000 - 39,000 K, and 19 - 39 $R_\odot$, respectively. Stellar luminosities are between $\log(L/L_\odot) = 5.6$ and 6.3.

We study the Ofpe/WN9 stars winds and examine their evolutionary status. We find that Ofpe/WN9 stars are intermediate between O and WR stars in terms of the wind momentum flux. We also find that the stellar properties and wind momentum of the Ofpe/WN9 sample place them in the evolutionary sequence: O $\rightarrow$ Of $\rightarrow$ H - rich WNL $\rightarrow$ Ofpe/WN9, for initial stellar masses less than ~ 100 $M_\odot$.

In view of persisting discrepancies of standard massive star models with observations, we compute massive main sequence models according to three different evolutionary scenarios. We find that both, higher mass-loss rate and enhanced mixing between core and envelope, are required in order to yield models compatible with the derived stellar and wind properties of Ofpe/WN9 stars. The emerging picture may be consistent with earlier evidence of Ofpe/WN9 stars being quiescent LBVs. This idea is further strengthened by the highly reduced surface H mass fractions of the Ofpe/WN9 stars. We derive X_s = 0.5 to 0.3, which still excludes Ofpe/WN9 stars from being core He burning object, but is almost identical to the X_s values recently measured in LBVs.

ASCA Observations of γ^2 Velorum (WC8+O9I): The Variable X-ray Spectrum of Colliding Winds

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We present an analysis of two observations of the nearby Wolf-Rayet + O-star binary system γ^2 Velorum with the Advanced Satellite for Cosmology and Astrophysics (*ASCA*). These observations were taken at orbital phases $\phi = 0.4$ and $\phi = 0.5$, when the O-star is close to being in front of the WR star. At phase $\phi = 0.5$, γ^2 Vel is approximately four times more luminous in X-rays than at $\phi = 0.4$. We fit the X-ray spectra using simple combinations of absorbed Raymond-Smith emission models. We find evidence of a cool ($kT \sim 0.3$ keV) and a hot ($kT \sim 1.3$ keV) component in each spectrum. The hotter component suffers from variable absorption which suggests that it originates in a localized region between the two stars. Between $\phi = 0.4$ and 0.5 the absorbing column for this hotter component drops by a factor of 3 which accounts for most of the corresponding increase in flux.

These observations are interpreted in terms of a colliding wind model. The collision between the winds from the O-star and WR star generates a region of hot X-ray emitting gas. When the WR-star is in front, the dense WR wind effectively absorbs all the X-ray flux from the wind collision. However, when the O-star is in front the more diffuse wind of the O-star allows substantially more flux from the wind collision to escape. Our *ASCA* data confirms the colliding–wind origin for the hard X–ray emission from γ^2 Velorum, first identified from *ROSAT* data by Willis, Schild & Stevens (1995). At $\phi = 0.5$ the emergent luminosity is $L_x \sim 3.9 \times 10^{32}$ ergs s^{-1}.

We also use hydrodynamic models of colliding winds to calculate synthetic X-ray spectra for γ^2 Vel, which we then fit to the *ASCA* spectra. This allows us to determine fundamental stellar wind parameters for both stellar components from the X-ray spectra. In particular we determine a mass-loss rate for the WC8 star of $\sim 3 \times 10^{-5} M_\odot$ yr^{-1}, a value $\times$ 3 lower than determined by radio observations. The consequences of this are discussed.

We consider that we are definitely seeing colliding wind emission and also show the great potential for X-ray spectroscopy in determining fundamental wind parameters of WR (and other hot luminous) stars.

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Stellar evolution with rotation II: a new approach for shear mixing

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Recent observations show He– and N–enhancements in fast rotating O–type stars, while studies on shear mixing in rotating stars have shown that the μ–gradients generally inhibit mixing processes. However, these studies (including ours) ignored the other sources of turbulence, such as semiconvection and horizontal turbulence, which may be present in the medium and may modify the onset of shear mixing. Indeed, in massive stars most of the zone where μ–gradients would inhibit mixing according to the Richardson criterion are semiconvective, i.e. such a zone would experience some turbulence anyway.

This leads us to introduce the following working hypothesis: in a semiconvection region (or in any zone with other sources of turbulence) *some fraction of the local energy excess in the shear is degraded by turbulence to change the local entropy gradient.* Consistently with this hypothesis we derive the effects of the shear on the entropy gradient, then on the T– and μ–gradients, and express the fraction of the μ–gradient which can be diffused. From the basic equations describing the evolution of temperature

perturbations we obtain the velocities of fluid elements under some specific conditions, and then we get the associated diffusion coefficient D. Interestingly enough, the values of D tend towards the diffusion coefficient for semiconvection, when the shears become negligible, and towards the coefficient by Zahn (1992; cf. also Maeder and Meynet 1996) when shears dominate.

We also examine the coupling of shear mixing and thermal transport; a third order equation expressing the combined effects is obtained. The solutions for shears in semiconvective and radiative zones are examined in detail. The main result of the above developments is the slight progressive erosion of the μ–barriers in stars, for cases where the usual form of the Richardson criterion would have imposed an unsuperable threshold.

In Appendices 1 and 2 we rediscuss the diffusion coefficient for semiconvection and find a more general expression, not limited to the adiabatic case.

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High S/N Echelle Spectroscopy in Young Stellar Groups II. Rotational Velocities of Early-Type Stars in Sco OB2

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We investigate the rotational velocities of early-type stars in the Sco OB2 association. We measure $v\sin i$ for 156 established and probable members of the association. The measurements are performed with three different techniques, which are in increasing order of expected $v\sin i$: 1) converting the widths of spectral lines directly to $v\sin i$, 2) comparing artificially broadened spectra of low $v\sin i$ stars to the target spectrum, 3) comparing the He I λ4026 line profile to theoretical models. The sample is extended with literature data for 47 established members of Sco OB2. Analysis of the $v\sin i$ distributions shows that there are no significant differences between the subgroups of Sco OB2. We find that members of the binary population of Sco OB2 on the whole rotate more slowly than the single stars. In addition, we find that the B7–B9 single star members rotate significantly faster than their B0–B6 counterparts. We test various hypotheses for the distribution of $v\sin i$ in the association. The results show that we cannot clearly exclude any form of random distribution of the direction and/or magnitude of the intrinsic rotational velocity vector. We also investigate the effects of rotation on colours in the Walraven photometric system. We show that positions of B7–B9 single dwarfs above the main sequence are a consequence of rotation. This establishes the influence of rotation on the Walraven colours, due primarily to surface gravity effects.

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Spectroscopic study of the outflowing disk winds of B[e] supergiants in the Magellanic Clouds

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We report on UV high resolution spectroscopic observations of R 50 in the Small Magellanic Cloud, and R 82 and Hen S22 in the Large Magellanic Cloud obtained with the International Ultraviolet Explorer. The observed stars are supposed to represent edge-on cases of B[e] supergiants for which a two-component stellar wind model has previously been suggested. The spectra are characterized by P Cygni-type lines of Fe II. The observations show that the three stars have very slowly expanding winds with terminal velocities derived from the blue absorption edges of 75, 100, and 120 $\mathrm{km\,s^{-1}}$, respectively. Fits of the Fe II lines of Hen S22 and R 82 using the SEI method lead to even slower velocities of about 60 to 80 $\mathrm{km\,s^{-1}}$, respectively. This is about a factor of ten slower than the terminal velocity of normal B-type supergiants. The results are consistent with the assumption that the observed stars are viewed edge-on. We derived optical depths of the absorption components of the Fe II resonance lines of Hen S22 and R 82 of larger than about 5, yielding lower limits for the disk mass-loss rates of the order of $6\,10^{-7}$ and $5\,10^{-7}\mathrm{M_{\odot}\,yr^{-1}}$, respectively. The very low terminal velocity of the disk can be explained by the fact that the disks of the B[e] supergiants are on the low-velocity side of the bi-stability jump of radiation driven winds (which reduces $v_{\infty}/v_{\rm esc}$) and a rotational velocity of about 0.75 of the critical rotation velocity (which reduces the effective $v_{\rm esc}$). The effective gravity derived from v_{∞} and $v_{\infty}/v_{\rm esc} = 1.3$ is very low. It is on the order of $\log g_{\rm eff} = 0.2$ to 0.7.

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Spectroscopy of bright blue objects in the field of M81

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We obtained spectra of the seven brightest blue supergiant candidates in the SbI-II spiral galaxy M 81 which so far had no spectroscopic identification. As members of M 81 the candidates would be about as bright as the blue supergiants in the ScIII spiral M 33 and the LMC, but $\approx 1^{\rm m}$ brighter than in the morphologically similar galaxy M 31. Five objects were observed at the 3.5m telescope on Calar Alto, Spain, in Jan. 1992 with the TWIN spectrograph. Spectra of two additional objects were obtained with the 2.1m telescope at the Guillermo Haro Observatory, Mexico, in Feb. 1993 and Jun. 1995. Four of the objects turned out to be compact HII regions, two are foreground dwarfs. One object, M81-642,

shows a spectrum with an A to F spectral type. However, the absorption lines appear too broad for a supergiant. It is most likely a foreground star or star cluster. Assuming the generally accepted values for the reddening and the true distance modulus of M 81 of $A_V = 1^{\rm m}$ and $m - M = 27.6$ we conclude that the visually brightest early-type supergiant in M 81 is less bright than $M_V \approx -9.5$. The next brightest candidate would have $M_V \approx -9.1$ which is about as bright as the brightest blue supergiant in M 31 for which $M_V \approx -9.2$ was found in recent studies. It seems therefore that the population of massive stars in the SbI-II spiral M 81 resembles that of the morphologically similar galaxy M 31 which shows a deficiency of the most massive stars.

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Submitted Papers

The Spectrophotometric Variability of the Galactic Luminous Blue Variables AG Carinae and HR Carinae from 1978 to 1995

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We present a long term multiwavelength spectrophotometric study of two representative Galactic luminous blue variables (LBVs), AG Carinae and HR Carinae. We find that the assumption of bolometric constancy leads independently to an extinction of E(B-V) = 0.67±0.03 mag for AG Car and 1.2±0.1 mag for HR Car. We derive a luminosity for AG Car, of order $10^6 L_\odot$ for a distance of 6 kpc, that is consistent with model atmosphere analyses. During outburst, the wavelength at which antiphase continuum variability occurs steadily increases as the optical depth of the envelope increases. The star is now in the largest outburst of the last 20 years and we suggest that it may be in the process of forming dust. For HR Car, we derive a similar luminosity to AG Car, of order $10^6 L_\odot$ for a distance of 6 kpc. The optical depth in the circumstellar environment appears to be greater, with the entire ultraviolet varying in antiphase with the visual. Both variables are characterized by similar ultraviolet behavior during quiescence and similar timescales, of about one decade, between outbursts. Finally, during the outburst, it appears in both stars that the conditions are physically conducive to the formation of dust.

Submitted to A J *Preprints from* `SSHORE@paladin.iusb.indiana.edu`

Atmospheric NLTE-Models for the Spectroscopic Analysis of Luminous Blue Stars with Winds

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We present a new, fast and easy to use NLTE line formation code for "unified atmospheres" with spherical extension and stellar winds, developed for the (routine) spectroscopic analysis of luminous blue stars, covering the spectral range from "A" to "O" and including central stars of planetary nebulae.

The major features of our code are: Data driven input of atomic models; consistent photospheric stratification including continuum radiative acceleration and photospheric extension; "β-velocity law" for the wind; comoving frame or Sobolev plus continuum line transfer; fast solution algorithm for calculating line profiles, allowing for a consistent treatment of incoherent electron scattering.

We describe the code and perform thorough tests for models with H/He opacity, especially with respect to a comparison with plane-parallel, hydrostatic models in cases of thin winds. Our conclusions are:

Due in particular to our numerical treatment of the radiative transfer in the ionization and recombination integrals, the convergence rate of the solution algorithm is fast. The flux conservation is good, (maximum flux errors of order 2 to 3%), unless the atmospheric conditions are extreme, either with respect to mass-loss or to a large extension of the photosphere. (In these cases, our treatment of the temperature structure has to be improved). A comparison with plane-parallel results shows perfect agreement with the thin wind case. However, this comparison also reveals two interesting effects: First, the strength of the He I lines in hot O-stars is very sensitive to the treatment of electron scattering in the EUV. This might affect the effective temperature scale of early O spectral types. Second, the effects of photospheric extension become decisive for the gravity determination of stars close to the Eddington limit.

Finally, we demonstrate the differences in using the Sobolev vs. the comoving line transfer in the rate equations. We conclude that, in cases of moderate wind densities, comoving frame line transfer is inevitable for accurate quantitative work.

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Quantitative Analysis of the FUV, UV and optical spectrum of the O3 star HD 93129A

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A quantitative analysis of the extremely hot and massive galactic O3 If* supergiant HD 93129A is carried out using stellar wind and pseudo photospheric lines observed in the FUV, UV and optical

spectrum together with hydrodynamical NLTE model atmospheres. The analysis in the FUV is combined with spectrum synthesis of the molecular and atomic/ionic interstellar spectrum to disentangle stellar and interstellar blends. It is demonstrated that the combined stellar/interstellar spectrum synthesis technique is crucial for the determination of both interstellar column densities and stellar properties.

The fraction of hydrogen atoms in molecular form in the Carina interstellar clouds is found to be 0.1, smaller than one would expect for its E(B-V) value of 0.54. We attribute this to dissociation by the strong FUV radiation field of HD 93129A. The excitation temperature of ortho-hydrogen (J=1) is about 80K, whereas the excitation to higher levels requires temperatures up to 230 K in accordance with NLTE effects for interstellar H_2 as discussed in the literature. The abundance of HD relative to H_2 is of the order of 10^{-5}. For CO we obtain an upper limit of 2.6×10^{-5}. Abundances for the interstellar atomic and ionic species are also derived.

The terminal velocity of the stellar wind of HD 93129A is 3200 $\pm$ 200 km/s and the rate of mass-loss is $18\times10^{-6}\ M_{\odot}$/yr. The ionization equilibrium of the optical emission and P-Cygni lines of N III, N IV and N V is used to determine the effective temperature as $T_{\rm eff}$=52000$\pm$1000 K in reasonable agreement with previous values obtained from the helium ionization equilibrium. This high temperature is confirmed independently by an analysis of the Ar VI/Ar VII ionization equilibrium in the FUV. The luminosity of HD 93129A is log $L/L_{\odot}$=6.4$\pm$0.1 corresponding to a zero age main sequence mass of slightly in excess of 120 $M_{\odot}$. This very high mass is consistent with the mass determined from the stellar gravity and with the mass derived from V_{∞} using the theory of radiation driven winds. HD 93129A is thus the most luminous and most massive star known in our galaxy. The abundance determinations yield clear evidence of contamination with CNO-cycled matter in the atmosphere. The abundances of heavier elements are about solar. The presence of high ionization stages such as O VI can be explained by X-ray emission due to stellar wind shocks of low temperature (2.5×10^{6} K) corresponding to the jump velocity of 500 km/s obtained from UV and FUV P-Cygni profiles. Their luminosity is 1.6 dex smaller than the luminosity of the high temperature shocks (1.1×10^{7} K) observed directly with the ROSAT PSPC. Using effective temperature, gravity, radius and abundances as input parameters we calculate radiation driven wind models for HD 93129A. We find that the theory is able to reproduce the extreme stellar wind properties very precisely.

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Inhibition of Wind Compressed Disk Formation by Nonradial Line-Forces in Rotating Hot-Star Winds

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We investigate the effects of nonradial line-forces on the formation of a "Wind Compressed Disk" (WCD) around a rapidly rotating B-star. Such nonradial forces can arise both from asymmetries in the line resonances in the rotating wind, and from rotational distortion of the stellar surface. They characteristically include a latitudinal force component directed *away* from the equator, and an azimuthal force component acting *against* the sense of rotation. Here we present results from radiation-hydrodynamical simulations showing that these nonradial forces can lead to an effective *suppression* of the equatorward flow needed to form a WCD, as well as a modest ($\sim$ 20%) *spin-down* of the wind rotation. Furthermore, contrary to previous expectations that the wind mass flux should

be enhanced by the reduced effective gravity near the equator, we show here that gravity darkening effects can actually lead to a *reduced* mass loss, and thus lower density, in the wind from the equatorial region.

Overall, the results here thus imply a flow configuration that is markedly different from that derived in previous models of winds from rotating early-type stars. In particular, they represent a serious challenge to the WCD paradigm as an explanation for disk formation around Be and other rapidly rotating hot stars with line-driven stellar winds.

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The Stellar Oxygen Abundance Gradient in M33

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We report first results concerning stellar oxygen abundances in M33. Non-LTE model atmosphere and non-LTE line formation calculations were used to determine the oxygen abundance of B-type supergiants. By choosing stars located at different projected radial distance to the center of M33, we are able to determine the O abundance gradient. This is the first time that the stellar abundance gradient is determined in a spiral galaxy other than the Milky Way.

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Optical Spectroscopy of EZ CMa: Evidence for Large-Scale Structures in a Wolf-Rayet Wind

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We have carried out optical spectroscopy of the Wolf-Rayet star EZ CMa during 20 consecutive nights in January 1995 in support of the *IUE* Mega-project (see Massa et al. 1995). In parallel with this optical spectroscopy, we also monitored EZ CMa using narrow-band photometry. The light curve was found to be remarkably stable when folded with the $\mathcal{P}$=3.77-day period, and had a peak-to-valley amplitude of 0.1 mag.

The P Cygni absorption components of He I ł3889 and He I ł5876 display a similar global pattern of variability as was found for the simultaneously acquired UV profiles. The strengthening of the P Cygni absorption component of these transitions is associated with the maximum of the continuum flux. Conversely, the absorption trough of N V ł4604 gradually disappears as the star brightens. Although the emission parts of the lines are variable at different levels, they all show the same pattern of variability, which consists of phase-dependent shifts of extra emission components superposed on the profiles.

A strong correlation is found between the continuum-light level and the equivalent width of most transitions. The line skewness and the full-width at half-maximum show a daily recurrence timescale,

reflecting the light curve changes. We have addressed in a rigorous, statistical way the significance of the variations by calculating the "temporal variance spectrum". For any given line, we found enhanced variability at some velocities, although the whole profile displays a statistically significant level of variability.

Arguments against a compact companion as the cause of the observed periodic variability are presented. Instead, our observations strongly support the suggestion in the *IUE* Mega analysis (St-Louis et al. 1995) that the atypical level of periodic variability results from the rotation of a structured wind. We propose that the wind variability of EZ CMa is triggered by photospheric activity, or that the wind is controlled by a large-scale magnetic field.

Submitted to the Ap J *Preprints from* `stlouis@astro.umontreal.ca`
or by anonymous ftp to `ftp.astro.umontreal.ca; cd incoming/stlouis/EZ`

Large-scale variability in the high-resolution ultraviolet spectra of HD 50896

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We present an analysis of a time series of high-resolution IUE spectra, obtained over 6 consecutive days in 1992, of the enigmatic, variable Wolf-Rayet star HD 50896 (WN5). Large-scale variations are observed in all the major P Cygni profiles as well as in most of the subordinate transitions, which are well correlated with the $3^{\rm d}.766$ periodicity revealed by optical data. An increase in the UV continuum emission is found to be correlated with additional emission (or less absorption) at intermediate negative velocities (~ 1000 km s^{-1}), and by extra absorption at high negative velocities in the P Cygni absorption troughs. We suggest that the variations are caused by a mechanism intrinsic to the stellar wind, and the $3^{\rm d}.766$ periodicity is introduced by stellar rotation. Corotating interaction regions provide a possible qualitative interpretation for the observed variability.

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Reviews

Numbers and Distribution of Wolf-Rayet Stars in Local Group Galaxies: Clues to Massive Star Evolution

Philip Massey

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I review the current observational data on the number and distribution of Wolf-Rayet stars in the galaxies of the Local Group, and what these may be telling us about the evolution of massive stars.

The emphasis of this review will be on the WC/WN number ratio as seen in various galaxies, and its interpretation in terms of the effects of metallicity on massive star evolution and in variations in the initial mass function. I will also discuss the spectral subtypes and spectral properties of WR stars, the turn-off masses in clusters containing WR stars, the relative number of massive, unevolved stars and WRs (the "O/WR" ratio), and red supergiants and WRs.

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Preprints from massey@noao.edu

In Proceedings

Ultraviolet Evidence of Ionization Stratification in WR Winds

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Ionization stratification can be used to study the structure of WR winds. In an accelerated outflow the stratification is observable through the Doppler effect as an inverse correlation of ionization potential (IP) with line width (FWHM). However, not only the average line widths of different ions, but also the line widths of one series of HeII show stratification. The evidence of both effects is demonstrated here as a part of ongoing study. The ultraviolet spectra of WR stars obtained from IUE archive are used to get the IP vs. FWHM diagrams as well as the principal quantum number n of HeII (n-3) transitions vs. FWHM velocity relations. A systematic insight into stratification in Fowler HeII lines is provided on the basis of observations.

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Theses

Theoretical and Observational Consequences of Stellar Rotation and Magnetic Fields for Stellar Winds

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My dissertation concerns the study of stellar wind structure from (1) the theoretical modeling of stellar rotation and magnetic fields and (2) the development of observational diagnostics. First, I have investigated the effects of stellar rotation for the wind structure of stars across the H-R Diagram using principles from the Wind Compressed Disk (WCD) model. Relative to a spherical wind, the effect of rotation is to increase the wind density at the equator while decreasing the density near the poles. An investigation of mild equatorial density enhancements has led to the development of the Wind

Compressed Zone (WCZ) model. The WCZ model predicts that equatorial wind compressions are most likely to occur for stellar winds with low terminal speeds and/or radial velocity distributions that increase gradually from the base of the wind. In favorable cases stellar rotation can produce significant equatorial density enhancements in the winds of Wolf-Rayet stars, B supergiants, Asymptotic Giant Branch stars, and even some novae at moderate stellar rotations of 20–30% break-up. A spectral line diagnostic based on multiline observations at Infrared wavelengths has been developed to measure the velocity law in the Wolf-Rayet winds, to determine whether they are likely susceptible to wind compression effects.

The second major part of the thesis relates to the result that the WCZ model predicts the magnetic field structure in the wind, if the field strength is relatively weak. However, there are generally no good spectral diagnostics of sub-kiloGauss stellar magnetic fields. Magnetic fields at these low strengths are difficult to measure with the Zeeman effect, because the Zeeman line splitting is significantly smaller than the Doppler broadening. Thus, I have explored applications of the Hanle effect, that is sensitive to weaker magnetic fields than is the Zeeman effect, for probing the magnetic properties of stellar winds. The Hanle effect concerns the modification of resonance line polarization by the magnetic field. It has been used in studies of the Solar atmosphere, but not in other stars. Solutions for the Hanle effect in optically thin axisymmetric extended stellar envelopes have been derived. Relative to the zero field case, the Hanle effect can result in significant changes of the total line polarization. Consequences of the Hanle effect for the polarization of line profiles is also investigated, and analytic results are presented for a few special cases. A magnetic field can cause strong variations of the polarized line profile shape as compared to the case without a magnetic field. With multiline observations the Hanle effect will be a valuable diagnostic of stellar magnetic fields in the range 1-1000 Gauss.

A dissertation completed under the supervision of Prof. J. P. Cassinelli. *Direct inquiries to* `rico@astro.wisc.edu`

Dynamical Models of Winds from Rotating Hot Stars

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The hottest and most massive stars (spectral types O, B, Wolf-Rayet) have strong stellar winds that are believed to be driven by line scattering of the star's continuum radiation field. The atmospheres and winds of many hot stars exhibit the effects of rapid rotation, pulsation, and possibly surface magnetic fields, inferred from observations of ultraviolet spectral lines and polarization. The complex time variability in these observations is not yet well understood. The purpose of this dissertation is to model the dynamics of winds around rotating hot stars and synthesize theoretical observational diagnostics to compare with actual data.

Before dealing with rotation, however, we derive the theory of radiative driving of stellar winds, and uncover several new useful aspects of the theory for spherical, nonrotating stars. The presence of *limb darkening* of the stellar radiation is found to be able to increase the mass flux $\dot{M}$ by 10–15% over standard models assuming a uniformly-bright star, and the wind's asymptotic terminal velocity v_∞ should decrease by the same amount. We also introduce a new approximation method for estimating the terminal velocity, which is both conceptually simpler and more physically transparent than existing approximation algorithms. Finally, from theoretical line profile modeling we find that observational determinations of v_∞ may be underestimated by several hundred km s^{-1} if *unsaturated* P Cygni lines are used.

Rotation affects a star by introducing centrifugal and Coriolis forces, decreasing the effective gravity and making the star oblate. This in turn redistributes the emerging radiative flux to preferentially heat the stellar poles, an effect known as *gravity darkening.* Although previous models have computed the increase in equatorial mass flux due to the lower effective gravity there, none have incorporated gravity darkening. We find that the brighter (darker) flux from the poles (equator) has a much stronger impact on the mass flux, increasing (decreasing) the mass loss and local wind density. This, in addition to the existence of *nonradial* radiation forces from a rotating star, which tend to point latitudinally away from the equator and azimuthally opposite the rotation, produces a net *poleward* deflection of wind streamlines. This is contrary to the "wind compressed disk" model of Bjorkman and Cassinelli, and also seems incompatible with observational inferences of equatorial density enhancements in some systems. This work is ongoing, and we are endeavoring to include all the relevant physics in hydrodynamical simulations.

We also dynamically model spectral-line *time variability* by inducing corotating nonaxisymmetric structure in the equatorial plane of a hot-star wind. By varying the radiation force over localized "star spots," the wind develops fast and slow streams which collide to form corotating interaction regions (CIRs) similar to those in the solar wind. We synthesize P Cygni type line profiles for a stationary observer, and find that "discrete absorption components" (DACs) accelerate slowly through the profiles as complex nonlinear structures rotate in front of the star. We also examine the photospheric origin of such variability, in a preliminary manner, by deriving the theory of stellar pulsations, waves, and discontinuities. Although most observed low-order pulsation modes are evanescently damped in the photosphere, we find that the presence of an accelerating wind can allow waves of *all* frequencies to propagate radially. We thus make a first attempt at outlining the possible "photospheric connection" between interior and wind variability that observations are beginning to confirm.

Ph.D. Dissertation completed at the University of Delaware, 2 August 1996, under the direction of Dr. Stanley Owocki. *For copies, contact* `cranmer@bartol.udel.edu`, *or download individual chapters as postscript from:*
`http://www.bartol.udel.edu/~cranmer/cranmer_thesis.html`

Meetings

ISO'S View on Stellar Evolution
July 1-4, 1997
Noordwijkerhout, The Netherlands

A scientific conference to highlight new results of the Infrared Space Observatory (ISO) in the area of stars and circumstellar matter.

Goal of the conference

The Infrared Space Observatory ISO was successfully launched on November 17, 1995 and has now entered its routine phase operations. First results of the four focal plane instruments have been presented at a workshop in ESTEC at the end of May of 1996. It is expected that by summer of next year (1997) many observers will have had the opportunity to study ISO data and therefore the time would be appropriate to organise a scientific meeting in the context of ISO.

We propose to organise a symposium on stars and circumstellar matter. It has become clear in the past decade that circumstellar matter plays a crucial role in stellar evolution, both when stars are in their infancy and when they approach the end of their life. It is expected that ISO will provide a major break-through in our understanding of the evolution of stars and their circumstellar environment. A large fraction of ISO's observing time is aimed at the study of circumstellar matter throughout the life of stars.

The conference has three major topics: (1) the birth of stars and planetary systems, (2) the winds of hot stars as viewed from the IR, (3) late stages of stellar evolution. While these three areas cover a wide scope, we believe that bringing researchers from these different disciplines together in the context of ISO will give important new impulses to these fields, since the physical and chemical conditions that prevail in circumstellar matter around objects in very different evolutionary stages are often similar, i.e. diagnostic tools are alike.

Scientific Organising Committee

Mike Barlow, Eric Becklin, Steve Beckwith, Thijs de Graauw, Harm Habing, Thomas Henning, Karel van der Hucht (chairman LOC), Teije de Jong, Rolf Kudritzki, Pierre-Olivier Lagage, Antonella Natta, Timo Prusti, Daniel Rouan, Takashi Tsuji, Christoffel Waelkens (co-chairman), Rens Waters (chairman)

More information

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