THE HOT STAR NEWSLETTER

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

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Accepted Papers

Pinwheel Nebula around WR 98a

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We present the first near-infrared images of dusty Wolf-Rayet star WR 98a. Aperture masking interferometry has been utilized to recover images at the diffraction-limit of the Keck-I telescope,$\lesssim$50 mas at 2.2μm . Multi-epoch observations spanning about one year have resolved the dust shell into a "pinwheel" nebula, the second example of a new class of dust shell first discovered around WR 104 (Tuthill, Monnier, & Danchi 1999). Interpreting the collimated dust outflow in terms of an interacting winds model, the binary orbital parameters and apparent wind speed are derived: a period of 565 ± 50 days, a viewing angle of $35° \pm 6°$ from the pole, and a wind speed of 99 ± 23mas/yr. This period is consistent with a possible ~588 day periodicity in the infrared light curve (Williams et al. 1995), linking the photometric variation to the binary orbit. Important implications for binary stellar evolution are discussed by identifying WR 104 and WR 98a as members of a class of massive, short-period binaries whose orbits were circularized during a previous red supergiant phase. The current component separation in each system is similar to the diameter of a red supergiant, indicating that the supergiant phase was likely terminated by Roche-lobe overflow, leading to the present Wolf-Rayet stage.

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Preprints from `jmonnier@cfa.harvard.edu`

The Wind Momentum - Luminosity Relationship of Galactic A- and B-Supergiant

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The Balmer lines of four A Ia - supergiants (spectral type A0 to A3) and fourteen B Ia and Ib - supergiants (spectral type B0 to B3) in the solar neighbourhood are analyzed by means of NLTE unified model atmospheres to determine the properties of their stellar winds, in particular their wind momenta. As in previous work for O-stars (Puls et al. 1996) a tight relationship between stellar wind momentum and luminosity ("WLR") is found. However, the WLR varies as function of spectral type. Wind momenta are strongest for O-supergiants, then decrease from early B (B0 and B1) to mid B (B1.5 to B3) spectral types and become stronger again for A-supergiants. The slope of the WLR appears to be steeper for A- and mid B-supergiants than for O-supergiants. The spectral type dependence is interpreted as an effect of ionization changing the effective number and the line strength distribution function of spectral lines absorbing photon momentum around the stellar flux maximum. This interpretation needs to be confirmed by theoretical calculations for radiation driven winds.

The "Pistol-Star" in the Galactic Centre, an extreme mid B-hypergiant recently identified as one of the most luminous stars (Figer et al. 1999) is found to coincide with the extrapolation of the mid B-supergiant WLR towards higher luminosities. However, the wind momentum of the Luminous Blue Variable P Cygni, a mid B-supergiant with extremely strong mass-loss, is 1.2 dex higher than the WLR of the "normal" supergiants. This significant difference is explained in terms of the well-known stellar wind bi-stability of supergiants very close to the Eddinton-limit in this particular range of effective temperatures. A-supergiants in M31 observed with HIRES at the Keck telescope have wind momenta compatible with their galactic counterparts.

The potential of the WLR as a new, independent extragalactic distance indicator is discussed. It is concluded that with ten to twenty objects, photometry with HST and medium resolution spectroscopy with 8m-telescopes from the ground distance moduli can be obtained with an accuracy of about $0.1 mag$ out to the Virgo and Fornax clusters of galaxies.

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Radiation driven winds of hot luminous stars – XIV. Line statistics and radiative driving

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This paper analyzes the inter-relation between line-statistics and radiative driving in massive stars with winds (excluding Wolf-Rayets) and provides insight into the qualitative behaviour of the well-known force-multiplier parameters $k_{\rm CAK}$, α and δ, with special emphasis on α.

After recapitulating some basic properties of radiative line driving, the correspondence of the local exponent of (almost) arbitrary line-strength distribution functions and α, which is the ratio of optically thick to total line-force, is discussed. Both quantities are found to be roughly equal as long as the local exponent is not too steep.

We compare the (conventional) parameterization applied in this paper with the so-called $\bar{Q}$-formalism introduced by Gayley (1995) and conclude that the latter can be applied alternatively in its *most general* form. Its "strongest form", however (requiring the Ansatz $\bar{Q} = Q_o$ to be valid, with Q_o the line-strength of the strongest line), is justified only under specific conditions, typically for Supergiants with $T_{\rm eff} \geq 35,000$ K.

The central part of this paper considers the question concerning the shape of the line-strength distribution function, with line-strength k_l as approximate depth independent ratio of line and Thomson opacity. Since k_l depends on the product of oscillator strength, excitation- and ionization fraction as well as on elemental abundance, all of these factors have their own, specific influence on the final result.

At first, we investigate the case of hydrogenic ions, which can be treated analytically. We find that the exponent of the differential distribution is $-4/3$ corresponding to $\alpha = 2/3$, as consequence of the underlying oscillator strength distribution. Furthermore, it is shown that for *trace* ions one stage below the major one (e.g., H I in hot winds) the equality $\alpha + \delta \approx 1$ is valid throughout the wind.

For the majority of non-hydrogenic ions, we follow the statistical approach suggested by Allen (1966), refined in a number of ways which allow, as a useful by-product, the validity of the underlying data bases to be checked. Per ion, it turns out that the typical line-strength distribution consists of two parts, where the first, steeper one is dominated by excitation effects and the second one follows the oscillator strength distribution of the specific ion.

By summing up the contributions of all participating ions, this *direct* influence of the oscillator strength distribution almost vanishes. It turns out, however, that there is a second, indirect influence controlling the absolute line numbers and thus $k_{\rm CAK}$. From the actual numbers, we find an average exponent of order $-1.2 \ldots -1.3$, similar to the value for hydrogen.

Most important for the shape of the *total* distribution is the difference in line-statistics between iron group and light ions as well as their different (mean) abundance. Since the former group comprises a large number of meta-stable levels, the line number from iron group elements is much higher, especially at intermediate and weak line-strengths. Additionally, this number increases significantly with decreasing temperature (more lines from lower ionization stages). In contrast, the line-strength distribution of light ions remains rather constant as function of temperature.

Since the line-strength depends linearly on the elemental abundance, this quantity controls the relative influence of the specific distributions on the total one and the overall shape. For solar composition, a much more constant slope is found, compared to the case if all abundances were equal.

In result, we find (for solar abundances) that iron group elements dominate the distribution at low and intermediate values of line-strength (corresponding to the acceleration in the inner wind part), whereas light ions (including hydrogen under A-star conditions) dominate the high k_l end (outer wind). Typically, this part of the distribution is steeper than the rest, due to excitation effects.

Finally, the influence of *global* metallicity z is discussed. We extend already known scaling relations (regarding mass-loss, terminal velocity and wind-momentum rate) with respect to this quantity. In particular, we demonstrate that, besides the well-known direct effect ($k_{\rm CAK} \propto z^{1-\alpha}$), the curvature of the line-strength distribution at its upper end induces a decrease of α for low metallicity and/or low wind density.

Summarizing the different processes investigated, the force-multiplier parameter α becomes a decreasing function of decreasing $T_{\rm eff}$, increasing $k_1 = dv/dr/\rho$ and decreasing *global* metallicity z, consistent with the findings of earlier and present empirical results and observations.

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or on the web at http://www.usm.uni-muenchen.de/people/puls/Puls.html

A Search for Intrinsic Polarization in O Stars with Variable Winds

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New observations of 9 of the brightest northern O stars have been made with the Breger polarimeter on the 0.9 m telescope at McDonald Observatory and the AnyPol polarimeter on the 0.4 m telescope at Limber Observatory, using the Johnson-Cousins UBVRI broadband filter system. Comparison with earlier measurements shows no clearly defined long-term polarization variability. For all 9 stars the wavelength dependence of the degree of polarization in the optical range can be fit by a normal interstellar polarization law. The polarization position angles are practically constant with wavelength and are consistent with those of neighboring stars. Thus the simplest conclusion is that the polarization of all the program stars is primarily interstellar.

The O stars chosen for this study are generally known from ultraviolet and optical spectroscopy to have substantial mass loss rates and variable winds, as well as occasional circumstellar emission. Their lack of intrinsic polarization in comparison with the similar Be stars may be explained by the dominance of radiation as a wind driving force due to higher luminosity, which results in lower density and less rotational flattening in the electron scattering inner envelopes where the polarization is produced. However, time series of polarization measurements taken simultaneously with Hα and UV spectroscopy during several coordinated multiwavelength campaigns suggest two cases of possible small-amplitude, periodic short-term polarization variability, and therefore intrinsic polarization, which may be correlated with the more widely recognized spectroscopic variations.

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Photometric variability of LBV-candidate stars and Hubble-Sandage Variables A, B, C and 2 in M 33

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We present the photometric history of some Luminous Blue Variable candidate stars in M 33. The search for outbursts was made in photographic plates taken in B band of the galaxy M 33 and cover an eight year period, 1982 — 1990. Twenty five plates, separated in seven groups, have been used. CCD UBV magnitudes of the star UIT003 are presented also. Only one (of 12) of the LBV candidates (UIT003) presents clear variability above the noise. The combination of photometric variability and a typical LBV spectrum make it a new LBV.

We present also the light curves of Hubble-Sandage Variables A, B, C and 2.

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A 0.4-20 μm spectroscopic study of the clumped wind of WR 147

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We present a detailed spectroscopic study of the WN8(h)+B0.5V binary system WR 147 using a non-LTE model (Hillier & Miller 1998, 1999) that incorporate advances in line blanketing and allows for clumping in the wind. Ground-based optical and near-infrared observations, and high-resolution spectra obtained with the *ISO Short Wavelength Spectrometer* are combined for this study. Previously derived interstellar extinction values of $E_{B-V} \simeq 4.1$ mag at $R_V \simeq 2.7$ are confirmed here. The distance to WR 147 is revised slightly upwards to 650 pc, based on Galactic and LMC WN8–9 calibrators in the K band. An infrared extinction curve for this sightline reveals absorption bands at 9.7 and 18 μm that are stronger than expected for the average ISM, but the nature and location of the intervening material is unknown.

He line profiles of the WN8 star exhibit clear evidence for clumping in the wind. We find that a volume filling factor f of 0.1 yields line profiles which match observations (emphasizing the electron scattering wings), though values of f in the range of 0.04 to 0.25 are reasonable. This leads to a mass-loss rate range of $(1.5–3.7)\times10^{-5}$ $M_\odot$ yr^{-1}, substantially lower than derived from optical or radio observations under assumptions of homogeneity. Additionally including the effects of line-blanketing, the wind performance factor, $\dot{M}v_\infty/(L_*/c)$, is reduced to $\sim$2.5.

Hydrogen is severely depleted, but present at 9% by mass. Observations of the [Ca IV] 3.21 μm, [S IV] 10.51 μm, and [Ne III] 15.56 μm fine structure lines, from which we measure a terminal wind velocity

of $\sim$950 km s^{-1}, allow us to place constraints on the surface abundances of these elements. In all cases we find good agreement with cosmic abundances (adjusted to a hydrogen-poor environment) and thus with evolutionary predictions for WN stars.

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The Structure of Wolf-Rayet Winds II: Observations of Ionization Stratification in the WN Subtype

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Motivated by the question of the importance of ionization stratification in solving the "momentum problem" of Wolf-Rayet stellar winds, we have chosen a sample of 14 WN stars for a systematic study. We performed measurements of the emission line widths on ultraviolet, optical and infrared spectra to obtain data spanning a large range of ionization potentials. We provide extensive tables of these measurements as well as line profile classifications. The presence of ionization stratification in the wind should result in a correlation between ionization potential and line width. We find most of the winds to be stratified, and discuss the level of stratification found in each star. To test the importance of ionization stratification to efficient radiation-to-wind momentum transfer, we compare our empirically-measured stratification strengths with two sets of theoretical performance numbers, and give the correlation statistics in each case.

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or on the web at http://www.phyast.pitt.edu/~jim/strat_pre.ps

Submitted Papers

A Multiwavelength Campaign on γ Cassiopeiae. IV. The Case for Illuminated Disk-Enhanced Wind Streams

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On 1996 March 14–15 we conducted a campaign with the *Hubble Space Telescope* GHRS to observe the Si 4 $\lambda\lambda$1394, 1403 lines of the B0.5e star γ Cas at high temporal and spectral resolution. As a part of this $\sim$22 hour campaign, the *Rossi X-ray Timing Explorer* (*RXTE*) was also used to monitor this star's copious and variable X-ray emission. In this fourth paper of a series we present an analysis of the rapid variations of the Discrete Absorption Components (DACs) of the Si 4 doublet. The DACs attain a maximum absorption at −1280 km s^{-1}, taper at higher velocities, and extend to −1800 km s^{-1}. The DACs in this star's resonance lines have been shown to be correlated with a $\gtrsim 6$ year cycle in the Balmer line emission V/R ratio, and in 1996 this DAC strength was near its maximum. We derive hydrogen densities of 10^9–10^{10} cm^{-3} in the DAC material using a curve of growth method and find that the plasma becomes marginally optically thick near −1280 km s^{-1}. The "mean DAC" probably represents a broad "plateau" with a volume density intermediate between the star's mid-latitude wind and equatorial disk. We also follow the blueward evolution of subfeatures in the DACs. These features appear to emanate primarily from one or two discrete azimuths on the star and accelerate much slower than expected for the background wind, thereby exhibiting an enhanced opacity spiral stream pattern embedded within the structure forming the DAC. In Papers I and II we suggested that active X-ray centers are associated with at least two major cool clouds forced into corotation. Several correlations of flickering in the Si 4 DACs are found in our data which support the idea that changes in stellar ionizing flux cause changes in the ionization of material at various sectors along the spiral pattern. We demonstrate that similar flickering is visible in archival *IUE* data from 1982 and may also be responsible for earlier reports from *Copernicus* of rapid changes in this star's UV and optical lines. Finally, we discovered that flickering of the DAC fluxes in the 1982 data is correlated with rotation phase and shows a modulation with a 7.5 hour cyclical cessation of X-ray flares that was observed recently by *RXTE*. This confirms our basic picture that lulls in X-ray activity close to the star's surface cause both a lower Si 5 ionization fraction and an increase in Si 4 variability within the DAC structures.

Submitted to the Astrophysical Journal
Preprints from `scranmer@cfa.harvard.edu`
or on the web at `http://cfa-www.harvard.edu/~scranmer/cranmer_preprint.html`

The OB Zoo: A Digital Atlas of Peculiar Spectra

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A digital atlas of 20 high-luminosity, peculiar OB spectra in the 3800-4900 Å range is presented. The atlas is organized and discussed in terms of the following four categories: WN-A or WNL stars, OB Iape or very late WN (WNVL) stars, iron stars, and B-supergiant Luminous Blue Variables (LBVs). Several objects in the earlier categories are also active or quiescent LBVs. Some (but not all) of these objects have been well studied, and extensive references are provided, as are comprehensive spectral- line identifications. Several new morphological relationships among the objects have been recognized through this presentation. In particular, attention is drawn to the occurrence of spatial pairing between nearly identical, unusual spectra, which may have implications for a particular mode of massive-star formation. This small sample includes one or both members of at least five such pairs. Physical explanations of these peculiar, likely transitional spectra and the relationships among them are essential for a complete understanding of massive stellar evolution.

Submitted to PASP
Preprints from `walborn@stsci.edu`

Coordinated Monitoring of the Eccentric O-star Binary Iota Orionis. II. Optical Spectroscopy and Photometry

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With the objective of investigating the wind-wind collision phenomena and supporting the contemporaneous X-ray observations (cf. Pittard et al. 1999), we organized a large-scale, coordinated optical monitoring campaign of the massive, highly eccentric O9III+B1III binary Iota Orionis. Successfully separating the spectra of the components, we refine the orbital elements and confirme the rapid apsidal motion in the system, also being able to see strong interaction between the components during periastron passage. We also detect phase-locked variability in the spectrum of the secondary star. However, we find no unambiguous signs of the bow shock crashing on the surface of the secondary, despite the predictions of hydrodynamic simulations. Combining all available photometric data, we find rapid, phase-locked variations and model them numerically, thus restricting the orbital inclination, $50^\circ \lesssim i \lesssim 70^\circ$.

Submitted to MNRAS

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Proceedings

X-ray Emission from Isolated Be Stars

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I discuss the X-ray observations of Be stars, and how their properties compare to non-emission B stars. I focus on several specific stars that show high flux levels and variability, but also report on several interesting survey results. The Be X-ray properties are discussed in the context of wind-shock X-ray emission from normal OB stars as well as in the context of general mechanisms that have been proposed to explain the Be phenomenon. Finally, I conclude with a discussion of the spectral diagnostics that will be available from the new generation of X-ray telescopes.

To appear in ***The Be Phenomenon in Early-Type Stars*****, A.S.P. Conference Series, 2000**
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or on the web at `www.bartol.udel.edu/ cohen/PAPERS/alicante_pp.ps`

Blue Compact Dwarf Galaxies – Home to the Latest of the First Stars?

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We review single-star photometry with the Hubble Space Telescope (HST) of five well resolved Blue Compact Dwarf (BCD) galaxies. Three BCDs exhibit well populated red giant branches. These galaxies are therefore at least 1-2 Gyr old, and possibly older than 10 Gyr. For two BCDs, the available HST data do not go deep enough to reveal the red giant branch. We argue that over a wide range of possible galaxy distances, the color-magnitude diagrams of these BCDs are nevertheless consistent with showing the evolved descendants of intermediate-mass stars on the asymptotic giant branch. Such stars are nucleosynthetic sites of nitrogen and carbon production. Their identification in BCDs contradicts recent conclusions that BCDs must be young galaxies in which primary production of these elements takes place exclusively in massive stars, and implies that BCDs are unlikely to be home to newly formed metal-free stars. Color-magnitude diagrams of BCDs thus point to difficulties in decoding star-formation histories of starburst galaxies from the metallicities of the ionized gas.

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Non-LTE models of WR winds

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"Standard" Non-LTE models for WR winds treat the radiation transfer in a spherically-expanding, homogeneous and stationary atmosphere. These models have been widely applied for the spectral analysis of WR stars in the Galaxy and LMC. WN spectra can be well reproduced in general, while some work is still to be done on WC spectra.

Accounting for wind inhomogeneities (clumping) in a first-order approximation has significantly improved the agreement between synthetic and observed spectra with respect to the electron-scattering wings of strong lines. Spectral analyses with clumped models yield considerably lower mass-loss rates than obtained from homogeneous models. In typical models, the ionization stratification shows a stepwise recombination with increasing distance from the star.

The applied models account for complex model atoms of He and CNO elements. In a new version of our model code, line blanketing by iron-group elements is additionally included. The iron model atom is simplified by introducing superlevels and superlines, but otherwise the radiation transfer is fully treated. In first test models the radiation pressure is almost (i.e. within a factor of two) consistent with the observed acceleration of the stellar wind.

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Thermal and Ionization Aspects of Flows from Hot Stars: Observations and Theory, Henny J.G.L.M. Lamers, and Arved Sapar (eds.), ASP Conference Series

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Complex wind dynamics and ionization structure in symbiotic binaries

Rolf Walder and Doris Folini

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Aspects of the wind-dynamics in symbiotic binaries, colliding winds and accretion, are reviewed. Inconsistencies between theory and observations of the hot star wind are discussed. If the hot star wind were governed by CAK theory, nearly all symbiotics would be colliding wind binaries. For the case of colliding winds, 3D hydrodynamical simulations reveal that the matter distribution is spirally shaped. Shock confined high-density shells as well as huge voids are found even in the immediate neighborhood of the stars. Synthetic spectra computed on the basis of different 3D hydrodynamical models suggest observational discrimination between them to be possible. Colliding wind models also provide a link between symbiotics and planetary nebulae. Accretion during some time is a necessary condition for symbiotics to exist. However, there is no proof of whether currently accreting systems show the symbiotic phenomenon. Existing accretion models are inconsistent amongst each other, predicting either extended disks or small, high-density accretion wakes. Synthetic spectra allowing to discriminate between two models do not yet exist.

Invited review at the Conference on Thermal and Ionization Aspects of Flows from Hot Stars: Observations and Theory
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Theory of thermal and ionization effects in colliding winds of WR+O binaries

Doris Folini and Rolf Walder

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The colliding winds interaction zone in WR+O binaries is a highly complex environment. In this review we summarize the progress made towards its theoretical understanding during the last years. We review the effect of different physical processes on the interaction zone, among them geometry and orbital motion, radiative forces, thermal conduction, instabilities and turbulence, ionizing radiation, dust formation, clumped winds, magnetic fields, and particle acceleration. Implications with regard to observations are discussed. Subsequently, we proceed to the important question of mutual interaction amongst these processes. Because of the wealth of physical processes involved, numerical simulations are usually mandatory. Finally, we turn to the combined role these processes play for the thermal and ionization properties of the colliding winds interaction zone in WR+O binaries.

Invited review at the Conference on Thermal and Ionization Aspects of Flows from Hot Stars: Observations and Theory

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or on the web at `http://www.astro.phys.ethz.ch/staff/folini/folini.html`

Theses

On the Nature of the Spectral and Photometric Periodic Variability of Apparently Single Wolf-Rayet Stars

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During the course of their evolution, massive close binaries are predicted to experience a short evolutionary phase where a Wolf-Rayet (WR) star is associated with a degenerate companion (neutron star or black hole). Appparently single WR stars displaying a cyclical pattern of variability (either in spectroscopy, photometry, and/or polarimetry) are prime candidates for such systems. However, since a number of studies have recently demonstrated the prevalence of largely aspherical winds among the OB-star population, the alternative scenario would be to consider that the periodic variability observed in these WR stars is not induced by the presence of a strongly ionizing, collapsed companion disturbing the global WR wind structure but is induced by orbital modulation of a largely anisotropic outflow.

This study presents the results of a vast campaign of (generally simultaneous) spectroscopic and photometric observations attempting to infer the exact nature of apparently single WR stars with well-established (WR 6) or suspected (WR 1, WR 134, WR 136) cyclical variations.

Our study allows us to confirm the existence of a 2.3-d periodicity in WR 134. We also present arguments challenging the possible association of WR 6 and WR 134 with a collapsed companion. Alternatively, we propose that the observed cyclical variability is more likely induced, as in many O stars, by the rotation of large-scale, azimuthally extended wind structures. Although largely qualitative, this model can more easily apprehend some aspects of the variability, notably the epoch-dependent nature of the pattern of variability or the cyclical variations presented by spectral lines formed in close vicinity of the stellar core. This assertion is also supported by the deficiency of observed X-ray flux in the context of an accretion of the wind material onto a degenerate object.

If this interpretation regarding the driver of the variability in WR 6 and WR 134 is correct, these large-scale wind streams are probably induced by some kind of photospheric activity whose exact nature remains to be determined. The existence of (non)radial pulsations of the stellar core or of magnetic structures ("photospheric" or more likely of fossil origin) may, however, be at the origin of this phenomenon.

Thesis work conducted at Département de Physique, Université de Montréal, Canada.
Ph.D. thesis directed by Nicole St-Louis; Ph.D. degree awarded 1999.
Thesis by anonymous ftp to `icstar5.ph.ic.ac.uk; cd pub/morel/thesis/`

Meetings

International Workshop on

"Interacting Winds from Massive Stars" (including single stars and binaries)

Québec, July 10-14, 2000

Preregistration for the Workshop can now be done at
`http://www.astro.umontreal.ca/iwinds/`

Workshop on:

ISO beyond the Peaks: The 2nd ISO workshop on analytical spectroscopy

Workshop Location: ISO Data Centre, ESA-VILSPA, Spain
Dates: 2-4 February 2000

http://www.iso.vilspa.esa.es/meetings/beyondthepeaks/

Workshop on:
Magnetic Fields across the Hertzsprung-Russell Diagram

Workshop Location: Santiago de Chile
Dates : from January 15 to January 19, 2001

Scientific topics:

Session 1: The Sun – Session 2: Non-degenerate stars – Session 3: Degenerate dwarfs – Session 4: Pre-main sequence stars – Session 5: Instrumentation and techniques: present and future – Session 6: Towards a global picture

- overview of the current status of magnetic field detection and measurements in the considered stars; - techniques of magnetic field diagnosis; - magnetic field properties; - other stellar properties and phenomena related to or induced by the magnetic fields; - theoretical aspects (e.g., origin of the magnetic field, evolution, magnetohydrodynamical processes, etc.)

Scientific Organizers:

Gautier Mathys (chair) `gmathys@eso.org`, John D. Landstreet, Egidio Landi Degl'Innocenti, Sami Solanki, Joseph Cassinelli, Paul Charbonneau, Steven Saar, Manfred Schuessler, Dayal Wickramasinghe, Lilia Ferrario

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