THE HOT STAR NEWSLETTER

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

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From the editor

The response to the call for abstracts for the first issue is of good omen. Many thanks, also to all those who wrote to express their interest or to make suggestions. One suggestion for the newsletter was to choose a name reflecting the range of topics broader than Wolf-Rayet stars. The delay in the parution of this first issue was due to unsuccessful attempts to contact the editor of the new B star newsletter to coordinate our efforts.

The newsletter will include abstracts of papers recently accepted for publication in refereed journals. Abstracts of doctoral dissertations are also welcome, as well as news (jobs, conferences, etc). Topics include all theoretical and observational aspects of research on massive luminous stars, from O stars to Wolf-Rayet stars. Supernovae fall outside the scope of this newsletter. Abstracts should be sent in electronic form. TeX or LaTeX style is preferred (avoiding personal macros). To speed up the editorial task, authors are invited to use the simple template provided at the end of the newsletter file (after “enddocument”).

The current mailing list contains over 200 addresses. Only a few messages bounced back. I would be grateful if readers could send me the correct e-mail address for the following people: Leung, Montmerle, Nichols, Richter.

Abstracts: theory

Momentum Deposition in Wolf-Rayet Winds: Non-Isotropic Diffusion with Effectively Gray Opacity

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We derive the velocity law and mass loss rate of a steady-state Wolf-Rayet wind using a non-isotropic diffusion approximation applied to the transfer between strongly overlapping spectral lines. Following the approach of Friend and Castor (1983), the line list is assumed to approximate a statistically

parametrized Poisson distribution in frequency, so that photon transport is controlled by an angle-dependent, *effectively gray* opacity. We show the non-isotropic diffusion approximation yields good agreement with more accurate numerical treatments of the radiative transfer, while providing analytic insight into wind driving by multiple scattering. We illustrate, in particular, that multiple radiative momentum deposition does *not* require that photons be repeatedly reflected across substantial distances within the spherical envelope, but indeed is greatest when photons undergo a nearly *local diffusion*, e.g. through scattering by many lines closely spaced in frequency.

Our results reiterate the view that the so-called "momentum problem" of Wolf-Rayet winds is better characterized as an "opacity problem" of simply identifying enough driving lines. One way of increasing the number of thick lines in Wolf-Rayet winds is to transfer opacity from saturated to unsaturated lines, yielding a steeper opacity distribution than that found in OB winds. We discuss the implications of this perspective for extending our approach to W-R wind models that incorporate a more fundamental treatment of the ionization and excitation processes that determine the line opacity. In particular, we argue that developing statistical descriptions of the lines to allow an improved effective opacity for the line ensemble would offer several advantages for deriving such more fundamental W-R wind models.

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Towards an understanding of very massive stars. A new evolutionary scenario relating O stars, LBVs and Wolf-Rayet stars

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Based on recent progress in the theory of stellar structure and evolution, in the theory of stellar atmospheres and winds, and in the observational data base, we propose a new scenario for the evolution of very massive stars ($M_{\rm ZAMS} \gtrsim 40 M_\odot$) in our Galaxy. A sample evolutionary calculation for a $60 M_\odot$ star, incorporating recent theoretical results about violent pulsational instabilities in very massive stars, is critically compared with a multitude of observational facts. The relation between those pulsational instabilities and observed line profile variability in O stars is discussed. New wind models for P Cygni are computed, with particular emphasis on the determination of its mass and surface He/H-ratio. A detailed comparison of our sequence with the Galactic WR population is performed, considering newly determined surface abundances.

Our results suggest a new interpretation of luminous hydrogen-rich late-type WN stars as core hydrogen burning objects, while hot WN stars with small or zero hydrogen abundance are core helium burning stars. P Cygni is identified with the hydrogen shell burning phase of our sequence. The observed upper luminosity limit for Galactic hydrogen-free WN stars appears to be consistent with our picture. Hence we propose the following evolutionary sequence for very massive stars:

O → Of → H-rich WN → LBV → H-poor WN → H-free WN → WC → SN.

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Electronic copies are available on machine 130.183.83.33 through anonymous ftp, file /pub/ntl/vms.ps

Abstracts: observations

ROSAT observation of the giant HII region RCW 49

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We have observed the southern emission nebula RCW 49 with the PSPC instrument on board the ROSAT satellite. Diffuse X–ray emission is seen to extend over a large portion of the detector. Two regions of X–ray emission can be identified: one associated to the core of the optical nebula, where the X–ray correlate with the optical, and a fainter one anticorrelated with the optical. The young star cluster Westerlund 2 is detected as peaked emission inside the core region, and is resolved in at least three point sources. The morphology and possible nature of the extended X–ray emission are discussed, together with their interrelation with other objects in the field. Among the additional point sources detected in the field, two of the three Wolf-Rayet stars present in this region are tentatively identified.

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Terminal velocities of Wolf-Rayet winds from infrared He I lines

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We have observed 1- μm and 2- μm spectra covering the He I 2s-2p triplet and singlet lines in a sample of Wolf-Rayet stars. Most of the He I lines have P Cygni profiles, which are fitted using the SEI (Sobolev with Exact Integration) method to derive terminal velocities. From our observations of 41 stars, the He I velocities are only about 70 percent of those measured at the violet edges of the P Cygni profiles of the C IV and Si IV resonance lines but in good agreement with those measured at the greatest displacements of the saturated absorption troughs in these lines (v_{black}). We discuss the advantages of the infrared method, and also the influence of binarity on the relation between measured displacement velocities and the stars' terminal wind velocities. For 19 stars not accessible to the IUE these are the first accurate values for the terminal velocities of their winds. The analysis of the He I profiles reveals differences in the radial structure of the winds between stars of the same subtype and having similar terminal velocities.

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The Properties of the WO Wolf-Rayet Stars

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We present optical spectrophotometry for five WO Wolf-Rayet stars, three of them in our own Galaxy and one in each of the SMC and LMC. *IUE* ultraviolet spectrophotometry has also been obtained for the two Magellanic Cloud WO stars, including a high resolution spectrum for one of them. Quantitative spectral typing criteria are defined for WO subtypes spanning WO1 to WO5, and for the case of the two WO stars in spectroscopic binaries, spectral types for the O-type primaries are derived. From our spectrophotometry we derive reddenings and magnitudes for each star. Absolute visual magnitudes of –2.5 and –1.8 are derived for a WO4 star and for a WO2 star, respectively, each star lying at a known distance. Wind terminal velocities ranging from 4200 km s^{-1} to 5500 km s^{-1} are derived from the black absorption edge of an ultraviolet P Cygni profile and from the FWZI of strong optical emission lines. The relative abundances of helium, carbon and oxygen in the winds of each of the WO stars are derived using a recombination theory analysis of selected ultraviolet and optical emission lines to determine the ionic abundances of He^{2+}, C^{4+}, O^{4+}, O^{5+} and O^{6+}. The derived abundance ratios show relatively narrow ranges. C/He number ratios of 0.51–0.52 are derived for two Galactic WO stars and one LMC WO star, with their C/O ratios ranging between 4.6 and 5.2, and their (C+O)/He ratios equal to 0.62. The one SMC WO star has a C/He ratio of 0.81, a C/O ratio of 2.7 and a (C+O)/He number ratio of 1.10. These abundance ratios are broadly consistent with evolutionary models for the advanced stages of massive stars, and promising agreement as a function of initial metallicity is found with the most recent evolutionary models.
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ASCA Observations of the Wolf-Rayet Binary HD193793 (WR140)

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ASCA observed the Wolf-Rayet binary HD193793 (WC7 + O4-5) in June 1993, only 3 months after periastron passage when the WC star was nearly in front of the O star. The X-ray spectra are heavily absorbed below ≈2 keV by the Wolf-Rayet wind and show a prominent emission line from He-like iron at 6.7 keV. A variable abundance Raymond-Smith model (optically thin plasma) gives a temperature of kT ≈ 3 keV (35 million K) and an equivalent hydrogen column density $N_H \approx 3 \times 10^{22}$ cm^{-2}. This column density is a factor of ≈10 larger than the interstellar contribution, confirming that the X-ray absorption is circumstellar. We derive an upper limit on the carbon abundance in the WC wind of ≈30 solar, and find evidence for a strong overabundance of neon as predicted by evolutionary models. The X-ray luminosity and derived column density agree well with predictions from colliding wind shock models, although comparison with a 1987 GINGA observation fails to reveal the expected change in hard flux (2 - 6 keV) with binary separation.
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Fundamental parameters of Wolf-Rayet stars I. Ofpe/WN9 stars

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A detailed study has been carried out for 4 LMC Ofpe/WN9 ('slash') stars, and the sole Galactic WN9 star WR108 (HDE 313846), using new high S/N spectroscopy and archive UV and near-IR spectroscopy.

Our observations reveal that photospheric Of features such as He II λ4542 are absent from the optical spectra of our sampled stars. All observed optical lines are formed in the stellar wind, and so we prefer WN9 or WN10 classifications based on the relative strengths of N II λ3995 and N III λ4634–41, with BE 381 and Sk$-66°$40 prototype WN9 and WN10 stars, respectively. HDE 269927c and R84 are given WN9 classifications, with WR108 newly assigned WN9+abs due to the spectral appearance of the upper Balmer series.

The distance to WR108 is determined from an analysis of its interstellar spectrum. Previously WR108 has been considered to be a possible member of Sgr OB1 (1.6 kpc, Lundström & Stenholm, 1984) which results in a uniquely low stellar luminosity for this type of object. Using the standard Galactic rotation curve of Fich et al. (1989) we derive 5±1 kpc, resulting in a luminosity very similar to R84.

Tailored analyses using the WR standard model, including metals, result in the following stellar parameters for all stars: T_*=29.5±1.0kK, $L/L_\odot=10^{5.65\pm0.2}$, $\dot{M}=3.5\pm1\times10^{-5}$ $M_\odot$ yr^{-1} and v_∞=400±100 km s^{-1} (v_∞=1170 km s^{-1} for WR108). The stellar parameters determined for R84 compare well with those determined previously by Schmutz et al. (1991) indicating that the effect of CNO elements is negligible for WN stars. The metallicity of the LMC stars is around Z$\sim$0.008 while Z$\sim$0.035 results for the Galactic WN9 star. Abundances for the LMC stars (H/He=2.5±1, N/He$\sim$0.003, C/N$\sim$0.1) are in reasonable agreement with the results of evolutionary models at low metallicity (Schaerer et al. 1993a) although observed luminosities are significantly lower than predictions for stars entering the WR phase.

The luminosity and chemistry of R84 are identical to that of the Luminous Blue Variable (LBV) R71 indicating that it is probably associated with an LBV phase rather than a post-red supergiant as suggested by Schmutz et al. (1991). The status of the remaining LMC stars is less clear, although their common spectral characteristics suggest that they are also related to LBVs, with Sk$-66°$40 the least evolved of the present sample.

For WR108, its spectral appearance, derived parameters and abundances (H/He=1.5, C/N$\sim$0.10) suggest an intimate relationship with extreme Galactic Ofpe stars, with the wind density being the principal difference, and evolution probably proceeding directly from Of to Wolf-Rayet.

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Fundamental parameters of Wolf-Rayet stars II. Tailored analyses of Galactic WNL stars

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Quantitative analyses of 9 Galactic WNL (WN7–8) stars, with particular reference to the hydrogen, helium, carbon and nitrogen abundances, are presented. These analyses are based on extensive UV, optical and IR spectroscopy, and have been undertaken using the Wolf-Rayet (WR) standard model.

Our results compare well with those from previous non-LTE analyses confirming that the influence of CNO elements is of minor importance for WN stars. Observed profiles of hydrogen and helium are generally reproduced to high precision, with some exceptions, while metal lines are simultaneously matched to within a factor of about two. We also investigate the influence of line blanketing on the resulting stellar parameters.

We find that WNL stars belong to two distinct groups. Firstly, the WN7–8 stars with a fairly strong He I signature, are found to have low terminal velocities (850 $\mathrm{km\,s^{-1}}$), moderate luminosities ($L/L_{\odot}\sim10^{5.5\pm0.3}$) and very low hydrogen contents (X_H=15±15%). Secondly, those single stars classified WN7+abs (i.e. absorption components present in the upper Balmer series) were found to have high velocity winds (2150 $\mathrm{km\,s^{-1}}$), high luminosities ($L/L_{\odot}\sim10^{5.9}$), and a considerable hydrogen content (X_H=48±4%). Carbon and nitrogen abundances are broadly in line with those expected for CNO-processed material from recent evolutionary models. A hydrogen content of <2% by mass was found for WR123 demonstrating that not all WNL stars contain substantial hydrogen. The evolutionary and mass-loss implications of our results are discussed elsewhere (Paper III, Crowther et al. 1994b).

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Fundamental parameters of Wolf-Rayet stars III. The evolutionary status of WNL stars

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New high S/N optical observations of 9 Galactic WNL (WN7–8) stars are presented. The spectra have been analysed using tailored non-LTE model atmospheres by Crowther et al. (1994c). Here we use the derived stellar parameters and abundances for a thorough investigation of the evolutionary status and mass-loss properties of WNL stars.

We have identified two distinct groups of WNL stars from their observed properties. The WNL+abs and WN7 stars have high luminosities (log $L/L_{\odot}\sim5.9$) and form a continuity in morphology and physical parameters from the Of stars. They appear to be intimately related to these stars, confirming the suspicion of Walborn (1973) and are descended from extremely massive progenitors ($M_{\mathrm{initial}}>60\,M_{\odot}$) through the sequence

O→Of→WNL+abs→WN7 (→WNE) →WC→SN.

In contrast, the evolutionary sequence for WN8 stars is identified as

O→LBV or RSG→WN8→WNE→WC→SN.

These stars, with lower luminosities (log $L/L_{\odot}\sim5.5$), are descended from less massive stars, and have either red supergiant (RSG, $25\,M_{\odot}<M_{\mathrm{initial}}<40\,M_{\odot}$) or Luminous Blue Variable (LBV, $40\,M_{\odot}<M_{\mathrm{initial}}<60\,M_{\odot}$) progenitors. Indeed, we identify many properties that WN8 stars have in common with LBVs, e.g. spatial distribution, association with ejecta nebulae, low binary frequency, large photometric variability. We also find that those stars with the highest terminal velocities (WN7+abs stars) have the lowest variability while the WN8 stars and LBVs (low wind velocities) are the most variable.

The smooth progression of mass loss properties from O supergiants to WNL stars found by Lamers & Leitherer (1993) is confirmed with the WNL+abs stars lying intermediately between the WN8 stars and O stars. The spectroscopic differences between Ofpe and WNL+abs stars appear to be attributable principally to a difference in wind density. This naturally explains the often ambiguous Of–WN spectral classification of some Of and WNL stars (Conti & Bohannan 1989).

Finally, interstellar reddenings are determined using two independent methods based on the model atmosphere continuum distributions and the observed *ubv* colours. We find that the UV reddening towards WR25 (WN7+abs) is highly anomalous (R=4.6), confiming the findings of Tapia et al. (1988) for stars in Tr 16 in the Carina nebula.

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A Study of the Moderately Wide Wolf-Rayet Spectroscopic Binary HD 190918

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Radial-velocity observations of the Wolf-Rayet spectroscopic binary HD 190918 obtained from 25 spectrograms covering the yellow-green range are presented. In general three absorption lines were measured to determine the line-of-sight motion of the O star and one unblended emission line, He II λ5411.52, for the Wolf-Rayet star. A sharp C III λ5696 emission line, as seen in most Of type spectra, was detected on each spectrogram and measured. This l ine follows the predicted radial-velocity curve of the O star fairly well when the radial velocities are shifted by an appropriate amount.

New orbital elements have been found for the O star, for the Wolf-Rayet star, and for the C III emission line, see Table 3. The estimated systemic velocity is –20.9 $\pm$ 0.7 km s^{-1} for the O star, +70.2 $\pm$ 4.6 km s^{-1} for the Wolf-Rayet star, and –34.2 $\pm$ 1.5 km s^{-1} for the sharp C III emission line. The systemic velocity of the O star is reasonable considering the expected line-of-sight component of motion due to the peculiar motion of Population I stars, galactic rotation, and reflex solar motion. We adopt the O-star systemic velocity as a fiducial radial velocity for the binary HD 190918. This shows that the He II λ5411 line of the WN4.5 star is displaced longward by 91.1 km s^{-1}, while the sharp C III line appears to be formed in a body of gas moving towards the observer by an additional 13.3 kms^{-1}.

The positive displacement of He II λ5411 is real; it indicates systematic motion of the plasma forming the He II lines relative to the line-of-sight motion of the center of mass of the binary system. We suggest that He^{++} ions are falling into the line emitting region of the Wolf-Rayet star from a remnant of the material from which the star is formed. In the case of HD 190918 the Wolf-Rayet star appears to pass through periastron 10.0 days (0.09 in phase) before the O star does. This may indicate that a density enhancement in the line-emitting region of the Wolf-Rayet star reaches periastron before the center of mass of the Wolf-Rayet star reaches its closest point opposite the O star.

Consideration of the size of the orbit, the known size range of O and Wolf-Rayet stars, and the minimum masses of the stars indicates that an internally consistent model is obtained when $i = 25°$ or $i = 20°$. In the first case the companion is a main-sequence O star, in the second it is an O-type supergiant. We discuss the implications of each possible solution including the swath traversed by the

O star in the outer part of the line-emitting region of the Wolf-Rayet star and the possible generation of X rays. We conclude that our observations of the sharp C III λ5696 emission line confirm the hydrodynamic models of Stevens, Blondin, & Pollock which show that extensive, chaotic tongues of cooling plasma are formed perpendicular to the line joing the stars in the case of colliding winds in massive binary systems. We describe observational tests which may be used to confirm what type of model is best for the line-emitting region of a Wolf-Rayet star.
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Helium chemistry of ONC supergiants

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We present high-resolution, high signal-to-noise spectroscopic observations of the Galactic late-O supergiants HD 154811 (OC9.7 Iab), HD 154368 (O9.5 Iab), and HD 123008 (ON9.5 Iab). The spectra of these stars exemplify the carbon and nitrogen line-strength anomalies characteristic of the ONC supergiants. A hydrogen/helium non-LTE model-atmosphere analysis is carried out using extensive model atoms. Helium abundances (by number) of 0.09, 0.13, and 0.17 are obtained for the OC, normal O, and ON stars respectively. These results are consistent with Walborn's hypothesis that OC supergiants have a normal (i.e., cosmic) helium abundance whereas the morphologically-normal O supergiants and, to a greater extent, the ON supergiants exhibit the products of nucleosynthetic processing at their surfaces. We note that the diagnostic line He II λ4200 is probably contaminated by a N III line in late-O supergiants.
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Spectroscopic evidence for photo-ionization wakes in Vela X-1 and 4U1700-37

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We present high-resolution, high signal-to-noise spectra of HD77581 and HD153919, the optical counterparts of the high-mass X-ray binaries Vela X-1 and 4U1700-37, respectively. The spectral lines exhibit variations related to the presence of the X-ray source in unprecedented detail. For HD77581, at inferior conjunction of the neutron star ($\phi = 0.5$), an extra absorption component appears in the blue wing of the absorption lines. This feature first increases in strength (up till binary phase $\phi = 0.6$) whereafter it slowly fades; at the same time it shifts towards higher negative velocities. The observed velocities are *low*: from -50 km s^{-1} at $\phi = 0.5$ up to -250 km s^{-1} at $\phi = 0.8$. For HD153919, the

observed variations are similar in character, but stronger and more complicated. For both systems we find significant variations in the emission part of the P Cygni-type profiles.

Based on the phase dependence of the velocity and strength of the absorption component, we show that it is unlikely that this component is related to an accretion wake, or to a gas stream through the inner Lagrangean point. These structures, although most likely present in the system, are not capable of providing sufficient obscuration of the supergiant, that would give the observed absorption. We suggest that this absorption component results from the presence of a *photo-ionization wake* in the system that trails the X-ray source. Furthermore, we predict that variations in X-ray luminosity will induce changes in the geometrical structure of the photo-ionization wake which might explain the observed orbit-to-orbit variations.

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Long-term spectroscopic monitoring of P Cygni-type stars II. Spectroscopic variations of P Cygni during 1990-1992

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We have monitored P Cygni from 1990 to 1992 with a fiber-linked echelle spectrograph and a CCD detector. The spectra cover the wavelength range 4050 Å $< \lambda <$ 6750 Å with a spectral resolution of $\lambda/\Delta\lambda \approx 12{,}000$. The S/N-ratio of the spectra depends on wavelength and weather conditions, but typically it is better than 100. Due to the linear detector, we can not only study radial velocities, but also the line strengths with good precision. We found variations in radial velocity of about 30 to 50 km sec^{-1} and line strength variations of the order of 30%. The typical timescales of the variations are months. Clear line splittings have not been found in our data.

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Dissertation abstracts

X-ray emission from instability-generated shocks in dynamical models of hot-star winds

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I describe a model of X-ray emission from shock-heated material in the radiation-driven winds of hot stars. This model treats the dynamical development of shocks caused by the instability of the spectral line driving force, and the resulting X-ray emission, within a single framework. The model extends the

time-dependent dynamical models of Owocki, Castor, and Rybicki (1988) to include energy balance, and incorporates the current version of the thermal emission code of J. Raymond (Raymond and Smith 1977) to calculate radiative energy losses and to calculate the X-ray spectrum emitted by the hot regions shown in the wind model. The model makes simple estimates of X-ray attenuation within the wind, using X-ray cross sections from Morrison and McCammon (1983).

I have modeled X-ray emission in a high density wind from a massive star such as that of ζ Pup (O4(n)f) and in a low density wind typical of a main sequence star such as τ Sco (B0 V) or μ Col (O9.5 V). In general, the instability of the wind line force generates many shocks, but only a small fraction of these are strong enough to heat shocked material to X-ray emitting temperatures. The modeled X-ray luminosity $L_{\rm x}$ can easily match, or even exceed, the observed value for the high density wind, since the emission measure inferred from observation is a small fraction of the entire wind. However, the observed $L_{\rm x}$ for the less dense winds of later-type main sequence stars is so high that a substantial fraction of the entire wind must be hot; this does not occur in the models unless the base of the wind undergoes large (25%) fluctuations in density or another parameter.

In this dissertation, I describe the development and testing of the model; in particular, I discuss difficulties that arise in trying to resolve the hot postshock cooling regions well, and approaches I have chosen to get around this difficulty. I give results for models of low and high density winds, and compare model spectra to observed spectra of τ Sco, μ Col, and ζ Pup.

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News

IUE campaign

An international campaign to observe an O–star, a B–star and a Wolf-Rayet star for P-Cygni profile variability was planned during the colloque at the Isle-aux-Coudres. The project has been allocated 45 IUE shifts in a continuous run. It would be most useful to get simultaneous optical/infrared spectroscopy/photometry observations. The scheduled IUE dates will be communicated as soon as they are known. Interested ground-based observers should contact Allan Willis (ajw@star.ucl.ac.uk).