# 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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editor: Philippe Eenens
eenens@carina.astro.ugto.mx


http://www.astro.ugto.mx/∼eenens/hot/
http://www.star.ucl.ac.uk/∼hsn/index.html


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## From the editor

### A New Review

A review on The Evolution of Rotating Stars has been written by André Maeder and Georges Meynet for *Annual Review of Astronomy & Astrophysics Vol. 38 (2000).* The abstract can be found in this newsletter.

### La Plata Proceedings on the Web

Virpi Niemela <virpi@colihue.fcaglp.unlp.edu.ar> communicates that the proceedings (including conference pictures!) of the La Plata Workshop on

*Hot Stars in Open Clusters of the Galaxy and the Magellanic Clouds*

are now *on the web at* `http://lilen.fcaglp.unlp.edu.ar/hoc97.html`

**The Wolf-Rayet Bibliography** has recently been updated by Karel van der Hucht and can be accessed by FTP at `ftp://saturn.sron.nl/pub/karelh/UPLOADS/WRBIB/` or on request from the author `K.A.van.der.Hucht@sron.nl`

**Jobs:** Stan Owocki is seeking a Post-doc replacement. More information in the last section of this newsletter.

**Meetings:** We have received the first announcement of a meeting in Brussels in August, on *the influence of binaries on stellar population studies*, as well as the second announcements for the Armagh and Hven meetings. The dates of the Armagh and Hven meetings allow participants to attend both full programs, but this is not the case of the Brussels meeting, which falls during the same week.

The following is a summary of some meetings of interest to the Hot Massive Star community during the rest of this year. Further information can be obtained from their Web sites or by e-mail.

| | |
|---|---|
| March 15-18<br>Chile | **Star, gas and dust in galaxies: exploring the links**<br>http://www.eso.org/gen-fac/meetings/sgd2000/2000.html<br>e-mail: olsen@ctiowd.ctio.noao.edu |
| July 10-14<br>Québec | **Interacting winds from massive stars**<br>http://www.astro.umontreal.ca/iwinds/<br>e-mail: Moffat@astro.uMontreal.ca |
| August 10<br>England | **Massive star birth** (IAU General Assembly)<br>http://www.iau-ga2000.org/<br>http://www.iau.org/ib85/sciprog.html#jd3<br>e-mail: pconti@jila.colorado.edu |
| August 21-23<br>Ireland | **P Cygni 2000: 400 years of progress**<br>http://www.arm.ac.uk/~mdg<br>e-mail: mdg@star.arm.ac.uk |
| August 21-25<br>Belgium | **The influence of binaries on stellar population studies**<br>http://homepages.vub.ac.be/~wvanrens/bin_conference/<br>e-mail: dvbevere@vub.ac.be |
| August 24-26<br>Sweden | $\eta$ **Car & other mysterious stars: a hidden opportunity for emission spectroscopy**<br>http://ferrum.fysik.lu.se/hven2000<br>e-mail: Hven2000@fysik.lu.se Fri |

## Accepted Papers

# The Evolution of Rotating Stars

**André Maeder and Georges Meynet**

Geneva Observatory, CH–1290 Sauverny, Switzerland

First, we review the main physical effects to be considered in the building of evolutionary models of rotating stars on the Upper Main-Sequence (MS). The internal rotation law evolves as a result of contraction and expansion, meridional circulation, diffusion processes and mass loss. In turn, differential rotation and mixing exert a feedback on circulation and diffusion, so that a consistent treatment is necessary.

We review recent results on the evolution of internal rotation and the surface rotational velocities for stars on the Upper MS, for red giants, supergiants and W–R stars. A fast rotation is enhancing the mass loss by stellar winds and reciprocally high mass loss is removing a lot of angular momentum. The problem of the "break–up" or Ω–limit is critically examined in connection with the origin of Be and LBV stars. The effects of rotation on the tracks in the HR diagram, the lifetimes, the isochrones, the blue to red supergiant ratios, the formation of W–R stars, the chemical abundances in massive stars as well as in red giants and AGB stars, are reviewed in relation to recent observations for stars in the Galaxy and Magellanic Clouds. The effects of rotation on the final stages and on the chemical yields are examined, as well as the constraints placed by the periods of pulsars. On the whole, this review points out that stellar evolution is not only a function of mass M and metallicity Z, but of angular velocity Ω as well.

**Accepted by Annual Review of Astronomy & Astrophysics Vol. 38 (2000)**
*Preprints from* Andre.Maeder@obs.unige.ch or Georges.Meynet@obs.unige.ch

## Near–Infrared Classification Spectroscopy: J–band Spectra of Fundamental MK Standards

**Lloyd Wallace[1], Michael R. Meyer[2], Kenneth H. Hinkle[1], and Suzan Edwards[3]**

[1] Kitt Peak National Observatory, National Optical Astronomy Observatories, Tucson, AZ 85721

[2] Steward Observatory, The University of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721–0065

[3] Astronomy Department, Smith College, Northampton, MA 01063

We present a catalog of J–band spectra for 88 fundamental MK standard stars observed at a resolving power of $R \sim 3000$. This contribution serves as a companion atlas to the K–band spectra published by Wallace and Hinkle (1997) and the H–band atlas of Meyer et al. (1998). We report data from 7400–9550 cm$^{-1}$ (1.05–1.34 $\mu$m) for stars of spectral types O7–M6 and luminosity classes I–V as defined in the MK system. In reducing these data, special care has been taken to remove time–variable telluric features of water vapor. We identify atomic and molecular indices which are both temperature and luminosity sensitive that aid in the classification of stellar spectra in the J–band. In addition to being useful in the classification of late–type stars, the J–band contains several features of interest in the study of early–type stellar photospheres. These data are available electronically for anonymous FTP in addition to being served on the World Wide Web.

**Accepted by the Astrophysical Journal.**
*Preprints from* mmeyer@as.arizona.edu
*or on the web at* http://gould.as.arizona.edu/origins/preprint.html
*Data available at* http://www.noao.edu/archives.html

## Modeling Non-Axisymmetric Bow Shocks: Solution Method and Exact Analytic Solutions

**Francis P. Wilkin[1]**

[1] California Institute of Technology, IPAC MS 100-22, Pasadena, CA 91125

A new solution method is presented for steady-state, momentum-conserving, non-axisymmetric bow shocks and colliding winds in the thin-shell limit. This is a generalization of previous formulations to include a density gradient in the pre-shock ambient medium, as well as anisotropy in the pre-shock wind. For cases where the wind is unaccelerated, the formalism yields exact, analytic solutions.

Solutions are presented for two bow shock cases: (1) that due to a star moving supersonically with respect to an ambient medium with a density gradient perpendicular to the stellar velocity, and (2) that due to a star with a misaligned, axisymmetric wind moving in a uniform medium. It is also shown under quite general circumstances that the total rate of energy thermalization in the bow shock is independent of the details of the wind asymmetry, including the orientation of the non-axisymmetric driving wind, provided the wind is non-accelerating and point-symmetric. A typical feature of the solutions is that the region near the standoff point is tilted, so that the star does not lie along the bisector of a parabolic fit to the standoff region. The principal use of this work is to infer the origin of bow shock asymmetries, whether due to the wind or ambient medium, or both.

**Accepted by Astrophys. J. to appear March 20, 2000**

*Preprints from* wilkin@ipac.caltech.edu

## The Stellar Content of Obscured Galactic Giant H II Regions: II. W42

**R. D. Blum[1], P. S. Conti[2], A. Damineli[3]**

[1] CTIO Casilla 603, La Serena, Chile

[2] JILA, University of Colorado, Campus Box 440, Boulder, CO, 80309, USA

[3] IAG, University of São Paulo, Av. Miguel Stefano 4200, 04301-904,
São Paulo, Brazil

We present near infrared J, H, and K images and K-band spectroscopy in the giant HII region W42. A massive star cluster is revealed; the color–color plot and K-band spectroscopic morphology of two of the brighter objects suggest the presence of young stellar objects. The spectrum of the bright central star is similar to unobscured stars with MK spectral types of O5–O6.5. If this star is on the zero age main sequence, then the derived spectrophotometric distance is considerably smaller than previous estimates. The Lyman continuum luminosity of the cluster is a few times that of the Trapezium. The slope of the K-band luminosity function is similar to that for the Trapezium cluster and significantly steeper than that for the massive star cluster in M17 or the Arches cluster near the Galactic center.

**Accepted by AJ**

*Preprints from* rblum@noao.edu
*or by anonymous ftp to* ftp://ftp.ctio.noao.edu/pub/blum/blumxxx.ps
*or on the web at* http://xxx.lanl.gov/abs/astro-ph/0001157

## Spectroscopy within 0′′.3 of Sgr A*

**D. F. Figer[1], E. E. Becklin[2], I. S. McLean[2],
A. M. Gilbert[3], J. R. Graham[3], J. E. Larkin[2], N. A. Levenson[4],
H. I. Teplitz[5], M. K. Wilcox[2] and M. Morris[2]**

[1] STScI  [2] UCLA  [3] UCB  [4] JHU  [5] GSFC

We present moderate (R ≈ 2,700) and high resolution (R ≈ 22,000) 2.0−2.4 $\mu$m spectroscopy of the central 0.1 square arcseconds of the Galaxy obtained with NIRSPEC, the facility near-infrared spectrometer for the Keck II telescope. The composite spectra do not have any features attributable

to the brightest stars in the central cluster, i.e. after background subtraction, $W_{^{12}CO(2-0)} < 2$ Å. This stringent limit leads us to conclude that the majority, if not all, of the stars are hotter than typical red giants. Coupled with previously reported photometry, we conclude that the sources are likely OB main sequence stars. In addition, the continuum slope in the composite spectrum is bluer than that of a red giant and is similar to that of the nearby hot star, IRS16NW. It is unlikely that they are late-type giants stripped of their outer envelopes because such sources would be much fainter than those observed. Given their inferred youth ($\tau_{\rm age} < 20$ *Myr*), we suggest the possibility that the stars have formed within 0.1 pc of the supermassive black hole. We find a newly-identified broad-line component ($V_{\rm FWHM} \approx 1{,}000$ km s$^{-1}$) to the 2.2178 $\mu$m [Fe 3] line located within a few arcseconds of Sgr A*. A similar component is not seen in the Br-$\gamma$ emission.

**Accepted by ApJ Letters**

*Preprints from* http://nemesis.stsci.edu/~figer/web/papers.html

## Wind properties of Wolf-Rayet stars at low metallicity: Sk 41 (SMC)

**Paul A. Crowther**

Department of Physics & Astronomy, University College London, Gower Street, London WC1E 6BT

The stellar properties of Sk 41 (AB4, WN5h), the only known single Wolf-Rayet star in the SMC, are derived from ultraviolet (IUE), optical (AAT) and near-IR (NTT) spectroscopy. Contrary to expectations, the stellar properties of Sk 41 are typical of equivalent WN stars in the Galaxy and LMC, with $T_*\sim$42kK, $\log(L/L_\odot)$=5.7, $v_\infty$=1300 km s$^{-1}$, $\dot{M}/\sqrt{f}=3\times10^{-5} M_\odot {\rm yr}^{-1}$, and H/He$\sim$2 by number, where $f$ is the volume filling factor. The stellar luminosity of Sk 41 is 50% below the minimum value predicted by single star evolutionary models at the metallicity of the SMC.

Emission line luminosities of He II λ4686 and C IV λλ5801-12 in SMC WR stars are not systematically lower than their Galactic and LMC counterparts. From 43 late-type and 59 early-type WN stars, log $L_\lambda^{\rm HeII}$= 36.0 erg s$^{-1}$ and 35.8 erg s$^{-1}$, respectively, while log $L_\lambda^{\rm CIV}$=36.5 erg s$^{-1}$ from 25 early-type WC stars. This new calibration has application in deriving WR populations in young starburst galaxies.

Synthetic WN models are calculated with identical parameters except that metal abundances are varied. Following the Smith et al. WN classification scheme, CNO equilibrium models reveal that earlier spectral types are predicted at lower metallicity, i.e. WN3–4 at $0.04Z_\odot$ versus WN6 at $1.0Z_\odot$. This provides an explanation for the trend towards earlier WN spectral types at low metallicity.

**To appear in** *Astronomy & Astrophysics*

*Preprints from* pac@star.ucl.ac.uk

*or by anonymous ftp to* ftp.star.ucl.ac.uk, in pub/pac/sk41.ps.gz

*or on the web at* http://www.star.ucl.ac.uk/~pac/publications.html

## A Second Luminous Blue Variable in the Quintuplet Cluster

**T. R. Geballe[1], F. Najarro[2], and D. F. Figer[3]**

[1] Gemini Observatory, 670 N. A'ohoku Pl., Hilo, HI 96720

[2] Instituto de Estructura de la Materia, CSIC, Serrano 121, 28006 Madrid, Spain

[3] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

H and K band moderate resolution and 4 $\mu$m high resolution spectra have been obtained for FMM362, a bright star in the Quintuplet Cluster near the Galactic Center. The spectral features in these bands closely match those of the Pistol Star, a luminous blue variable and one of the most luminous stars known. The new spectra and previously-obtained photometry imply a very high luminosity for FMM362, $L \geq 10^6 L_\odot$, and a temperature of 10,000 – 13,000 K. Based on its luminosity, temperature, photometric variability, and similarities to the Pistol Star, we conclude that FMM362 is a luminous blue variable.

**To appear in ApJ Letters, 530L, 93 (2000)**
*Preprints from* `tgeballe@gemini.edu`
*or on the web at* `http://xxx.lanl.gov/abs/astro-ph/9912415`

## Spectroscopy of WC9 Wolf-Rayet stars: a search for companions

**P.M. Williams[1] and K.A. van der Hucht[2]**

[1] Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, United Kingdom

[2] Space Research Organization Netherlands, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

A spectroscopic search for luminous companions to WC9 type Wolf-Rayet stars making circumstellar dust reveals the presence of absorption lines attributable to companions in the blue spectra of WR 69 (HD 136488) and WR 104 (Ve2–45). Comparison of spectra of WR 104 observed in 1995 and 1997 found the absorption lines to be more conspicuous in the latter observation and the emission lines weaker, suggesting a selective eclipse of the WC9 star similar to that observed by Crowther in 1996. The WC9 emission-line spectra are shown to be less uniform than previously thought, showing a significant range of O II line strengths. The only two WC9 stars in the observed sample which do not make circumstellar dust, WR 81 (He3–1316) and WR 92 (HD 157451), are found to have anomalously weak O II and strong He II lines. We suugest that these spectroscopic differences may reflect a compositional difference which plays a role in determining which of the WC9 stars make dust.

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*Preprints from* `pmw@roe.ac.uk`
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## $\eta$ Carinae: Binarity Confirmed

**Augusto Damineli[1], Andreas Kaufer[2], Bernhard Wolf[3], Otmar Stahl[3], Dalton F. Lopes[4] and Francisco X. de Araújo[4]**

[1] Instituto Astronômico e Geofísico da USP, Av. Miguel Stefano 4200, 04301-904 São Paulo, Brazil

[2] European Southern Observatory, Alonso de Cordova 3107, Santiago 19, Chile

[3] Landessternwarte, Königstuhl, D-69117 Heidelberg, Federal Republic of Germany

[4] Observatório Nacional, R. General José Cristino 77, 20921-400 Rio de Janeiro, Brazil

We report the recovery of a spectroscopic event in $\eta$ Carinae in 1997/98 after a prediction by Damineli (1996). A true periodicity with $P = 2020 \pm 5$ days (0.2% uncertainty) is obtained. The line intensities

and the radial-velocity curve display a phase-locked behavior implying that the energy and dynamics of the event repeat from cycle to cycle. This rules out S Doradus oscillation or multiple shell ejection by an unstable star as the explanation of the spectroscopic events. A colliding-wind binary scenario is supported by our spectroscopic data and by X-ray observations. Although deviations from a simple case exist around periastron, intensive monitoring during the next event (mid 2003) will be crucial to the understanding of the system.

**Accepted by ApJ Letters, 528, 101 (10 January 2000)**
*Preprints from* damineli@iagusp.usp.br
*Or on the web at* http://carina.iagusp.usp.br/preprints.html

## Multiple variations in the radio light-curve of the colliding wind binary WR 146 (WC6+O): evidence for a third component

**Diah Y.A. Setia Gunawan[1,2], A. Ger de Bruyn[1,3], Karel A. van der Hucht[2], Peredur M. Williams[4]**

[1] Kapteyn Astronomical Institute, P.O. Box No. 800, NL-9700 AV Groningen, The Netherlands
[2] Space Research Organization Netherlands, Sorbonnelaan 2, NL-3584 CA Utrecht, The Netherlands
[3] Netherlands Foundation for Research in Astrophysics, P.O. Box No. 2, NL-7990 AA Dwingeloo, The Netherlands
[4] Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, U.K.

The Wolf-Rayet star WR 146 (HM19-3, WC6+O) is the brightest WR star at radio wavelengths. We have been monitoring this system with the Westerbork Synthesis Radio Telescope (*WSRT*) at 1.4 and 5 GHz (21 and 6 cm) since 1989. The time-averaged spectral index $\alpha_{5-1.4\,\mathrm{GHz}} \simeq -0.62$ clearly points to a domination by non-thermal radiation, which we associate with colliding winds in this binary system. The non-thermal radio flux distribution shows a turn-over at low frequency, which we suggest to be due to free-free absorption of the synchrotron emission from the colliding wind region by plasma around the system.

In the period 1989 – 1997 the average 1.4-GHz flux density increased from $\sim$61 to $\sim$73 mJy; in the the period 1989 – 1999 the average 5-GHz flux density increased from $\sim$29 to $\sim$37 mJy. The light-curves show three different kinds of variations: *(i)* a slow linear rise in a time-span of a decade; *(ii)* a 3.38 yr periodic variation; and, *(iii)* rapid non-periodic variations on a time-scale of weeks.

We examine whether the slow rise of the flux density could be explained by decreasing free-free absorption in the line-of-sight through the radiophotosphere of the O component, while moving in an eccentric orbit around the WR component. However, the similarity of the amplitudes ($\sim$ 22% in 10 yr) of the rises at 1.4 and 5 GHz argues against a change in free-free absorption, expected to be strongly wavelength dependent. This points to an intrinsic flux-density variation, possibly due to modulation of the magnetic field strength resulting from orbital motion in a very-long-period eccentric binary system. The relation between the flux-density increase and orbital motion is supported by positional measurements of the 5-GHz data.

We detect a possible motion of the shock zone relative to one of the control sources (Control A) of $\sim 0\farcs05$ in the 10 yr observing span. At a distance of 1250 pc this motion corresponds to a projected tangential velocity of about 30 km s$^{-1}$, which is a plausible orbital velocity for a system like WR 146.

Superimposed on the 1.4-GHz slow rise, we find a sinusoidal variation with a period $P = 3.38 \pm 0.02$ yr and a semi-amplitude of $4.3 \pm 0.2$ mJy. Adopting a distance of 1250 pc to the system and a 162 mas

WR+O separation, we consider the observed 3.38 yr period too short to be the WR+O binary period by at least two orders of magnitude. We suggest that the periodic variability is caused by a third, low-mass object, modulating the mass flow and/or the magnetic-field of the O component. Unfortunately, our 5-GHz data are far too few and not adequately spread over the whole phase to confirm that they consistently follow the 3.38 yr period found in the 1.4-GHz data.

The erratic 'micro'-variation in the 1.4-GHz light-curve is about $4\sigma$ of the typical 0.5 mJy observational uncertainty, on a time-scale of weeks to months. When irregularities in the mass flow (clumps, inhomogeneities and/or turbulence in the O and/or WR star winds) reach the wind collision region, variation in the non-thermal emission can be expected. Such irregularities can also affect the free-free line-of-sight absorption at the lowest observing frequencies.

**Accepted by Astronomy & Astrophysics Main Journal**
*Preprints from* `diah@astro.rug.nl`
*or on the web at* `http://www.astro.rug.nl/~diah`

## The porous atmosphere of $\eta$-Carinae

**Nir J. Shaviv**[1]

[1] Canadian Institute for Theoretical Astrophysics, University of Toronto
60 St. George St., Toronto, ON M5S 3H8, Canada

We analyze the wind generated by the great 20 year long super-Eddington outburst of $\eta$-Carinae. We show that using classical stellar atmospheres and winds theory, it is impossible to construct a consistent wind model in which a sufficiently *small* amount of mass, like the one observed, is shed. One expects the super-Eddington luminosity to drive a thick wind with a mass loss rate substantially higher than the observed one. The easiest way to resolve the inconsistency is if we alleviate the implicit notion that atmospheres are homogeneous. An inhomogeneous atmosphere, or "porous", allows more radiation to escape while exerting a smaller average force. Consequently, such an atmosphere yields a considerably lower mass loss rate for the same total luminosity. Moreover, all the applications of the Eddington Luminosity as a strict luminosity limit should be revised, or at least reanalyzed carefully.

**Accepted by ApJ Lett**
*Preprints from* `shaviv@cita.utoronto.ca`
*or on the web at* `http://www.cita.utoronto.ca/~shaviv/preprints/articles.html`

## The Strange Case of $\theta^1$ Orionis A

**D. J. Stickland and C. Lloyd**

Rutherford Appleton Laboratory, Didcot, OX11 0QX, UK

We review the binary properties of the bright Orion Trapezium star $\theta^1$ Ori A and include radial velocities from IUE in a new orbital solution; meanwhile, times of primary minimum are used to determine a new ephemeris. With these revised parameters, we strongly encourage further observations, especially a search for secondary minimum. Probably the system consists of a main sequence early B primary and a cooler pre-main-sequence companion.

**Accepted by The Observatory**
*Preprints from* `obs@astro1.bnsc.rl.ac.uk`

# Infrared imaging and spectroscopy of the Luminous Blue Variables Wra 751 and AG Car

**R.H.M. Voors[1,2,3], L.B.F.M. Waters[3,4], A. de Koter[3], , J. Bouwman[3], P.W. Morris[1,3], M.J. Barlow[5], R.J. Sylvester[5], N.R. Trams[6] and H.J.G.L.M. Lamers[2,1]**

[1] SRON Laboratory for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands [2] Astronomical Institute, University of Utrecht, Princetonplein 5, 3584 CC Utrecht, The Netherlands [3] Astronomical Institute Anton Pannekoek, University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands [4] Instituut voor Sterrenkunde, Katholieke Universiteit Leuven, Celestijnenlaan 200B, B-3001 Heverlee, Belgium [5] Department of Physics and Astronomy, University College London, Gower St., London WC1E 6BT, UK [6] Integral Science Operations, Astrophysics Division of ESA, ESTEC SCI-SAG, PO Box 299, 2200 AG Noordwijk, The Netherlands

We present ground-based infrared imaging and *ISO* spectroscopy of the luminous blue variables Wra 751 and AG Car. The images show in both cases a detached shell with a roughly circular distribution of emission. The infrared images of AG Car coincide very well with the optical images. The optical (H$\alpha$) image of Wra 751 is different from the infrared image; the H$\alpha$ nebula is suggested to be a scattering nebula containing cold dust particles.

Fitting both the images and the spectra consistently with a 1-D radiative transfer model, we derive properties of their dust shells. Wra 751 is surrounded by a dust shell with inner and outer radii of 0.17 and 0.34 pc respectively and a dust mass of 0.017 $M_\odot$. The dust shell of AG Car has inner and outer radii of 0.37 and 0.81 pc respectively and a total dust mass of 0.25 $M_\odot$. Dust mass-loss rates during the formation of the shells are $2.7\times10^{-6}$ and $3.4\times10^{-5}$ $M_\odot\,yr^{-1}$, respectively. The total dust mass and hence the derived dust mass-loss rates are uncertain by at least a factor of two. For AG Car, the derived dust mass and mass-loss rate are higher than previous estimates. This is mainly caused by the fact that a contribution of very large grains ($> 10\ \mu$m) is needed to explain the flux levels at longer wavelengths.

Dust models for both objects fail to explain the flux shortward of 15 to 20 $\mu$m: a population of small warm grains, not in thermal equilibrium with the central star is necessary to explain this excess. Similarities between dust shells around Wolf-Rayet stars and Wra 751 and AG Car (mass, grain size population, morphology) suggest a similar formation history and imply an evolutionary connection. A similar connection with red supergiants is suggested on the basis of the dust composition and derived time-averaged mass-loss rates.

**Accepted by** *Astronomy and Astrophysics*
*Preprints from* `voors@astro.uva.nl`
*or by anonymous ftp to* `ceres.astro.uva.nl/pub/voors/dustfits.ps`

# Synthesis of $^{19}$F in Wolf-Rayet stars

**G. Meynet[1] and M. Arnould[2]**

[1] Geneva Observatory, CH-1290 Sauverny, Switzerland

[2] Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Campus Plaine, CP 226, B-1050 Brussels, Belgium

Meynet & Arnould (1993a) have suggested that Wolf-Rayet (WR) stars could significantly contaminate the Galaxy with $^{19}$F. In their scenario, $^{19}$F is synthesized at the beginning of the He-burning phase from the $^{14}$N left over by the previous CNO-burning core, and is ejected in the interstellar medium when the star enters its WC phase. Recourse to CNO seeds makes the $^{19}$F yields metallicity-dependent.

These yields are calculated on grounds of detailed stellar evolutionary sequences for an extended range of initial masses (from 25 to 120 $M_\odot$) and metallicities ($Z = 0.008$, 0.02 and 0.04). The adopted mass loss rate prescription enables to account for the observed variations of WR populations in different environments.

The $^{19}$F abundance in the WR winds of 60 $M_\odot$ model stars is found to be about 10 to 70 times higher than its initial value, depending on the metallicity. This prediction is used in conjunction with a very simple model for the chemical evolution of the Galaxy to predict that WR stars could be significant (dominant ?) contributors to the solar system fluorine content. We also briefly discuss the implications of our model on the possible detection of fluorine at high redshift.

**Accepted by Astronomy & Astrophysics**

*Preprints from* Georges.Meynet@obs.unige.ch

# Long-term photometry of the Wolf-Rayet stars WR 137, WR 140, WR 148, and WR 153

Kiril P. Panov[1], Martin Altmann[2], and Wilhelm Seggewiss[2]

[1] Institute of Astronomy, Bulgarian Academy of Sciences, Sofia, Bulgaria

[2] Universitätssternwarte Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany

In 1991, a long term $UBV$-photometry campaign of four Wolf-Rayet stars was started using the 60 cm telescope of the National Astronomical Observatory Rozhen, Bulgaria. Here we report on our observational results and discuss the light variations.

The star WR 137 was observed during 1991 - 1998. No indications of eclipses were found, though random light variations with small amplitudes exist, which are probably due to dynamical wind instabilities.

WR 140 was also monitored between 1991 and 1998. In 1993, a dip in the light curve in all passbands was observed shortly after periastron passage, with amplitude of 0.03 mag in $V$. This is interpreted in terms of an "eclipse" by dust condensation in the WR-wind. The amplitude of the eclipse increases towards shorter wavelengths; thus, electron scattering alone is not sufficient to explain the observations. An additional source of opacity is required, possibly Rayleigh scattering. After the eclipse, the light in all passbands gradually increased to reach the "pre-eclipse" level in 1998. The very broad shape of the light minimum suggests that a dust envelope was built up around the WR-star at periastron passage by wind-wind interaction, and was gradually dispersed after 1993.

Our observations of WR 148 (WR + c?) confirm the 4.3 d period; however, they also show additional significant scatter. Another interesting finding is a long-term variation of the mean light (and, possibly, of the amplitude) on a time scale of years. There is some indication of a 4 year cycle of that long-term variation. We discuss the implications for the binary model.

Our photometry of WR 153 is consistent with the quadruple model of this star by showing that both orbital periods, 6.7 d (pair A) and 3.5 d (pair B), exist in the light variations. A search in the HIPPARCOS photometric data also reveals both periods, which is an independant confirmation. No other periods in the light variability of that star are found. The longer period light curve shows only one minimum, which might be due to an atmospheric eclipse; the shorter period light curve shows two minima, indicating that both stars in pair B are eclipsing each other.

**Accepted by Astronomy & Astrophysics**
*Preprints from* `seggewis@astro.uni-bonn.de`

## Properties and nature of Be stars 19. Spectral and light variability of 60 Cygni

**P. Koubský[1], P. Harmanec[1,2], A.M. Hubert[3], M. Floquet[3], J. Kubát[1], D. Ballereau[3], J. Chauville[3], H. Božić[4], D. Holmgren[1,9], S. Yang[8,10], H. Cao[5], P. Eenens[6], L. Huang[5], and J.R. Percy[7]**

[1] Astronomický ústav, Akademie věd České republiky, 251 65 Ondřejov, Czech Republic
e-mail: koubsky, hec, kubat, david@sunstel.asu.cas.cz

[2] Astronomický ústav, Matematicko-fyzikální fakulta, Karlova Univerzita, V Holešovičkách 2, 180 00 Praha 8, Czech Republic ; e-mail: hec@sirrah.troja.mff.cuni.cz

[3] DASGAL/UMR 8633 du CNRS, Observatoire de Paris-Meudon, 92195-Meudon Principal Cedex, France
e-mail: Dominique.Ballereau, Jacques.Chauville, Michele.Floquet, Anne-Marie.Hubert@obspm.fr

[4] Opservatorij Hvar Geodetskog fakulteta Sveučilišta u Zagrebu, Kačićeva 26, 10000 Zagreb, Croatia
e-mail: hbozic@geodet.geof.hr

[5] Beijing Astronomical Observatory, Chinese Academy of Sciences, Beijing 100080, China
e-mail: hling@bao01.bao.ac.cn

[6] Departamento de Astronomia, Universidad de Guanajuato, Apartado 144, 36000 Guanajuato, GTO, Mexico
e-mail: eenens@carina.astro.ugto.mx

[7] Erindale College and Department of Astronomy, University of Toronto, Mississauga, ON L5L IC6, Canada ; e-mail: jpercy@erin.utoronto.ca

[8] Department of Physics and Astronomy, University of Victoria, PO Box 3055 STN CSC, Victoria B.C. V8W 3P6, Canada
e-mail: yang@uvastro.phys.uvic.ca

[9] Department of Physics and Astronomy, Brandon University, Brandon, MA R7A 6A9, Canada
e-mail: holmgren@brandonu.ca

An analysis of electronic spectra secured between 1992 and 1999 at the Haute Provence, Ondřejov and Dominion Astrophysical Observatories and of differential $UBV$ measurements of 60 Cyg obtained between 1984 and 1999 at Hvar, San Pedro Mártir, Toronto and Xinglong Observatories, the all-sky Hipparcos satellite $H_{\rm p}$ photometry transformed to Johnson $V$ and $B$ magnitudes, and all-sky $UBV$ observations published by several authors and dating back to fifties, led to the following findings:

1. 60 Cyg exhibits pronounced long-term spectral variations characterized by the B $\rightarrow$ Be $\rightarrow$ B phase transitions. These long-term spectral changes of 60 Cyg are also accompanied by corresponding,

though rather mild, secular light and colour variations. The character of these variations is indicative of a positive correlation between the brightness and emission-line strength.

2. NLTE model atmosphere analysis of spectra secured during the quiescence state (B phase) of 60 Cyg shows that the star has overabundance of helium. Best results were obtained for $N_{\rm He}/N_{\rm H} = 0.2$.

3. The presence of periodic medium-term changes, with a period of $146\overset{\rm d}{.}6 \pm 0\overset{\rm d}{.}6$ was found in the radial-velocity of the H$\alpha$ and He I 6678 Å lines. If confirmed by future observations, these variations could indicate that 60 Cyg is a spectroscopic binary.

4. There are clear rapid periodic line-profile changes of (a) overall line asymmetry, and (b) weak sub-features passing across the line profiles every about $0\overset{\rm d}{.}1$. The radial velocity and asymmetry of He I lines vary with a period of $1\overset{\rm d}{.}0647$ and a double-wave curve. There is no evidence of this period in photometry, however.

5. The rapid light variations of 60 Cyg are dominated by rapid changes with a full amplitude of almost $0\overset{\rm m}{.}1$. A period analysis of $V$ magnitude data prewhitened for the long-term changes indicates a period of $0\overset{\rm d}{.}2997029$, reported earlier. The most interesting finding is that also all recorded series of moving sub-features in the line profiles can be reconciled with this period: the sub-features reappear at the same phase intervals of the $0\overset{\rm d}{.}2997$ period in the line profiles over an interval of several years. Considering the acceleration of these sub-features, 1900 km $\rm s^{-1}d^{-1}$, it is conceivable that the true physical (super) period of these changes is either $0\overset{\rm d}{.}8991$ or $1\overset{\rm d}{.}1988$.

6. The findings mentioned in points 4 and 5 represent a challenge for the NRP scenario since the light changes would be dominated by a high-order mode instead of a low-order one.

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## Calibration of Nebular Emission-Line Diagnostics: I. Stellar Effective Temperatures

**M. S. Oey[1], M. A. Dopita[2], J. C. Shields[3], and R. C. Smith[4]**

[1] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

[2] Research School of Astronomy and Astrophysics, Institute of Advanced Study, The Australian National University, Private Bag, Weston Creek P.O., ACT 2611, Australia

[3] Ohio University, Dept. of Physics and Astronomy, Clippinger Research Labs. 251B, Athens, OH 45701-2979, USA

[4] Cerro Tololo Inter-American Observatory Casilla 603, La Serena, Chile

We present a detailed comparison of optical H II region spectra to photoionization models based on modern stellar atmosphere models. We examine both spatially resolved and integrated emission-line spectra of the H II regions DEM L323, DEM L243, DEM L199, and DEM L301 in the Large Magellanic Cloud. The published spectral classifications of the dominant stars range from O7 to WN3, and morphologies range from Strömgren sphere to shell structure. Two of the objects include SNR contamination. The overall agreement with the predictions is generally within 0.2 dex for major diagnostic line ratios. An apparent pattern in the remaining discrepancies is that the predicted electron temperature is $\sim 1000$ K hotter than observed. [Ne III] intensities are also slightly *over*predicted, which may or may not be related. We model the shock emission for the SNR-contaminated objects, and find excellent agreement with the observations for composite shock and photoionized spectra. DEM L301's emission apparently results from both shocks and density-bounded photoionization. The existence of contaminating shocks can be difficult to ascertain in the spatially integrated spectra.

Our analysis of the complex DEM L199 allows a nebular emission-line test of unprecedented detail for WR atmospheres. Surprisingly, we find no nebular He II $\lambda4686$ emission, despite the fact that both of the dominant WN3 stars should be hot enough to fully ionize He I in their atmospheres. The nebular diagnostics are again in excellent agreement with the data, for stellar models not producing $He^{+}$-ionizing photons. The optical diagnostics are furthermore quite insensitive to the ionizing energy distribution for these early WR stars.

We confirm that the $\eta'$ emission-line parameter is not as useful as hoped for determining the ionizing stellar effective temperature, $T_\star$. Both empirically and theoretically, we find that it is insensitive for $T_\star \gtrsim 40$ kK, and that it also varies spatially. The shock-contaminated objects show that $\eta'$ will also yield a spuriously high $T_\star$ in the presence of shocks. It is furthermore sensitive to shell morphology. We suggest [Ne III]/H$\beta$ as an additional probe of $T_\star$. Although it is abundance-dependent, [Ne III]/H$\beta$ has higher sensitivity to $T_\star$, is independent of morphology, and is insensitive to shocks in our objects. These observations should be useful data points for a first empirical calibration of nebular diagnostics of $T_\star$, which we attempt for LMC metallicity.

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## The Progenitor Masses of Wolf-Rayet Stars and Luminous Blue Variables Determined from Cluster Turn-offs. I. Results from 19 OB Associations in the Magellanic Clouds

**Philip Massey[1], Elizabth Waterhouse[2], and Kathleen DeGioia-Eastwood[2]**

[1] National Optical Astronomy Observatory, P.O. 26732, Tucson, AZ 85726-6732

[2] Dept. Physics and Astronomy, Northern Arizona University, P.O. 6010, Flagstaff, AZ 86011-6010

We combine new CCD *UBV* photometry and spectroscopy with that from the literature to investigate 19 Magellanic Cloud OB associations that contain Wolf-Rayet (WR) and other types of evolved massive stars. Our spectroscopy reveals a wealth of newly identified interesting objects, including early O-type supergiants, a high mass double-lined binary in the SMC, and, in the LMC, a newly confirmed LBV (R 85), a newly discovered WR star (Sk−69°194), and a newly found luminous B[e] star (LH85-10). We use these data to provide precise reddening determinations and construct physical H-R diagrams for the associations. We find that about half of the associations may be highly coeval, with the massive stars having formed over a short period ($\Delta\tau < 1$ Myr). The (initial) masses of the highest mass *unevolved* stars in the coeval clusters may be used to estimate the masses of the progenitors of WR and other evolved stars found in these clusters. Similarly the bolometric luminosities of the highest mass unevolved stars can be used to determine the bolometric corrections for the evolved stars, providing a valuable observational basis for evaluating recent models of these complicated atmospheres. What we find is the following: (1) Although their numbers are small, it appears that the WRs in the SMC come from only the highest mass ($> 70\mathcal{M}_\odot$) stars. This is in accord with our expectations that at low metallicities only the most massive and luminous stars will have sufficient mass-loss to become WRs. (2) In the LMC, the early-type WN stars (WNEs) occur in clusters clusters whose turn-off masses range from $30\mathcal{M}_\odot$ to 100 $\mathcal{M}_\odot$ or more. This suggests that possibly all stars with mass $> 30\mathcal{M}_\odot$ pass through an WNE stage at LMC metallicities. (3) The one WC star in the SMC is found in a cluster with a turn-off mass of $70\mathcal{M}_\odot$, the same as for the SMC WNs. In the LMC, the WCs

are found in clusters with turn-off masses of $45\mathcal{M}_\odot$ or higher, similar to what is found for the LMC WNs. Thus we conclude that WC stars come from essentially the same mass range as do the WNs, and indeed are often found in the same clusters. This has important implications for interpreting the relationship between metallicity and the WC/WN ratio found in Local Group galaxies, which we discuss. (3) The LBVs in our sample come from very high mass stars ($> 85\mathcal{M}_\odot$), similar to what is k nown for the Galactic LBV $\eta$ Car, suggesting that only the most massive stars go through an LBV phase. Recently, Ofpe/WN9 stars have been implicated as LBVs after one such star underwent an LBV-like outburst. However, our study includes two Ofpe/WN9 stars, BE 381 and Br 18, which we find in clusters with much lower turn-off masses ($25 - 35\mathcal{M}_\odot$). We suggest that Ofpe/WN9 stars are unrelated to "true" LBVs: not all "LBV-like outbursts" may have the same cause. Similarly, the B[e] stars have sometimes been described as LBV-like. Yet, the two stars in our sample appear to come from a large mass range ($> 30 - 60\mathcal{M}_\odot$). This is consistent with other studies suggesting that B[e] stars cover a large range in bolometric luminosities. (4) The bolometric corrections of early WN and WC stars are found to be extreme, with an average BC(WNE)=$-6.0$ mag, and an average BC(WC4)=$-5.5$ mag. These values are considerably more negative than those of even the hottest O-type stars. However, similar values have been found for WNE stars by applying Hillier's "standard model" for WR atmospheres. We find more modest BCs for the Ofpe/WN9 stars (BC=$-2$ to $-4$ mag), also consistent with recent analysis done with the standard model. Extension of these studies to the Galactic clusters will provide insight into how massive stars evolve at different metallicities.

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## Possible detection of an old bipolar shell associated with $\eta$ Carinae

**J. Bohigas[1], M. Tapia[1], M.T. Ruiz[2] and M. Roth[3]**

[1] Insstituto de Astronomia, UNAM, Ensenada, Mexico
[2] Departamento de Astronomia, Universidad de Chile
[3] Las Campanas Observatory, CIW, La Serena, Chile

Continuum subtracted dereddened images in the light of several atomic lines show the presence of an extended bipolar nebula surrounding $\eta$ Carinae with size $\sim 100 \times 45$ arcsec ($1.3 \times 0.5$ pc). This feature is best delineated in [OIII]5007. The geometrical disposition and mass of the shell suggest that it was formed by mass ejections from $\eta$ Carinae. The dynamic age of the nebula is $\sim$ $13000/V_7$ yr, where $V_7$ is the mean expansion velocity in 100 km s$^{-1}$, and its mass is between 5 and 10 $M_\odot$. The nebula is photoionized and composed of unprocessed material. The major axes of the nebula and of the Homunculus are nearly perpendicular. We also report the discovery of elongated emission knots prominent in [NII] located 64 to 100 arcsec away from $\eta$ Carinae, which implies that they were either ejected centuries ago or in a more recent date but with extremely large velocities.

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*Preprints from* jbb@atsrosen.unam.mx

## HST ultraviolet observations of rapid variability in the accretion-disc wind of BZ Cam

**Raman K. Prinja[1], F. A. Ringwald[2], Richard A. Wade[3] & Christian Knigge[4,5]**

[1] Department of Physics and Astronomy, University College London, Gower St., London, WC1E 6BT, UK

[2] Dept. of Physics and Space Sciences, Florida Inst. of Technology, 150 West University Boulevard, Melbourne, FL 32901-6988, USA

[3] Dept of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802-6305, USA

[4] Hubble Fellow ; [5] Department of Astronomy, Columbia University, 555 West 120th Street, New York, NY 10027, USA

We present results from time-resolved *HST* GHRS ultraviolet spectroscopy of the nova-like cataclysmic variable, BZ Cam. Extensive changes are recorded in the extended absorption troughs of the UV resonance line profiles, which betray a highly unsteady and continuously variable supersonic outflow. The large-scale line profile changes are almost exclusively confined to blue-shifted velocities, although the Si IV and C IV emission components reveal orbital phase-linked velocity shifts. The character of the accretion-disc wind of BZ Cam can alter radically on time scales down to 100 *seconds* or less. Correlated behaviour is noted in lines of low and high ionization stages, which may reflect localised density changes.

Aside from the incidence of enormous line profile changes on remarkably short time scales, BZ Cam provides an important benchmark for the simultaneous presence of very strong absorption and well-developed emission components in Si IV, C III and C IV, for an estimated low-inclination ($i < 40^o$), or possibly even face-on, system. We illustrate the problems posed for pure-scattering line synthesis models in matching the UV line profiles of BZ Cam, and set constraints for alternative thermal emission sources.

A phenomenological interpretation is that the high-speed wind of BZ Cam is highly irregular in nature, and the outflow is riddled with structure arising from localised density enhancements. It is tempting to link our empirical results to recent hydrodynamic simulations of unsteady radiatively-driven accretion-disc winds (e.g. Proga, Drew & Stone 1998). Ultimately, line profiles synthesised from the hydrodynamic codes would have to match the substantial absorption equivalent width changes in the UV lines of BZ Cam, over the very short flow times across the line formation regions, i.e. the overall contribution of the structured, disc-projected wind has to be substantially variable.

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# Submitted Papers

## 2-D non-LTE models of radiation driven winds from rotating early-type stars

**Peter Petrenz[1] and Joachim Puls[1]**

[1] Observatory of the University of Munich, Scheinerstr. 1 81679 Munich, Germany

We extend previous 2-D models of line-driven winds from rotating hot stars by accounting for the dependence of ionization structure and occupation numbers on local physical properties (density, velocity field) and the non-local stellar radiation field.

For this purpose, we formulate for the first time an approximate non-LTE description of 2-D winds. We propose the concept of a "mean irradiating atmosphere", which allows, in a computationally effective way and for all locations in the stellar wind, to consider the *frequency dependence* of the incident photospheric radiation field, which decisively determines the local ionization equilibrium.

Employing 2-D NLTE occupation numbers, force-multipliers and according force-multiplier parameters as function of $(r, \Theta)$, our hydrodynamic models are entirely self-consistent.

To estimate maximum effects arising from rotation and a consistent non-LTE approach, we concentrate on rapidly rotating B-star winds, since for this spectral regime the ionization structure is most sensitive to local conditions and variations of the radiation field. In order to avoid any contamination by the bi-stability effect (Lamers & Pauldrach 1991), we further restrict ourselves to winds with an optically thin Lyman continuum.

For all considered models, we find a *prolate* wind structure if gravity darkening and non-radial line forces are accounted for. Thus, the "$\kappa$-effect" suggested by Maeder, aiming at the possibility to obtain an oblate wind morphology, is actually *not* present for winds with an optically thin continuum. This result should be valid at least in the OB-star range.

The density contrast between the polar and the equatorial flow grows with rotation rate and decreases from thin winds ($\dot{M} \gtrsim 10^{-8}\,M_\odot$/yr: $\rho_{\rm pol}/\rho_{\rm eq} \lesssim 20\ldots30$) to denser ones ($\dot{M} \gtrsim 10^{-6}\,M_\odot$/yr: $\rho_{\rm pol}/\rho_{\rm eq} \lesssim 5$). The latter values are valid for winds rotating at 85 % of the break-up velocity. The variation of terminal velocity as function of latitude, however, is only small.

In comparison to simplified models with *global averages* for the force-multiplier parameters, the self-consistent calculation results in a density contrast $\rho_{\rm pol}/\rho_{\rm eq}$ larger by roughly a factor of two, with a moderately enhanced concentration of wind material over the poles and a significant reduction in the equatorial plane. This difference is shown to be the consequence of ionization effects, related to the specific *radial* dependence of the mean radiation temperature over the poles and about the equatorial plane, respectively.

We conclude that a quantitatively correct description of line-driven winds from rapidly rotating hot stars requires a self-consistent approach if the variation of $T_{\rm rad}(\Theta)$ at the stellar surface can induce a (significantly) stratified ionization equilibrium and should be included especially for B-stars with lower luminosities and thinner winds.

Our most important finding with regard to the influence of rotation on *global* wind properties is that the total mass-loss rate $\dot{M}_{\rm total}$ deviates from its 1-D value $\dot{M}_{\rm 1-D}$ (for $v_{\rm rot} = 0$) by at most 10. . . 20 %, even for very high rotation rates ($v_{\rm rot} \lesssim 0.85 v_{\rm crit}$), except for winds from supergiants close to the Eddington-limit, where differences up to a factor of 2 become possible. We explain this remarkable coincidence by appropriate scaling relations and finally discuss our results with special emphasis regarding the wind-momentum luminosity relation of rapidly rotating stars.

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Preprints: *uh101bv@usm.uni-muenchen.de*

In Proceedings

## Probing the young OB stars in ultra-compact H II regions

**L. Kaper[1], F. Comerón[2], M.M. Hanson[3]**

[1] Astronomical Institute, University of Amsterdam, Kruislaan 403, 1068 PM Amsterdam, The Netherlands

[2] European Southern Observatory, Garching, Germany

[3] Department of Physics, University of Cincinnati, USA

Ultra-compact H II regions (UCHIIs) represent the earliest recognizable stage of massive-star formation. We report on recent observations with the new near-infrared camera SOFI mounted at ESO's *New Technology Telescope* for a sample of about fourty "southern" UCHIIs. In most of the fields we find the expected, but previously undetected, highly reddened stars (sometimes a whole cluster!) at or close to the position of the UCHII. Often, the embedded stars are observable in the K band only; for some stars we estimate a visual extinction exceeding 50 magnitudes. Furthermore, the narrow-band $P\beta$, $H_2$, and $Br\gamma$ images show detailed structures in the surrounding material containing information on the formation history of the young massive stars.

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## Observations of the Wind Structure of OB-type Stars

**L. Kaper[1]**

[1] Astronomical Institute, University of Amsterdam, Kruislaan 403, 1098 SJ, Amsterdam, The Netherlands

The last decade, extensive optical and ultraviolet spectroscopic monitoring campaigns have shown that OB-star winds are strongly variable. The search for the origin of wind variability has lead to a better understanding of the structure in and of OB-star winds. The most prominent features of wind variability are the so-called *discrete absorption components* (DACs), which migrate through the UV P Cygni profiles on a timescale of hours to days. One of the major breakthroughs in this field of research has been the recognition that wind variability is cyclical in nature. This suggests that stellar rotation is an important piece in the unsolved puzzle of the wind-variability mechanism. The current idea is that Corotating Interaction Regions (CIRs) are responsible for the observed wind variations. In this model, the large-scale structure in the stellar wind is caused by the interaction of fast and slow streams that originate at neighbouring locations on the stellar surface. Due to the rotation of the star the streams are curved, causing fast wind material to collide with slow material in front. The dense interaction region has a spiral shape and corotates with the star, and is responsible for the periodical recurrence of DACs. In order to work, the CIR model needs a certain structure imposed at the stellar surface to produce flows with different kinematic properties. Two candidate physical mechanisms are: (i) non-radial pulsations (NRP), and (ii) surface magnetic fields. The nature of this photospheric connection is the subject of current investigations.

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## The ionization of hot star winds

**Alex de Koter[1], Jorick S. Vink[2] and Henny J.G.L.M. Lamers[2]**

[1] Institute 'Anton Pannekoek', University of Amsterdam, Kruislaan 403, NL-1098 SJ Amsterdam, The Netherlands

[2] Astronomical Institute, Utrecht University, P.O.Box 80000, NL-3508 TA Utrecht, The Netherlands

We discuss the ionization of the winds of OB-stars and Wolf-Rayet stars. Important physical processes expected to control this ionization are identified. They are: line blanketing effects, the velocity gradient of the stellar wind, and shock induced soft X-ray emission. It is concluded that predictions of the ionization stratifications from first principles are not yet feasible, each model at some point resorts to an empirical description of part of the relevant physics. This implies that the ionization still has to be constrained using empirical methods. Three of such methods are discussed, which focus on *(i)* combining spectroscopic and nebular analysis; *(ii)* comparing mass-loss determination using different diagnostics, and *(iii)* investigating the nature of the wind driving lines.

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## Evolution of rotating massive stars into the Wolf–Rayet phase at solar metallicity

**G. Meynet**

Geneva Observatory, CH–1290 Sauverny, Switzerland

In this work we study the impact of rotational mixing on the W–R star formation process and deduce some consequences for the W–R population expected at solar metallicity. More precisely we obtain that :

• The rotating models with initial masses superior to about 60 $M_\odot$ reach the break–up limit when the core contracts at the beginning of the He–burning phase, reinforcing the possible link between the Luminous Blue Variables (LBV) phenomenon and the approach of the break–up limit (Langer 1998; Maeder 1999).

• With respect to non–rotating models, models with mean rotational velocities on the Main–Sequence comparable to the observed ones, have a W–R lifetime increased by about a factor 2.5 – 3.5 at solar metallicity.

• The minimum initial mass for stars going through a W–R phase is decreased by rotation.

• The observed number ratio of W–R to O-type stars in the solar neighbourhood is much better accounted for by the rotating models than by the non–rotating ones. The number ratio of WC to WN stars is decreased by rotation.

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# Wolf–Rayet Stars and Radioisotopes Production

**G. Meynet[1] and M. Arnould[2]**

[1] Geneva Observatory, CH-1290 Sauverny

[2] Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles
C.P. 226, Bd. du Triomphe, B-1050 Brussels, Belgium

Radioisotopes are natural clocks which can be used to estimate the age of the solar system and of the universe (see e.g. Takahashi 1998; Chen & Tilton 1976; see also the recent review by Arnould & Prantzos 1999). They are responsible for the steady decline of the luminosity curves of supernovae (see e.g. Clayton 1982). The diffuse emission at 1.8 MeV from the decay of $^{26}$Al (Mahoney et al 1984; Oberlack et al 1996) may also provide a measure of the present day nucleosynthetic activity in our Galaxy. Therefore even if radionuclides represent only a tiny fraction of the cosmic matter they carry pieces of information which are unique with respect to the other isotopes.

A great number of radioisotopes are produced by massive stars at the time of the supernova explosion. A small number of them are also produced, at least in part, during the previous hydrostatic burning phases. These elements are then ejected either at the time of the supernova event or during the hydrostatic burning phases themselves through stellar winds. In this paper we shall focus our attention on this last category of elements *i.e.* on those produced and ejected by the Wolf-Rayet (W–R) stars.

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# The dependence of mass loss on the stellar parameters

**Henny J.G.L.M. Lamers[1] and Jorick S. Vink[1] and Alex de Koter[2]**

[1] Astronomical Institute and SRON Laboratory for Space Research, Utrecht University, Princetonplein 5, NL-3584CC, Utrecht, the Netherlands

[2] Astronomical Institute, 'Anton Pannekoek', University of Amsterdam, Kruislaan 403, NL-1098SJ, Amsterdam, the Netherlands

We discuss the dependence of the mass loss rates of OBA-stars, Central Stars of Planetary Nebulae and Wolf-Rayet stars on the stellar parameters. The winds of OBA stars have bi-stability jumps near $T_{\rm eff} \simeq 21\,000$ and 10 000 K, where the terminal velocity, and probably also the mass loss, changes drastically. This indicates a change of force multiplier parameters at these temperatures. We derive linear regression relations to describe the modified wind momentum and the terminal wind velocity of the OBA-stars in the Galaxy and we derive the metallicity dependence from the comparison with LMC and SMC stars. The modified wind momentum of the CSPN stars separates into two groups: one with a 30 times higher modified wind momentum than the other group. We derive regression relations for the momentum transfer efficiency $\eta$ and the mass loss rates of WR-stars, using clumping-corrected mass loss rates. Both $\eta$ and $\dot{M}$ depend on $L$ but also on composition, $Y$ and $Z$. We discuss the possible reasons for the high mass loss rates of WR-stars.

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## The Bi-stability jump in winds of earlytype supergiants

**Jorick S. Vink[1], Alex de Koter[2] and Henny J.G.L.M. Lamers[1]**

[1] Astronomical Institute, Utrecht University, P.O.Box 80000, NL-3508 TA Utrecht, The Netherlands

[2] Institute 'Anton Pannekoek', University of Amsterdam, Kruislaan 403, NL-1098 SJ Amsterdam, The Netherlands

We study the origin of the bi-stability jump in the terminal velocity of the winds of supergiants near spectral type B1. Here, the ratio $v_\infty/v_{\rm esc}$ drops steeply from about 2.6 at types earlier than B1 to a value of 1.3 at types later than B2. To this purpose, we have calculated wind models and mass-loss rates for early-type supergiants in a $T_{\rm eff}$ grid covering the range between $T_{\rm eff} = 12\ 500$ and 40 000 K. These models show the existence of a bi-stability jump in mass loss around $T_{\rm eff} = 25\ 000$ K for normal supergiants, with $\dot{M}$ increasing by about a factor five from $T_{\rm eff} \simeq 27\ 500$ to 22 500 K for constant luminosity. The wind efficiency number $\eta = \dot{M} v_\infty/(L_*/c)$ also increases drastically by a factor of 2 - 3 near that temperature.

To understand the origin of the bi-stability jump, we have investigated the line acceleration for models around the jump in detail. We argue that the mass-loss rate of radiation driven winds is determined by the radiation pressure in the *subsonic* part of the wind, just above the photosphere. Our models demonstrate that Fe dominates the line acceleration in this region of the wind and that $\dot{M}$ increases at the bi-stability jump due to an increase in the line acceleration of Fe III *below* the sonic point as iron recombines from Fe IV to Fe III.

Finally, we show that the elements C, N and O are important line drivers in the *supersonic* part of the wind. Therefore, CNO-processing is expected *not* to have a large impact on $\dot{M}$, but it might have impact on the terminal velocities.

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# Theses

## On the origin of cyclical variability in the winds of massive stars

**Jeroen A. de Jong**

Astronomical Institute "Anton Pannekoek", University of Amsterdam Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

The goal of this thesis work is the search for the origin of the widely observed cyclical variability of winds of hot, massive stars. This is one of the most challenging problems in the research of massive stars during the past 15 years.

At present, two different mechanisms are proposed as a possible cause of the variability of winds of massive stars: non-radial pulsations (where the phase of the oscillation varies over the surface) and magnetic fields, both of which being surface phenomena that are very difficult to observe in these stars. This thesis describes the results of studies towards these phenomena.

The contents of this thesis is:

Chapter 1 Introduction and summary
Chapter 2 Simultaneous UV and optical observations including magnetic field measurements of the O7.5III star $\xi$ Persei
Chapter 3 First results of the November 1996 MUSICOS campaign on the O7.5III star $\xi$ Persei
Chapter 4 Non-radial pulsations in the O stars $\xi$ Persei and $\lambda$ Cephei
Chapter 5 A search for the magnetic field of the O7.5III star $\xi$ Persei, including an analysis of profile variability in multiple lines
Chapter 6 The magnetic field of $\beta$ Cephei - a key system towards understanding the Be phenomenon?
Chapter 7 Modeling cyclical H$\alpha$ line profile variability in O-type stars

Chapter 2 and 3 describe the results of two multisite and multiwavelength campaigns. The first campaign, held in October 1994, included 10 days of IUE observations and simultaneous multi-site groundbased observations of $\xi$ Per (and a few other O stars). This campaign provided a wealth of information about the wind structure. All the UV lines and the H$\alpha$ line show a periodicity of 2.09 d and are strongly correlated. Only an upper limit to the magnetic field could be obtained. The second multi-site (MuSiCoS, "MultiSite Continuous Spectroscopy") campaign on $\xi$ Per in 1996 was focussed towards the optical line profile variability. All telescopes were equipped with échelle spectrographs which covered the whole optical range.

In chapter 4 the discoveries of NRPs in the O stars $\xi$ Per ($P$=3.45 h, $\ell$=3) and $\lambda$ Cep ($P$=12.3 h, $\ell$=5 and $P$=6.6 h, $\ell$=5) are reported. The NRP in $\xi$ Per can most probably not account for the DAC period of 2.09 d, because its pattern speed and time scale are incompatible.

Chapter 5 describes the best attempt to measure the field of the O7.5 III star $\xi$ Persei (December 1998 Pic du Midi), and an upper limit of 47 G on the disk-averaged longitudinal component of the field was obtained. From this we estimate an upper limit of 400-500 G on the polar field strength. In Chapter 6 measurements are presented of a sinusoidally varying magnetic field in the B1 IIIe star $\beta$ Cephei which correlates very accurately with the 12 day period observed in the variations of the UV wind lines.

Finally, we modeled the H$\alpha$ variability using a 2D kinematic model in which spiral like structures are accounted for (Chapter 7). A genetic algorithm was used to infer the right model parameters from observations. No quantitative fits were obtained yet, but the results are an essential first step in understanding these variations.

Chapter 4 appeared earlier in A&A. The other chapters are to be submitted to A&A.

**PhD Thesis**, under the directtion of Prof.dr. E.P.J. van den Heuvel and Dr. H.F. Henrichs, University of Amsterdam (February 2000)
*Preprints from* jdj@astro.uva.nl

Jobs

## Post-Doctoral Position at the University of Delaware

Dear Colleagues/Friends:

David Cohen, who is currently doing research with me under support of our NASA Long-Term-Space-Astrophysics (LTSA) grant, has recently accepted a tenure-track faculty position at nearby Swarthmore College. This opens up an opportunity to hire a replacement post-doc to work here at Bartol/UDel starting fall 2000 under support of this grant for its final 2 years. I would thus appreciate your assistance in calling attention of this opening to possible candidates.

The general focus of the research is to understand X-ray emission from hot, luminous (early-type) stars. There is more information at the web site:
www.bartol.udel.edu/∼owocki/postdoc.html

Of course, anyone can also get further information by contacting me by email, phone, or post at the address below.

Thanks for your attention.
Regards,

Stan Owocki
Bartol Research Institute, University of Delaware, Newark, DE 19716 USA

email: owocki@bartol.udel.edu
phone: 302-831-8357
fax: 302-831-1843