THE HOT STAR NEWSLETTER

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

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Commentaries

Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies: IAU Symposium 193

P. Conti

The conference was held in Puerto Vallarta, Mexico, November 1998. The proceedings will be edited by K.A. van der Hucht, G. Koenigsberger, & P.R.J. Eenens

The international hot star community organized IAU Symposium #193 at the Camino Real Hotel in Puerto Vallarta as part of their continuing series of "beach symposia". There was very active participation from astronomers from Mexico, who hosted the conference; 186 individuals attended from 24 countries and 54 oral papers and 130 posters were presented. The weather was warm and sunny, the surroundings peaceful, and informal discussions occurred while dining, drinking, and sitting on the beach. The poster sessions co-located with the meeting rooms were particularly well attended and remained up for the entire conference.

W-R *phenomena* as strong broad emission lines were first identified in stars in 1867. We now know that this is due to intense stellar winds. W-R *stars* are initially high mass, very luminous objects which are undergoing processes which result in a great deal of mass loss, much of which is currently observable. Models for single star evolution with extensive mass loss indicate that the anomalous composition of W-R stars (subtypes: WN, nitrogen and helium rich; WC, helium and carbon rich) is a result of core burning products being present at the stellar "surface" due to previous mass loss and or mixing. Starburst *galaxies* are those systems in which strong (narrow) nebular recombination lines are seen, indicating the presence of large number of hot exciting stars, mostly of type O. Those starburst galaxies with broad emission lines in the integrated spectrum from W-R *stars* are referred to as W-R *galaxies*. Roughly 70% of the Symposium was devoted to issues concerned with W-R stars; the remainder to that of galaxies. It is a measure of the explosion of studies in the past few years in this field that this was by far the best attended "hot star" Symposium and one in which there was a substantial interaction between astrophysicists with "stellar" and "galaxy" backgrounds.

In highlighting the Symposium for this publication I must necessarily be brief and so will forego enumerating the numerous authors. I also admit this report is a personal appraisal, one which might well be very different in the hands of another reporter.

The imminent publication of new catalogs of W-R *stars* in the Galaxy and Magellanic Clouds was announced; the census amounts to 211 stars in the former, 132 in the LMC and 9 in the SMC. An analysis of the W-R populations of the other Local Group galaxies was given. A new catalog of W-R *galaxies* lists 126 members; indicating a doubling time of 3.5 years since the initial serendipitous discovery in 1976. W-R stars radiate from the X- ray to radio region which is, from the UV longwards, mostly thermal, but anomalous strong non-thermal emission is found in some cases. The thermal radiation is primarily emitted from dramatically different levels in the strong stellar winds; a "photosphere" is not present. While most objects appear to have spherically symmetric wind geometry, a small fraction are asymmetric; high angular momentum may play a role. Most (all?) of the stellar winds are non-homogeneous in which "clumping" is present (providing the X-ray emission from the resultant shocks) and lowering the inferred mass loss rates compared to that obtained with an assumption of uniform flow. Many stars also show variability at low levels. It is fair to say that the physics of these variable phenomena are not yet well understood but considerable progress was reported.

The driving mechanism of the winds of luminous OB stars is well established to be radiative in nature, from the myriad of lines present in the bright UV part of the spectrum. A "single scattering" mode of photons is sufficient to account for the winds of these stars but the inferred momentum of W-R star winds had seemed to have been too large given their luminosities and mass loss rates. Several lines of evidence at the conference suggested that the W-R star luminosities were higher, and the mass loss rates lower, than previously inferred. Up to 10 multiple scatterings would be required for radiatively driven winds which seems within the realm of possibilities in the energetics; detailed predictions are needed.

The physics of W-R star winds are becoming clearer with improved observations of line profiles and comparison to theoretical predictions. The "standard model" of non-LTE detailed line transfer with H and He composition (only) has been newly enhanced with the addition of metal (Z) line blanketing, in which substantial effects (e.g., "backwarming") are predicted, and observed, in the emergent continuum radiation. In particular, the emission below the He II ionization edge is substantially affected and highly dependent on Z. In low Z objects, sufficient radiation can be emitted to doubly ionize helium in the surrounding H II region, thus explaining the presence of a *narrow* λ 4686 He II recombination line. Some low Z W-R galaxies show this feature in addition to the normal recombination lines of hydrogen and (neutral) helium.

Single star evolution models of W-R stars generated by several groups have been able to predict many of their observational aspects. The importance of "mixing" of material from the core to the "surface" has recently become appreciated and new results were presented. Both the mass loss and differential rotation (meridional circulation leading to mixing) in W-R stars and their predecessors are important and while the details are not yet entirely in place, the overall picture is becoming clearer.

Binary W-R systems provide both opportunities and problems for stellar astrophysicists. Orbital solutions lead to estimates of the masses of the stars; it was realized long ago that W-R stars are typically overluminous for their masses, thus establishing the concept of their helium burning nature. There is an extensive literature of orbits of Galactic W-R stars; those in the MCs are just now being produced. Close binary evolution undoubtedly will influence how a massive star would have evolved compared to what would have been were it single. The close binary *fraction* and its overall impact on the evolution of massive stars remains, however, controversial. Wide binary W-R stars provide an opportunity to explain the non-thermal emission as originating in the colliding winds of the two hot components. While the physics is not totally yet understood, considerable progress in observations and in the theory was presented. Close binary interaction effects can have major impact on observations over all wavelength bands. The very luminous object HD5980 in the SMC is an example of this effect. Indeed, a separate informal workshop on this Luminous Blue Variable (LBV) plus WN star was scheduled the day before the Symposium. This short period eccentric orbit binary, which rivals η Car in luminosity, recently went through a substantial outburst, coupled with a change in the overall spectral type. It is fair to say that while the event is somehow related to the binary interaction, the system is far from being understood.

The substantial Lyman continuum emission and the strong stellar winds of W- R stars affects their environments, often with observational consequences. The ionized Stromgren spheres may be analyzed for, say, the composition. The stellar winds may overtake and excite previously slower moving ejected material. So-called "ring nebulae" are observed surrounding some W-R stars. In many cases, the composition and outward velocity of the ring material can be identified with a previous red supergiant phase for the W-R star. Probably the initially most luminous stars do not go through such a phase, but rather loose mass both while an O star and in a subsequent not well modeled LBV process.

Luminous clusters of hot stars found within the Local Group are the bridge between nearby individually resolved objects and the distant, more luminous starburst galaxies. Observations of NGC 3603 and some clusters in and near the center of the Galaxy, R136-30 Dor in the LMC and NGC 604 in M33 were presented. Each has a number of very luminous O and W-R type stars. Solar mass stars on a tight sequence are identified in NGC 3603 showing that low mass objects can be produced in the presence of very luminous hot stars. These clusters have a few hundred O stars each; sometimes referred to as "mini-starbursts", they are at the low luminosity end of starbursts.

The parameters of starburst galaxies, that is their ages, burst durations, stellar populations, etc., may be directly inferred from observations of the integrated emergent continua and their stellar spectral line features; analyses of the nebular recombination lines provide indirect estimates of the numbers of exciting (OB + W-R) stars. Spectral synthesis models have been provided by several groups to predict these various signatures. The stars and ionized gas may not be co-spatial in some cases, thus caution needs to be exercised when comparing the various methods although for a number of objects studied the inter-agreement is not bad. From the predictions of the single star evolutionary models, one would expect the presence of W-R stars in starbursts with ages from between 3-6 Myr, in rough agreement with the observations. The frequency of WN and WC types also follow expectations; future work will need to include the effects of stellar mixing. The impact of close binary evolution on starburst parameters might be important if this fraction is large.

In many (all?) examples of starbursts examined with high spatial resolution, the luminosity comes from smaller but even more intense starburst knots; these have been called "super star clusters"

(SSC). These *may* evolve into globular clusters as had been suggested in the literature but this is not accepted by all. HST observations and analyses of SSC in several starburst galaxies was presented; most of these objects seems to be relatively young, not unexpected considering the sample was of W-R galaxies. The SSC range in luminosity (and mass) upwards from R136 by a factor 100. Their colors and luminosity functions are similar to those SSC observed in other well known merger galaxies once account is taken of their youth.

W-R starburst galaxies may all (?) be the result of recent mergers and interactions, as several examples of objects previously thought to be isolated were shown to have fainter nearby companions. It is suggestive that this interaction feature has also been invoked to explain the luminous events in IR luminous galaxies, and there may be a generic relationship. There is a clear similarity in spectral morphology between UV spectra of relatively nearby SSC in (W-R) starburst galaxies, and those star forming regions recently found at high redshift (z). W-R phenomena, as indicative of intense star formation activity, are also noted in connection with AGN; the presence of such events near to an active nucleus is surprising, to say the least.

Not only are W-R phenomena in massive *stars* a natural consequence of stellar evolution, a similar appearance in starburst *galaxies* may always follow "if the time is right". Studying nearby stars and individually resolved luminous clusters can shed light on more energetic, but more distant, starburst galaxies; and conversely.

Highlights to appear in PASP

Special Session on HD 5980, Puerto Vallarta, November 1998

A. Moffat

On Monday November 2nd before the regular meeting began, a group of 31 astronomers (see below) met for 5 hours to discuss HD 5980, a massive binary in which one of its components erupted in 1994 as a luminous blue variable (LBV), thus making HD 5980 the most luminous star in all the SMC for about 6 months.

The presentations and debates were intense but friendly. Among the issues that most participants agreed on are:

1. The observed spectrum changed slowly at first, then more rapidly, from WNE + O in the 1970's through WN6, WN7, WN8 to WN11 around maximum light, when HD 5980 had brightened by 3 full magnitudes.

2. The eruption occurred in star A that is defined to be the component that passes in front at primary light minimum in an eclipsing binary system with period of 19.265 days and moderate ellipticity e = 0.27. Star B is the component that passes in front at secondary minimum at phase 0.36.

3. This is the first known case of an LBV eruption of a massive star in a very close binary, with important potential consequences for mass exchange in rapidly evolving binaries.

4. Although HD 5980 lies close to the SMC's youngest massive cluster NGC 346, it does not appear to be directly related in any obvious way to the cluster. Along with the nearby O7Iaf+ supergiant Sk80, HD 5980 = Sk78 probably belongs to a somewhat older, spatially extended population of field OB stars.

Among the issues still unclear are:

5. Although the orbital shape is known fairly well, its size (based on the poorly known radial velocity amplitudes) is not. Nevertheless, both stars must be quite massive, with current masses in the range of c. 30 - 80 $M_{\odot}$for star A and c. 10 - 30 $M_{\odot}$for star B.

6. The true spectral types of the stars before the eruption remain elusive. Star A may be a hot, luminous Of star, while star B may be a relatively hydrogen-poor WN star. Alternatively, both orbiting stars might be WNE, based on RV data from photographic spectra for the very weak and variable NIV 4058 and NV 4603 emission lines that appeared to move in antiphase. In the latter case, the photospheric absorption lines seen before the eruption must have come from a third star, whose presence is a subject of debate. The former scenario, in which an evolved O star goes LBV, is more orthodox than the second scenario, in which a WNE star goes LBV. The jury is still out, though, since no-one knows what really can happen at the tenth Solar metallicity of the SMC.

7. Why did star A erupt only to WN11, like the LBV AG Carinae at minimum light? Perhaps HD 5980 went further without having been noticed, since there were gaps in the observations around maximum light, or perhaps the eruption was "throttled" by the presence of a close companion.

8. During and after the eruption, double-line emission profiles were seen, implying that mass may be leaving the system. It is not clear how much mass left the system as a result of the eruption, although it is unlikely to be more than the deduced mass loss from the spectrum of the erupting star, 0.001 $M_{\odot}$. The change in orbital period expected (maxiumum 1 part in 10^5) was not detectable.

9. Does line emission from colliding winds dominate the pre-eruption spectrum? This appears to be a viable explanation for the spectacular phase-dependent line profile variations in the pre-eruption spectrum, although other explanations cannot be entirely excluded. Energy requirements to produce such high line flux from wind collision may or may not be a problem, depending on the detailed history of the collision shock process, which must have been different from what occurs in the WR wind.

In an attempt to resolve some of these issues, coordinated campaigns on HD 5980 should be pursued. Two such campaigns were suggested:

a. Long-slit spectroscopy with HST to search for ejecta in the immediate surroundings of HD 5980, and if the system returns to WN + O, search for the photospheric lines of star A (and B?) and a possible 3rd component in the system.

b. Observe NGC 346 along with HD 5980 using the high-resolution X-ray imager on AXAF, in search of interacting winds.

Tony Moffat & Gloria Koenigsberger, organisers.

Participants:

Jane Arthur, Jacques Breysacher, Jorge Canto, Mike Corcoran, Luis Corral, Paul Crowther, Orsola De Marco, Sean Dougherty, Aaron Flores, Guillermo Garcia-Segura, Leonid Georgiev, Eric Gosset, Lex Kaper, Gloria Koenigsberger, Chris Lloyd, Siegfried Luehrs, Sergey Marchenko, Divakara Mayya, Tony Moffat, Virpi Niemela, Julian Pittard, V.F. Polcaro, Corinne Rossi, Pierre Royer, Werner Schmutz, Mike Shara, Ian Stevens, Dany Vanbeveren, Karel van der Hucht, Nolan Walborn, Debra Wallace

Accepted Papers

A non-LTE spherical line-blanketed stellar atmosphere model of the early B giant β CMa

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The observed multi-wavelength spectrum of the B1 II-III star β CMa is successfully reproduced, including the extreme ultraviolet (EUV) continuum observed by *Extreme Ultraviolet Explorer*, with a non-LTE fully line-blanketed spherical hydrostatic model atmosphere. The available spectrophotometry of β CMa from 500 Å to 25 μm is best fit with model parameters $T_{\rm eff} = 24000\,{\rm K}$, $\log g = 3.5$, and an angular diameter of $\theta_{\rm LD} = 0.565$ mas. We find that a neutral interstellar hydrogen column of $N({\rm H}^0) \simeq 2 \times 10^{18}$ cm^{-2} provides the best agreement between the model EUV flux and that observed by *EUVE.*

We use model atmosphere fits together with *Hipparcos* distances to calculate radii, luminosities, and ionising fluxes for β CMa and α Vir. An investigation of spherical and plane-parallel models shows that the Lyman continuum predictions are quite sensitive to model geometry and surface gravity between effective temperatures 18000 K to 33000 K. This result provides an explanation for the reported excesses between the observed EUV fluxes from β CMa and ϵ CMa and plane parallel model atmosphere predications.

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2 μm Narrow–Band Imaging of the Sagittarius D H II Region

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We present 2 μm narrow–band images of the core H II region in the Galactic star forming region Sagittarius D. The emission–line images are centered on 2.17 μm (Brγ) and 2.06 μm (He I). The H II region appears at the edge of a well defined dark cloud, and the morphology suggests a blister geometry as pointed out in earlier radio continuum work. There is a deficit of stars in general in front of the associated dark cloud indicating the H II region is located in-between the Galactic center and the sun. The lesser spatial extent of the He I line emission relative to Brγ places the effective temperature of the ionizing radiation field below 40,000 K. The He I 2.06 μm to Brγ ratio and Brγ / far infrared dust emission put $T_{\rm eff}$ at about 36,500 K to 40,000 K as derived from ionization models.

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The interstellar and intrinsic polarizations of EZ CMa

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We present multi-epoch, intermediate-dispersion linear spectropolarimetry of the pathological Wolf-Rayet star EZ CMa. The continuum polarization shows long-term quasi-periodic variations, both in polarization magnitude (range 0.8%) and position angle (60°), and we observe changes in the polarization vector at emission-line wavelengths. We argue that the interstellar polarization (ISP) can be estimated from the convergence point of continuum-to-line polarization vectors, and we find that the ISP at 5800Å is $0.47 \pm 0.02\%$ at a position angle of $164 \pm 2°$.

We subtract the new ISP estimate from our spectra to yield intrinsic polarized line-profiles of unprecedented quality. We discuss the characteristics of the profiles, and compare them with synthetic profiles computed using radiative-transfer codes. Measurements of the line profiles provides some evidence for ionization stratification in the wind.

The polarization variation produced by rotational modulation of an azimuthally structured wind is investigated by using a simple single-scattering model. An 'orange-segment' wind structure is capable of reproducing the amplitude of the observed polarization variations, although the shape of the polarized-light curve cannot be matched using a simple model.

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On the magnetic field and circumstellar environment of the young O7 star θ^1 Orionis C

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Text of abstract We present new circular spectropolarimetric observations of the young O-type star θ^1 Orionis C obtained with the MuSiCoS échelle spectropolarimeter and the 2 m Télescope Bernard Lyot, in an attempt to detect the surface magnetic field structure invoked to explain the periodic variability of θ^1 Ori C at X-ray, UV and optical wavelengths. We obtain null detections with 250 G 1σ error bars for the disc-averaged line-of-sight (i.e. longitudinal) component of the surface magnetic field vector, from which we conclude that the polar strength of the dipole field structure is lower than 1.6 to 2.0 kG (with a confidence level of 87%), depending on the exact orientation of the magnetic and rotation axes with respect to the line of sight.

We report as well the unexpected discovery of strong, time variable continuum circular polarisation in the spectrum of θ^1 Ori C, as well as depolarisation structures associated with nebular emission lines, indicating that this continuum polarisation (the nature of which is as yet unclear) is produced within the immediate circumstellar environment.

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The Hanle Effect as a Diagnostic of Magnetic Fields in Stellar Envelopes II. Some Theoretical Results for Resolved Line Profiles

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A magnetic field diagnostic of stellar winds that uses the Hanle effect is discussed. This diagnostic pertains to the modification of resonance line scattering polarization in the presence of magnetic fields. The case for resolved polarized profiles of optically thin emission lines is considered, and some analytic results for an expanding equatorial disk are derived. Numerical results for a dipole magnetic field embedded in a spherical outflow are also presented. Although the considerations are somewhat simplified, the primary conclusion is that the modification or creation of line profile polarization by the Hanle effect can be used to discriminate between different magnetic field geometries and to estimate the magnetic field strength in the region of line formation.

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The Stellar Content of Obscured Galactic Giant H II Regions: I. W43

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Near infrared images of the Galactic giant H II region W43 reveal a dense stellar cluster at its center. Broad band JHK photometry of the young cluster and $K-$band spectra of three of its bright stars are presented. The 2 μm spectrum of the brightest star in the cluster is very well matched to the spectra of Wolf–Rayet stars of sub–type WN7. Two other stars are identified as O type giants or supergiants by their N 3 and C 4 emission. The close spatial clustering of O and the hydrogen WN type stars is analogous to the intense star burst clusters R136 in the Large Magellanic Cloud and NGC 3603 in the Galaxy.

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Wind inhomogeneities in Wolf-Rayet stars. II. Investigation of emission-line profile variations.

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We present high-resolution spectroscopic monitoring of the line profile variations (LPV) in the He II $\lambda5411$ emission-line of 4 Wolf-Rayet (WR) stars of the WN sequence (HD96548, HD191765, HD192163, and HD193077), and in the C III $\lambda5696$ emission-line of 5 WR stars of the WC sequence (HD164270, HD165763, HD192103, HD192641, and HD193793). The LPV are shown to present systematic patterns: they all consist of a number of relatively narrow emission subpeaks which tend to move from the line center towards the line edges.

We introduce a phenomenological model which depicts WR winds as being made up of a large number of randomly distributed, radially propagating, discrete wind emission elements (DWEEs). This working model is used to simulate LPV patterns in emission-lines from a clumped wind. General properties of the LPV patterns are analyzed with the help of novel numerical tools (based on multi-scale, wavelet analysis), and simulations are compared to the data. We investigate the effects on the LPV of local velocity gradients, optical depths, various numbers of discrete wind elements, and a statistical distribution in the line-flux from individual elements. We also investigate how the LPV patterns are affected by the velocity structure of the wind, and by the extension of the line-emission region (LER).

Eight of the stars in our sample are shown to possess strong similarities in their LPV patterns, which can all be explained in terms of our simple model of local wind inhomogeneities. We find, however, that a very large number ($\gtrsim 10^4$) of DWEEs must be used to account for the LPV. Large velocity dispersions must occur within DWEEs, which give rise to the $\overline{\sigma_\xi} \sim 100$ km s^{-1} line-of-sight velocity dispersions. We find evidence for anisotropy in the velocity dispersion within DWEEs with $\sigma_{v_r} \sim 4\sigma_{v_\theta}$, where σ_{v_r} and σ_{v_θ} are the velocity dispersions in the radial and azimuthal directions, respectively. We find marginal evidence for optical depth effects within inhomogeneous features, with the escape probability being slightly smaller in the radial direction. The kinematics of the variable features reveals lower-than-expected radial accelerations, with $20 < \beta R_*(R_\odot) < 80$, where β and R_* are parameters of the commonly used velocity law $v(r) = v_\infty(1 - R_* r^{-1})^\beta$, with v_∞ the terminal wind velocity. The mean duration of subpeak events, interpreted as the crossing time of DWEEs through the LER, is found to be consistent with a relatively thin LER. As a consequence, the large emission-line broadening cannot be accounted for by the systematic radial velocity gradient from the accelerating wind. Rather, emission-line broadening must be dominated by the large "turbulent" velocity dispersion σ_{v_r} suggested by the LPV patterns.

The remaining WR star in our sample (HD191765) is shown to present significant differences in its LPV pattern. In particular, the associated mean velocity dispersion is found to be especially large ($\overline{\sigma_\xi} \sim 350$ km s^{-1} compared to $\overline{\sigma_\xi} \sim 100$ km s^{-1} in other stars). Accordingly, the LPV patterns in HD191765 cannot be satisfactorily accounted for with our model, requiring a different origin.

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Wind Inhomogeneities in Wolf-Rayet Stars. III. Unusual Emission-Line Profile Variations in γ^2 Velorum.

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We present very high resolution, very high signal-to-noise spectra from the 3.6m CFH telescope for the strong C III λ5696 emission line in γ^2 Velorum, the brightest Wolf-Rayet (WR) star in the sky. From two nights of spectroscopic monitoring, we have detected line-profile variations (LPVs) in the form of moving emission features (subpeaks) on the broad, "flat-topped" underlying profile.

We use the working model from Lépine & Moffat (1998, Paper II) to study these LPVs in terms of inhomogeneities in the radially expanding stellar wind. A comparison between simulations and the data suggests the variable subpeaks to consist of a superposition of two distinct components: (1) narrow moving subpeaks with a mean line-of-sight velocity dispersion $\overline{\sigma_\xi} \simeq 80$ km s^{-1}, and (2) broad moving subpeaks with $\overline{\sigma_\xi} \simeq 200$ km s^{-1}. Both narrow and broad subpeak components are seen to move systematically in a direction from the line center ($\xi = 0$) towards the line edges. This motion is found to be consistent with a radial wind expansion at a mean acceleration rate $a_r = 13 \pm 3$ m s^{-2}.

The narrow subpeaks are found to be similar to the stochastic subpeaks seen in the LPVs from several single and long-period binary WR stars. On the other hand, the broad features are reminiscent of the recurrent subpeaks observed in the LPVs from a few peculiar WR stars (HD4004, HD191765, and EZ CMa), although in γ^2 Vel, we find no evidence for a recurrent behavior.

We investigate the possibility that, in γ^2 Vel, these broad variable subpeaks arise from the shock-cone region, at the interface where the wind from the WR star collides with that of its O companion. We find no convincing evidence to support this hypothesis, although we suspect that there could be a relation between the existence of broad LPV subpeaks and the presence of the more massive O companion.

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Physical Structure of Small Wolf-Rayet Ring Nebulae

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We have selected the seven most well-defined WR ring nebulae in the LMC (Br 2, Br 10, Br 13, Br 40a, Br 48, Br 52, and Br 100) to study their physical nature and evolutionary stages. New CCD imaging and echelle observations have been obtained for five of these nebulae; previous photographic imaging and echelle observations are available for the remaining two nebulae. Using the nebular dynamics and abundances, we find that the Br 13 nebula is a circumstellar bubble, and that the Br 2 nebula may represent a circumstellar bubble merging with a fossil main-sequence interstellar bubble. The nebulae around Br 10, Br 52, and Br 100 all show influence of the ambient interstellar medium. Their regular expansion patterns suggest that they still contain significant amounts of circumstellar material. Their nebular abundances would be extremely interesting, as their central stars are WC5 and WN3-4 stars whose nebular abundances have not been derived previously. Intriguing and tantalizing implications are obtained from comparisons of the LMC WR ring nebulae with ring nebulae around Galactic WR stars, Galactic LBVs, LMC LBVs, and LMC BSGs; however, these implications may be limited by small-number statistics. A SNR candidate close to Br 2 is diagnosed by its large expansion velocity and nonthermal radio emission. There is no indication that Br 2's ring nebula interacts dynamically with this SNR candidate.

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Variable central stars of young Planetary Nebulae. A photometric study of the central star of M2-54

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We acquired 63.8 hours of time-series photometry of the variable central star of the young Planetary Nebula M2-54. This object exhibits light variations with a peak-to-peak amplitude of up to 0.3 mag in Johnson V. Two different time scales (several days and several hours) are present. While the long-term variations appear to be nonperiodic, the short-term modulations are (quasi)periodic with a time scale of either 8.9 or 14.3 hours. An analysis of the HIPPARCOS photometry of this object did not allow us to infer which of these two time scales is the correct one.

The possible causes for the observed variability are examined. The slow variations can be explained by either a spot hypothesis or variations in the stellar mass loss, while the short-term modulations are most consistent with stellar pulsation. All this behaviour is strikingly similar to that of best studied representative of this class of variable star, the central star of IC 418, strongly suggesting that the physical cause of the variability of these two objects is the same.

While it appears quite attractive to suspect that we are in the presence of a new class of pulsating variables, further work is needed to confirm or reject this. Consequently, some suggestions in this direction are given.

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Dust in R71: first detection of crystalline silicates in the LMC

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We present infrared spectroscopy taken with the Infrared Space Observatory (ISO) of the Luminous Blue Variable (LBV) R71 in the Large Magellanic Cloud (LMC). The spectrum shows clear evidence for the presence of crystalline olivine at 23.5 μm. This is the first detection of circumstellar crystalline silicates outside our galaxy. In addition, we identify emission at 6.2, 7.7 and possibly 8.6 μm from C-rich small grains (PAHs). The presence of C-rich grains is not expected in an environment where C/O is less than 1. We fit the dust spectrum using a radiative transfer model and find a dust mass of 0.02 $M_\odot$. R71 was probably a Red Supergiant when it produced the dust shell and had a time-averaged mass loss rate of the order of 7×10^{-4} $M_\odot\,yr^{-1}$ for a gas/dust ratio of 100.

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or by anonymous ftp to ruunat.phys.uu.nl/pub/astronomy/voors/r71/r71.ps
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Spectroscopic Binary Orbits from Ultraviolet Radial Velocities. Paper 30: HD 164402

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Radial velocities measured from high-resolution IUE spectra of the B0Ib star HD 164402 indicate that it is a single-line spectroscopic binary with a period of 425 days; it may be the first spectroscopic binary *discovered* through the use of IUE data. With $K = 28$ km s^{-1}, the companion could be a mid B-type main sequence star. The primary is probably about 5 million years old, in the late stages of core hydrogen burning.

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Properties of hot stars in the Wolf-Rayet galaxy NGC 5253 from ISO-SWS spectroscopy

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ISO-SWS spectroscopy of the WR galaxy NGC 5253 is presented, and analysed to provide estimates of its hot young star population. Our approach differs from previous investigations in that we are able to distinguish between the regions in which different infrared fine-structure lines form, using

complementary ground-based observations. The high excitation nebular [S IV] emission is formed in a very compact region, which we attribute to the central super-star-nucleus, and lower excitation [Ne II] nebular emission originates in the galactic core. We use photo-ionization modelling coupled with the latest theoretical O-star flux distributions to derive effective stellar temperatures and ionization parameters of $T_{\rm eff} \geq$ 38kK, log $Q \sim 8.25$ for the compact nucleus, with $T_{\rm eff}$ ~35kK, log $Q \leq 8$ for the larger core. Results are supported by more sophisticated calculations using evolutionary synthesis models. We assess the contribution that Wolf-Rayet stars may make to highly ionized nebular lines (e.g. [O IV]).

From our Brα flux, the $2''$ nucleus contains the equivalent of approximately 1 000 O7 V star equivalents and the starburst there is 2–3 Myr old; the $20''$ core contains about 2 500 O7 V star equivalents, with a representative age of ~5 Myr. The Lyman ionizing flux of the nucleus is equivalent to the 30 Doradus region. These quantities are in good agreement with the observed mid-IR dust luminosity of $7.8\times10^8 L_\odot$. Since this structure of hot clusters embedded in cooler emission may be common in dwarf starbursts, observing a galaxy solely with a large aperture may result in confusion. Neglecting the spatial distribution of nebular emission in NGC 5253, implies 'global' stellar temperatures (or ages) of 36kK (4.8 Myr) and 39kK (2.9 or 4.4 Myr) from the observed [Ne III/II] and [S IV/III] line ratios, assuming log Q=8.

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Spatially Resolved Nebulae around the Ofpe/WN9 stars S61 and BE381

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We present new high-resolution coronographic imaging and medium-resolution spectroscopy of the circumstellar region around S61 and BE381, two Ofpe/WN9 stars in the Large Magellanic Cloud. The observations were carried out at the ESO/NTT (La Silla) in January 1996 and July 1998. The excellent seeing conditions allowed the circumstellar nebulae associated with both S61 and BE381 to be spatially resolved for the first time. The nebula surrounding S61 has the appearance of a shell with a mild central axisymmetry. The surface brightness is not uniform, and the northern region of the nebula is the brightest. The nebula exhibits a bipolar structure with an overall morphology very similar to nebulae around other LBVs or Opfe/WN9 stars, especially S119. The diameter of the shell is $7.3''$, corresponding to a linear size of 1.8 pc. From the profile of nebular emission lines we clearly detect an expansion motion with a velocity of 28 km s^{-1}, which indicates a dynamical age of $\sim$ 30000 yrs. We find an electron density of 400 cm^{-3} and an electron temperature of 6120 K. The nebula is simular to other LBV nebulae in that it is nitrogen enriched. The observed chemical and dynamical properties confirm that the nebula is associated with the central star and is of stellar origin. This result implies that S61 is likely to have undergone a LBV-type ouburst and, therefore, strenghtens the suggestion that Ofpe/WN9 stars are quiescent LBVs. The situation is different for BE381. The Hα images of BE381 also reveal the presence of a faint nebulosity around the star; most of the nebular flux appears to be emitted by an arc of gas located to the east of BE381, while a much dimmer arc is

detectable on the western side. The arcs delineate a shell of 13″ in diameter, corresponding to a linear size of 3.2 pc, which appears to be expanding with a velocity of 14 km s^{-1}. From the nebular emission lines we derive an electron density ranging between 30 cm^{-3} and 120 cm^{-3} (assuming T_e = 10000 K), and a N^+/S^+ ratio between 1.5 and 2.3, which are typical of HII regions. We therefore conclude that the shell detected around BE381 is not of stellar origin and probably represents the relic of the interstellar bubble blown by BE381 during its O main-sequence phase.

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Submitted Papers

The optical spectrum of HD 4004 (WN 4b). Evidence of variability.

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We describe the optical spectrum of Wolf-Rayet star HD 4004 (WN 4b) in the wavelength range from 3 900 to 7 000 Å. Present observations reveal the stratification effects in the envelope of this star. Presented is also evidence for variability of HeII line λ 5411. Since no radial velocity variations are observed in the optical spectrum of this star we conclude that HD 4004 is a single Wolf-Rayet star and the observed emission line profile changes are of intrinsic nature.

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In Proceedings

Disks formed by Rotation Induced Bi-stability

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We discuss the evidence for the existence of bi-stable stellar winds of early type stars, both theoretically and observationally. The ratio between the terminal wind velocity and the escape velocity drops steeply from about 2.6 for stars with $T_{\rm eff} > 21\,000$ K to about 1.3 at $T_{\rm eff} < 21\,000$ K. This is the *bi-stability jump*, which is due to a change in the ionization of the wind and in the wind driving lines. The mass

loss rate increases across the jump by about a factor 2 to 5 from the hotter to the cooler stars. The mass flux from rapidly rotating stars can also show the bi-stability jump at some lattitude between the pole and the equator, with a slow high density wind in the equatorial region and a faster low density wind from the poles. This might explain the disks of rapidly rotating B[e] stars, formed by the *Rotation Induced Bi-stability* mechanism. We discuss the RIB mechanism and its properties. We also describe some future improvements of the model.

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η Car: Overview of 18.3 Years of Ultraviolet IUE Observations

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η Car was frequently pointed by IUE between April 1978 and July 1996. We summarize the most important discoveries, and describe the UV behaviour of η Car during the 1992–1996 monitoring, when the flux of the high excitation emission lines varied in agreement with Damineli's 5.52 y cycle. One most important result is the identification of a weak and variable C III] 1909 Å emission, possibly in agreement with a fairly lower carbon abundance in the star's atmospheric envelope. The possibly larger carbon deficiency in the circumstellar nebula is attributed to the continuous condensation of dust grains in the stellar wind, which still is in act as found by Andriesse et al. (1978). The possible presence of the He II 1640 Å line is discussed. The long term variability of the emission line flux curve are interpreted as a gradual variation of the ionization of the hot region. The July 1995 IUE spectrum appears nearly identical in shape to the "core" (0.22") HST observations of October 1995, supporting that IUE is actually seeing the star radiation scattered by the circumstellar dust. We question the claimed evidence for high velocity features other than that of Si IV.
Proc. Conference *Eta Carinae at the Millennium* **ASP Conf. Ser. in press**
Preprints from uvspace@ias.rm.cnr.it
or by anonymous ftp to ftp.ias.rm.cnr.it/pub/uvspace/eta98_iue.ps.gz
or on the web at http://www.ias.rm.cnr.it/ias-home/procee.htm

η Car: BeppoSAX Observations During High and Low States

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The broad band X–ray spectrum of η Car was observed with BeppoSAX in December 1996 and March 1998, when η Car was near phase 0.82 and 1.04 of the 5.52 y cycle, respectively. The comparison of the two epochs revealed a large flux defect between 1.5 and ∼4 keV in March 1998, indicating that the "low state" corresponding to the last spectroscopic event of late December 1997 was still in progress.

The flux defect is attributed to a larger amount of absorbing matter in front of the harder X–ray component (ηHX), whose temperature and luminosity was probably close to that during the "high state". The softer source ηSX appears stable, as expected. These results suggest that after the minimum of the event, the ηHX component rapidly recovered its "high state" luminosity, but in the meantime it was partly masked by the presence of a large amount of neutral absorbing matter formed (or recombined) after the minimum, confirming the "asymmetry" of the X–ray light curve. In the framework of the binary model the diffuse matter could be a wake following the LBV star.

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Preprints from `uvspace@ias.rm.cnr.it`
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η Car: Self Absorption Curve Analysis of [Fe II] and Fe II Emission Lines

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The fluxes of the narrow peak components of the Fe II and [Fe II] emission lines in the 1995 "high state" optical spectrum of η Car are analysed with the Self–Absorption–Curve method (SAC), which allows the determination of the level population also for optically thick emission lines. (The Manual of the method is available at the ftp address below as *sacmanual.ps.gz*). We find that in η Car the [Fe II] lines are optically thin and suggest for the 2.7–3.2 eV levels an excitation temperature of around 12 000 K. The permitted lines are formed in a very optically thick medium, pressure broadening probably being the dominant self absorption effect for the lower excitation lines. The high E.P. Fe II lines are also optically thick. The large scatter of the population of their upper levels (in particular of the 8490 Å line), is in agreement with the presence in many cases of effective selective pumping mechanisms. We conclude that in the narrow line emitting region of η Car, the metastable levels of Fe^+ are in equilibrium with the electron gas, and the ~5 eV levels are populated by the diluted UV stellar radiation, while resonance fluorescence is important in many high excitation levels.

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Preprints from `uvspace@ias.rm.cnr.it`
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or on the web at `http://www.ias.rm.cnr.it/ias-home/procee.htm`

Using Spectropolarimetry to Determine Envelope Geometry and Test Variability Models for Hot Star Circumstellar Envelopes

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A survey and monitoring of the spectropolarimetric characteristics of hot stars over the entire visible

wavelength range has been carried out over the past 8 years using the HPOL instrument at the Pine Bluff Observatory. Data from these projects is being used to derive physical characteristics of circumstellar envelopes. Quantitative modeling of the polarization, in combination with optical interferometry, has shown that the circumstellar disks of classical Be stars are geometrically thin, consistent with either the wind-compressed disk model or with hydrostatically supported Keplerian disks. Furthermore, spectropolarimetric variability, which is significant in a large fraction of the hot stars observed, provides information about changes occuring in the circumstellar envelope. For example, polarimetric changes provide a critical test of the one-armed density wave models proposed to explain observed V/R variations.

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Preprints from karen@astro.utoledo.edu
or on the web at ardbeg.astro.utoledo.edu/~karen/

The Effects of Magnetic Fields on the Winds from Luminous Hot Stars

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We explore three types of models in which the combination of magnetic fields with line driving forces leads to faster winds than line forces alone. The fields can change the flow geometry; they can couple with rotation and transmit angular momentum; and they can carry transverse Alfvén waves. All three can lead to a deposition of momentum beyond the critical point and accelerate winds. Some history of the attempts to use magnetic fields to understand hot star winds is discussed and several new models for magnetic rotator B[e] winds are presented.

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Preprints from nmiller@uwast.astro.wisc.edu
or on the web at http://www.astro.wisc.edu/prints/nmiller/ lumi_mag_rot.ps

A Near Eddington Limit Wind Scenario for the Great Eruption of η Car

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The continuum driven wind mechanism is considered as a possible explanation for the great eruption and the bipolar nebula of η Car. A multi-phase scenario appears to be required to explain both the large mass loss and the presence of axial symmetry of the ejected nebula. It is proposed that the central star approached the Eddington limit or Langer's "Ω Limit", then crossed to a zone of stability on the cool side of the HR diagram, here called the "cool apex region" While in that region above the Humphreys-Davidson boundary, it is proposed that a tidal interaction or grazing-collision with the companion star led to a spin up of the primary star. Subsequently, the primary star encountered an Ω limit for cool stars, which produced a geometrically thick disk around the star. The Owocki

and Cranmer "tired photon" model for continuum driven winds is used to describe the changing wind properties that allow the star to produce the different envelopes needed at critical phases in the scenario. It is suggested that the great event occurred because the star happened to undergo an LBV expansion to the cool side of the HR diagram during the short period of time when the companion star was near periastron.

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Spectroscopy of the Pistol and Quintuplet stars in the Galactic Centre

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We present initial results of a spectroscopic study of the Pistol and of the cocoon stars in the Quintuplet Cluster. From ISOCAM CVF 5—17 μm spectroscopy of the field of the Pistol Star, we have discovered a nearly spherical shell of hot dust surrounding this star, a probable LBV. This shell is most prominent at $\lambda \gtrsim 12\,\mu$m, and its morphology clearly indicates that the shell is stellar ejecta. Emission line images show that most of the ionised material is along the northern border of this shell, and its morphology is very similar to that of the Pistol HII region (Yusef-Zadeh & Morris, 1987). We thus confirm that the ionisation comes from very hot stars in the core of the Quintuplet Cluster. An SWS spectrum of the Pistol Nebula indicates a harder ionising radiation than could be provided by the Pistol Star, but which is consistent with ionisation from Wolf-Rayet stars in the Quintuplet Cluster. The CVF 5—17 μm spectra of the cocoon stars in the Quintuplet do not show any emission feature that could help elucidate their nature.

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On the web at `http://www.iso.vilspa.esa.es/science/publications.html`

Theses

On the Binary Frequency of a Complete Sample of Magellanic, WC Wolf-Rayet Stars and a Spectroscopic Study of WC Binary Colliding Winds

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A spectroscopic and photometric study of all 24 known WC/WO Wolf-Rayet stars of the Magellanic

Clouds is made in an effort to determine the binary frequency of WR-stars in environments of low metallicity. This is followed by an investigation of colliding winds in those stars revealed to be binary.

Low metallicity has been postulated in the literature as the prime cause for the low WR/O number ratio in the Clouds. This follows from the fact that progenitor O-star winds at low Z have insufficient strength to repel the outer hydrogen envelope of all but the most massive, luminous O-stars. This removal is needed to produce a WR-star. Low-to-medium mass O-stars in low-Z environments require a companion to reduce their gravitational potential and thus ease the removal of the outer layers. By studying absolute magnitudes, line equivalent widths, and radial velocity variability, a binary frequency of only thirteen percent is found for the Large Magellanic Cloud. (The Small Cloud contains only one WC-star.) This is far less than the $52\% \pm 14\%$ frequency predicted by theory. The stellar winds appear powerful enough to accomplish the task themselves, even in a low-metallicity milieu.

As O-star winds are also strong, they should collide with the WR winds in WR+O binaries to form a bow-shaped shock front. The shocked material is heated to high temperature near its head, after which it flows along a shock cone that wraps around the weaker-wind O-star. Rapid cooling of the dense shock zone yields radiation much like that seen from the WR wind itself. Such excess emission is seen in many WR emission lines; it generally produces double-peaked spectral profiles that can be described by the model of Lührs. These profiles depend on orbital phase, orbital plane inclination, streaming velocity of the shocked material and cone opening angle. Such profiles are modelled for C III 5696 Å in Br22 (the only WC/WO system in the MC's to reveal significant C III excess) in an attempt to determine these parameters. However, a Lührs' model fit to the observed C III excess in Br22 gives only qualitative agreement. A new global approach proves more successful. The excess profile is characterised by the full width at half-maximum and mean velocity. A fit of the simplified Lührs' model in this case is used in an attempt to determine the cone parameters and orbital inclination. However, because of observational errors, the solution appears to be numerically degenerate in orbital inclination. The method, however, shows promise if more high-quality data can be used to reduce the noise. The presence of excess emission in the form of Lührs' profiles in the C IV 5808 Å line, present in all binaries of the sub-sample, shows that the colliding wind phenomenon is universal amongst close WC/WO binary stars.

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The Presupernova Evolution of Rotating Massive Stars

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This work presents the first numerical simulation of the evolution of rotating massive stars from the ignition of nuclear burning until the supernova stage. Emphasis has been placed on the modification of the evolution induced by rotation. This includes an examination of the transport process for redistributing angular momentum and composition and the resultant changes that occur in the stellar structure and nucleosynthesis. The distribution of angular momentum in the presupernova stage has also been of particular interest.

For this investigation, two different one-dimensional hydrodynamic stellar evolution codes were extended to include angular momentum as a new local variable. The effects of centrifugal forces on

the stellar structure were treated in latitudinally averaged way. Rotationally induced instabilities were included. They comprise secular and dynamic shear instabilities, the Solberg-Høiland instability, the Eddington-Sweet circulation, and the Goldreich-Schubert-Fricke instability. Uncertain parameters of rotationally induced mixing were calibrated using observational constraints, namely the surface abundances of massive main sequence stars.

The evolution of stars of approximately solar composition in the mass range from $10\,\mathrm{M}_\odot$ to $25\,\mathrm{M}_\odot$ was modeled up to iron core collapse, the immediate presupernova stage. Models with different initial rotation rates in the range of $100 \ldots 470\,\mathrm{km\,s}^{-1}$ were investigated, and non-rotating stars were calculated for comparison. Models that used different assumptions about the stabilizing effect of gradients in the mean molecular weight on rotationally induced instabilities were computed and compared.

In the HR diagram the rotating stars ignite central hydrogen burning at lower effective temperatures and luminosities than their non-rotating counterparts of same initial mass. In the course of central hydrogen burning they evolve to the higher luminosities the more internal mixing occurs, i.e., the higher the initial angular momentum of the star. A widening of the main sequence results.

During central hydrogen burning, the products of the burning are mixed into the stellar envelope and new fuel is supplied to the convectively burning stellar core by rotationally induced mixing. If rotationally induced mixing occurs by processes that depend sensitively upon composition gradients, they can act as a barrier and mixing between the core and the envelope is inhibited.

As the evolution of the star proceeds to later stages, the time-scale for rotationally induced mixing becomes too long in comparison to the evolutionary time-scales to constitute an important source of large-scale mixing. The evolution of the star from this point until core collapse is similar to that of a non-rotating star of same structure at this time, except for the differences in the nucleosynthesis discussed below.

Similar to the chemical mixing, the transport of angular momentum by rotationally induced instabilities becomes unimportant during the late stages of stellar evolution. Only convective processes are rapid enough to notably redistribute angular momentum. This has interesting consequence for the final angular momentum in the core. A neutron star that forms on this core would rotate close to break-up if angular momentum were conserved during the collapse.

The nucleosynthesis occurring in the rotating massive stars has been studied in detail using an extended 200 isotope nuclear reaction network. The rotationally induced mixing during central hydrogen burning leads to larger cores and therefore to higher production factors of the α elements. Due to this, the lower mass limits for Type II SN and WR formation are lowered. One of most prominent features, however, is a large production of $^{19}\mathrm{F}$ and of $^{15}\mathrm{N}$, which usually is destroyed in massive stars.

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First announcement

The Be Phenomenon in Early-Type Stars

IAU Colloquium No. 175

Dates: 28 June – 2 July, 1999
Location: Alicante, Spain
Contact: msmith@nebula.gsfc.nasa.gov
URL: http://www.bestars.ua.es/be99/

Scientific Rationale:

Just what makes Be stars be so baffling? Although these stars have been recognized as a subclass of variable stars for a full century, the cause of their irregular episodes of enhanced mass loss ("the Be phenomenon") remains mysterious. These stars show varying degrees of similarities to the Oe, Wolf-Rayet, B supergiant, Bp, and B[e] variables. Together these subclasses constitute arguably the last frontier in the study of stellar variability on the main sequence.

Since the last dedicated meeting on Be stars (IAU Colloquium 92 in 1986), great strides have been made in their study. Nevertheless, the origin of variability on practically every timescale remains elusive despite concentrated observational efforts from instruments on spaceborne and ground-based observatories. Studies of Be stars in each of the accessible wavelength domains have revealed unique information: UV studies have emphasized the duality between Balmer line emission and the star's radiative wind flux. X-ray analyses have drawn a distinction between the high energy flux emitted from interacting binaries and most isolated Be stars. Infrared and polarimetric studies have explored the shape and extent of circumstellar disks. Optical studies have spatially imaged their disks, while temporal studies have suggested that nonradial pulsation modes probably exist in some stars. They have also established the reality of very rapid changes in spectra and light which so far have eluded interpretation. On the theoretical side, wind-compressed disk and one-armed spiral density-wave pictures have been proposed as quasi-steady state models of the decretion disks fed by the activity in an unknown way. The search is still underway for mechanisms to transfer angular momentum from the star to a stable orbiting disk.

Evidence is accumulating that no single cause (e.g. nonradial pulsations, magnetic flaring, mass transfer through binary Roche lobes) is capable of producing the emission in all or even most Be stars. Each of these might play a role in certain circumstances, but some combination of them is likely to be required. Thus, an understanding of the observed phenomena necessitates the merging of several subdisciplines, including the theory of massive star evolution, the dynamics of radiative winds, nonlinear nonradial pulsations, and magnetohydrodynamics in nonconvective stars.

The Alicante conference will bring together experts in all of these areas to assess our current understanding of Be instability mechanisms and to identify areas where progress can be made. The physical problems to be considered will include: the instabilities in single Be stars, the formation of Be disks, the interactions between the Be stars and their disks, and interacting Be binary systems. The next two years will see evaluations of the IUE monitoring activity, systematic parallax and photometric studies from Hipparcos, spectrophotometry of Be disks by ISO, and a general closure to these analyses.

A new generation of satellites and ground-based networks are being inaugurated to follow variability patterns of stars over long timescales, to image star-disk systems over long spatial base-lines, and to examine the high-energy output of both single and binary hot stars. Out of the evaluation of the old programs, new ideas will arise and be tested. We seek to place the Be phenomenon into a broader context of stellar activity. This colloquium is intended to be the vehicle for this process of evaluation of context and discovery.

The topics for this colloquium include:

– definitions and background of the Be phenomenon – new relevant missions and technologies – temporal variability (periodic and nonperiodic) – winds and circumstellar environment – interacting Be binary stars

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