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WORKING GROUP ON HOT MASSIVE STARS

(GROUPE DE TRAVAIL SUR LES ETOILES MASSIVES CHAUDES)

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1. INTRODUCTION

The Working Group on Hot Massive Stars has been officially recognized by the IAU Executive Committee during the XXIII General Assembly in August 1997. Its origins are the *Hot Star Newsletter*, launched in 1994, and a long tradition of interaction and collaborative research strengthened by a series of meetings on *hot beaches*. It gathers over 500 researchers working on OB stars, Luminous Blue Variables, Wolf-Rayet stars, and in general all topics related to the evolution of massive stars and to the physics and consequences of winds from hot stars. The very successful recent symposium on "Wolf-Rayet phenomena in massive stars and starburst galaxies" is an indicator of the increasing interest of the extragalactic community in the study of these extraordinary stars.

The main activities of the Working Group are the rapid exchange of information (through its newsletter), the maintenance of databases (e. g. the Wolf-Rayet bibliography maintained by Karel van der Hucht), the coordination of observing campaigns (e. g. the XMEGA campaign, cf Corcoran 1999) and the organization of specialized workshops as well as broader meetings. Its production can be assessed by the growing number of papers: in three years, over 850 papers on Wolf-Rayet stars alone.

In consequence, this report cannot possibly be complete, but hopes to give a flavor of some of the most interesting lines of research. Section 2 was prepared in collaboration with Lex Kaper. Section 4 was written by Michael Corcoran and section 5 by Anthony Moffat. Recent work on Be stars and progress in the modelling of hot star winds are reported elsewhere in this volume.

2. HOT MASSIVE STARS IN GENERAL (OB, LBV, WR STARS)

During the last three years the astronomical research focussed on massive stars has strongly benefitted from the new developments in both astronomical instrumentation (e. g. infrared detectors) and computer software and the availability of space telescopes and large aperture ground-based telescopes. The relevance of massive-star research for our understanding of key issues in astronomy, such as stellar evolution, star formation, galaxy formation, starburst galaxies, the physics of the interstellar medium, or gamma-ray bursts, becomes more and more obvious.

To study the deeply embedded, newly formed massive stars, the near-infrared wavelength domain seems to be the most promising: the extinction is dramatically lower compared to the optical, while the emission by dust in the natal cloud has not yet set in. Watson & Hanson (1997) demonstrate the potential of this method by the observation of the photospheric K-band spectrum of the ionizing O star in an ultra-compact H II region. Obviously, state-of-the-art infrared model spectra are required to classify massive stars in this spectral domain. The availability of the large database of mid-infrared spectra provided by the *Infrared Space Observatory (ISO)* makes this work on model atmospheres even more important. Fortunately, several groups have realized this and are making a lot of progress in this field. A good example is provided by the work on the spectrum of P Cygni by Najarro et al. (1997).

According to Kudritzki (1998), massive stars may provide the diagnostics to accurately determine the distance to galaxies up to the Virgo cluster, using the wind-momentum luminosity relation to derive the star's luminosity and the optical (and ultraviolet) spectrum to determine the stellar-wind parameters.

2.1. Variability

The variability of "normal" hot-star winds seems to be due to processes acting at two very different scales. At a scale comparable to the Sobolev length the radiatively driven wind is structured due to the instability of the acceleration mechanism (cf. Owocki 1998). The interaction of different shocks or clumps might explain the observed X-ray emission (Berghöfer, Schmitt, Cassinelli 1997; Feldmeier et al. 1997). Individual clumps might be traced by the variable optical emission profiles (e. g. Eversberg et al. 1998). The most prominent type of wind variability originates at much larger spatial scales, on the order of several stellar radii. It becomes more and more clear that so-called corotating interaction regions, as proposed by Mullan (1984) and recently worked out by Cranmer & Owocki (1996), are responsible for the observed cyclical appearance of discrete absorption components in (or in some cases the modulation of) ultraviolet resonance lines (e. g. Kaper et al. 1999; Fullerton et al. 1997; Kaufer 1998). The physical origin of the fast and slow streams that interact further down the wind is not clear. Currently the two best candidates are non-radial pulsations and surface magnetic fields.

Non-radial pulsations are detected in many early-type stars, though up to now only in half a dozen O stars (e. g. Townsend 1997; Howarth et al. 1998; De Jong et al. 1999). Magnetic fields are gaining in interest in the hot-star community. Unfortunately, they are very difficult to measure. One of the best candidates, θ^1 Ori C, exhibits a very strong periodicity of 15.4 days in the variability of its wind which must be the rotation period of the star (Stahl et al. 1996). This periodicity is also detected in X-rays (Gagné et al. 1997) and well explained by the presence of a large-scale magnetic field (Babel & Montmerle 1997). However, Donati & Wade (1999) could only derive an upper limit for the magnetic field strength.

In two Wolf-Rayet stars believed to be single stars, EZ CMa and WR 134, the variability has been attributed to pulsations or co-rotating structures (Morel et al. 1998; 1999). The evidence for clumping in Wolf-Rayet winds has been summarized by Willis (1999). As shown by the models of Nugis et al. (1998), clumping will result in an overestimation of the mass-loss rates derived e. g. from radio data (Leitherer et al. 1997). The Wolf-Rayet winds were also shown to be stratified (Rochowicz 1999; Schulte-Ladbeck et al. 2000).

2.2. Non-sphericity

The non-sphericity of the winds of several types of hot stars is most often thought to be due to an increase in wind density towards the stellar equator. Although the wind-compressed disk model by Bjorkman & Cassinelli (1993) has caused a lot of excitement, it is not clear yet whether the physics of radiation-driven winds permit the formation of such a wind structure. Obviously, we have to wait for the final answer until two-, or preferably three-dimensional, time-dependent hydrodynamical codes are available that take stellar rotation, gravity darkening, instabilities (and perhaps even magnetic fields) into account.

Stellar rotation is also being incorporated in stellar structure and stellar evolution models. It turns out that this has several important implications due to meridional circulations and shear (cf. Maeder 1999). The occurrence of the so-called omega limit would have an important impact on the (final) evolution of massive stars (cf. Langer & Heger 1999).

Excluding known binaries, non-sphericity has been confirmed in five Wolf-Rayet stars by means of polarization line effects (Harries, Hillier & Howarth 1998), likely because of equatorial density enhancements produced by rotation.

2.3. Census and classification

Some 30 new Wolf-Rayet were discovered in the Galaxy over the past three years (van der Hucht 1999), bringing the total number to 218, a 40 percent increase since the 1981 Catalogue. In the LMC, a similar increase in the number of known Wolf-Rayet stars is registered in the VIth Catalogue (Breysacher et al. 1999). New candidate Luminous Blue Variables are also being found, e.g in M31 (King & Walterbos 1999).

The terminology has been refined for Luminous Variable Stars (Conti 1997) and B[e] stars (Lamers et al. 1998). Several improvements and extensions have been added to the Wolf-Rayet classification scheme (cf references in van der Hucht 1999) With, however, a caveat by Conti (1999a).

3. WOLF-RAYET BINARIES AND COLLIDING WINDS

Research on Wolf-Rayet (WR) binaries has provided a wealth of new information not only on the orbital and stellar parameters, but also on the winds of both components and their colliding process. In the Galaxy, approximately 40 WR stars are confirmed binaries (Niemela et al 1999). A new mass of around 72 $M_\odot$ (Rauw et al. 1996) or 55 $M_\odot$ (Schweickhardt et al. 1999) has been derived for WR 22, implying that it must still be in its H-burning stage. Orbital periods have been determined for the WR 29 and WR 30a systems (Niemela et al. 1999; Gosset et al. 1999).

A predominant feature of WR binaries (and to a lesser extent, O+O binaries) is the strong interaction between the winds of the two stellar components. Observational evidence for colliding winds comes from resolved radio and infrared images, excess non-thermal continuous radio emission, variable continuous X-ray and infrared emission, as well as excess spectral-line emission associated with phase-dependent line-profile variability.

Surveys of radio emission revealed the existence of non-thermal emission in 25-50% of hot stars (Scuderi et al. 1998; Chapman et al. 1999), most of them in binary systems (Dougherty 1999). Radio observations of WR 146 and WR 147 have shown that in both cases the non-thermal emission is emitted from a region between the WR star and its companion, where the two winds are believed to collide (Dougherty et al. 1996; Williams et al. 1997). The measured positions were confirmed by HST optical images (Niemela et al. 1998). The observed shape and location of the non-thermal emission region fit well the colliding wind model and allow the derivation of the mass-loss rate of the companion (Dougherty & Williams 1999; Williams 1999) and of the inclination of the orbital plane (Contreras & Rodriguez 1999). A similar system, Cyg OB5 No5 = V729 Cyg, involves a close Of+Of binary and a faint early B star. Again the non-thermal emission source is located between them (Contreras et al. 1997) as is part of the line emission region (Rauw et al. 1999). WR 39 is suspected to be yet another similar system (Chapman et al. 1999).

Systematic infrared monitoring of the 7.94-yr binary WR 140 has shown that the episodes of dust formation occur always at the same orbital phase, as if triggered by periastron approach in this highly eccentric system. It is believed that a sudden density enhancement in the colliding wind region provides at that phase the density and the shielding from the stellar radiation needed to form dust (Williams 1997). Six other episodic dust-making WR systems are also being monitored (Williams 1999). HST-NICMOS2 imaging of WR 137 was able to resolve the dust emission for the first time: three distinct clumps are clearly seen (Marchenko, Moffat, Grosdidier 1999). Remarkable Keck images show plumes of dust spiralling around WR 104 and WR 98a, with periods of 243 days and 565 days respectively (Tuthill et al. 1999; Monnier et al. 1999). The former star is also known for transient visual fadings attributed to dust clouds (Crowther 1997).

The observed X-ray variations in the continuum flux and the line emission have provided confirmations of the wind-collision models of V444 Cyg (Pittard & Stevens 1999), WR 140 (Pollock et al. 1999), γ^2 Vel (Stevens & Pittard 1999) and η Car (see below). The model by Pollock (1998) dispenses with the need for the flattened wind claimed earlier for WR 140.

Studies of line-profile variability (LPV) offer the extra advantage of providing Doppler information. LPV is common in WR+O binaries, at least for periods < 100 days (Moffat 1999a). Hydrodynamical calculations have been applied to observations of the He I line at 1.083 μm in five systems (Stevens & Howarth 1999). An easier, simplified analytical approach has been developed by Lührs (1997) for circular orbits. It allows the determination of the geometry of the wind-wind collision cone, the flow speed along the interaction region and the inclination of the orbit. It has been successfully applied to the Magellanic Clouds WR binaries (Bartzakos 1998). A refined model for elliptical orbits has been applied to γ Vel by Eversberg et al. (1999) and to HD5980 by Moffat (1998). Further refinements should include radiative breaking (Gayley et al. 1997), Coriolis effects (Cantó et al. 1999), wind eclipses and tidally induced oscillations (Koenigsberger et al. 1999). A detailed analysis of LPV in V444 Cyg (Marchenko et al. 1997) has provided constraints on the geometry (stellar radii, location of the wind wind collision zone, absolute dimension of the line formation zones) and physics of the system (wind electron temperature and density, physics of the shocked gas).

4. η CAR

There continues to be a great deal of observational and theoretical interest in the extremely massive star η Carinae and its surrounding nebulosity. Davidson and Humphreys (1997) offers a recent review, and η Car was the subject of a recent workshop, "Eta Carinae at the Millennium". Due to space constraints we concentrate on the star itself and defer recent studies of the circumstellar material, but mention these highlights: the formation of the homunculus is discussed by Langer, Garcia-Segura & MacLow (1999), Dwarkadas & Balick (1998) and Frank, Ryu and Davidson (1998); Morse et al. (1998) discuss WFPC2 images; Zethson et al. (1999) study the velocity of material in the equatorial ejecta and report unusual fluorescent processes; Weis, Duschl & Chu (1999) present their observations of peculiar "strings" in the nebula, and Gull et al. (1999) present the first HST/STIS observations of η Car and the homunculus, showing the intriguing "integral nebula".

Much of the recent interest in the star has been driven by the fortuitous observation of a "low state" in mid-1992, simultaneously seen in the He I 1083 nm line strength (Damineli 1996), and in radio (Duncan et al. 1995) and X-ray (Corcoran et al., 1995) continuum maps. Damineli (1996) presented evidence of a 5.52 year periodicity in the He I 1083 nm and predicted another low state near 1998.0. This He I 1083 nm low state did indeed occur very near 1998.0 (Damineli et al., 1999) along with recurrence of the X-ray (Ishibashi et al., 1999) and radio minima (Duncan et al. 1999), and an abrupt brightening/fading of the star in the near-IR (Whitelock & Laney, 1999). Damineli, Conti & Lopes (1997) presented evidence of phase-locked radial velocity variations at Pa-γ and suggested that η Car is a massive binary in an eccentric, 5.52 year orbit. Corcoran et al. (1998) noted that such a binary system could explain some peculiarities of the X-ray emission, while Pittard et al. (1998) and Ishibashi et al. (1999) noted qualitative similarities between the observed 2–10 keV lightcurve and the expected variations produced by wind-wind collisions in a massive binary system. If η Car is really a binary, studies of the orbit offer the best opportunity to determine the physical parameters (mass, radius, mass loss rate) of η Car (and its companion).

η Car continues to show complex behavior in addition to the 5.52 year periodic variability. Van Genderen et al. (1999) presented 24 years of ground-based photometry. Corcoran et al. (1997) reported detection of X-ray flaring with a period near 84 days. Ground-based photometry (Sterken et al. 1999) and HST/STIS measures (Davidson et al. 1999) have shown that the apparent brightness of the central star has increased at a rate not seen in decades and the star is now brighter than it has been in 130 years (apparently on the way to becoming a naked eye object once again). The cause of this brightening is unknown; Davidson et al. (1999) suggested destruction of dust grains in the vicinity of the star and/or an increase in stellar bolometric luminosity, while Sterken et al. (1999) suggested an "S-

Dor" type of variation common to Luminous Blue Variables. At present it is unclear how this long-term brightening relates to the 5.52-year cycle.

5. WOLF-RAYET AND OTHER HOT MASSIVE STARS IN STARBURST REGIONS...

5.1. ... in the Local Group, including the Galaxy

Before launching into studies of distant, unresolved starbursts, it is imperative to first look in detail at nearby resolved starbursts, even if they appear to be more modest. The most luminous optically visible starburst region in the Galaxy is the extremely compact, rich cluster NGC 3603 (Drissen 1999). While a clone of R136a at the core of 30 Dor in the LMC, NGC 3603 is easier to study in view of its 7x closer distance. Remarkably, NGC 3603 contains 3 of the most luminous known WR stars, all H-rich, along with a host of very hot early-type O stars, but also a well-developed pre main sequence down to below a Solar mass. Isochrone fitting to the upper and lower main sequences yields conflicting ages (~ 2 Myr and ~ 0.5 Myr, respectively), although there are still serious problems to overcome in the stellar models.

R136a also contains 3 bright, H-rich WR stars in its 1 pc diameter region, along with a prominent pre main sequence (Heap 1999). Modeling of the spectra of the brightest stars yields very high mass-loss rates, probably a result of rapid rotation. The WR stars here are probably very massive main sequence stars whose winds are strong enough to yield WR-like emission lines. The masses are in the range of 60 rather than 100 $M_\odot$, without allowing for rotation. Large variations in the ratio of wind terminal to escape velocity show that something is missing in the theory of radiation-driven winds. As for NGC 3603 (Tapia & Perez 1999), R136 is surrounded by second generation, triggered star formation, so young that some O stars are still embedded in dense nebular knots and dust pillars (Walborn & Barba 1999), as seen in spectacular HST images.

Other resolvable starburst regions in the Local Group (LG) include 30 Dor and Constellation III in the LMC, NGC 604 in M33 and NGC 206 in M31. With diameters of $\sim$ 1 kpc, they are the equivalent of $\sim$ 1000 Orions, and being considerably larger than NGC 3603 or R136a, reveal age spreads of $\sim$ 10 Myr, although not correlated with radius (Hunter 1999). Each region contains internal knots of stars, whose richness curiously ranges over orders of magnitude.

Another starburst is NGC 346 in the SMC. Although not a current member of its dense core, the nearby massive binary HD 5980 had one of its components erupt in 1994 as a Luminous Blue Variable, making this object the most luminous star in all of the SMC for some 6 months (Moffat 1999b). This is the first, very important case of an LBV eruption of a massive star in a very close binary. However, the true nature of HD 5980's components has yet to be deciphered.

The content of LG galaxies in resolved WR stars is important for constraining stellar evolution of the most massive stars (Massey 1999). In particular, the increase of the WC/WN number ratio with increased ambient metallicity shows that the corresponding increased mass-loss rates do in fact drive progressively lower mass, massive stars all the way to WC, the final pre-SN state. At lower metallicity, an increase in the RSG/WR number ratio implies that massive stars at low Z spend more of their He-burning lives as RSGs than as WR stars and vice versa. A new insight into the nature of WC stars is that the various subclasses reflect an influence of Z, rather than mass or luminosity, on the atmospheric structure. It is emphasized that spectroscopy, not just photometry, is essential for proper study of massive star populations.

At only 8 kpc, the Galactic centre is by far the closest galactic nucleus. Hidden by some 30 mag of visual extinction, the central pc of our Galaxy is powered by a cluster of young, massive hot stars formed a few Myr ago (Eckart et al. 1999). Now, after 6 years of near IR study, the distribution and motions of these massive stars has clinched the argument favouring a central dark mass of 2.6 10^6 $M_\odot$, most likely a massive black hole, associated with the compact non-thermal radio source Sgr A*, which defines the true dynamic centre of our Galaxy. Among the bright supergiants, the HeI star IRS 16SW has been revealed to be an eclipsing binary with mass exceeding 100 $M_\odot$.

Besides the Centre cluster, two other massive, young dense clusters (dubbed Arches and Quintuplet) have been found and studied using HST IR imaging, in the central 50 pc of the Galactic centre (Figer et al. 1999). These 3 clusters are the most massive young clusters in the Galaxy and together harbour more WR stars than any other starburst region in the LG. The Arches cluster is denser than most Globular clusters. They therefore are excellent places to investigate at close range the stellar content, with emphasis on WR phenomena, in starburst galaxies and galactic nuclei. The two new clusters have disintegration times below 10 Myr in the strong tidal field of the Galactic centre, consistent with the lack of clusters older than 5 Myr in the central 50 pc. While the Galactic centre region occupies some 1% of the Galactic volume, it contains 10% of the star formation, mostly at 2 $Z_\odot$, which in itself is unique. Blum & Damineli (1999) are IR surveying larger portions of the inner Galaxy for more massive emission-line stars.

5.2. ... in W-R starburst galaxies

Wolf-Rayet galaxies represent a rapidly expanding class of starburst systems in which the presence of WR stars is inferred from the appearance of broad emission lines (at 4700 Å and 5800 Å) (Conti 1999b). With over 140 now known, all contain WN stars, while some half contain WC stars (Schaerer et al. 1999). With equivalent widths of these lines no greater than a few Å, compared to several 100 Å in single WR stars, dilution factors provide an observational challenge. WR stars are important tracers in starbursts: they reveal ages (typically $\sim$ 2 - 6 Myr, maybe beyond, if rejuvenated Roche-lobe overflow binaries are important: Vanbeveren et al. 1998; Mas-Hesse & Cervino 1999) and the very proof of the presence of luminous hot stars. This is especially important at high redshift, where improved statistics are moderated by loss of spatial resolution. When sufficient spatial resolution is available, WR galaxies often break up into large numbers of super star clusters, each one like 30 Dor (Johnson 1999).

The study of WR galaxies is very active, with plenty of controversy. E. g. Leitherer (1999) claims that observations are not (yet?) capable of constraining starburst models satisfactorily; it is better to use them to improve WR atmospheres and evolutionary models than to derive the star formation history and the IMF. On the other hand, Schaerer (1999) finds that WR galaxies (1) require instantaneous bursts (i.e. $\Delta t <\sim$ 2-4 Myr), (2) reveal mostly a Salpeter IMF populated to high masses, and (3) WC/WN ratios that favour high mass-loss evolutionary models. Nebular HeII 4686 Å emission is also important to constrain models of hot WR stars, especially in regions of low Z, which are inaccessible in the LG. Contini et al. (1999) use the systematic detection for the first time of broad CIV 5808 Å in WR galaxies to place serious constraints on the WR/O and WC/WN populations.

6. MAJOR SCIENTIFIC CONFERENCES

- Colloquium on "Wolf-Rayet stars in the framework of stellar evolution", Liège, Belgium, 1996 July 1-3, ed. J.M. Vreux, A. Detal, D. Fraipont, E. Gosset & G. Rauw (U. Liège, 1997)
- Workshop on "Luminous Blue Variables: massive stars in transition", Kona, Hawaii, 1996 October 6-12, ed. A. Nota & H.J.G.L.M. Lamers (ASP Conf. Ser. 120, 1997)
- Workshop on "B[e] stars", Paris, France, 1997 June 9-12, ed. C. Jaschek & A.-M. Hubert (Kluwer, 1998)
- Second Boulder-Münich workshop on "Properties of hot, luminous stars", Windsor, England, 1997 July 21-24, ed. I.D. Howarth (ASP Conf. Ser. 131, 1998)

- ESO workshop on "Cyclical variability in stellar winds", München, Germany, 1997 October 14-17, ed. L. Kaper & A.W. Fullerton (Berlin, Springer, 1998)
- Workshop on "Hot stars in open clusters of the Galaxy and Magellanic Clouds", La Plata, Argentina, 1997 December, ed. N. Morrell & V. Niemela
- IAU Colloquium No. 169 on "Variable and non-spherical stellar winds in luminous hot stars", Heidelberg, Germany, 1998 June 15-19, ed. B. Wolf, O. Stahl & A. Fullerton (Berlin, Springer)
- Workshop on "eta Carinae at the Millenium", Gallatin Canyon, Montana, 1998 July 19-23, ed. Morse, J. A., Humphreys, R. M. & Damineli, A. (PASP Conf. Ser. 179)
- IAU Symposium No 193 on "Wolf-Rayet phenomena in massive stars and starburst galaxies", Puerto Vallarta, Mexico, 1998 November 3-7, ed. K.A. van der Hucht, G. Koenigsberger & P.R.J. Eenens (ASP, 1999)
- IAU Colloquium No. 175 on "The Be phenomena in early-type stars", Alicante, Spain, 1999 July, ed. M.A. Smith, H. Henrichs & J. Fabregat
- Workshop on "Thermal and ionization aspects of flows from hot stars: observations and theory", Tartu, Estonia, 1999 August 23-27, ed. H.J.G.L.M. Lamers & A. Sapar
- JENAM workshop on "The interplay between massive stars and the ISM", Toulouse, France, 1999 September 10-11, ed. D. Schaerer & R. Gonzalez Delgado (New Astron. Rev., 2000)

7. MAJOR PUBLICATIONS

A much needed book on "Introduction to stellar winds" has been written by Henny Lamers and Joseph Cassinelli and published by Cambridge University Press (1999). A book on "The brightest binaries", by D. Vanbeveren, van W. Rensbergen and C. de Loore was published by Kluwer (1998). Many reviews can be found in the proceedings of the conferences listed above. Kris Davidson and Roberta Humphreys (1997) have reviewed the work on η Car. An article on "Wolf-Rayet stars" has been written by John Hillier for the Encyclopedia of Astronomy and Astrophysics to be published by MacMillan.

8. SOURCES OF FURTHER INFORMATION

The Hot Star Newsletter, edited by Philippe Eenens (`eenens@astro.ugto.mx`) is distributed ~ monthly by electronic mail and provides abstracts of recent journal and proceedings papers, news and information on observing campaigns, conferences, jobs, etc. It can be found on the Web, together with other material related to Hot Massive Stars (bibliography, catalogues, atlases, information on meetings, etc), at
`http://www.astro.ugto.mx/~eenens/`
or its mirror `http://www.star.ucl.ac.uk/~hsn/index.html`

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