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Accepted Papers

Non-thermal radio emission from single hot stars

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We present a theoretical model for the non-thermal radio emission from single hot stars, in terms of synchrotron radiation from electrons accelerated in wind-embedded shocks. The model is described by five independent parameters each with a straightforward physical interpretation. Applying the model to a high-quality observation of Cyg OB2 No. 9 (O5 If), we obtain meaningful constraints on most parameters. The most important result is that the outer boundary of the synchrotron emission region must lie between 500 and 2200 stellar radii. This means that shocks must persist up to that distance. We also find that relatively weak shocks (with a compression ratio < 3) are needed to produce the observed radio spectrum. These results are compatible with current hydrodynamical predictions. Most of our models also show a relativistic electron fraction that increases outwards. This points to an increasing efficiency of the acceleration mechanism, perhaps due to multiple acceleration, or an increase in the strength of the shocks. Implications of our results for non-thermal X-ray emission are discussed.

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Three-dimensional dust radiative-transfer models: The Pinwheel Nebula of WR104

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We present radiative-transfer modelling of the dusty spiral Pinwheel Nebula observed around the Wolf-Rayet/OB-star binary WR104. The models are based on the three-dimensional radiative-transfer code TORUS, modified to include an adaptive mesh that allows us to adequately resolve both the inner spiral turns (sub-AU scales) and the outer regions of the nebula (distances of 10^4 AU from the central source). The spiral model provides a good fit to both the spectral energy distribution and Keck aperture masking interferometry, reproducing both the maximum entropy recovered images and the visibility curves. We deduce a dust creation rate of $8 \pm 1 \times 10^{-7}$ $M_\odot$ yr^{-1}, corresponding to approximately 2% by mass of the carbon produced by the Wolf-Rayet star. Simultaneous modelling of the imaging and spectral data enables us to constrain both the opening-angle of the wind-wind collision interface and the dust grain size. We conclude that the dust grains in the inner part of the Pinwheel nebula are small ($\sim$ 100Å), in agreement with theoretical predictions, although we cannot rule out the presence of larger grains ($\sim 1\mu$m) further from the central binary. The opening angle of the wind-wind collision interface appears to be about 40°, in broad agreement with the wind parameters estimated for the central binary. We discuss the success and deficiencies of the model, and the likely benefits of applying similar techniques to the more complex nebulae observed around other WR/O star binaries.

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A Very Large Array 3.6 cm continuum survey of Galactic Wolf-Rayet stars

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We report the results of a survey of radio continuum emission of Galactic Wolf-Rayet stars north of $\delta = -46°$. The observations were obtained at 8.46 GHz (3.6 cm) using the Very Large Array (VLA), with an angular resolution of $\sim 6'' \times 9''$ and typical rms noise of ~ 0.04 mJy beam^{-1}. Our survey of 34 WR stars resulted in 15 definite and 5 probable detections, 13 of these for the first time at radio wavelengths. All detections are unresolved ($\theta \lesssim 5''$). Time variations in flux are confirmed in the cases of WR 98a, WR 104, WR 105, and WR 125. WR 79a and WR 89 are also variable in flux and we suspect they are also non-thermal emitters. Thus, of our sample 20 - 30 % of the detected stars are non-thermal emiters. Average mass loss rates determinations obtained excluding definite and suspected non-thermal cases give similar values for WN (all subtypes) and WC5-7 stars ($\dot{M}$(WN) = $[4 \pm 3] \times 10^{-5}$ $M_\odot$ yr^{-1} and $\dot{M}$(WC5-7) = $[4 \pm 2] \times 10^{-5}$ $M_\odot$ yr^{-1}), while a lower value was obtained for WC8-9 stars ($\dot{M}$(WC8-9) = $[2 \pm 1] \times 10^{-5}$ $M_\odot$ yr^{-1}). Uncertainties in stellar distances largely contribute to the observed scatter in mass loss rates. Upper limits to the mass loss rates were

obtained in cases of undetected sources or for sources which probably show additional non-thermal emission.

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BeppoSAX broad X-ray range observations of η Car during high and low spectroscopic states

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We report on the June 2000 long (100 ks) BeppoSAX exposure that has unveiled above 10 keV a new very high energy component of the X-ray spectrum of η Car extending to at least 50 keV. We find that the 2-150 keV spectrum is best reproduced by a thermal + non-thermal model. The thermal component dominates the 2-10 keV spectral range with kT_h=5.5±0.3 keV and $\log NH_h$=22.68±0.01. The spectrum displays a prominent iron emission line centred at 6.70 keV. Its equivalent width of 0.94 keV, if produced by the thermal source, gives a slightly sub-solar iron abundance ([Fe/H]=−0.15±0.02). The high energy tail above 10 keV is best fitted by a power law with a photon index of 2.42±0.04. The integrated 13-150 keV luminosity of $\sim$12 $L_\odot$ is comparable to that of the 2-10 keV thermal component (19 $L_\odot$). The present result can be explained, in the η Car binary star scenario, by Comptonisation of low frequency radiation by high energy electrons, probably generated in the colliding wind shock front, or in instabilities in the wind of the S Dor primary star. It is possible that the high energy tail had largely weakened near the minimum of the 5.53 yr cycle. With respect to the thermal component, it probably has a longer recovering time like that of the highest excitation optical emission lines. Both features can be associated with the large absorption measured by BeppoSAX at phase 0.05.
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Nitrogen and Oxygen Abundance Variations in the Outer Ejecta of Eta Carinae: Evidence for Recent Chemical Enrichment

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We present optical spectra of the ionized ‘Outer Ejecta’ of η Carinae that reveal differences in chemical composition at various positions. In particular, young condensations just outside the dusty Homunculus Nebula show strong nitrogen lines and little or no oxygen — but farther away, nitrogen lines

weaken and oxygen lines become stronger. The observed variations in the apparent N/O ratio may signify either that the various blobs were ejected with different abundances, or more likely, that the more distant condensations are interacting with normal-composition material. The second hypothesis is supported by various other clues involving kinematics and X-ray emission, and would suggest that η Car is enveloped in a "cocoon" deposited by previous stellar-wind mass loss. In particular, all emission features where we detect strong oxygen lines are coincident with or outside the soft X-ray shell. In either case, the observed abundance variations suggest that η Car's ejection of nitrogen-rich material is a *recent* phenomenon — taking place in just the last few thousand years. Thus, η Carinae may be at a critical stage of evolution when ashes of the CNO cycle have just appeared at its surface. Finally, these spectra reveal some extremely fast nitrogen-rich material, with Doppler velocities up to 3200 km s^{-1}, and actual space velocities that may be much higher. This is the fastest material yet seen in η Car's nebula, but with unknown projection angles its age is uncertain.

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Kinematics and UV-to-IR Morphology of the Inner Homunculus of Eta Carinae

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We present the first ultraviolet and optical images of η Carinae and its circumstellar Homunculus Nebula obtained with the Advanced Camera for Surveys/High Resolution Camera (ACS/HRC) on-board the *Hubble Space Telescope* (*HST*). Compared to visual wavelengths, UV images reveal excess emission $0\farcs1$ to $0\farcs6$ from the central source along the minor axis that may emanate from the outer parts of η Car's non-spherical stellar wind, which dominates the UV flux from η Car. The UV emission fills the cavity inside a dust torus measured from infrared data; within $0\farcs2$ of the star it projects a morphology reminiscent of the IR torus, but it is a factor of 10 smaller. This 'little torus' seen in the UV may be related to the 'Little Homunculus' discovered recently, signifying recurrent mass ejections with the same geometry. Finally, we re-examine the kinematics of nebular condensations near the star (Weigelt objects C and D) in *HST* images and spectra obtained over the past decade. We measure heliocentric velocities slower than previous estimates, and from proper motions we derive an ejection date of 1908 ±12 yr, assuming linear motion. However, because of radiative acceleration, they may have been ejected earlier — perhaps during the 1890 outburst of η Carinae.

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Spatially extended K I λ7699 emission in the nebula of VY CMa: Kinematics and geometry

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Long-slit echelle spectra reveal bright extended emission from the K I λ7699 resonance line in the reflection nebula surrounding the extreme red supergiant VY Canis Majoris. The central star has long been known for its unusually-bright K I emission lines, but this is the first report of intrinsic emission from K I in the nebula. The extended emission is not just a reflected spectrum of the star, but is due to resonant scattering by K atoms in the outer nebula itself, and is therefore a valuable probe of the kinematics and geometry of VY CMa's circumstellar environment. Dramatic velocity structure is seen in the long-slit spectra, and most lines of sight through the nebula intersect multiple distinct velocity components. A faint "halo" at large distances from the star does appear to show a reflected spectrum, however, and suggests a systemic velocity of +40 km/s with respect to the Sun. The most striking feature is blueshifted emission from the filled interior of a large shell seen in images; the kinematic structure is reminiscent of a Hubble flow, and provides strong evidence for asymmetric and episodic mass loss due to localized eruptions on the star's surface.

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A Phase-Resolved XMM-Newton Campaign on the Colliding Wind Binary HD 152248

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We report the first results of an XMM-Newton monitoring campaign of the NGC 6231 open cluster in the Sco OB1 association. This first paper focuses on the massive colliding wind binary HD 152248, which is the brightest X-ray source of the cluster. The campaign, with a total duration of 180 ksec, was split into six separate observations, following the orbital motion of HD 152248. The X-ray flux from this system presents a clear, asymmetric modulation with the phase and ranges from 0.73 to $1.18\,10^{-12}$ erg s^{-1} cm^{-2} in the [0.5-10.0 keV] energy band. The maximum of the emission is reached slightly after apastron. The EPIC spectra are quite soft and peak around 0.8-0.9 keV. We characterize their shape using several combinations of MEKAL models and power-law spectra and we detect significant spectral variability in the [0.5-2.5 keV] energy band.

We also perform 2-D hydrodynamical simulations using different sets of parameters that closely reproduce the physical and orbital configuration of the HD 152248 system at the time of the six XMM-Newton pointings. This allows a direct confrontation of the model predictions with the constraints deduced from the X-ray observations of the system. We show that the observed variation of the flux can be explained by a variation of the X-ray emission from the colliding wind zone, diluted by the softer X-ray contribution of the two O-type stars of the system. Our simulations also reveal that the interaction region of HD 152248 should be highly unstable, giving rise to shells of dense gas that are separated by low density regions.

Finally, we perform a search for short-term variability in the light curves of the system and we show that trends are present within several of the 30 ksec exposures of our campaign. Further, most of these trends are in good agreement with the orbital motion and provide a direct constraint on the first order derivative of the flux. In the same context, we also search for long-range correlations in the X-ray data of the system, but we only marginally detect them in the high energy tail of the signal.

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The Physical Properties and Effective Temperature Scale of O-type Stars as a Function of Metallicity. I. A Sample of 20 Stars in the Magellanic Clouds

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We have obtained *HST* and ground-based observations of a sample of 20 O-type stars in the LMC and SMC, including six of the hottest massive stars known (subtypes O2-3) in the R136 cluster. In general, these data include (a) the *HST* UV spectra in order to measure the terminal velocities of the stellar winds, (b) high signal-to-noise, blue-optical data where the primary temperature- and gravity-sensitive photospheric lines are found, and (c) nebular-free Hα profiles, which provide the mass-loss rates. We find that the older (FOS) *HST* data of the R136 stars (which were obtained without the benefits of sky measurements) suffered from significant nebular emission, which would increase the derived mass-loss rates by factors of ~ 3, all other factors being equal. We also find several stars in the SMC for which the N III $\lambda\lambda 4634, 42$ and He II$\lambda 4686$ emission "f" characteristics do not appear to follow the same pattern as in Galactic stars. Since He II emission is due to the stellar wind (which will be weaker in SMC for stars of the same luminosity), while N III emission is a complex NLTE effect affected mostly by temperature, it would not be surprising to find that these features do not correlate with each other or with luminosity in SMC stars in the same was as they do in Galactic stars, but theory does not provide a clean answer, and analysis of more stars (both SMC and Galactic) are needed to resolve this issue. The line-blanketed non-LTE atmosphere code FASTWIND was then used to determine the physical parameters of this sample of stars. We find good agreement between the synthetic line profiles for the hydrogen, He I, and He II lines in the majority of the stars we analyzed; the three exceptions show evidence of being incipiently resolved spectroscopic binaries or otherwise spectral composites. One such system is apparently an O3 V+O3 V eclipsing binary, and a follow-up radial

velocity study is planned to obtain Keplerian masses. Although we did not use them to constrain the fits, good agreement is also found for the He I $\lambda3187$ and He II $\lambda3203$ lines in the near-UV, which we plan to exploit in future studies. Our effective temperatures are compared to those recently obtained by Repolust, Puls & Herrero for a sample of Galactic stars using the same techniques. We find that the Magellanic Cloud sample is 3,000-4,000°K hotter than their Galactic counterparts for the early through mid-O's. These higher temperatures are the consequence of a decreased importance of wind emission, wind blanketing, and metal-line blanketing at lower metallicities.

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XMM-Newton observations of the giant HII region N 11 in the LMC

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Using the sensitive *XMM-Newton* observatory, we have observed the giant HII region N 11 in the LMC for ∼30 ks. We have detected several large areas of soft diffuse X-ray emission along with 37 point sources. One of the most interesting results is the possible association of a faint X-ray source with BSDL 188, a small extended object of uncertain nature.

The OB associations in the field-of-view (LH9, LH10 and LH13) are all detected with *XMM-Newton*, but they appear very different from one another. The diffuse soft X-ray emission associated with LH9 peaks near HD 32228, a dense cluster of massive stars. The combined emission of all individual massive stars of LH9 and of the superbubble they have created is not sufficient to explain the high level of emission observed: hidden SNRs, colliding-wind binaries and the numerous pre-main sequence stars of the cluster are most likely the cause of this discrepancy. The superbubble may also be leaking some hot gas in the ISM since faint, soft emission can be observed to the south of the cluster. The X-ray emission from LH10 consists of three pointlike sources and a soft extended emission of low intensity. The two brightest point sources are clearly associated with the fastest expanding bubbles blown by hot stars in the SW part of the cluster. The total X-ray emission from LH10 is rather soft, although it presents a higher temperature than the other soft emissions of the field. The discrepancy between the combined emission of the stars and the observed luminosity is here less severe than for LH9 and could be explained in terms of hot gas filling the wind-blown bubbles. On the other hand, the case of LH13 is different: it does not harbour any extended emission and its X-ray emission could most probably be explained by the Sk $-66°41$ cluster alone.

Finally, our *XMM-Newton* observation included simultaneous observations with the OM camera that provide us with unique UV photometry of more than 6000 sources and enable the discovery of the UV emission from the SNR N11L.

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An X-ray investigation of the NGC 346 field in the SMC (3): *XMM-Newton* data

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We present new *XMM-Newton* results on the field around the NGC 346 star cluster in the SMC. This continues and extends previously published work on *Chandra* observations of the same field. The two *XMM-Newton* observations were obtained, respectively, six months before and six months after the previously published *Chandra* data. Of the 51 X-ray sources detected with *XMM-Newton*, 29 were already detected with *Chandra*. Comparing the properties of these X-ray sources in each of our three datasets has enabled us to investigate their variability on times scales of a year. Changes in the flux levels and/or spectral properties were observed for 21 of these sources. In addition, we discovered long-term variations in the X-ray properties of the peculiar system HD 5980, a luminous blue variable star, that is likely to be a colliding wind binary system, which displayed the largest luminosity during the first *XMM-Newton* observation.

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Quasi-simultaneous *XMM-Newton* and VLA observation of the non-thermal radio emitter HD 168112 (O5.5III(f^+))

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We report the results of a multiwavelength study of the non-thermal radio emitter HD 168112 (O5.5III(f^+)). The detailed analysis of two quasi-simultaneous *XMM-Newton* and VLA observations reveals strong variability of this star both in the X-ray and radio ranges. The X-ray observations separated by five months reveal a *decrease* of the X-ray flux of $\sim 30\,\%$. The radio emission on the other hand *increases* by a factor 5–7 between the two observations obtained roughly simultaneously with the *XMM-Newton* pointings. The X-ray data reveal a hard emission that is most likely produced by a thermal plasma at kT $\sim$ 2–3 keV while the VLA data confirm the non-thermal status of this star in the radio waveband. Comparison with archive X-ray and radio data confirms the variability of this source in both wavelength ranges over a yet ill defined time scale. The properties of HD 168112 in the X-ray and

radio domain point towards a binary system with a significant eccentricity and an orbital period of a few years. However, our optical spectra reveal no significant changes of the star's radial velocity suggesting that if HD 168112 is indeed a binary, it must be seen under a fairly low inclination.

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Puzzling wind properties of young massive stars in SMC-N81

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We present a quantitative study of massive stars in the High Excitation Blob N81, a compact star forming region in the SMC. The stellar content was resolved by HST and STIS was used to obtain medium resolution spectra. The qualitative analysis of the stellar properties presented in Heydari-Malayeri et al. (2002) is extended using non-LTE spherically extended atmosphere models including line-blanketing computed with the code CMFGEN (Hillier & Miller 1998), and the wind properties are investigated. The main results are the following:

1) The SMC-N81 components are young ($\sim$ 0–4 Myrs) O stars with effective temperatures compatible with medium to late subtypes and with luminosities lower than average Galactic O dwarfs, rendering them possible ZAMS candidates.

2) The winds are extremely weak: with values of the order $10^{-8}/10^{-9}$ $M_\odot$ yr^{-1}, the mass loss rates are lower than observed so far for Galactic dwarfs. Only the recent study of SMC stars by Bouret et al. (2003) show the same trend. The modified wind momenta ($\dot{M}$ v_∞ $\sqrt{R}$) are also 1 to 2 orders of magnitude lower than observed for Galactic stars. Both the mass loss rates and the modified wind momenta are lower than the predictions of the most recent hydrodynamical models.

The accuracy of the UV based mass loss rate determination, relying in particular on the predicted ionisation fractions, are carefully examined. We find that $\dot{M}$ could be underestimated by a factor of up to 10. Even in this unlikely case, the above conclusions remain valid *qualitatively.*

The reasons for such weak winds are investigated with special emphasis on the modified wind momenta:

1) There may be a break-down of the wind momentum - luminosity relation (WLR) for dwarf stars at low luminosity (log $L/L_\odot$ ¡ 5.5). However, reasons for such a breakdown remain unknown.

2) The slope of the WLR may be steeper at low metallicity. This is predicted by the radiation driven wind theory, but the current hydrodynamical simulations do not show any change of the slope at SMC metallicity. Moreover, there are indications that some Galactic objects have wind momenta similar to those of the SMC stars.

3) Decoupling may take place in the atmosphere of the SMC-N81 stars, leading to multicomponent winds. However, various tests indicate that this is not likely to be the case.

The origin of the weakness of the wind observed in the SMC-N81 stars remains unknown. We suggest that this weakness may be linked with the youth of these stars and represents possibly the onset of

stellar winds in recently formed massive stars.

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Light variations of massive stars (α Cyg variables): The late-type supergiants R 59, HDE 268822, HDE 269355, HDE 269612 and HDE 270025 in the LMC

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We present and discuss $VBLUW$ photometry (Walraven system) of five supergiants in the LMC. For one well-known variable, the hypergiant R 59 = HDE 268757 (G7 Ia$^+$) also Hipparcos photometry and numerous visual observations are available. The second variable is HDE 269612 (F0 Ia), and a third one is HDE 268822 (F6 Ia). Two F6 Ia supergiants turned out to be constant: HDE 269355 and HDE 270025.

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Near IR Spectroscopic monitoring of WR 140 during the 2001 periastron passage

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We present new spectra of WR 140 (HD 193793) in the JHK bands with some covering the 1.083-μm He I emission line at higher resolution, observed between 2000 October and 2003 May to cover its 2001 periastron passage and maximum colliding-wind activity. The WC7 + O4-5 spectroscopic binary WR 140 is the prototype of colliding-wind, episodic dust-making Wolf-Rayet systems which also show strong variations in radio and X-ray emission. The JHK spectra showed changes in continuum and in the equivalent widths of the WC emission lines, consistent with formation of dust starting between 2001 January 3 and March 26 (orbital phases 0.989 and 0.017) and its subsequent fading and cooling. The 1.083-μm He I line has a P-Cygni profile which showed variations in both absorption and emission components as WR 140 went through periastron passage. The variation of the absorption component of the profile yielded tight constraints on the geometry of the wind-collision region, giving $\theta = 50^\circ \pm 8^\circ$ for the opening semi-angle of the interaction region 'cone', indicating a wind-momentum ratio $(\dot{M}v_\infty)_{\rm O}/(\dot{M}v_\infty)_{\rm WR} = 0.10$, about three times larger than previously believed. As the system approached periastron, the normally flat-topped emission component of 1.083-μm line profile showed the appearance of a significant sub-peak. The movement of the sub-peak across the profile was seen

to be consistent with its formation in wind material flowing along the contact discontinuity between the WC7 and O4-5 stellar winds and the changing orientation of the colliding wind region as the stars moved in their orbits. The flux carried in the sub-peak was significant, exceeding the X-ray fluxes measured at previous periastron passages. This additional source of radiative cooling of the shock-heated gas probably causes it to depart from being adiabatic around periastron passage, thereby accounting for the departure of the X-ray flux from its previously expected $1/d$-dependency.

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An exceptional population of late-type WC stars in the metal-rich spiral galaxy M 83

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We have surveyed the metal-rich spiral galaxy M 83 (NGC 5236) for its Wolf-Rayet population using VLT-FORS2 narrow-band imaging and follow-up spectroscopy. From a total of 280 candidates identified using He II λ4686 imaging, Multi Object Spectroscopy of 198 sources was carried out, revealing 132 objects containing bona-fide Wolf-Rayet features. From this sample, an exceptional W-R content of $\sim$1030 is inferred, with N(WC)/N(WN)$\sim$1.3, continuing the trend to larger values at higher metallicity amongst Local Group galaxies. More dramatic is the dominance of late-type WC stars in M 83 with N(WC8–9)/N(WC4–7)=9 which we attribute to the sensitivity of the classification line C III λ5696 to mass-loss, providing the strength of WC winds scale with metallicity. One young massive compact cluster, #74 in our catalogue, hosts 20% of the entire galactic population, namely $\sim$180 late WC stars and $\sim$50 late WN stars.

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Free-Free Spectral Energy Distributions of Hierarchically Clumped HII Regions

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In an effort to understand unusual power-law spectral slopes observed in some hypercompact HII regions, we consider the radio continuum energy distribution from an ensemble of spherical clumps. An analytic expression for the free-free emission from a single spherical clump is derived. The radio continuum slope (with $F_\nu \propto \nu^\alpha$) is governed by the population of clump optical depths $N(\tau)$, such that (a) at frequencies where all clumps are thick, a continuum slope of $+2$ is found, (b) at frequencies where all clumps are optically thin, a flattened slope of -0.11 is found, and (c) at intermediate frequencies, a

power-law segment of significant bandwidth with slopes between these two limiting values can result. For the ensemble distribution, we adopt a power-law distribution $N(\tau) \propto \tau^{-\gamma}$, and find that significant power-law segments in the SED with slopes from +2 to −0.11 result only for a relatively restricted range of γ values of 1 to 2. Further, a greater range of clump optical depths for this distribution leads to a wider bandwidth over which the intermediate power-law segment exists. The model is applied to the source W49N-B2 with an observed slope of $\alpha \approx +0.9$, but that may be turning over to become optically thin around 2 mm. An adequate fit is found in which most clumps are optically thin and there is little "shadowing" of rearward clumps by foreground clumps (i.e., the geometrical covering factor $C \ll 1$). The primary insight gained from our study is that in the Rayleigh-Jeans limit for the Planck function that applies for the radio band, it is the distribution in optical depth of the clump population that is solely responsible for setting the continuum shape, with variations in the size and temperature of clumps serving to modulate the level of free-free emission.

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Resolving OB Systems in the Carina Nebula with Hubble Space Telescope's Fine Guidance Sensor

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We observed 23 OB stars in the Carina Nebula (NGC 3372) with the *Hubble Space Telescope's* Fine Guidance Sensor 1r (FGS1r) in its high angular resolution mode. Five of these OB stars are newly resolved binaries with projected separations ranging from $0\farcs015$ to $0\farcs352$ (37 to 880 AU at a distance of 2.5 kpc), and V-band magnitude differences ranging from 0.9 to 2.8. The most important astrophysical result is the unexpected resolution of the prototype O2 If* star HD 93129A as a 55 milliarcsec double with a Δm_V of 0.9. This object has served as a spectroscopic benchmark for the analysis of the most massive hot stars and their winds on the prior assumption that it is a single star. This discovery supports the interpretation of recent radio and X-ray observations as evidence of colliding wind phenomena in HD 93129A. Another interesting result is the determination of an upper limit of about 35 AU for the projected separation of the binary pairs in the hierarchical double spectroscopic binary HD 93206. The high incidence of resolved binaries provides motivation for a more thorough, statistically meaningful study of multiplicity among the most massive stars in the young ionizing clusters of the nebula to obtain a complete sample of the long-period systems that have evaded spectroscopic detection. However, considering that the 9 spectroscopic binaries with accurate orbits in the Carina Nebula have orbital dimensions $\lesssim$1 AU, which at a distance of 2.5 kpc subtends an angle of only 0.4 mas, well below the $\simeq$ 10 mas angular resolution of FGS1r, there remains a significant range of orbital periods & separations over which it is very difficult to detect multiplicity in the nebula with currently available instruments.

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Large-scale wind structures in OB supergiants: a search for rotationally modulated Hα variability

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We present the results of a long-term monitoring campaign of the Hα line in a sample of bright OB-supergiants (O7.5–B9) that aims at detecting rotationally modulated changes potentially related to the existence of large-scale wind structures. A total of 22 objects were monitored during 36 nights spread over 6 months in 2001–2002. Coordinated broad-band photometric observations were also obtained for some targets. Conspicuous evidence for variability in Hα is found for the stars displaying a feature contaminated by wind emission. Most changes take place on a daily time-scale, although hourly variations are also occasionally detected. Convincing evidence for a cyclical pattern of variability in Hα has been found in 2 stars: HD 14134 and HD 42087 (periodic signals are also detected in other stars, but independent confirmation is required). Rotational modulation is suggested from the similarity between the observed recurrence time-scales (in the range 13–25 days) and estimated periods of stellar rotation. We call attention to the atypical case of HD 14134 which exhibits a clear 12.8-d periodicity both in the photometric and in the spectroscopic data sets. This places this object among a handful of early-type stars where one may observe a clear link between extended wind structures and photospheric disturbances. Further modelling may test the hypothesis that azimuthally-extended wind streams are responsible for the patterns of spectral variability in our target stars.

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Wolf-Rayet Stars in M 33. I: Optical Spectroscopy using CFHT-MOS

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We have obtained spectroscopy of a large sample of Wolf-Rayet stars in M 33 with CFHT-MOS, including 26 WC stars, 15 WN stars plus a WN/C star. In general, spectral types are merely refined, although the spectral type of X9 from Massey & Johnson is revised from WNL?+abs to WC4+abs,

whilst their G1 and C21 candidates are not confirmed as Wolf-Rayet stars. We also re-examine the metallicity gradient of M 33 from H II regions and identify the present sample, lying in the inner disk, with 8.6≤ log(O/H)≤8.9. Spectral types are in accord with similar regions in the Milky Way. Our large sample has allowed us to examine the claimed anti-correlation between WC line widths and galactocentric distance by Schild et al. We find a much larger scatter, though there remains an absence of broad-line WC stars in the inner disk and narrow-line WC stars in the outer galaxy.

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Metallicity and the spectral energy distribution and spectral types of dwarf O-stars

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We present a systematic study of the effect of metallicity on the stellar spectral energy distribution (SED) of O main sequence (dwarf) stars, focussing on the hydrogen and helium ionizing continua, and on the optical and near-IR lines used for spectral classification. The spectra are based on non-LTE line blanketed atmosphere models with stellar winds calculated using the CMFGEN code of Hillier & Miller (1998). We draw the following conclusions. First, we find that the total number of Lyman photons emitted is almost independent of line blanketing effects and metallicity for a given effective temperature. This is because the flux that is blocked by the forest of metal lines at $\lambda < 600$ Å is redistributed mainly within the Lyman continuum. Second, the spectral type, as defined by the ratio of the equivalent widths of He I λ4471 and He II λ4542, is shown to depend noticeably on the microturbulent velocity in the atmosphere, on metallicity and, within the luminosity class of dwarfs, on gravity. Third, we confirm the decrease in $T_{\rm eff}$ for a given spectral type due to the inclusion of line blanketing recently found by e.g. Martins et al. 2002. Finally, we find that the SED below ~ 450 Å is highly dependent on metallicity. This is reflected in the behaviour of nebular fine-structure line ratios such as [Ne III]/[Ne II] 15.5/12.8 and [Ar III]/[Ar II] 9.0/7.0 μm. This dependence complicates the use of these nebular ratios as diagnostic tools for the effective temperature determination of the ionizing stars in H II regions and for age dating of starburst regions in galaxies.

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Photospheric and stellar wind variability in ϵ Ori (B0 Ia)

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We provide direct observational evidence for a link between photospheric activity and perturbations in the dense inner-most stellar wind regions of the B supergiant star ϵ Ori. The results, which are relevant to our understanding of the origin of wind structure, are based on a multi-spectral line analysis of optical time-series data secured in 1998 using the HEROS spectrograph on the ESO Dutch 0.9-m telescope in La Silla. A period of $\sim$ 1.9-days is consistently identified in Balmer, He I absorption, and weak metal lines such as Si III and C II. The primary characteristic is a large-amplitude swaying of the central absorption trough of the line, with differential velocities in lines formed at varying depths in the atmosphere. The variance resulting from the 'S-wave' velocity behaviour of the lines is constrained within $\pm$ the projected rotation velocity ($\sim$ 80 km s^{-1}) in the weakest absorption lines, but extends blue-ward to over -200 km s^{-1} in Hα. A second (superimposed) 1.9-day signal is present at more extended blue-ward velocities (to ~ -300 km s^{-1}) in lines containing stronger circumstellar components. Inspection of archival optical data from 1996 provides evidence that this modulation signal has persisted for at least 2.5 years. Non-radial pulsational modelling is carried out in an attempt to reproduce the key observational characteristics of the line profile variability. Only limited success is obtained with prograde (m=-1) modes. The principal S-wave pattern cannot be matched by these models and remains enigmatic.

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Discovery of a WO star in the Scutum-Crux arm of the inner Galaxy

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We report the discovery of only the fourth massive WO star to be found in the Milky Way, and only the seventh identified within the Local Group. This has resulted from the first observations made in a programme of follow-up spectroscopy of candidate emission line stars from the AAO/UK Schmidt Southern Galactic Plane Hα Survey. The optical spectrum of this star, to become WR 93b in the Catalogue of Galactic Wolf-Rayet stars, is presented and described. WR 93b is classified as WO3 and is shown to be highly reddened ($E_{B-V} = 2.1 \pm 0.1$). A recombination line analysis of the emission lines yields the abundance ratios C/He = 0.95 and O/He = 0.13 (by number). Comparisons at near infrared wavelengths of reddening corrected photometry between WR 93b and both of Sand 2 (WO3, D = 49 kpc) and Sand 5 (WO2, D = 1.75 kpc) yields a consistent distance to WR 93b of 3.4 kpc. Positioned at Galactic co-ordinates $\ell = 353.27^{\circ}$, $b = -0.85^{\circ}$, the star is most likely located in the Scutum-Crux Arm of the inner Milky Way. We note that none of the four Galactic WO stars lies significantly beyond the Solar Circle (with two well inside).

Estimation of the wind terminal velocity in WR 93b at 5750 km s^{-1} makes this star the current wind speed record holder among all non-degenerate stars.

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Maximum mass-loss rates of line-driven winds of massive stars: the effect of rotation and an application to η Carinae

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We investigate the effect of rotation on the maximum mass-loss rate due to an optically-thin radiatively-driven wind according to a formalism which takes into account the possible presence of any instability at the base of the wind that might increase the mass-loss rate. We include the Von Zeipel effect and the oblateness of the star in our calculations. We determine the maximum surface-integrated mass that can be lost from a star by line driving as a function of rotation for a number of relevant stellar models of massive OB stars with luminosities in the range of $5.0 < \log(L/L_{\odot}) < 6.0$. We also determine the corresponding maximum loss of angular momentum. We find that rotation increases the maximum mass-loss rate by a moderate factor for stars far from the Eddington limit as long as the ratio of equatorial to critical velocity remains below 0.7. For higher ratios, however, the temperature, flux and Eddington factor distributions change considerably over the stellar surface such that extreme mass loss is induced. Stars close to the Eddington-Gamma limit suffer extreme mass loss already for a low equatorial rotation velocity. We compare the maximum mass-loss rates as a function of rotation velocity with other predicted relations available in the literature which do not take into account possible instabilities at the stellar surface and we find that the inclusion thereof leads to extreme mass loss at much lower rotation rates. We present a scaling law to predict maximum mass-loss rates. Finally, we provide a mass-loss model for the LBV η Carinae that is able to explain the large observed current mass-loss rate of $\sim 10^{-3}\,M_{\odot}\,\mathrm{yr}^{-1}$ but that leads to too low wind velocities compared to those derived from observations.

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Stellar populations associated with the LMC Papillon Nebula

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We study the Large Magellanic Cloud Papillon Nebula (N 159-5), a conspicuous High Excitation Blob (HEB) lying in the star forming complex N 159. Using *JHK* near-infrared photometry obtained at the ESO VLT with the ISAAC camera, we examine the stellar populations associated with the Papillon, tracing their history using stellar evolution models. Two populations are revealed: one composed of young, massive stars with an age $\sim$ 3 Myr, and a second consisting of older lower mass stars of age spreading between 1 and 10 Gyr. We analyze the properties of those populations and discuss their significance in the context of N 159. We also estimate that if the star at the center of the Papillon is single its initial mass is $\sim 50\,M_{\odot}$ and it is affected by an extinction $A_V \sim 7$ mag.

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Broad Radio Recombination Lines from Hypercompact H II Regions

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The H92α recombination line was observed toward six massive star formation regions (MSFRs) and the H76α line was observed toward one MSFR. All seven MSFRs were suspected of harboring hypercompact (HC) H II regions. The goal was to detect broad-line sources and to investigate their properties. The sources were selected according to their small sizes, high brightness temperatures, and rising continuum spectra (typical spectral index $\alpha \sim +1$, $S_\nu \propto \nu^\alpha$) at centimeter wavelengths. Two of the HC H II candidates, G25.5+0.2 and NGC 7538 (IRS 1), were previously known to have extremely broad lines (line widths of 160 and 180 km s^{-1}, respectively).

Sixteen separate, compact, radio continuum components were detected, fourteen of which were detected in either the H92α or H76α line. Eight sources have line widths (FWHMs) greater than 40 km s^{-1}; typical ultracompact (UC) H II region line widths are 25-30 km s^{-1}. These broad lines may be produced by a combination of thermal, turbulent, electron impact broadening, and large scale motions (rotation, expansion, jets, shocks, inflow, disk, etc.). On the basis of one line and a relatively low spatial resolution, we are unable to determine the relative contributions from each mechanism.

All the MSFRs in the current sample are composed of two or more continuum components. The large projected separations between the continuum components within a given MSFR indicate that they are unlikely to be gravitationally bound massive protostars.

Possible origins of the observed intermediate sloped power-law spectral energy distributions (SEDs) are discussed. It is suggested that hierarchal clumping in HC H II regions (Ignace and Churchwell 2004) may produce the observed power-law SEDs.

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The Hanle Effect as a Diagnostic of Magnetic Fields in Stellar Envelopes IV. Application to Polarized P Cygni Wind Lines

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The Hanle effect has been proposed as a new diagnostic of circumstellar magnetic fields for early-type stars, for which it is sensitive to field strengths in the 1-300 G range. In this paper we compute the polarized P-Cygni line profiles that result from the Hanle effect. For modeling the polarization, we employ a variant of the "last scattering approximation". For cases in which the Sobolev optical depths are greater than unity, the emergent line intensity is assumed to be unpolarized; while for smaller optical depths, the Stokes source functions for the Hanle effect with optically thin line scattering are used. For a typical P Cygni line, the polarized emission forms in the outer wind, because the Sobolev optical depth is large at the inner wind. For low surface field strengths, weak P Cygni lines are needed to measure the circumstellar field. For high values of the surface fields, both the Zeeman and Hanle diagnostics can be used, with the Zeeman effect probing the photospheric magnetic fields, and the Hanle effect measuring the magnetic field in the wind flow. Polarized line profiles are calculated for a self-consistent structure of the flow and the magnetic geometry based on the WCFields model, which is applicable to slowly rotating stellar winds with magnetic fields drawn out by the gas flow. For surface fields of a few hundred Gauss, we find that the Hanle effect can produce line polarizations at the level of a few tenths of a percent up to a 1–2%.

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X-ray emission lines from inhomogeneous stellar winds

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It is commonly adopted that X-rays from O stars are produced deep inside the stellar wind, and transported outwards through the bulk of the expanding matter which attenuates the radiation and affects the shape of emission line profiles. The ability of the X-ray observatories Chandra and XMM-Newton to resolve these lines spectroscopically provided a stringent test for the theory of the X-ray production. It turned out that none of the existing models was able to fit the observations consistently. The possible caveat of these models was the underlying assumption of a smooth stellar wind. Motivated by the various evidences that the stellar winds are in fact structured, we present a 2-D numerical model of a stochastic, inhomogeneous wind. Small parcels of hot, X-ray emitting gas are permeated with cool, absorbing wind material which is compressed into thin shell fragments. Wind fragmentation alters the radiative transfer drastically, compared to homogeneous models of the same mass-loss rate. X-rays produced deep inside the wind, which would be totally absorbed in a homogeneous flow, can effectively escape from a fragmented wind. The wind absorption becomes wavelength independent if the individual fragments are optically thick. The X-ray line profiles are flat-topped in the blue part and decline steeply in the red part for the winds with short acceleration zone. For the winds where the acceleration extends over significant distances, the lines can appear nearly symmetric and only slightly blueshifted, in contrast to the skewed, triangular line profiles typically obtained from homogeneous wind models of high optical depth. We show that profiles from a fragmented wind model can reproduce the observed line profiles from ζ Orionis. The present numerical modeling confirms the results from a previous study, where we derived analytical formulae from a statistical treatment.

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In Proceedings

The Local Group as an Astrophysical Laboratory for Massive Star Feedback

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The feedback effects of massive stars on their galactic and intergalactic environments can dominate evolutionary processes in galaxies and affect cosmic structure in the Universe. Only the Local Group offers the spatial resolution to quantitatively study feedback processes on a variety of scales. Lyman continuum radiation from hot, luminous stars ionizes H II regions and is believed to dominate production of the warm component of the interstellar medium (ISM). Some of this radiation apparently escapes from galaxies into the intergalactic environment. Supernovae and strong stellar winds generate shell structures such as supernova remnants, stellar wind bubbles, and superbubbles around OB associations. Hot (10^6 K) gas is generated within these shells, and is believed to be the origin of the hot component of the ISM. Superbubble activity thus is likely to dominate the ISM structure, kinematics, and phase balance in star-forming galaxies. Galactic superwinds in starburst galaxies enable the escape of mass, ionizing radiation, and heavy elements. Although many important issues remain to be resolved, there is little doubt that feedback processes plays a fundamental role in energy cycles on scales ranging from individual stars to cosmic structure. This contribution reviews studies of radiative and mechanical feedback in the Local Group.

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Multiwavelength Cross-Identifications of Stars. Application to Stellar Populations in the Magellanic Clouds and to Young Stars of our Galaxy.

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My thesis benefits from the recently released infrared and visible large surveys and takes place within the framework of the ongoing Virtual Observatory.

I built a Master Catalogue of stars towards the Magellanic Clouds (MC2) based on multiwavelength cross-identifications of the DENIS, 2MASS, GSC-II and UCAC point source catalogues. I derived important results on the astro-photometric accuracy and calibration of the cross-identified catalogues. The MC2 can be queried on-line through a dedicated web interface I designed to handle its composite nature. See http://vizier.u-strasbg.fr/MC2/. I produced multispectral views of the LMC where its various populations discriminate remarkably well in colour-colour and colour-magnitude diagrams based on both infrared and visible wavelengths. The MC2 provides an unprecedented basis for the study of stellar populations in the Magellanic Clouds and for further cross-identifications with catalogues at other wavelengths.

I calibrated the absolute magnitudes of the B-type stars in the near-infrared, as a function of their spectral types. I combined high quality Hipparcos-based distance measurements with homogeneous photometry from the near-infrared 2MASS point sources. I corrected the data from extinction effect and assessed by means of simulations the contribution of various measurement errors and physical effects (binarity, rotation) to the scatter observed in the calibration. It is a mandatory step towards the determination of the structure of the young Galactic disk and of the distances and properties of young open clusters revealed by large area infrared surveys such as 2MASS.

I started a morphological and multiwavelength analysis of ionized regions and their stars in the LMC, observed in narrow-band imaging. Massive stars and their reciprocal interaction with the surrounding interstellar medium enable to gain insight into the local star formation history and stellar contents of these regions and to obtain a sketch of their dynamical evolution.

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Conducted both at CDS, Strasbourg, France and ESO, Germany
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Also available from http://www.eso.org/~ndelmott/PhD/
and from http://tel.ccsd.cnrs.fr/documents/archives0/00/00/42/38/index.html

Probing the interactions of early-type stars with their surroundings through X-ray and optical observations

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This work is devoted to the study of the interactions of massive stars with their environment, either through their intense radiation fields or through their powerful stellar winds.

First, we have studied the close neighbourhood of the peculiar Of?p star HD108, i.e. its stellar wind and associated emissions. We have notably uncovered the important variations of the emission lines seen in the visible domain. At the same time, in contrast, the X-ray emission remained stable. To better understand the X-rays emitted by the star, we have developed a program for modelling the ionisation of the stellar wind, that enabled us to determine the absorption of this ionised wind in the X-ray domain. Our X-ray observations have then permitted us to discard several models proposed to explain the nature of the system, and we have discussed the remaining possibilities in the light of the behaviour of the two other Of?p stars, the possible "twins" of HD108. The wind modelling program was also used to study the properties, in the X-ray range, of the Wolf-Rayet star WR40: combined to the observations taken by XMM-Newton, we have shown that the non-detection of X-rays from this star can be explained by the very large opacity of its wind. The study of the ionisation of the surrounding gas by Wolf-Rayet stars was extended through the analysis of HeII nebulae. For the first time, high quality images of the highly excited regions surrounding Wolf-Rayet stars were taken and analysed, enabling to derive the extreme UV flux of these stars, and thus their temperature, from ground-based observations.

In addition to the ionisation by massive stars, the impact of their stellar winds was also considered in this work, especially the wind-blown structures called "bubbles". These bubbles arise from the action of the winds of massive stars, in isolation or in clusters, onto the interstellar medium. We first focused on the bubbles blown by isolated stars, and we started by the study of the high energy properties of the bubble blown by WR40. Thanks to XMM-Newton data, we showed that even the most recent theoretical models cannot account for the lack of X-ray emission of this bubble. To better understand the discrepancies between the theory and the observations of wind-blown bubbles, we then turned to the most simple structures, the ones blown by single main sequence massive stars. Several bubbles have been discovered in N11B, N180B, and N44, and their properties agree better with theoretical expectations than in the case of WR bubbles and superbubbles. Before our study, only a few interstellar bubbles were known: we showed that a simple morphological search was insufficient, and that kinematic studies were essential. In fact, the low-velocity expansion of these bubbles implies a weak compression of the gas, that can inhibit the morphological detection. Finally, we investigated the properties of the interaction of massive star clusters with their surroundings in the high-energy range. The clusters of N11 were observed in X-rays and UV thanks to the XMM-Newton satellite: their differences or similarities appear clearly at these energies, and we note that the diffuse X-ray emission always exceeded the expected level. Moreover, a unique dataset composed of Chandra and XMM-Newton observations enabled us to study the largest star formation region of the Small Magellanic Cloud, NGC346. Notably, the X-ray emissions from the NGC346 cluster itself and from the peculiar WR binary system HD5980 were discovered and analysed in details.

Our work underlines the complementarity between the visible, UV and X-ray domains, and the necessity to have observatories on the ground as well as in space. It also illustrates the important contribution of multiwavelength datasets to the study of massive stars. These observations indeed play a crucial role in the determination of the properties of early-type stars but they also provide critical tests for theoretical models (present or future).

17 March 2004
Advisor : Dr Gregor Rauw
University : Institut d'Astrophysique et de Géophysique, Université de Liège (Belgium)

Jobs

Postdoctoral position on: Starbursts from the local Universe to high redshift

The Geneva Observatory in Geneva, Switzerland, announces the availability of a research position at the postdoctoral level, open to applicants of all nationalities.

The succesfull candidate will work on a project aimed at studying starbursts nearby, at intermediate redshift (z$\sim$2-3), or in the early Universe (z>7), involving multi-wavelength observations and/or theoretical modeling.The successfull applicant will in particular have access to ground-based observational data covering the optical to near-IR (including ESO/VLT data), and state-of-the-art modeling tools. He/she will mostly work in collaboration with Prof. Daniel Schaerer in Geneva.

The Geneva Observatory and the associated Laboratory of Astrophysics of the Swiss Federal Institute of Technology in Lausanne carry out observational, interpretative and theoretical research in the fields of extra-solar planets, stellar evolution, stellar physics, high energy astrophysics, galaxy evolution and dynamics, and observational cosmology.

The appointment will be for one to two years starting around October 1, 2004 (negotiable).

Qualified candidates are encouraged to send their application including a CV and publication list, description of research experience and interests, and contact information of three references preferably via email to the above address. All applications received by 1 May, 2004 will receive full consideration. Informal enquiries with Daniel Schaerer (daniel.schaerer@obs.unige.ch) are welcome.

Contact `daniel.schaerer@obs.unige.ch`
Related information also available from the URL
`http://obswww.unige.ch/sfr`

SAO Predoctoral Fellowships 2004

The Smithsonian Astrophysical Observatory announces the availability of predoctoral fellowships beginning in July 2004, designed to allow students from other institutions throughout the world to do all or part of their thesis research at SAO. A wide variety of research projects may be proposed, with about 200 SAO scientific staff available as research advisors. Facilities at SAO include the MMT, Magellan, and other optical and infrared telescopes; radio telescopes, including the Submillimeter Array being constructed on Mauna Kea, Hawaii; a large network of workstations; a number of specialized laboratories; an outstanding library system; and access to data from a wide range of space missions.

Further information on the program can be found at

http://cfa-www.harvard.edu/predoc/

Applicants can contact directly Smithsonian scientists in their areas of interest, or the Program Scientist at predoc@cfa.harvard.edu, to discuss possible research topics.

Applicants must be ready to begin dissertation research at the time of the award. Fellowships are awarded for one year at a time with possible renewal for up to three years, contingent upon funding. Stipends will be $24,600 for the coming year. Applications are due by 15 April 2004. Application forms can be found at the web address above, and should be completed and mailed to SAO. Electronic or fax submissions will not be accepted.

The CfA is an Equal Opportunity/Affirmative Action Employer where all qualified applicants receive consideration for employment without regard to race, creed, sex or national origin.

Meetings

Announcement for the Workshop on The Nature and Evolution of Disks around Hot Stars

To be held 2004 July 7, 8, and 9 in Johnson City, TN, at the Carnegie Hotel.

A reminder that the deadline for submission of abstracts is April 1st. The deadline for registration is May 1st (beyond which, a late fee will be assessed).

The website for the workshop has moved to:

www.etsu.edu/physics/astronomy/

where one can find information about the workshop (the Second Announcement), a registration form, a macro for submission of abstracts, and links for the Carnegie Hotel and surrounding area.

Please direct questions to the SOC/LOC via email to:

hotstars@etsu.edu