MSFR Research Training Network
Contributions from Strasbourg Observatory

This document presents the proposed contributions of Strasbourg Observatory to the MSFR Network. Motivation for being part of the RTN is very high, and the site offers an environment that is appropriate for the training of young scientists.

We apply for the status of a Node in the MSFR Network.

1 Applicants

Strasbourg Observatory staff members co-signing this proposal, in alphabetical order :

Agnès Acker Professor. acker@astro.u-strasbg.fr
WR stars, stellar winds, interactions between winds and ISM
Percentage of research time to be invested : **15%** (provisional retirement date 2006).

Christian Boily Assistant professor (maître de conférences). boily@astro.u-strasbg.fr.
Dynamics of young stellar clusters, effects of stellar evolution, of binaries and of the environment on the dynamical evolution. Percentage of research time to be invested : **20%**

Joachim Köppen . Associated professor (1/2 time in Strasbourg, 1/2 time in Kiel, Germany).
koppen@astro.u-strasbg.fr
Effects of star formation on chemical evolution of galaxies.
Percentage of research time to be invested : **15%**

Ariane Lançon . Assistant professor (maître de conférences). lancon@astro.u-strasbg.fr.
Red supergiants, interpretation of multi-wavelengths spectra of starburst galaxies.
Percentage of research time to be invested : **70%**

Christian Motch . Astronomer. motch@astro.u-strasbg.fr.
X-ray binaries, X-ray emission from galaxies, responsible for SSC Strasbourg, XMM, CHANDRA
Percentage of research time to be invested : **15%**

Manfred Pakull . Astronomer. pakull@astro.u-strasbg.fr.
X ray emission from the ISM and from point-sources in starburst galaxies, multi-wavelengths study of starbursts, XMM, CHANDRA; ionizing radiation from Wolf-Rayet stars
Percentage of research time to be invested : **70%**

2 Project Objectives

This section provides an abstract for each of the projects that will be worked on in the framework of the MSFR network.

Projects 1, 2 and 3 are our highest priorities. Detailed proposals are given for these three in a subsequent section. They will lead to PhD and post-doctoral fellowship applications.

2.1 X-ray sources in starburst galaxies

Starburst galaxies are strong sources of high energy photons emitted by the hot phase of the ISM and by individual sources such as supernova remnants, massive X-ray binaries and ultraluminous X-ray sources. The satellites Chandra, XMM and Integral have just started to allow us to explore this part of the emission spectrum in detail, and will continue to provide unprecedented data for almost a decade. The High Energy group of Strasbourg Observatory hosts a part of the XMM-Survey Science Center, and group members have started to receive data from personal science programs. Manfred Pakull leads a long term program on nearby starburst galaxies, which involves the interpretation of both X-ray observations and complementary observations at other wavelengths from the ground or from space. Clearly, this young and promising field of astrophysics is still in strong need of development and new trainees. Research on X-ray sources in starburst galaxies covers aspects of high energy astrophysics, the physics of the interstellar medium and the evolution of stellar populations. These topics are represented in part at Strasbourg Observatory, but progress will benefit from interactions with network partners such as the University of Goettingen, INAOE, etc.

2.2 Red supergiants and their use in the analysis of young stellar populations

Obscured starburst regions in galaxies are often observed at near-infrared wavelengths where, over a wide range of ages (typically 5-75 Myr at solar metallicity) red supergiants are the dominant source of light. The light of these stars is then used for purposes as various as age and metallicity evaluation or dynamical mass determination. Unfortunately, these stars are poorly understood. Current telescopes provide outstanding near-IR extragalactic data, and instruments are continuously being developed for this wavelength range. Today, it is our theoretical understanding rather than our observational capabilities that limit our interpretation of extragalactic starburst regions. Ariane Lançon and collaborators have started a detailed investigation of the effects of two sources of uncertainties: (i) spectra of red supergiants are not reproduced properly by current model atmospheres, (ii) effects of stellar rotation modify red supergiant evolutionary tracks significantly and tracks with rotation are only just becoming available. In order to make progress, it will be necessary to create links between theory groups specialised in stellar evolution (e.g. Geneva or Padova within the proposed RTN), population synthesis specialists (Strasbourg Observatory, IAP, Göttingen within the RTN), and theory groups specialised in stellar atmospheres (collaborators outside the RTN in Montpellier, Lyon, Hamburg, Heidelberg).

2.3 The dynamics of young stellar clusters

A significant fraction of the universal star formation occurs in star clusters. Today, star cluster systems are being studied in starbursts and in evolved environment. The link between these two types of cluster systems remains to be understood. Much of the evolution occurs in early time, as clusters free themselves from their birth environment. Christian Boily develops N-body simulations of young clusters. Among others, these studies have shown how mass loss due to the winds of massive stars affects the final mass of a stellar cluster, and that the existence of gradients in the gravitational potential of a cluster's environment induces cluster rotation and shortens evolutionary timescales. Today, the effects of stellar evolution, of stellar binaries, and of the environment must be taken into account more completely. The proposed RTN will in particular facilitate collaborations with groups specialised in the detailed processes of the formation of stars (IoA, Sheffield, St Andrews) and stellar evolution with mass loss (Geneva, Padova, Univ. Coll. London). Rapid development of hardware and software are critical in this field, and training is particularly important to avoid that the knowledge of code subtilities are lost between developers and users.

2.4 WR stars, stellar winds

The winds of massive stars deposit energy, momentum and material with modified chemical abundance ratios in the ISM. Using repeated high resolution spectroscopic observations, Agnès Acker and collaborators have recently discovered time-dependent substructure in the wind and evidence for turbulence in the surrounding nebulae of several WR stars. These features and their relation to the central star set new constraints on the mechanisms driving the winds and on the history of these winds. To exploit such data quantitatively, a larger sample of WR stars and ejected nebulae is being studied. The analysis of the results will require to establish new interactions with groups specialising in the evolution of massive stars (Geneva, Padova within the RTN), the theory of stellar winds (Geneva, Univ. Coll. London within the RTN) and the interaction between stellar winds and the ISM (Mexico within the RTN), as well as to maintain existing collaborations outside the proposed network (Univ. MacGill and Univ. of Montreal, Canada; Astrophysical Instit. of Torun, Poland).

M. W. Pakull maintains a deep interest on ionizing radiation from WR stars (in particular in the He^{++} Lyman continuum) and from stellar populations in starburst galaxies.

2.5 Massive star formation and chemical evolution

Massive stars - whether formed in a quiescent mode or as part of starbursts - have a profound impact on the chemical and dynamical evolution of the gas in galaxies. Current modeling of the evolution of galaxies with chemodynamical and SPH/N-body codes incorporate detailed physical descriptions of the gas/star interactions, and are successful in reproducing many observational features. However, the large computational effort necessary does not facilitate a satisfactory understanding of how the results depend on the physical parameters or on the approximations mandatory for the descriptions of the local physics. Joachim Köppen has been employing suitably simplified models to identify essential modes of evolution in the gas/star interactions, showing e.g. that chemodynamical models always evolve with self-regulated star formation. These studies are now being extended incorporating the global dynamics of the gas and stars. This is expected to shed light in particular on which process is responsable for radial abundance gradients in elliptical and spiral galaxies. The RTN would facilitate existing and envisaged collaborations with groups working on chemical and dynamic evolution models (Kiel, Bonn, Goettingen, Trieste, Bologna).

3 Research projects for PhD students and postdoctoral fellows

3.1 X-ray emission in regions of violent star formation

Thanks to the new generation of X-ray observatories which now provide high spatial resolution (1 arc s, Chandra) and unprecedented sensitivity (XMM/Newton), the study of high energy phenomena in normal and in starburst galaxies have become a major instrument to understand the physics and evolution of violently star forming regions. Starburst galaxies can be spectacular X-ray emitters, since the star burst activity results in luminous X-ray emission from individual X-ray sources and from hot interstellar gas as well as from superwinds in the most extreme cases. It has recently been recognized that X-ray luminosity is indeed a very good tracer of star formation rate in these galaxies.

Moreover, the X ray luminosity function (XLF)of young massive X-ray binaries which account for more than 50% of the emission appears to be significantly skewed towards higher luminosities as compared to the Galactic or M 31 population. Some individual sources apparently emit 10^{40} erg/s surpassing the total high energy output of the Local Group of Galaxies ! Such values correspond to limiting Eddington luminosities for a compact object (presumably a black hole) of some 100 $M_{\odot}$, if we do not hypothesise strong beaming into our line of sight. One well-advertised suggestion to account for the ultraluminous X-ray sources (ULX) has therefore been the existence of "intermediate-mass black holes" bridging the gap between the stellar ($\leq$10 $M_{\odot}$) and the AGN-type variety.

In Strasbourg we have begun a long-term project of XMM/Newton and ground-based observations of star forming galaxies and of galacic OB associations with the aim to understand the physics and evolution of the X-ray source population - in particular the ULX - and to study the interaction of the hot X-ray emitting gas with the warm H_{α} emitting phase of the ISM. Among the early results (Pakull & Mirioni 2002, astro-ph/0202488; Pakull & Mirioni 2003, Rev.Mex.A.A. 15, 197) we mention the discovery of large (several hundred pc) shock-ionized bubbles around a significant fraction of ULX which are probably powered by a mildly relativistic wind reminiscent of the famous galactic jet source SS433 with its SNR-like cocoon W50. The total energy amount to some 10^{52} erg, i.e. more than ten times the kinetic energy injected by a typical SN. The detection of an X-ray ionized nebula around Holmberg II X-1 has moreover allowed to independently confirm from He IIλ4686 photon counting arguments (and CLOUDY photoionisation modeling) a total isotropic X-ray luminosity of at least 10^{40} erg/s, and thus to exclude significant beaming effects, at least for this source.

Another possibly decisive result of our study is the conclusion that metal-poor environments (like in the starforming dwarfs) are much more effective in creating ULX than the more metall-rich galaxies. We believe that the key for understanding the physics of these sources, i.e. the formation of massive black holes of some 50 $M_{\odot}$) lies in the reduced mass-loss history of metal-poor massive stars.

We are currently analysing our XMM/Newton observations and archival Chandra data of several nearby star foming galaxies. The sample includes I Zw 18, Holmberg II, Holmberg IX, NGC 4449, and NGC 7714. One early result is that previously claimed luminous hot superbubbles or outflows in many star forming dwarfs (like in I Zw 18 or VII Zw 403 and IC 2574) do not exist, and that the emission is in several cases rather dominated by one or a few ULX.

Our work on X-ray emission from non-AGN galaxies naturally leads to several possible research projects for PhD student and postdocs on the subject of the present Research Training Network. We concentrate on subjects that would mostly benefit from the know-how within and the infrastructure of the network.

1) The physics of ULX in starbursts: This project combines information collected from different wavelength (X-ray/optical/radio) and draws on new results of massive (binary) stellar evolution at different metallicities. The aim is understand the formation and mass-loss history of ULX that among others gives rise to the bubbles seen around several such sources including SS 433.

2) Hot gas in the halos of starburst galaxies: The aim of this project is to test current theoretical concepts of metal enrichment of the ISM and of the physics of superwinds that gives rise to the enrichement and heating of the intergalactic medium. Since most of the freshly synthesised elements are thought to be at coronal temperatures, X-ray observations are instrumental to understand the this feedback. Unfortunately, measuring metal abundances from medium-resolution CCD X-ray spectra is far from straight forward (differences by factors of 3 or higher have been reported in the literature) and needs to take into account temperature structure and a well-determined continuum free of contribution of possible point sources.

3) X-ray emission as a measure of star formation rate: This project would utilize the unique database of serendipitous XMM/Newton X-ray sources that is maintained by the Survey Science Center (XMM-SSC) with Strasbourg being one of the member institutes. One of the aims of the project would be to test whether X-ray luminosity being an trustworthy indicator of SFR.

Possible collaborations in the Network So far, there are few collaborations with scientists of the present Network. Also, not all institutes that will be part of the Network are known to us (also, Strasbourg has not yet appeared in the list). We expect that we can be more specific once a more list of collaborators/institutes becomes available.

Nevertheless, possible cooperations might well include the following:

- item 1 (ULX): Saclay, Genève, Göttingen, Meudon, Padova (UCL, Sheffield ?)
- item 2 (superwind): INAOE (Silich), Göttingen,
- item 3 (X-ray SFR): IAP, Göttingen, ...

3.2 Red supergiants in stellar populations

This project consists of two related parts. The first, main part, could be the subject of either a thesis or a post-doctoral experience; the second part crosses topics 2 and 3 summarized in Section 2 and would be preferentially offered to young scientists at the post-doc level.

Detailed description :

Starburst regions tend to be obscured by dust, which makes observations at optical or ultraviolet wavelengths difficult and explains the observed correlation between the star formation rate and the mid-infrared luminosities. The stellar populations of such starbursts are therefore most easily accessed at near-IR wavelengths. There, after a brief episode where recombination emission from HII regions is dominant (the first few Myr after the peak of star formation), red supergiants are the main contributors to the light.

Near-IR spectra of red supergiants are characterized by absorption bands of CO and CN (e.g. spectral library of Lançon & Wood 2000). While CN bands have not been exploited much, the CO bands around 2.3 mu have been used extensively. Their strength evolves with spectral type, and the dominant spectral type of a stellar population gives clues to the age and metallicity of the population. At the high spectral resolution now available on 10m class telescopes, the shapes of the CO bands can also be used to evaluated stellar velocity distributions. Based on these, dynamical masses of star clusters in starburst galaxies have been measured at distances of several tens of Mpc (e.g. Mengel et al. 2002). Other studies have used the CaII triplet around 8600 Å, a wavelength at which the contribution of blue stars to the light is significant but the red supergiants cannot be neglected (Smith & Gallagher 2001). When compared to the total light of the clusters, these dynamical masses constrain the stellar Initial Mass Function (IMF) : the current claim is that a top-heavy IMF is needed in regions of extreme star formation.

The use of red supergiants for the above-mentioned purposes is hampered by several fundamental uncertainties, that authors have (partly) mentioned without actually solving the problems. The quality of the starburst observations that are possible today makes it essential to look into these problems rapidly: the link between observation and theory, rather than observational capabilities, are the limiting factors in the interpretation.

Project part 1. The first difficulty lies in the stellar evolution tracks. Teams specialised in the computation of such tracks are co-proposers of this RTN. The proportion of red supergiants in a stellar population depends strongly on physical model assumptions, leading to large differences between the theoretical tracks produced by various groups. For instance, at solar metallicity the Geneva group predicts significantly cooler red supergiants than the Padova group. The predicted proportion of red supergiants with "standard" tracks also depends strongly on metallicity (e.g. Cerviño & Mas-Hesse 1994), but unfortunately with trends that are contradicted by star counts (Langer & Maeder 1995). As a consequence, the ages derived for young star clusters in starbursts are poorly determined, and in view of the strong age-dependence of mass-to-light ratios this invalidates constraints on the stellar IMF. One solution to this contradiction is the inclusion of stellar rotation in the computations, and this has been done by the Geneva group recently (Maeder & Meynet 2001). The relevance of these tracks to extragalactic populations now has to be assessed more extensively, and the new tracks must be included in the population synthesis codes to reevaluated constraints on the IMF.

The second difficulty is the definition of a proper library of stellar spectra, and the association between a point on a theoretical evolutionary track and one of these spectra. Stellar atmosphere models are needed for this association. Today, several groups are developing specific models for cool stars (the most widely known are PHOENIX by P. Hauschildt and F. Allard, NMARCS by B. Gustafsson and B. Plez, the Heidelberg models of M. Scholz). The trouble is, none of these actually reproduces the optical+near-IR spectra of red supergiants accurately enough. We have started collaborations with these groups, in order to identify the origin of the discrepancies and improve the situation. One important task is to compare observed spectra with models that adopt more realistic surface abundances : even if scaled solar abundances were a reasonable assumption at the formation of a star on the main sequence, nucleosynthesis and mixing (due to convection or global flows associated with stellar rotation) will have modified the abundance ratios by the time a star becomes a red supergiant. Surface abundance ratios are given by evolutionary tracks, which, as already mentioned, are computed by groups within the proposed RTN (e.g. Geneva, Padova).

Project part 2.

Finally, this project includes a local collaboration between A. Lancon & C. Boily. Red supergiants are always among the most massive stars present in a young star cluster. Due to various phenomena that induce mass segregation within clusters, their velocity distribution is unlikely to be representative of the star cluster as a whole. In addition, these young clusters may not be at equilibrium, because of the mass loss due to stellar winds. Detailed N-body simulations that include a distribution of stellar masses are necessary to evaluate the resulting biases in cluster mass determinations quantitatively. This aspect of the red supergiant project can be studied within about a year, provided the participants are familiar with up-to-date N-body simulations. It would therefore be tackled best at the post-doctoral level.

Main publications of the Strasbourg group related to the above topic:

• **Boily**, Kroupa 2003, MNRAS 338, 665 and 338, 673: *The impact of mass loss on star cluster formation. I. Analytical results. II. Numerical N-body integration.*
• Kroupa & **Boily** 2002, MNRAS 336, 1188: *On the mass function of star clusters.*
• **Lançon** & Rocca-Volmerange 1996, New Astronomy 1, 215 : *Near-IR spectral evolution of dusty starburst galaxies.*
• **Lançon**, Mouhcine, Fioc, Silva 1999, A&A 344, L21: *How to search for AGB stars in near-IR post-starburst spectra.*
• **Lançon** & Wood 2000, A&AS 146, 217: *A library of 0.5-2.5 micron spectra of luminous cool stars.*
• **Lançon**, Goldader, Leitherer, Gonzalez-Delgado 2001: *Multiwavelength study of the starburst galaxy NGC 7714. II. The balance between young, intermediate-age and old stars.*
• Mouhcine, **Lançon** 2002, A&A 393, 149: *The modelling of intermediate age stellar populations. I. Near-infrared properties.*

Other references cited above (RTN proposers of other laboratories are highlighted)

• **Cerviño** & Mas-Hesse 1994, A&A 284, 749: *Metallicity effects in star-forming regions.*
• Langer & **Maeder** 1995, A&A 295, 685: *The problem of the blue-to-red supergiant ratio in galaxies.*
• **Maeder** & **Meynet** 2001, A&A 373, 555: *Stellar evolution with rotation. VII. Low metallicity models and the blue to red supergiant ratio in the SMC.*
• Mengel, Lehnert, Thatte, Genzel 2002, A&A 383, 137: *Dynamical masses of young star clusters in NGC 4038/4039.*
• **Smith** & Gallagher 2001, MNRAS 326, 1027: *M82-F: a doomed super star cluster.*

4 Strasbourg as a host for network trainees

4.1 Environment

The Strasbourg Observatory is a laboratory of the Louis Pasteur University, one of the largest science-oriented universities in France. Together with Universite Robert Schumann, Universite Marc Bloch and the International Space University, this provides for a lively environment for young researchers.

Université Louis Pasteur and associated organisations provide welcoming facilities for foreign visitors (e.g. Association Alfred Kastler) and PhD students (e.g. Association Bernard Gregory). Language courses are available on campus. By setting up a "College Doctoral Europeen", that among others provides a framework for preparing European PhDs (since 1999), the University has developed a significant experience in related international matters.

The Observatory itself offers the preparation of a Masters degree in astrophysics. Local PhD students are then encouraged to extend their knowledge by attending classes on astrophysical research topics, that are designed specifically for them. In addition, they are invited to attend the weekly astronomy research seminar, and to participate in the Observatory life (journal clubs, organisation of workshops).

4.2 Astrophysical Research

Strasbourg Observatory hosts 20 staff astronomers from the three main french research organisations (CNRS, CNAP, University).

Research activities are organised within four teams:
– High Energy Astrophysics (Includes a branch of the XMM satellite Survey Science Centre)
– The physics and evolution of galaxies
– Stellar physics
– The development of astrophysical databases (Centre de Donnees de Strasbourg, partner of the European Virtual Observatory project).

These themes provide a broad background of expertise in theory, simulation, statistics and observations.

4.3 Hardware

The Observatory members, be they staff members or students, enjoy access to parallel computers at Louis Pasteur University. Time at the IDRIS national facility has also been obtained. But more importantly, local computing capabilities have recently been improved. The Galaxy group has set up a cluster of 12 dual-processor machines. The four fastest nodes of the cluster can for example host codes such as the N-body code NBODY6++ (used and developed by C. Boily, cf. science proposal) in production mode (1 Gb/s ethernet link), while the other 8 are adequate for software development and collisionless dynamics. Other Observatory groups have acquired specific machines around the XMM project, hydrodynamical simulation projects and the CDS services.

4.4 Management experience at Strasbourg Observatory

The Observatory has a large experience in the participation in or the management of large collaborations, for instance through the CDS (Centre de Données de Strasbourg) and through the XMM Survey Science Centre.

It has been signed several european contracts over the last few years, and administrated the ressources thus obtained. Examples include:

– PLATON, a RTN network in the field of solar physics, funded within FP5
– The organisation of a european school on the GAIA project
– OPTICON, a european network for developments in astronomical databases
– AVO, the european Virtual Observatory project

Expertise is thus available in scientific organisation and in administrative management.