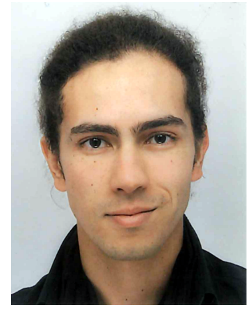
CONCOURS ASTRONOME-ADJOINT 2017 – FICHE RÉCAPITULATIVE



NOM, Prénom : EL MELLAH, Ileyk
Date de naissance : 5 Avril 1989
Nombre de candidatures antérieures : 0
Interruption(s) d'activité(s) : -
Établissement et équipe d'accueil demandés :
Observatoire de Paris | Laboratoire de l'Univers et des ses Théories
Equipe *Phénomènes aux Hautes Energies*

Post-doctorats et situation actuelle :
Mai 2017 - Juin 2020 | Bourse FWO [Pegasus]^2 Marie Skłodowska-Curie | 3 ans | KU Leuven
Octobre 2016 - Mai2017 | Contrat postdoctoral | 8 mois | KU Leuven

Thèse : *Wind accretion onto compact objects*, supervisé par Fabien Casse & Andrea Goldwurm au laboratoire AstroParticule & Cosmologie de Paris 7 (équipe *Astrophysique des hautes énergies*). Soutenance le 7 Septembre 2016 (après 3 ans).

Thèmes des recherches effectuées : Stellar remnant : neutron star (NS), black hole (BH), white dwarf (WD) - Accretion : Roche lobe overflow, wind accretion - Binary system : X-ray binary (XB), Cataclysmic variable (CV) - Stellar outflow : line-driven wind

Méthodologies : Théorie – Modélisation – Simulations

Tâches de service effectuées et/ou envisagées :
ANO5 Centres de traitement, d'archivage et de diffusion de données - Eric Slezak - Development of web application frameworks to provide the community with interactive visualization tools of complex data sets, issued either from observations or numerical simulations.

Enseignements effectués :

2016-17	Computational methods for Astrophysics	60h TD	5th year	KU Leuven
2014-16	Classical Mechanics	128h TD	1st year	Paris 7
2013	Physics for Medical studies	32h TD	1st year	Paris 7
2013	Deterministic systems and signals	32h TP	4th year	Paris 7
2009-10	Teaching assistant	16h CM-TP	high school Gustave Eiffel	

Résultats principaux :
2017: impact of inhomogeneities in the wind of Supergiant (Sg) stars on the time-variability of accretion and absorption in SgXB. Confrontation to observations of Vela X-1 with Chandra. 2016: orbital shearing of the stellar wind in SgXB and formation of wind-capture discs. 2015: accretion of a supersonic planar uniform flow by a compact object (structure of the bow shock, quantification of the mass accretion rate, topology of the inner sonic surface).

Programme de recherche : 1. Evaluation of the impact of the magnetic field of the NS or WD on the innermost regions of the accreted flow in SgXB and CV. Synthetic observations and confrontation to observations of Vela X-1 and to the intermediate polar CV V4743 Sgr. 2. Accretion of a low angular momentum flow onto a BH to determine whether there might be a disc-like structure lying near the last stable orbit. Comparisons to observations of Sgr A* by GRAVITY and the EHT, using the ray-tracing code GYOTO to produce synthetic observations.

Compétences acquises et points forts de votre candidature : Wide expertise in Computational Astrophysics. Improvements of `MPI-AMRVAC`, a finite volume code to numerically solve the equations of MHD, on an adaptive grid whose geometry can be adapted to the needs of a physical problem. I also gained experience in adjacent domains such as visualization, high performance computing, hardware, cluster and data management, profiling and code optimization.

Publications

Nombre de publications de rang A publiées et sous presse: 8

Nombre de publications de rang A soumises: 0

Nombre de communications et/ou de posters présentés à des conférences: 11

Autres (participation à des ouvrages, rapports techniques, codes, logiciels, sites web, etc...) :

2017 Radio show *Faconde* on scientific outreach (Radio Campus, Bruxelles)

2016 PhD manuscript

2015 Festival of Sciences (Paris 7) and 3D-printing of Roche potentials

2015 Personal webpage

2015 Website of the *Rencontres des Jeunes Physiciens 2015*

2015 Community manager of the *Rencontres des Jeunes Physiciens 2015*

2015 Wolfram demonstration *Trajectory of a Test Mass in a Roche Potential*

Liste des 5 publications de rang A, par ordre d'importance, qui illustrent le mieux votre travail et vos compétences (avec liens) :

[1] **El Mellah I.**, Sundqvist J. O. & Keppens R.
Accretion from a clumpy massive-star wind in Supergiant X-ray binaries (2017) - MNRAS

[2] **El Mellah I.** & Casse F.
A numerical simulations of axisymmetric hydrodynamical Bondi-Hoyle accretion on to a compact object (2015) - MNRAS

[3] **El Mellah I.** & Casse F.
A numerical investigation of wind accretion in persistent Supergiant X-ray Binaries I - Structure of the flow at the orbital scale (2016) - MNRAS

[4] Grinberg V., Hell N., **El Mellah I.**, Neilsen J., Sander A. A. C., Leutenegger M. A., Fürst F., Huenemoerder D. P., Kretschmar P., Kühnel M., Martínez-Núñez S., Niu S., Pottschmidt K., Schulz N. S., Wilms J. & Nowak M. A.
The clumpy absorber in the high mass X-ray binary Vela X-1 (2017) - A&A

[5] Xia C., Teunissen J., **El Mellah I.**, Chané E. & Keppens R.
MPI-AMRVAC 2.0 for solar and astrophysical applications (2017) - ApJS

January 10th, 2018

To whom it may concern,

I am a [Pegasus]^2 Marie Skłodowska-Curie fellow in KU Leuven, at the Center for mathematical Plasma Astrophysics (CmPA), working in Computational Astrophysics with Rony Keppens. I joined the CmPA in October 2016 after defending my PhD on *Wind accretion onto compact objects*, under the supervision of Andrea Goldwurm and Fabien Casse. I apply to the position of *Astronome-adjoint* at the OSU Observatoire de Paris for I believe my profile could match the expected requirements and since it would be a valuable support to pursue and develop further my emerging academic career. I wish to be assigned to the ANO 5, *Centres de traitement, d'archivage et de diffusion de données*, in the SNO *Astronomie Astrophysique*.

After my undergraduate studies at the Ecole Normale Supérieure, I volunteered to join the Kepler satellite data analysis effort under Saul Rappaport's lead at MIT. There, I was introduced to stellar evolution and binary systems and took an active part in the discovery and characterization of the first disintegrating exoplanet in 2012. My involvement also contributed to the identification of 30 new triple star systems and to a detailed analysis of the shortest-period exoplanets, those right in the spotlight of their host star. This seminal long term experience in Research laid the foundations of my scientific program : a better understanding of stellar objects and remnants in interaction with their environment.

As I started my PhD, I turned to numerical tools to complement the analytical skills I had acquired during the previous years and model the turbulent twilight of binary systems, the X-ray binaries. I got familiar with advanced techniques such as solvers for hyperbolic partial differential equations and parallel computing, in the context of the finite volume MHD code `MPI-AMRVAC`. With several successful proposals on Tier-1 clusters and the code development I carried out, I could run the widest dynamics simulations of wind accretion onto compact objects.

By the end of my first postdoctoral year in KU Leuven, I was granted a 3-years [Pegasus]^2 Marie Skłodowska-Curie fellowship. I also joined an ISSI sponsored collaboration led by Silvia Martínez-Núñez (IFCA) and Peter Kretschmar (ESAC) to gather observers and theoreticians from the X-ray binaries and massive stars winds communities. It enabled me to design and confront simulations of the accretion process in Supergiant X-ray binaries to the most recent observations of Vela X-1. Thanks to Jon Sundqvist and collaborators' simulations of the internal shocks in the wind of isolated massive stars, we could evaluate the impact of the wind micro-structure on the time variability of the mass accretion rate onto the neutron star.

I am now willing to extend my investigations closer from the accretor, where most of the high energy emission we observe comes from. The expertise already available at the Observatoire de Paris in the domain of compact objects would be a decisive asset to pursue this goal. May you judge my application admissible, I remain fully available to bring further information you might need.

Sincerely,

Ileyk El Mellah

Ileyk El Mellah

http://homes.esat.kuleuven.be/~ileyk

Education

2013-16	**PhD supervised by Fabien Casse & Andrea Goldwurm on** ***Numerical simulations of wind accretion onto compact bodies*** AstroParticule & Cosmology laboratory (APC) - Univ. of Paris 7 Diderot
2012-13	**Master degree in Astrophysics** - Observatory of Paris Obtained with distinction
2010-12	**Normalien at the *Ecole Normale Supérieure* of Cachan**
2011-12	**Research internship and graduate courses** - MIT, Cambridge
2010-11	**French *Agrégation* of Physics & Chemistry** - ENS of Cachan, FR Rank : 2^{nd} in 1,409 candidates
2008-10	**Bachelor degree in Fundamental Physics** - ENS / Paris 6 University Obtained with honours
2006-08	**Preparatory classes to *Grandes Ecoles*** - Lycée Janson-de-Sailly, Paris

Research

Since 2016	**FWO [Pegasus]^2 Marie Skłodowska-Curie fellowship under the supervision of Rony Keppens** Center for mathematical Plasma Astrophysics - KU Leuven
2013-16	**PhD thesis supervised by Fabien Casse & Andrea Goldwurm on** ***Numerical simulations of wind accretion onto compact bodies*** APC - Univ. of Paris 7 Diderot
2011-12	**One-year internship supervised by Saul Rappaport on** ***Monitoring of close-in binary stars and short period exoplanets*** Data analysis and models of light curves from the Kepler satellite Kavli Institute for Astrophysics - MIT
Ap-Ag 2010	**Internship supervised by Jean-François Lestrade on** ***Gravitational perturbations of debris discs by a passing-by star*** LESIA - Paris Observatory
Jn-Jl 2009	**Internship supervised by Gérard Belmont & Patrick Robert on** ***Resampling of the CLUSTER satellites data*** Plasma Physics Laboratory - Vélizy

Communication

Oral contributions

Dc 2017	Radboud University Nijmegen - seminar
Nv 2017	ESAC Madrid - seminar
Sp 2017	Observatory of Paris - seminar
Sp 2017	KU Leuven - Frontiers of Astrophysical Modeling
Ag 2017	Köln - Numerical techniques in MHD simulations
Jl 2017	Paris - Journées de la SF2A
Mr 2017	Brussels Royal Observatory - CHARM meeting
Fb 2017	Stellar winds in massive X-ray binaries - ISSI workshop
Sp 2016	Arbatax - Super-Eddington accretion on compact objects
Sp 2016	Aarhus University - seminar
My 2016	Ecole des Houches - International school of Computational Astrophysics
Ap 2016	Paris 7 University - seminar
Ap 2016	KU Leuven - seminar
Oc 2015	AIM laboratory (CEA, Paris) - Computational Astrophysics meeting
Jn 2015	Toulouse - Journées de la SF2A
Mr 2015	Ecole des Houches - Turbulence, magnetic fields and self organization

Posters

Jn 2017	**Clumpy wind accretion in Supergiant X-ray binaries** EWASS - Prague
Dc 2015	**Numerical simulations of wind accretion onto compact objects** Texas symposium - Geneva
Nv 2014	**Numerical simulations of wind accretion undergoing flip-flop instability** IAP - Paris

Grants & awards

2017	**Computing time on the Tier-1 VSC cluster : 1 Mh·CPU**
2016	**3-years FWO [Pegasus]^2 Marie Skłodowska-Curie fellowship**
2016	**Computing time on the Tier-1 CINES cluster : 300 kh·CPU**
2015	**Computing time on the Tier-1 CINES cluster : 300 kh·CPU**
2013	**3-years PhD fellowship from the Ecole Normale Supérieure of Cachan**
2013	**3-years teaching assistant grant from the Université of Paris 7 Diderot**
2012	**1-week observing time at the Mont Mégantic Observatory (Canada)**
2011	**French *Agrégation* of Physics and Chemistry - Rank : 2nd / 1,409**
2010	**2-years fellowship from the ENS of Cachan as a *normalien***

Selected skills

Programming languages
Fortran, C, C++, **Python**, Idl, Java, Perl, XML, **Csh**, Bash, **HTML**, **CSS**, JavaScript, CoffeeScript, HTML5

Codes & softwares
MPI-AMRVAC, Mathematica, VisIt, Paraview, Vampir, VampirTrace, Atom, Emacs, Pyke, Inkscape, Gnuplot, DS9, XSPEC

Data analysis
Extended Fourier and wavelet analysis, resampling and interpolation of time/space series

Languages
French (native), English (fluent), Italian (B1)

Research

Because most stars belong to a multiple stellar system, stellar evolution in binary systems is a topic of prime importance to shed light both on the planets which orbit them and on the galaxies which host them. Stars do not only impact their surroundings when they perform thermonuclear fusion but also as stellar remnants, once the core has long shut down, especially when they are orbited by a close-by stellar companion. In this case, the interplay between the two bodies gives birth to spectacular phenomena which help us to understand the specificities of each body.

One of the most impressive possible outcomes of the evolution of binary systems are X-ray binaries. They host a compact object - a neutron star (NS) or a black hole (BH) - orbiting a stellar companion whose gas is accreted by the former and emits copious amounts of X-rays. Since the discovery of the first extrasolar X-ray source in the early sixties (Giacconi et al. 1962), continuous observations of these systems have revealed a broad range of spectral and photometric behaviors with a special emphasis on their incredible time variability : flares, hysteresis loops in hardness-luminosity diagrams, off-states, quasi-periodic oscillations... The core of my research activity has been to explore the possible origins of this time variability.

The observation of these systems is made possible thanks to satellites funded, designed and maintained by international collaborations. By the end of the next decade, the ESA Athena X-ray observatory will provide unprecedented insights on high energy phenomena taking place in X-ray binaries (scientific goals 8.3 and 8.4 and observatory scientific goals 3) but also in Active Galactic Nuclei. Meanwhile, the harvest of data being still obtained by predecessors like Chandra or XMM-Newton constantly enlarges the number of X-ray binaries identified. The diversity of behaviors observed requires a versatile though constraining set of models. Given the level of complexity of the Physics at stake in X-ray binaries, we need to supply the analytical approach with a complementary tool : high resolution numerical simulations of fluid dynamics, enabled by the surge in modern computational capacities. Supercomputers have been widely established in the research landscape for the last 15 years and now offer a brand new approach.

As a daily user and advocate of this new scientific method, I have learned how to tune numerical analogues of astrophysical objects, in close partnership with European observers. These models require specific efforts to accurately reproduce the phenomena we wish to investigate, and yield results which must be interpreted and checked with particular care. I describe in the present statement the conclusions derived during my research activity and how a position of Astronome-adjoint would enable me to extend my studies further.

Selected skills

On top of my academic education in Physics, my experience in research made me develop extended skills including but not limited to :

Astrophysics

- radiative hydrodynamics (HD) : line-driven winds, optically thin and thick cooling/heating
- magneto-HD (MHD) : magnetosphere of a degenerate star

Computational Fluid Dynamics

- hyperbolic partial differential equations : Riemnann solvers, slope limiters
- High Performance Computing (HPC) : parallelization, multithreading, Tier-1 clusters

Data analysis

- Python programming : NumPy, SciPy, pandas
- 3D data visualization softwares : VisIt, Paraview, Tecplot
- Graphical User Interface (GUI) : applets (with Wolfram language and Spyre framework)
- Fourier and wavelet data analysis

Code development

- advanced Fortran 2003 programming : procedure pointers
- Perl and bash scripting : pre-processors, serial job runs
- parallel code debugging : Allinea Forge's DDT
- parallel code profiling and optimization : VampirTrace
- interactive and responsive web design : HTML5, CSS and Javascript

Project management

- version control : GIT
- team time scheduling : Gantt charts

Research activity report

PhD research activity

During my PhD, I focused on mass transfer in binaries via wind accretion, the low angular momentum counterpart of the more comprehensively understood Roche lobe overflow (RLOF) mechanism. Supergiant X-ray binaries (SgXB), where a compact object (generally a NS) orbits an evolved O/B supergiant, are the ideal stage for wind accretion to occur. Indeed, the latter displays intense outflows, a fraction of which being captured by the NS. The rapid increase since the late 2000's in the number of SgXB (Walter et al. 2015) and the ambiguous status of the newly discovered Supergiant Fast X-ray Transients (SFXT, Negueruela et al. 2006) only increased the appeal of this burning topic.

In a first attempt to better understand the wind accretion process, I confronted the analytical prescriptions derived by Bondi, Hoyle and Lyttleton (BHL, Hoyle & Lyttleton 1939, Bondi & Hoyle 1944) to a more realistic HD representation of the flow. To do so, I used and developed the explicitely flux-conserving finite volume transport code `MPI-AMRVAC` (Xia et al. 2017). The new version I contributed to now addresses HD or magneto-HD (MHD) problems, in Cartesian, cylindrical or spherical geometry, with or without polytropic prescriptions, source terms, etc. For wind speeds similar to the ones observed in SgXB ($\sim$1,000km$\cdot$s^{-1}), the main challenge is the contrast between the scale at which the gravitational beaming of the fast inflow by the accretor becomes significant (the accretion radius) and the size of the compact accretor, typically 4 to 5 orders of magnitude smaller. Since most of the emitted light comes from the immediate vicinity of the accretor, it is important to follow the flow through these scales. To uniformly resolve the incoming planar flow, I implemented a radially stretched grid in a 2D spherical geometry. With suitable boundary conditions, I reached a numerically relaxed state and spanned the 5 required orders of magnitude thanks to the computing time I was granted on the CINES Tier-1 cluster (see Figure 1). In El Mellah & Casse (2015), we characterized the structure of the flow, which forms a stable detached bow shocked as it is beamed towards the wake of the accretor, and the dependence of the mass accretion rate on the Mach number of the inflow. For the first time, we monitored the flow deep enough to confirm the analytical prediction by Foglizzo & Ruffert (1997) concerning the topology of the inner sonic surface (where the shocked flow becomes supersonic again) which has to be anchored into the accretor.

In a realistic SgXB though, the incoming wind is not planar due to the orbital bending. It carries a non-zero angular momentum which could, in some cases, lead to the formation of a wind-capture disc. To identify the favorable configurations, I designed a model of supersonic line-driven wind propagation in SgXB, coupling the stellar, orbital, wind and accretion parameters (El Mellah & Casse 2016). I identified the minimal set of dimensionless degrees of freedom of the problem to optimally explore the space of parameters. This investigation showed how sheared and beamed the wind is when it enters the region around the accretor where the shock is expected to develop - i.e. where the ballistic assumption breaks up and where HD simulations similar to the ones above are required. The need to connect the orbital scale motion, essentially ballistic, and the accretion region, centered on the compact object, became apparent.

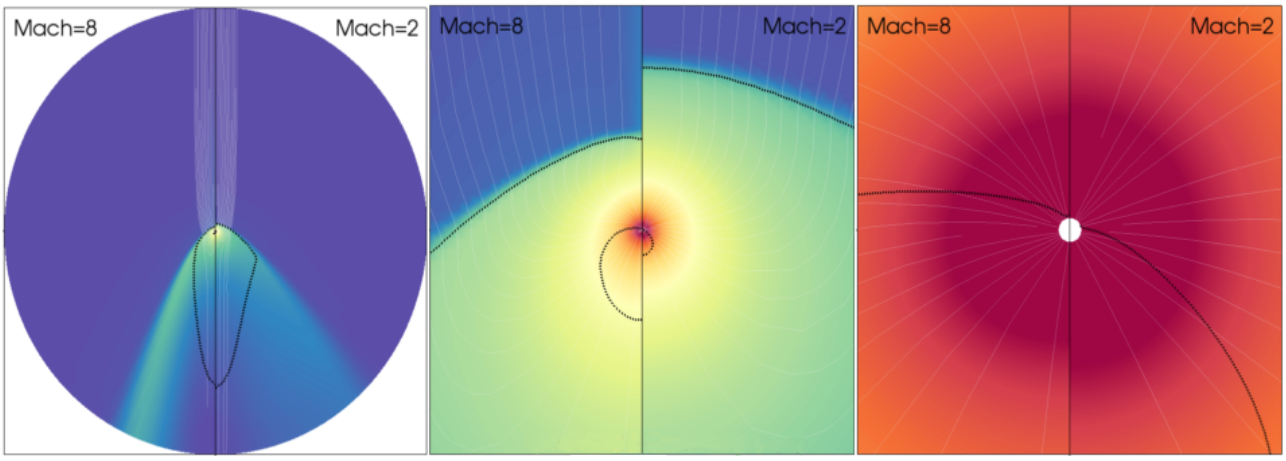


Figure 1: Successive zoom in on the innermost parts of a planar flow (coming from the top) being deflected by a central accretor for different Mach numbers at infinity. In white are represented the streamlines while the dotted black lines represent the Mach-1 surfaces. The colormap is logarithmic mass density.

Postdoctoral research activity

Since the beginning of my postdoctoral activity one year ago, I started to consider more realistic internal structure for the incoming wind in SgXB than the uniform flow I had worked with during my PhD. Indeed, the line-driven winds of massive stars are notoriously inhomogeneous, due to the line-deshadowing instability (Owocki & Rybicki 1984) which leads to the formation of internal shocks. The serendipituous accretion of these overdense regions, or clumps, has been suggested as a possible explanation to the time variability of the X-ray luminosity in SgXB, of the order of 100 peak-to-peak. Using a 2D pseudo-planar grid sampling a restricted angular region, Sundqvist et al. (2017) recently managed to compute the dimensions and shapes of the clumps, for an isolated massive stars. To evaluate the impact of clumps on the accretion process, I plunged a compact object in the wind ("CO" in the left panel in Figure 2), at different orbital separations, and injected the corresponding wind computed by Sundqvist et al. (2017) within the simulation space (right panel in Figure 2). By coupling the stretching of the mesh to the Adaptive Mesh Refinement (AMR) of `MPI-AMRVAC`, I could design 3D spherical setups spanning several orders of magnitude at an affordable computational cost and resolve small scale off-centered features like clumps injected from the upstream hemisphere. In El Mellah et al. (2017), we followed the clumps as they cross the shock and monitored the time variability at the inner border of the simulation space, corresponding approximately to the dimensions of the NS magnetosphere. With this work, we discovered how tempering the shock could be, which led to variations of the inner mass accretion rate an order of magnitude smaller than the observed variations of the X-ray luminosity in these systems. Thus, if the stochastic variations at low X-ray luminosity seem to match the variability induced by the clumps alone (see Figure 3), the high luminosity levels can only be reached due to other underlying mechanisms, possibly within the NS magnetosphere (e.g. the propeller effect, Bozzo

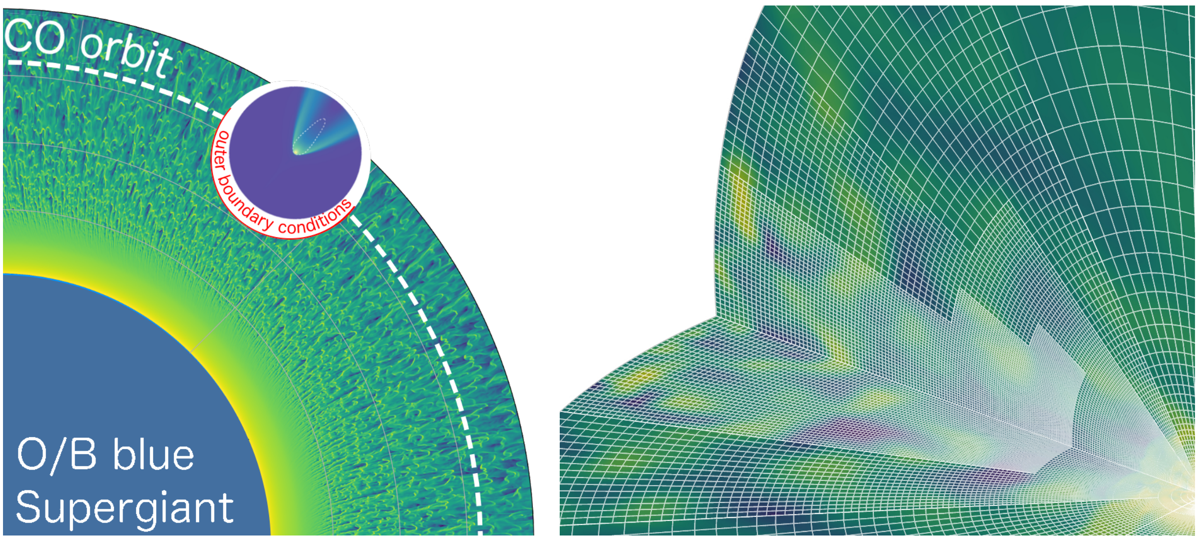


Figure 2: (*left*) Principle of the clumpy wind accretion simulations : we inject into the simulation space (upper right insert) a wind whose micro-structure has been computed out of radiative HD simulations by Sundqvist et al. (2017). (*right*) Two-slices representation of the upstream hemisphere of the simulation space, with the wind coming from the upper left. We overlaid a logarithmic density map to show the typical size of the inhomogeneities to resolve. The accretor lies in the bottom right corner.

et al. 2016). Concerning the column density levels, we retrieve average values compatible with what has been observed recently in Vela X-1 by Grinberg et al. (2017).

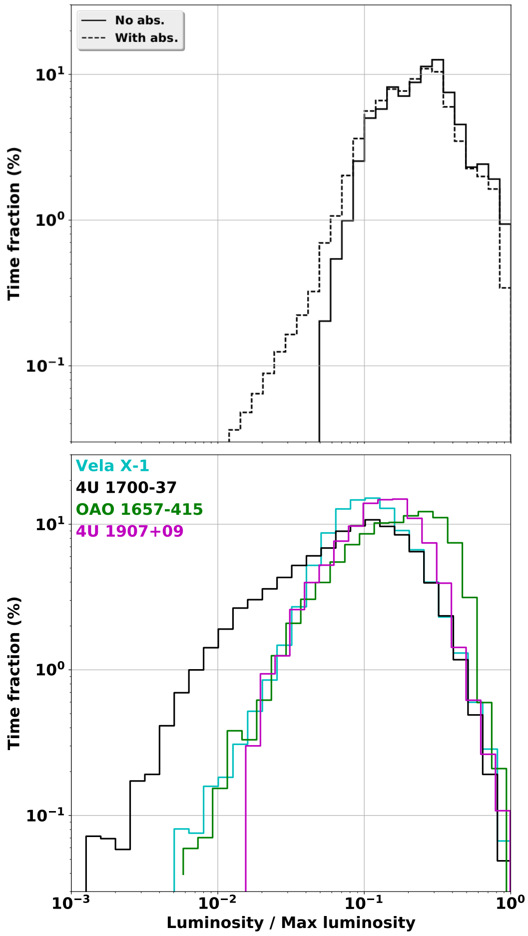


Figure 3: (upper panel) Simulated luminosity histograms, with and without accounting for absorption. (bottom panel) Observed luminosity histograms for 4 classic SgXB (from El Mellah et al. 2017).

I also participated to Grinberg et al. (2017) to evaluate the time variability associated to unaccreted clumps passing by the line-of-sight and concluded that this type of micro-structure within the wind can not explain by itself the variations in column density we observed. This contribution has been made possible thanks to the ISSI team I have been invited to join in February 2017, at the occasion of their second workshop in Bern. In November 2017, I gathered at ESAC (Madrid) with Peter Kretschmar (ESAC), Silvia Martínez-Núñez (IFCA), Victoria Grinberg (ESTEC) and Felix Fürst (ESAC) to provide the theoretical expertise to the X-Wind collaboration which aims at developing further the work carried out by the ISSI team : providing a more comprehensive view of the stellar wind in Supergiant X-ray binaries thanks to a synergy between specialists in winds of isolated massive stars and specialists in high mass X-ray binaries.

Eventually, in Xia et al. (2017), I carried out a numerical validation of the stretched grid implementation I had made during my PhD by confronting quantitative simulation results of Bondi spherical accretion to the analytical expectations on the mass accretion rate and the location of the sonic point for different adiabatic indexes. We also studied the propagation of a trans-Alvénic wind from the solar surface to the Earth orbit to validate the compatibility of the stretched grid with the MHD solver and Powell's method for the cleaning of the divergence of the magnetic field.

Research project

Since most of the X-ray emission we observe comes from the immediate vicinity of the accretor, we want to study the high energy phenomena at stake within a few hundreds of Schwarzschild radii around the accretor. In SgXB, the magnetic field of the accreting NS can no longer be discarded in this zone. We now need to investigate other sources of time variability than the clumps to interpret the observations :

- the presence of a transient disc-like structure around the accretor could lead to specific disc instabilities (e.g. the magneto-rotational instability).
- magnetic and centrifugal gatings at the edge of the NS magnetosphere are expected to contribute to break up the accreted flow, along with thermodynamical considerations which modulate the entry within the NS magnetosphere.
- the X-ray ionizing feedback from the immediate vicinity of the accretor alters the dynamics of the wind at the orbital scale.

These 3 trails form the backbone of my research project in the following years. If it is mostly aimed at SgXB and SFXT, it has also ramifications to similar systems such as Cataclysmic Variables (CV), low mass X-ray binaries or Be X-ray binaries. Thanks to the suited numerical framework I contributed to develop over the last years, we can aspire to obtain, by the end of the next decade, a consistent overview of the mass transfer process, from the Dantean stellar surface down to the magnetic vicinity of a NS, if not the relativistic surroundings of a black hole. Current missions (e.g. XMM-Newton, Chandra and Integral) provide us with the guiding constrains of our numerical investigations, while future ones (e.g. SVOM, LOFT and Athena) will bring unprecedented observations which will confront theoretical expectations even further.

Wind-capture discs

The first step of this research project addresses the capacity of the accreted flow to form a disc, depending on the speed of the flow compared to the orbital speed. In the low speed-limit, a RLOF star pours matter at the first Lagrangian point directly into the Roche lobe of the accretor (see Figure 4). The flow winds up around the accretor and forms a large permanent disc. In the high-speed limit, long thought to be valid for SgXB, the line-driven wind coming from a high mass donor star carries little angular momentum : the flow structure is described by the BHL solution and no disc is expected. However, Mohamed & Podsiadlowski (2011) laid the foundations for a treatment of the intermediate case or *wind-RLOF*. In El Mellah & Casse (2016), I adapted it for SgXB. Recent observational and numerical results on the wind speed in the classic SgXB Vela X-1 suggest that neither of the 2 aforementioned asymptotic cases apply (Gimenez-Garcia et al. 2016, Sander et al. 2017) and a wind-RLOF approach is required. I plan to study this case to identify the conditions of formation of wind-captured discs (see Figure 5). Discs are known to be fruitful landscapes for a plethora of instabilities which might partly contribute to the time variability in some SgXB.

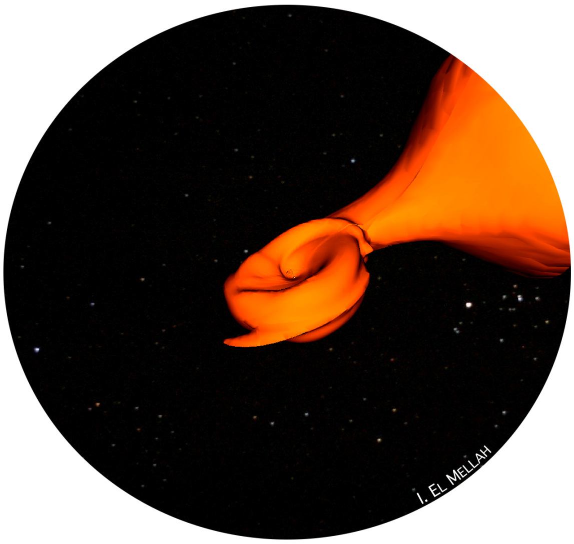


Figure 4: Isodensity surface of a 3D flow from a RLOF star (upper right) to an accretor, 1,000 times smaller than the orbital separation between the two bodies.

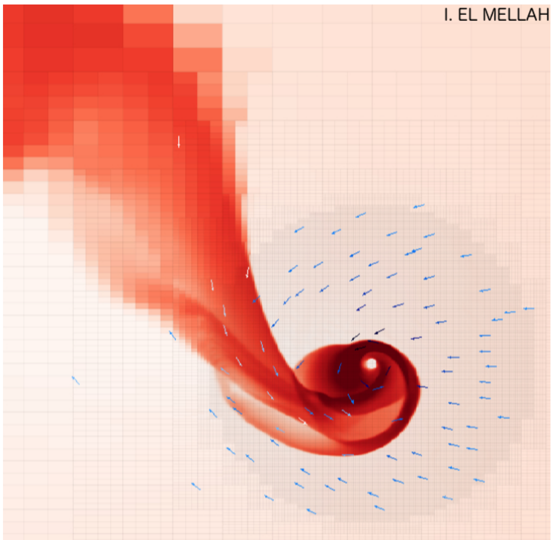


Figure 5: Density and velocity map of a slow wind (coming from the right) being accreted onto a compact object. The detached bow shock becomes a disc-like structure.

These questions strongly connect to the domains of interest of the Observatoire de Paris, in particular of the LUTh and the LESIA. Indeed, accretion of low angular momentum flow onto a compact object might accurately describe the accretion process taking place in the Galactic Center, Sagittarius A*, observed with the GRAVITY instrument managed, among others, by the LESIA. Furthermore, these simulations need to be processed with ray-tracing tools such as `GYOTO` (developed among others by Frédéric Vincent now at the LESIA, Vincent et al. 2011) to yield synthetic observations (e.g. for Cygnus X-1). The insights it would bring on the environment of accreting compact objects would be valuable for the theoretical models developed at the LUTh (e.g. by Eric Gourgoulhon or Fabrice Mottez).

The NS magnetosphere

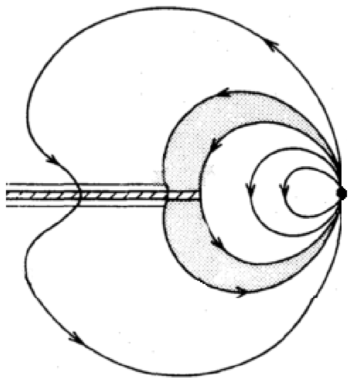


Figure 6: Truncation of the inner disc by the NS magnetosphere. From Ghosh & Lamb (1978).

The NS in SgXB are strongly magnetized since their young age did not allow for a significant decay of their pristine dipolar field. Within the magnetosphere, magnetically-funneled accretion onto the poles takes place. Yet, the contrast between the size of the NS and the orbital separation makes it challenging to develop a numerical setup suitable for magneto-hydrodynamical problems. To alleviate this obstacle, we started with Zakaria Meliani (LUTh) to study a family of binaries where the accretor is one hundred times larger and where the orbital separation is ten times smaller : cataclysmic variables, hosting a white dwarf (WD). These systems still retain the main qualitative ingredients as SgXB while being much more computationally affordable. In intermediate polars, a sub-class of CV, a RLOF star feeds an accretion disc truncated at its innermost border by the magnetic field of the accreting white dwarf (see Figure 6). The flow is then funneled to the WD poles where it is shocked and heated to high temperatures, emitting copious amounts of light. We are currently implementing a grey cooling method into our code, `MPI-AMRVAC`, to see the interplay between a physically-motivated stratified disc and the WD magnetic field. Coupled to the adaptive mesh stretched grid I developed during my PhD, this approach could improve our understanding of the WD spinning down. More generally, such a setup will be also used to set constrains on the disc reformation after a nova (Ness et al. 2012) : with U Scorpii expected to go off in a couple of years, I started to collaborate with Jan-Uwe Ness (ESAC) to write together an observation proposal by summer 2018.

This twofold setup also serves another purpose : diving into the magnetosphere of the accreting NS in SgXB, where the magnetic field is larger. Numerically, we recently implemented and validated a numerical algorithm of magnetic splitting generalized to non-potential fields (Xia et al. 2017). It enables us to handle more accurately the magnetic field evolution, in particular in magnetically-dominated plasmas, and to clean more easily the non-zero divergence. With this new feature available, we want to study how the innermost parts of the wind behave. Depending on how the magnetosphere radius compares with other characteristic length scales such as the accretion and corotation radii, the flow might be halted and cascade later on within the magnetosphere (Bozzo et al. 2008). We can now study this modulation with physical inputs accounting for the variability at the upper scales derived in El Mellah et al. (2017). We also want to address the case where the NS magnetospheric radius is much larger, of the order of the accretion radius. How does it alter the shock? This topic connects to the studies on the NS structure which are conducted at the LUTh by Jérôme Novak and collaborators.

X-ray ionizing feedback

In the European X-wind collaboration I joined early 2017, my role is to connect the information we get from state-of-the-art numerical simulations of line-driven winds of isolated massive stars to the variability of the X-ray emission and absorbing column density observed in SgXB. The next step to perform this connection in a self-consistent way is to evaluate the radiative influence of the X-rays emitted in the immediate vicinity of the accretor on the inflowing wind. Indeed, the efficiency of line-driven acceleration drops when the wind gets excessively ionized i.e. as it gets closer from the accretor it feeds. In the continuation of Blondin et al. (1990), Manousakis & Walter (2015) performed 2D simulations where they accounted for this effect but prescribed an a priori fixed X-ray luminosity. We aim at dynamically computing this X-ray luminosity from the mass accretion rate at the inner border of the large scale contrast simulation space introduced in El Mellah et al. (2017). The X-wind collaboration workshop of October 2018 in Santander will be the occasion to confront these results to new observations, while our monthly telecons allow us to keep track of the intermediate steps performed by each of the 20 members or so.

Since the end of my PhD, I have built up multiple collaborations to embed the numerical tool into the scientific method, as a binder between the theoretical approach, limited by the mathematical tools available, and the observational approach, limited by the instruments at our disposal. Thanks to the HPC technologies, Computational Astrophysics has ushered in a particularly exciting period to address a wide range of questions pertaining to accretion, from Active Galactic Nuclei to X-ray binaries and planetary formation. Concomitantly, the multiple confirmed detections of gravitational waves from coalescing compact objects have urged even more the community to evaluate the impact of binarity on the evolutionary tracks of massive stars. To this extent, high mass X-ray binaries represent a decisive stage whose understanding would shed light on many fundamental questions, from the scarcity of intermediate mass black holes to the equation-of-state of matter at supernuclear densities in neutron stars. A position as an *astronome-adjoint* at the Observatoire de Paris, in LESIA or LUTh whose members show a shared interest in compact objects and their surroundings, would enable me to carry on this research program and reinforce the connections I built up with the scientific community in France. I would also strengthen the numerical expertise of Observatoire de Paris-Meudon.

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Tâche de service

Type (ANO1 à ANO6)	ANO5
Nom du service	SO5 - Plateforme MIS et Jets
Nom de la tâche	ISM map inversion
Labellisation	oui
Nom du responsable scientifique correspondant	Franck Le Petit
Laboratoire et OSU dont elle relève	Observatoire de Paris - LERMA

Stellar systems in a galaxy are embedded in a diffuse environment called the InterStellar Medium (ISM). The densest and coldest components of the ISM such as molecular clouds condition stellar formation. They host the stellar nurseries where the Toomre's instability criterion is matched, causing the gravitational collapse of Jeans mass fragments of the cloud into stellar embryos. The stellar feedback on the ISM (e.g. via stellar winds, planetary nebulae, supernovae) influences in return its structure and its evolution through time. Beyond this active role in the galactic ecology, the ISM, omnipresent around us, alters the light which crosses it. It absorbs, diffuse and reemits light, leaving an imprint we have to identify to guarantee an unbiased analysis of the background objects we observe, either in or out of the Milky Way.

The wide scope of length scales and thermodynamical conditions witnessed in the ISM gives rise to a rich chemistry. The ISM is made mostly of neutral Hydrogen, which emits only at the 21cm spectral line. Since the latter has a low transition probability, it requires large amounts of Hydrogen to be seen. However, the interaction of massive clouds with the ambient UV radiation field produces a layer structure. Each of them is characterized by a chemical and ionization state and can give birth to species susceptible to emit light. For instance, [C II] plays an important role in the cooling of the ISM through its fine structure $158\mu m$-line. The absorption of the background UV field by the Galactic dust also produces a far infrared continuous emission. Together, these two emission processes offer an alternative way to probe the ISM and determine its properties.

In particular, zones of early stellar formation such as molecular clouds are surrounded by photodissociation regions (PDR) that separate the bulk of the cloud from the [H II] regions ionized by the interstellar radiation field. Cosmic rays also provide a heat and ionization, enabling a rich sequence of chemical reactions to occur. Given the typical PDR densities, H_2 dissociation is not dominated by collisions but by photoabsorption of the incident UV radiation field. Deeper into the PDR, shelf-shielding of H_2 occurs but since Carbon has a lower ionization energy, it can still be ionized into [C II] whose emission is a key testimony of the cloud environment and properties.

Among others, the Herschel Space Observatory and the Spitzer Space Telescope have provided a harvest of data we need to analyze and interpret with advanced numerical tools. The interaction with the ambient radiation fields or cosmic rays produces a complex multi-scale environment which can only be addressed with sophisticated models. The complexity of the ISM properties (chemistry, MHD, turbulence, dust...) requires to develop syncretic frameworks coupling multiple databases, assumptions and physical processes. It is in this context that has been written the Meudon PDR code, a cornerstone of the *Plateforme MIS et Jets*. It solves, for a given MHD solution of the ISM structure, the radiative transfer and chemical network equations within the clouds. The maintenance, development and diffusion of this code is the object of the present *Tâche de service* application.

Description

Map inversion

Galactic ISM maps

The contemporary detectors used to study the ISM are spectral imaging instruments such as the Photoconductor Array Camera and Spectrometer (PACS) embarked on the Herschel Space Observatory. Each pixel of the CCD camera measures a spectrum, coupling 2D spatial photometry and spectroscopy. To deduce the properties of the ISM from these observations, we need to jointly invert the spectro-photometric information from each pixel. This map inversion requires both physical models of the ISM and mathematical optimization techniques. The former is provided by the thousands of models which have been considered in the Meudon PDR code to derive synthetic observations such as :

- line emission maps
- absorbing species column densities, from the integration of the photodissociation cross-sections with the interstellar radiation field
- dust absorption
- molecular formation rates with computation of H_2 formation efficiency

The plethora of models and parameters to fit for makes the optimization step particularly challenging though. The likelihood computation to identify the most accurate models need to be done coupling the information from all the pixels together. Otherwise, the information on the consistency of the detector is lost and separate inversion of the information from each pixel is bound to yield a set of local optima with properties excessively discontinuous. Advanced methods of statistical analysis must be summoned such as genetic algorithms or simulated annealing in conjunction with smoothing terms to account for the connection between the pixels.

Ideally, such a task should be performed directly via a web interface, designed in cooperation with the engineering service of the PDR code. Users could provide formatted observations which would be fitted with the available models of the PDR code, yielding the best matching.

Component separation for observations of extragalactic sources

The recent observations of the Cosmic Microwave Background (CMB) by Planck and BICEP2 reminded us the need to constrain the foreground Galactic dust distribution. More generally, observations of extragalactic sources bring up the issue of the component separation : as the sources get further, the risk of blending with foreground point or diffuse sources increases, and so does the requirement for a proper disentangling. Eventually, the massive amount of data on extragalactic sources could be processed by algorithms empirically designed based on machine learning methods. It would quickly identify the fraction of the emission due to interstellar shocks, diffuse emission or from molecular clouds.

Among extragalactic observations which would enjoy such an improved component separation, one can find Active Galactic Nuclei (AGN). AGNs are believed to be accreting supermassive black holes, laying at the center of galaxies. Their spectacular luminosity makes them visible at high redshift and the source of their luminosity connects to my current research program : accretion of low angular momentum gas onto a compact object.

Virtual observatory

In an attempt to pool the available observational and synthetic data, the International Virtual Observatory Alliance (IVOA) has defined a set of standards to facilitate the cross-use of diverse sources of information. The Observatory of Paris has been involved in the definition of common formats through the Simulation Data Model, along with a set of meta-data to retrieve data from MHD or N-body simulations for instance (the Simulation Data Access Layer protocol). Now, we need to provide the Astrophysics and Cosmology communities with tools to make their codes produce suitably formatted outputs. This translation tool could also be part of the *tâche de service*. As a user and developer of the `MPI-AMRVAC` code, similar to the RAMSES code, I am familiar with the importance of well-defined input/output formats. I could contribute to make this family of MHD finite volume codes compatible with the IVOA standards.

Selected skills and conclusion

My PhD and postdoc work has been essentially devoted to numerically solving hyperbolic systems of partial differential equations on non necessarily Cartesian meshes, with features like Adaptive Mesh Refinement common to the RAMSES code. Consequently, my expertise in statistical analysis did not build up on a daily use during my PhD. However, during my Master degree, I did get familiar with advanced data analysis techniques such as Internal Linear Combination[1], which got extended by Tegmark & Efstathiou in 1996 to take advantage of the correlation between neighboring pixels on the detector rather than subtracting foregrounds on a pixel by pixel basis. I used the latter to separate the different diffuse components in the WMAP data and retrieve the background CMB emission, under the supervision of Guilaine Lagache (LAM) and Alexandre Beelen (IAS). I realize that it is merely a scientific case and does not compare to the complexity of more advanced goals such as the one described by the present *tâche de service*, but I believe it illustrates well enough the steep learning curve I am prepared to address. Furthermore, being a computational astrophysicist in close collaboration with observers, I am fully aware of the cautious synergy required between the theoretical models available and the data processing to produce a consistent and scientifically satisfactory explanation.

[1] For an application to WMAP data, see Benett C. L. et al 2003 ApJS 148 97.

Enseignement

Après une première expérience d'enseignement dans le cadre de mes études à l'ENS de Cachan, j'ai passé l'Agrégation de Physique en 2011 où j'ai été classé second. La diversité des sujets abordés pendant cette année, ainsi que la nécessité de se les réapproprier pour pouvoir les restituer en un cours construit, ont considérablement renforcé ma culture en Physique générale et mon souhait de participer aux activités d'enseignement supérieur.

La 1^{e} année de mon monitorat de thèse, ma mission d'enseignement s'est déroulée pour moitié (32h TD) en Première Année Commune aux Etudes de Santé (PACES) sous la direction d'Isabelle Grenier. J'y étais responsable de 2 groupes de TD d'environ 40 étudiants chacun. Le programme de Physique de PACES porte sur un vaste panel de problèmes, de la mécanique des fluides aux intéractions rayonnement-matière. Rendre abordable et compréhensible des notions aussi diverses et dont la maîtrise sérieuse nécessite des outils mathématiques hors de portée des étudiants en première année a représenté un effort aussi considérable qu'instructif. D'Octobre à Décembre 2013, j'encadrais les travaux pratiques associés au cours de M1 "Traitement du signal - Signaux déterministes" de Laurent Daudet, à hauteur de 32h TD. L'intérêt pédagogique portait sur la transmission de savoirs plus avancés, sur les plans théorique (signaux discrets, analyse de Fourier, convolutions, spectre de puissance, filtrage, etc) et pratique (Matlab).

Les 2 années suivantes, j'ai rejoint l'équipe de Cécile Roucelle à l'Université Paris 7 Diderot où j'ai encadré les TDs de Mécanique du point au niveau L1. Durant les 128h qui m'ont été assignées, j'ai eu le plaisir non seulement de participer à la rédaction des sujets d'exercice mais surtout à former les étudiants néophytes aux spécificités du raisonnement physique. A mon sens, la première année d'études supérieures représente un moment charnière dans le cursus des étudiants et requiert donc un encadrement étroit et exigeant pour éviter que les étudiants ne perdent un temps précieux.

A Leuven, j'ai encadré des projets scientifiques de Master dans l'unité d'enseignement "Computational Methods for Astrophysical Applications" dirigée par Rony Keppens (~60h TD au cours de ma première année de postdoctorat). Poursuivre mon travail de recherche tout en restant en contact avec les étudiants est une chance qui m'a permis de replacer mes travaux et les outils numériques que j'utilise au quotidien dans une perspective plus didactique. L'organisation logistique de l'enseignement, en mettant en place un réseau de machines virtuelles accessibles aux étudiants, a aussi été une composante importante, à garder à l'esprit lorsque l'on souhaite intégrer la dimension numérique à l'enseignement.

L'outil numérique offre de nouvelles opportunités pour l'activité scientifique, à condition de s'assurer que les étudiants qui seront amenés à la porter dans les années à venir aient pleinement conscience de sa centralité. Il s'agit de rendre l'Informatique familière aux étudiants dès leur première année afin qu'elle nourrisse leur réflexion scientifique au lieu d'apparaître comme une contrainte à laquelle ils seraient obligés de se soumettre. Au quotidien, la recherche en Physique ne peut pas plus se passer de compétences avancées en Informatique qu'en Mathématiques. C'est pourquoi je souhaite soumettre aux étudiants une base de donnée de sujets numériques d'exercices. Ils seraient écrits de façon à encourager l'acquisition et le déploiement de compétences telle que la mise en ligne d'exposés intéractifs de leurs réponses via la programmation d'applets. Au sein du Master de l'Observatoire de Paris-Meudon, je souhaiterais aussi initier les étudiants aux techniques modernes de calcul intensif (parallélisation, optimisation, visualisation et stockage des données, etc), indispensables tant pour l'analyse de données que pour la résolution numérique de problèmes physiques.

Responsabilités diverses

En collaboration avec Rony Keppens et Jon Sundqvist, j'encadre cette année la thèse de M2 de Nicolas Moens sur les vents d'étoiles massives. Je l'assiste dans la phase d'implémentation des modèles physiques de lancement dit "radiatif" de ces vents dans le code de résolution sur grille des systèmes d'équations hyperboliques, `MPI-AMRVAC`. Après avoir testé avec succès un premier modèle, nous souhaitons désormais décrire de façon plus réaliste le transport radiatif dans le vent avec un algorithme de *flux-limited diffusion*. A terme, cette option devrait permettre à `MPI-AMRVAC` de traiter le refroidissement dans les environnements optiquement épais.

Afin de tisser des liens forts entre jeunes chercheurs, la Société Française de Physique a initié en 2013, sous l'égide de Samuel Guibal (Paris 7), un évènement annuel intitulé les Rencontres Jeunes Physiciens (RJP). En deuxième année de thèse, je me suis engagé au sein du comité d'organisation des RJP 2015 en tant que community manager. Mon rôle était d'assurer aux RJP une visibilité médiatique maximum, tant sur les réseaux sociaux qu'à travers sa principale vitrine, son site Web, dont j'ai adapté la mise en page et le contenu. Pour garantir la pérennité des RJP, j'ai aussi procédé, avec l'aide du personnel du Conservatoire National des Arts et Métiers où se déroulait l'évènement, à la captation audio et vidéo des interventions orales qui rythmaient la journée, ainsi qu'à leur traitement puis à leur diffusion. L'évènement, qui a rassemblé quelque 200 doctorants et post-doctorants d'Ile-de-France, a reçu le soutien de nombreuses universités, écoles doctorales et institutions. Grâce à elles, nous avons pu rassembler près de 15k€ qui nous ont permis de faire de cette journée un temps fort de la vie sociale des jeunes physiciens et physiciennes d'Ile-de-France. En tant que membre du comité d'organisation, j'ai aussi participé à la sélection des 16 interventions orales parmi la quarantaine de résumés qui nous avaient été soumis.

Dans mon laboratoire de thèse, l'APC, j'ai animé des Présentations hebdomadaires des Doctorants (ou *PhD*) dévolues à des aspects méthodologiques de l'activité scientifique telles que les éditeurs de codes, la veille bibliographique ou encore la gestion de versions avec des outils comme Git. Afin d'assurer de s'assurer que chaque doctorant soit opérationnel à l'issue de ces présentations, nous organisions des ateliers d'une durée de 3h où chacun ramenait sa propre machine de travail sur laquelle avait été installés au préalables les outils nécessaires à la session. Moins formels et plus spécialisés que les ateliers de formation génériques proposés à tous les doctorants de l'université, ces sessions permettaient de partager rapidement et efficacement des méthodes de travail qui permettent des gains de temps considérables.

Pendant ma thèse, j'ai aussi publié une page personnelle à même de rendre compte de mes travaux au sein de la communauté scientifique.

Diffusion des connaissances & vulgarisation

En Novembre 2017, j'ai participé à une émission radiophonique, la Faconde, sur la radio universitaire de l'Université Libre de Bruxelles. J'y ai discuté de la communication scientifique et promu sa composante sensible et esthétique, par opposition à la transmission mécanique de résultats scientifiques formatés qui désenchante et, in fine, suscite un détachement et un relativisme généralisé au sein de la population.

Dans une perspective plus pédagogique, j'ai animé un atelier sur la notion de potentiel en mécanique à destination d'élèves de lycée en Octobre 2016, à l'occasion de la Fête de la Science. Pour ce faire, j'ai mis à profit des maquettes de potentiels de Roche que j'ai pu imprimées en 3D grâce à l'assistance technique de Hubert Halloin et Marco Agnan et à un financement DIM ACAV[1]. En parallèle, j'ai produit une application intéractive en ligne qui permet d'appréhender empiriquement la notion de potentiel lorsqu'elle est utilisée conjointement avec la maquette suscitée : la maquette sert à visualiser le potentiel en 3D pour un paramètre donné (le rapport de masse entre les deux corps), alors que l'application en ligne permet de modifier ce paramètre à souhait et de visualiser les trajectoires associées.

[1]Domaine d'Intérêt Majeur en Astrophysique et Conditions d'Apparition de la Vie.

Fabien Casse

Zakaria Meliani

Rony Keppens

Peer-reviewed publications[1]

[1]* **El Mellah I.**, Sundqvist J. O., & Keppens R.
Accretion from a clumpy massive-star wind in Supergiant X-ray binaries (2017) - MNRAS

[2]* Grinberg V., Hell N., **El Mellah I.**, Neilsen J., Sander A. A. C., Leutenegger M. A., Fürst F., Huenemoerder D. P., Kretschmar P., Kühnel M., Martínez-Núñez S., Niu S., Pottschmidt K., Schulz N. S., Wilms J. & Nowak M. A.
The clumpy absorber in the high mass X-ray binary Vela X-1 (2017) - A&A

[3]* Xia C., Teunissen J., **El Mellah I.**, Chané E. & Keppens R.
MPI-AMRVAC 2.0 for solar and astrophysical applications (2017) - ApJS

[4]* **El Mellah I.** & Casse F.
A numerical investigation of wind accretion in persistent Supergiant X-ray Binaries I - Structure of the flow at the orbital scale (2017) - MNRAS

[5]* **El Mellah I.** & Casse F.
Numerical simulations of axisymmetric hydrodynamical Bondi-Hoyle accretion on to a compact object (2015) - MNRAS

[6] Sanchis-Ojeda R., Rappaport S., Winn J., Kotson M., Levine A., **El Mellah I.**
A Study of the Shortest-period Planets Found with Kepler (2014) - ApJ

[7] Rappaport S., Deck K., Levine A., Borkovits T., Carter J., **El Mellah I.**, Sanchis-Ojeda R., Kalomeni B.
Triple-star Candidates among the Kepler Binaries (2013) - ApJ

[8]* Rappaport S., Levine A., Chiang E., **El Mellah I.**, Jenkins J., Kalomeni B., Kite E. S., Kotson M., Nelson L., Rousseau-Nepton L., Tran K.
Possible Disintegrating Short-Period Super-Mercury Orbiting KIC 12557548 (2012) - ApJ

Proceedings & PhD manuscript

[9] **El Mellah I.**, Sundqvist J. O., & Keppens R.
Clumpy wind accretion in Supergiant X-ray Binaries (2017)
Proceedings des Journées de la Société française d'Astronomie & d'Astrophysique

[10] **El Mellah I.**
Wind accretion onto compact objects (2016)
PhD manuscript

[11] **El Mellah I.** & Casse F.
Numerical simulations of axisymmetric Bondi-Hoyle accretion onto a compact object (2015)
Proceedings des Journées de la Société française d'Astronomie & d'Astrophysique

[1] The stars indicate the papers in which I made an important contribution.

Conferences & workshops

Sp 2017 Frontiers of Astrophysical Modeling - KU Leuven (BE)
Ag 2017 Numerical techniques in MHD simulations - Köln (GE)
Jl 2017 Journées de la SF2A - Paris (FR)
Mr 2017 CHARM meeting - Brussels (BE)
Mr 2017 Stellar winds in massive X-ray binaries (ISSI workshop) - Bern (SW) - **invited**
Sp 2016 Super-Eddington accretion on compact objects - Arbatax (IT)
Mr 2015 International school of Computational Astrophysics - Les Houches (FR)
Jn 2015 Journées de la SF2A - Toulouse (FR)
Mr 2015 Turbulence, magnetic fields and self organization - Les Houches (FR)

Seminars

Dc 2017 Radboud University Nijmegen (NL)
Nv 2017 ESAC, Madrid (SP)
Sp 2017 LUTh, Observatory of Paris (FR)
Sp 2016 Aarhus University (DN)
Ap 2016 APC, Paris 7 University (FR)
Ap 2016 CmPA, KU Leuven (BE)
Oc 2015 AIM, CEA (FR)

Posters

Jn 2017 Clumpy wind accretion in Supergiant X-ray binaries, EWASS, Prague (CZ)
Dc 2015 Wind accretion onto compact objects, Texas symposium, Geneva (SW)
Nv 2014 Wind accretion undergoing flip-flop instability, IAP, Paris (FR)