Ileyk El Mellah
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Research

Since 2016	**FWO [Pegasus]² Marie Skłodowska-Curie fellowship with Rony Keppens** Center for mathematical Plasma Astrophysics – KU Leuven
2013-16	**PhD with Fabien Casse & Andrea Goldwurm** – Paris Diderot University ***Wind accretion onto compact bodies***
2011-12	**One-year volunteer internship supervised by Saul Rappaport on** ***Monitoring of close-in binaries and short period exoplanets with Kepler*** Kavli Institute for Astrophysics – MIT
Ap-Ag 2010	**BSc internship supervised by Jean-François Lestrade on** ***Gravitational perturbations of debris discs by a passing-by star*** LESIA – Paris Observatory
Jn-Jl 2009	**BSc internship supervised by Gérard Belmont & Patrick Robert on** ***Resampling of the CLUSTER satellites data*** Plasma Physics Laboratory – Paris

Education

2013-16	**PhD with Fabien Casse & Andrea Goldwurm** – Paris Diderot University ***Wind accretion onto compact bodies***
2012-13	**Master degree in Astrophysics, with distinction** – Paris Observatory
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 : 2nd in 1,409 candidates
2008-10	**Bachelor degree in Fundamental Physics, with honours** – ENS
2006-08	**Preparatory classes to *Grandes Ecoles*** – Lycée Janson-de-Sailly, Paris

Communication

Conferences

Jn 2019	European Week of Astronomy and Space Science - Lyon, Fr
Fb 2019	12th INTEGRAL conference - Geneva, SW
Oc 2018	Stellar Winds in Massive X-ray Binaries workshop - Santander, SP
Oc 2018	Leuven-Amsterdam-Bonn massive stars meeting - Leuven, BE
Ag 2018	IAU General Assembly - High Mass X-ray Binaries symposium - Vienna, AT
Jl 2018	COSPAR Assembly - Pasadena, US
Jn 2018	Belgium FNRS meeting - Brussels, BE
Sp 2017	Frontiers of Astrophysical Modeling - Leuven, BE
Ag 2017	Numerical techniques in MHD simulations - Cologne, DE
Jl 2017	French Astronomy Society meeting - Paris, FR
Jn 2017	European Week of Astronomy and Space Science - Prague, CZ
Mr 2017	CHARM meeting - Brussels, BE
Fb 2017	Stellar Winds in Massive X-ray Binaries workshop - ISSI Bern, SW
Oc 2016	CHARM meeting - Ghent, BE
Sp 2016	Super-Eddington accretion on compact objects - Arbatax, IT
My 2016	International school of Computational Astrophysics - Les Houches, FR
Dc 2015	Texas symposium - Geneva, SW
Jn 2015	French Astronomy Society meeting - Toulouse, FR
Mr 2015	Turbulence, magnetic fields and self organization - Les Houches, FR
Nv 2014	Magnetic fields from the sun to black holes - Paris, FR
My 2013	Cosmic Accelerators - Institute for scientific studies - Cargése, FR

Seminars

Fb 2019	APC laboratory - FR
Fb 2019	Observatory of Geneva - SW
Nv 2018	IRAP Toulouse - FR
Jl 2018	TAPIR Caltech - US
Fb 2018	LUPM Montpellier - FR
Dc 2017	Radboud University Nijmegen - NL
Nv 2017	ESAC Madrid - SP
Sp 2017	Observatory of Paris - FR
Sp 2016	Aarhus University - DK
Ap 2016	Paris 7 University - FR
Ap 2016	KU Leuven - BE
Oc 2015	CEA Paris, AIM laboratory - FR

Posters

Jl 2018	Formation of wind-captured discs in high mass X-ray binaries - COSPAR
Jn 2017	Clumpy wind accretion in Supergiant X-ray binaries - EWASS
Dc 2015	Wind accretion onto compact objects - Texas symposium
Nv 2014	Wind accretion undergoing flip-flop instability - IAP Paris

Grants & awards

2016	3-years FWO [Pegasus]^2 Marie Skłodowska-Curie fellowship
2013-16	3-years PhD fellowship from the Ecole Normale Supérieure of Cachan
2013-16	3-years teaching assistant grant from the Université of Paris 7 Diderot
2011	French *Agrégation* of Physics and Chemistry - Rank : 2nd
2010-12	2-years *normalien* study fellowship from the ENS of Cachan

Computing & observing time

2018	Mapping the wind and accretion in Vela X-1 - XMM-Newton (co-I.)
2017-18	Computing time on the Flemish Tier-1 VSC cluster : 2.5 Mh·CPU
2015-16	Computing time on the French CINES Tier-1 cluster : 600 kh·CPU
2012	1-week observing time at the Mont Mégantic Observatory (Canada)

Supervision & teaching

2018-22	Teaching qualification in section 34 - Astronomy & Astrophysics

Supervision

2018-...	Co-supervisor with Jon Sundqvist of a graduate student, Nicolas Moens
2018-...	Member of the supervisory committee of a graduate student, Luka Poniatowski
2018	Reader for Florian Driessen's Master thesis supervised by Jon Sundqvist
2018	Reader for Prem Kumar Bulusu's Master thesis supervised by Hugues Sana

Teaching

2018-19	Lecturer in Computational methods for Astrophysics, 5th year - KU Leuven
2017-18	Teaching assistant (TA) Linear Algebra, 1st year - KU Leuven
2016-17	TA Computational methods for Astrophysics, 5th year - KU Leuven
2014-16	TA Classical Mechanics, 1st year - Univ. of Paris 7 Diderot
2013	TA Physics for Medical studies, 1st year - Univ. of Paris 7 Diderot
2013	TA Deterministic systems and signals, 4th year - Univ. of Paris 7 Diderot
2012-13	Private lessons with the company *Cours Thalès* - Paris
2011	French *Agrégation* of Physics & Chemistry
2009-10	High school Gustave Eiffel - Cachan

Community service

Reviewing

2019	Reviewer for Astronomy & Astrophysics
2018	Reviewer for The Astrophysical Journal
2018	Reviewer for DiRAC High Performance Computing Tier-1

Outreach

Oc 2017	1h30 radio interview on scientific communication in *Faconde* - Brussels
Nv 2015	Community manager and webmaster of the Young Physicists Meeting - Paris
Oc 2015	Festival of Science - Paris Diderot University
Sp 2015	3D-printed models and Wolfram interactive applet for the Roche potential
2013	Java applet on Turing theory of morphogenesis - Paris Observatory

Publications in peer-reviewed journals

[1] **El Mellah I.**, Sundqvist J. O. & Keppens R.
Wind Roche lobe overflow in high mass X-ray binaries :
A possible mass transfer mechanism for Ultraluminous X-ray sources - A&A 2019

[2] Decin L., Homan W., Danilovich T., de Koter A., Engels D., Waters L. B. F. M., Muller S., Gielen C., García-Hernández D. A., Stancliffe R. J., Van de Sande M., Molenberghs G., Kerschbaum F., Zijlstra A. A., **El Mellah I.**
Reduced maximum mass-loss rate of OH/IR stars
due to overlooked binary interaction - Nature Astronomy 2019

[3] **El Mellah I.**, Sander A. A. C., Sundqvist J. O. & Keppens R.
Formation of wind-captured discs in Supergiant X-ray binaries :
Consequences for Vela X-1 and Cygnus X-1 - A&A 2019

[4] **El Mellah I.**, Sundqvist J. O. & Keppens R.
Accretion from a clumpy massive-star wind in Supergiant X-ray binaries
MNRAS 2018

[5] Xia C., Teunissen J., **El Mellah I.**, Chané E. & Keppens R.
MPI-AMRVAC 2.0 for solar and astrophysical applications - ApJS 2018

[6] 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 - A&A 2017

[7] **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 - MNRAS 2017

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

[9] Sanchis-Ojeda R., Rappaport S., Winn J., Kotson M., Levine A., **El Mellah I.**
The shortest-period planets found with Kepler - ApJ 2014

[10] 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 - ApJ 2013

[11] 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 KIC12557548 - ApJ 2012

Proceedings

[12] **El Mellah I.**, Sundqvist J. O. & Keppens R.
Wind-captured discs in Supergiant X-ray binaries - IAU Vienna 2018

[13] Fürst F., Kretschmar P., Grinberg V., Pottschmidt Katja, Wilms J., Kühnel M., **El Mellah I.**, Martínez-Núñez S.
Variability in High Mass X-ray Binaries - XMM-Newton workshop 2018

[14] **El Mellah I.**, Sundqvist J. O. & Keppens R.
Clumpy wind accretion in Supergiant X-ray binaries - SF2A 2017

[15] **El Mellah I.** & Casse F.
Numerical simulations of Bondi-Hoyle accretion onto a compact object - SF2A 2015

RESEARCH SUMMARY

In Supergiant X-ray binaries (SgXBs), a sub-family of high mass X-ray binaries, a neutron star (NS) or a black hole orbits a supergiant O/B star and captures part of its stellar wind. SgXBs are thought to be the progenitors of the double compact object binaries whose final merger produces flares of gravitational waves similar to the ones first observed by the LIGO/Virgo collaboration in 2015. So as to make the most of the data from these merging compact objects, we need to study their evolution and understand how binarity has affected their properties. In simulations of secular long-term evolution (Tauris et al., 2006), proxies are used to deduce a mass and angular momentum transfer rate from elementary parameters such as the mass ratio, but the efficiency of accretion onto the compact companion and of the associated spin-up from mass transfer is still highly uncertain. This flaw hampers our capacity to interpret the gravitational wave observations and to predict accurate merging rates. On the other hand, the observing X-ray facilities in orbit tell us about the short term variability of SgXBs, within the reach of a mission lifetime (Fürst et al., 2018). Numerical models of the accretion flow provide the missing link between the two and have brought unprecedented insights on the geometry of these unresolved objects (Blondin et al., 1991).

In this context, I have used and developed state-of-the-art magneto-hydrodynamics codes in an attempt to follow the flow from the Dantean stellar surface down to the magnetic vicinity of the NS or the relativistic surroundings of the black hole. I have laid the foundations of a **consistent representation of the accretion process in SgXBs** by isolating the appropriate physics at stake at each scale, accounting for the complexity of the flow geometry (accretion tail in the wake of the compact object, photoionized and shocked regions, etc) and neatly linking the scales together. My work has helped to interpret observations of the **time variability we observed in Vela X-1** with the Chandra X-ray observatory (see section 1). It brought new insights on the accretion process and the mass and angular momentum transfer mechanism which shapes the secular evolution of massive binaries and determines their final fate. **In agreement with observations of Cygnus X-1 and the ULX M101 ULX-1**, I have shown that **wind-captured discs could form around a wind-fed accretor**, without Roche lobe overflow of the donor star (see section 2). For accreting NSs, where the applied torques on the magnetosphere depend strongly on the geometry of the accreting flow, **the implications for the spinning up/down of the NS might be substantial**. Finally, the versatility of the numerical setups I have designed enabled me to look at a totally different type of binaries. Around two asymptotic giant branch stars, I contributed to the **discovery of the imprints left in the stellar wind by the presence of a previously unseen orbiting companion**, with dramatic consequences on the maximum mass loss rate of this type of stars.

1 Time variability in Supergiant X-ray binaries

[1] ***Axisymmetric hydrodynamical Bondi-Hoyle accretion onto a compact object***
El Mellah & Casse, MNRAS 2015
[2] ***Accretion from a clumpy massive-star wind in Supergiant X-ray binaries***
El Mellah, Sundqvist & Keppens, MNRAS 2018
[3] ***The clumpy absorber in the high mass X-ray binary Vela X-1***
Grinberg, Hell, El Mellah et al., A&A 2017

Continuous monitoring of SgXBs has revealed an incredible time variability (e.g. off-states and flares) which could shed light on the micro-structure of the stellar wind. Using the orbiting X-ray source as a backlight, we could evaluate the degree of inhomogeneity or "clumpiness" of the wind. Since clumpiness systematically alters the values of the mass loss rates we derive from observations, improved constraints on the wind clumpiness would be of tremendous importance to predict the properties of the compact remnants massive stars eventually collapse into, for instance their mass distribution.

During my PhD, I developed a hydrodynamical representation of the ideal wind accretion configuration, where a compact object captures material from a planar homogeneous supersonic wind (upper right insert in the left panel in Figure 1). I implemented semi-analytic boundary conditions to avoid spurious reflections of acoustic waves at the inner boundary and enable the computation to numerically relax. Since the scale at which the flow is significantly perturbed by the presence of the accretor is orders of magnitude larger than the compact object for realistic wind speeds, we designed, with my PhD advisor Fabien Casse (APC) a stretched self-similar spherical grid centered on the accretor. We then characterized the structure of the bow shock and the accretion tail which form as the flow is beamed towards the compact accretor, but also the actual mass accretion rate onto the compact object and the dependence on the Mach number of the incoming flow [1].

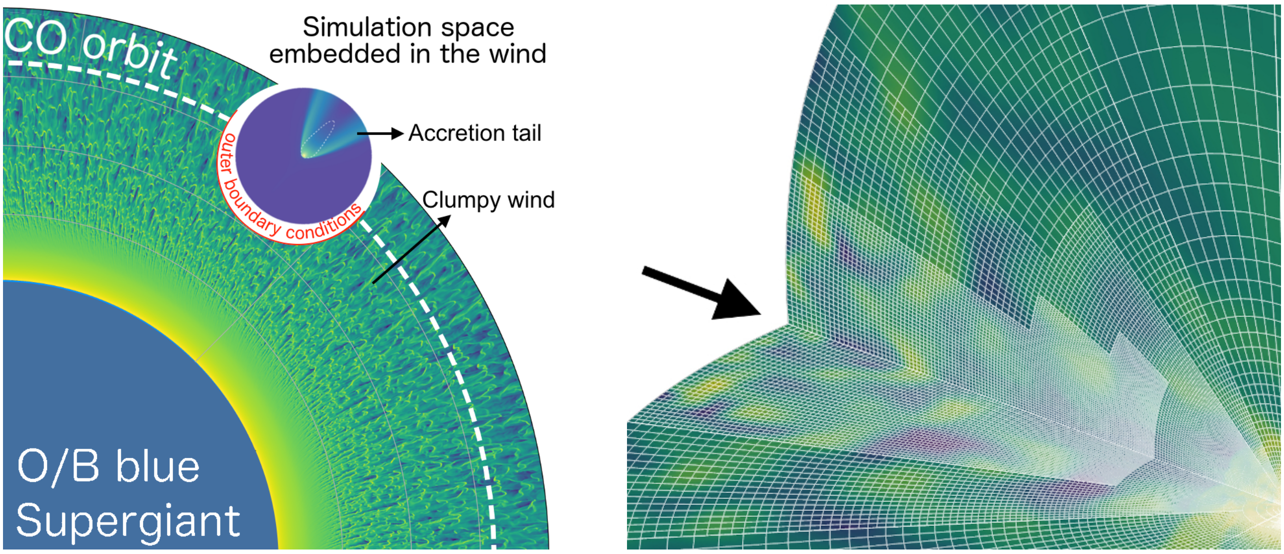

Figure 1: (*left*) Simulations where the multi-dimensional micro-structure of the wind of the hot donor star is for the first time resolved and followed as it is accreted by the compact object (CO). (*right*) The clumps enter the simulation, perturb the shock and form transient disc-like structures around the accretor in the bottom right corner (see Figure 2). The 3D mesh illustrates how the coupling between a radially stretched grid and the adaptive mesh refinement algorithm enables us to monitor all the flow at once up to five orders of magnitude.

During my first postdoctoral year, this setup served as a reference to study the effect of the clumps formed by internal shocks in the line-driven winds of hot stars. For long, it was proposed that the observed flares in a SgXB like Vela X-1 could be provoked by the serendipitous capture of a clump. However, with Rony Keppens and Jon Sundqvist (KU Leuven), we showed in [2] that realistic clumps computed from radiative-HD simulations do not undergo direct accretion (Figure 1). For the first time, we characterized how the material redistributes after the clumps impact the shock. The induced flares do not directly relate to individual clumps but are rather triggered by instantaneous angular momentum cancellation within the shocked region. Our results drove the community into exploring additional instabilities at the outer rim of the NS magnetosphere to reproduce the observed variability in SgXBs (Bozzo et al., 2008).

In [3], we reported coherent absorption events in Vela X-1. I was responsible for the interpretation and showed that these events could only be due to unaccreted clumps passing by the line-of-sight, provided the clumps were larger and the wind slower than expected. This result inspired the second part of my work on enhanced wind accretion.

2 Enhanced accretion, wind-captured discs and orbital compression

[4] ***A numerical investigation of wind accretion in persistent Supergiant X-ray binaries***
El Mellah & Casse, MNRAS 2017
[5] ***Formation of wind-captured discs in SgXBs: consequences for Vela X-1 & Cygnus X-1***
El Mellah, Sanders, Sundqvist & Keppens, A&A 2019
[6] ***Wind Roche lobe overflow in HMXBs: a mass transfer mechanism for ULXs***
El Mellah, Sundqvist & Keppens, A&A 2019
[7] ***Reduced maximum mass loss rates of OH/IR stars due to unnoticed binary interaction***
Decin et al., Nature Astronomy 2019

In my last year of PhD, I designed a model to study how the coupling between stellar, wind, orbital and accretion parameters in SgXBs could provide reliable estimates of the amount of angular momentum captured by the compact object [4]. I identified the configurations suitable to accrete enough angular momentum to form disc-like structures within the Roche lobe of the accretor. It seemed to require stringent conditions on the speed of the wind, which had to be very low compared to what was considered at that time in the literature. However, refined observations and stellar atmosphere computations later on suggested that line-driven acceleration might be more progressive than initially thought, leading to low speeds at the orbital separation. It drove me into performing full 3D hydrodynamics simulations with the appropriate sets of parameters I had found in [4]. In [5], I showed that, below a certain ratio of wind speed by the orbital speed and provided radiative cooling was accounted for, a centrifugally-maintained structure could form between the shock and the NS magnetosphere below which the disc is truncated (see Figure 2, Ghosh et al., 1979).

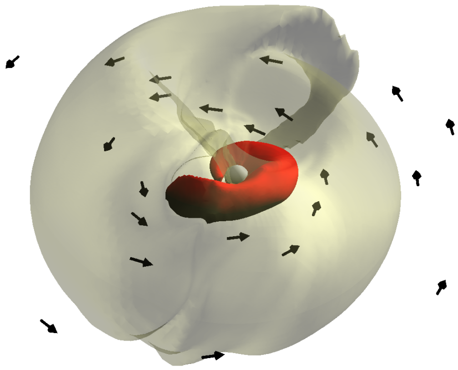

Figure 2: In simulations of wind accretion in SgXBs, I discovered a wind-captured geometrically thick disc around the central NS, while this type of flow was previously thought to be spherical. It was made possible by the five orders of magnitude spanned by these simulations, from the orbital scale down to the magnetosphere.

With these simulations, I noticed that this regime known as wind - Roche lobe overflow (Mohamed et al., 2011) was also associated to a surge of the rate at which mass is transferred due to the compression of the wind into the orbital plane. Therefore, I proposed a new mechanism for mass transfer in Ultra-luminous X-ray sources which, because it does not require Roche lobe overflow, explains how a small donor star like in M101 ULX-1 can feed a compact object accreting at a super-Eddington rate [6].

In [7], we invoked binarity to solve the controversy on the existence of a superwind phase which was claimed to end the life of cool giant stars such as AGB stars : the orbital density enhancement of the wind induced by the presence of a previously unseen companion is large and leads to significant overestimates of the mass loss rate when the wind is wrongly assumed to be isotropic. In ALMA observations of molecular lines around two OH/IR stars, a subclass of asymptotic giant branch stars, we detected spiral structures identifying them as wide binary systems. In the corresponding paper, I adapted the codes I had developed for SgXBs to show that for realistic parameters, the wind of the OH/IR stars was strongly compressed into the orbital plane due to the presence of this previously undetected binary companion. It showed that the reported OH/IR star mass loss rates assuming an isolated star had been overestimated by a factor of a few to a few 10, depending on the binary orbit parameters, which has important consequences for the secular evolution of these objects.

3 Code development & Kepler data analysis

[8] *MPI-AMRVAC 2.0 for Solar and Astrophysical Applications*
Xia, Teunissen, El Mellah et al., ApJS 2018

[9] *A study of the shortest-period planets found with Kepler*, Sanchis-Ojeda et al., ApJ 2014

[10] *Triple-star candidates among the Kepler binaries*, Rappaport et al., ApJ 2013

[11] *Possible disintegrating short-period super-Mercury orbiting KIC 12557548*
Rappaport, Levine, Chiang, El Mellah et al., ApJ 2012

For the last years, I have extensively developed the magneto-hydrodynamics finite volume code `MPI-AMRVAC`. I implemented an angular momentum preserving scheme to guarantee the conservation of angular momentum to machine precision. This step was decisive to insure the robustness of the disc properties I reported on in [5]. I designed a radially stretched spherical grid and coupled it to an adaptive mesh refinement algorithm to monitor the accretion flow over several orders of magnitude at an affordable computational cost (see Figure 1, right panel). I made this new functionality public, documented its usage and validated it on the classic 1D Bondi spherical accretion in a paper describing new numerical techniques we developed for `MPI-AMRVAC 2.0` [8]. I also wrote a conservative scheme to handle viscosity as a flux term and apply the slope-limiting methods which enable us to combine high-order accuracy and stability in the solvers we use. On my own, I coded a ballistic integrator adapted to explore the effects of binarity on different types of winds (e.g. from O/B supergiant stars or asymptotic giant branch stars) that I used in [5], [6] and [7].

Finally, I volunteered to join the Kavli Institute for Astrophysics and Space Research (MIT) from September 2011 to July 2012 and took an active part in the Kepler satellite data analysis effort under the supervision of Saul Rappaport. I used a prospective method to measure masses of very low mass stars in orbit around an F/G companion by using the Doppler boosting of light to get a photometric access to the radial velocity. Using the PyKE data reduction pipeline, I filtered thousands of Kepler light curves before Fourier transform to highlight potential short orbital period signatures. I would then fold and bin the data at the identified period, and that is how I ran into the peculiar transits of Kepler-1520b, the first disintegrating and super-Mercury exoplanet that we characterized in [11]. I also developed a pipeline to systematically look for eclipse timing variations, typical of the presence of a perturbing third body. It contributed to the identification of 30 new hierarchical triple star systems which could not have been detected with the transit method [10] and to a detailed analysis of the shortest-period exoplanets [9]. This seminal experience in Research laid the foundations of my scientific program : a better understanding of stellar bodies and remnants in interaction with their environment.

[1] J. M. Blondin, I. R. Stevens, and T. R. Kallman, Astrophys. J. (1991).
[2] E. Bozzo, M. Falanga, and L. Stella, Astrophys. J. (2008).
[3] F. Fürst, P. Kretschmar, V. Grinberg, et al., XMM-Newton workshop proceedings (2018).
[4] P. Ghosh, and F. K. Lamb, Astrophys. J. (1979).
[5] S Mohamed, and P. Podsiadlowski, ASP Conf. Ser. (2011).
[6] T. M. Tauris, and E. van den Heuvel, Compact stellar X-ray sources (2006).

Electromagnetic counterparts of NS-NS/BH-NS coalescences

What they tell us about the ultimate moments of merging compact objects

The discovery of the first gravitational wave (GW) signal three years ago marked the dawn of a new multi-messenger astronomy (The LIGO/Virgo Collaboration, 2016). Four decades after the indirect GW detection by Hulse and Taylor in an inspiralling pulsar binary (Hulse et al., 1974), we are now fully able to capture the very last moments of the epic life of massive stars through the burst of GW emitted when the compact remnants eventually merge. If the first detections were interpreted as merging black holes (BHs), without any electromagnetic counterpart, a GW signal from two merging neutron stars (NSs) was observed in 2017 in association with a short gamma ray burst (GRB) and a subsequent luminous blue kilonova (The LIGO/Virgo Collaboration, 2017). The crossed analysis of these three signals can unearth invaluable information on a multitude of aspects: the equation-of-state of condensed matter in NSs, the nucleosynthesis of the heaviest elements and new constrains on gravity in the strong field regime are only a few examples of the promising breakthroughs ahead.

The short GRB and kilonova emission which followed this double NS merger were particularly unusual. The host galaxy turned out to be an early-type galaxy and the short GRB was faint while the kilonova was luminous and blue. Although unusual, these properties were certainly not marginal: searching the archival data, Troja et al. (2018) identified another pair short GRB/kilonova with a similar unexpected behavior, albeit without GW detection due to instrument limitations at the time of this event, early 2015.

Although much uncertainty remains on the exact coalescence rates of NS-NS and BH-NS binaries, the current and incoming facilities (Advanced LIGO in the US, Advanced Virgo in Europe, KAGRA in Japan, LIGO-India and, on a longer time scale, LISA) are expected to detect from a few to one hundred GW events per year (Kim et al., 2015). Observers have sketched new diagnostics (Gill et al., 2018) to analyze the incoming mergers but their efforts will be partly wasted if they cannot rely on robust numerical results to put their data into perspectives. Typically, it was previously thought that the first NS-NS mergers would not be associated to a GRB because of the low probability to be aligned with the relativistic jet whose emission is strongly beamed. To figure out whether the GRB/GW common detection of 2017 was a mere coincidence or a symptom of flaws in the models, we need to carry out full three-dimensional numerical simulations to evaluate the bias introduced by the inclination of the system with respect to our line-of-sight. In this research project, I propose to bring a new complimentary tool and expertise to the IAP with numerical simulations based on advanced high-performance computing techniques. I intend to make use of the finite volume code `MPI-AMRVAC` I have used and co-developed, to characterize the geometry of the different components associated to a NS-NS/BH-NS coalescence (see Figure 1). This code provides a versatile environment to solve the equations of magneto-hydrodynamics (MHD) in their conservative form, in a classical or relativistic framework.

During the last decade, numerical simulations have revolutionized the field of core-collapse supernovae and provided an inestimable support to understand long GRBs. They showed how important three-dimensional dynamics and micro-physics (e.g. neutrino heating) could be to solve the old conundrum of the stalling shock. Thanks to the improved computing capacities, the gap was finally filled between observations performed with instruments such as Fermi and semi-analytical models developed by theoreticians such as Frédéric Daigne (IAP) and Thierry Foglizzo (CEA/Irfu). Now that compact object mergers are directly within our reach, it is time

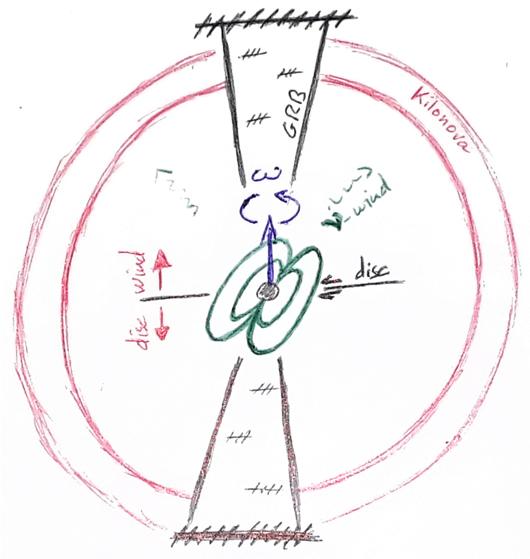

Figure 1: Simplified sketch of the different physical components at stake during a NS-NS/BH-NS coalescence. The central black dot stands for the merger remnant. If it is a NS, a magnetosphere is expected (green dipole), along with a magnetar wind nebula containing copious amounts of neutrinos ("ν-wind"). Material ejected in the equatorial plane of the fastly rotating remnant might sometimes form a disc from which a neutrino-driven wind can depart. The jets responsible for the short GRB are represented in black (with double lines indicating internal and external shocks). The kilonova (in red) comes from outflowing material. The details of these pictures depend strongly on the initial merger and the nature of the remnant.

to deploy the same efforts for short GRBs and kilonovae. Supercomputers such as the ones I daily use already exist at the national (e.g. CINES in France and VSC in Flanders) and European levels to carry out this computational investigation, and so do the massively parallel codes such as `MPI-AMRVAC`.

The IAP gathers many experts of gravitation theory and explosive high-energy phenomena, two key aspects to fulfill the aims of my research project. In the GreCo team (Gravitation et Cosmologie), led by Guillaume Faye, people study the GW signals produced by the coalescence of two compact objects, along with the imprints left by departures from current theories of gravitation in the strong field regime. In the ASTHUP team (Astrophysique des Hautes Energies et Univers Précoce), led by Frédéric Daigne, GRBs and quasars are extensively modeled to understand their emission of high-energy radiations and particles. Beyond the wide theoretical knowledge available at IAP, the institute also takes part in observational campaigns of direct interest for the study of short GRBs such as the upcoming French-Chinese multi-wavelength *SVOM* mission (Space-based multiband astronomical Variable Objects Monitor) whose launch is scheduled for 2021. I apply to join the ASTHUP team at IAP for I believe the skills I have developed in numerical simulations will be a precious complimentary asset in the study of high-energy phenomena associated to GW emission. Reciprocally, the semi-analytical models developed at IAP are vital to guide the designing of appropriate numerical setups and validate the robustness of the simulations, as were the theoretical predictions of Foglizzo et al. (1997) on the topology of the flow when I modeled the Bondi-Hoyle-Lyttleton accretion regime (El Mellah et al., 2015). In parallel, I intend to join the *SVOM* team at IAP to confront emission properties derived from my numerical simulations to observations, as we did in Grinberg et al. (2017) with Chandra observations of Vela X-1. The following sections explain in more detail which questions I propose to address and how I would build upon the expertise available in the ASTHUP and GreCo teams.

1 Gamma-ray bursts

Short GRBs are intense non-repeating flares of approximately 10^{51} ergs released as gamma-rays over less than two seconds (Berger, 2014). With the discovery of an X-ray afterglow by Gehrels et al. (2005) came the identification of the host galaxy of a short GRB and the confirmation of their cosmological origin. They have long been thought to be powered by the accretion of a massive remnant disc onto the compact object formed after a NS-NS/BH-NS merger (Eichler et al., 1989). The interplay between accretion and rapid rotation of the central engine can drive a collimated ultra-relativistic outflow or a jet (Piran, 2005). Relativistically beamed gamma-ray emission arises from energy dissipation via internal shocks within the jet (Rees et al., 1992) and external shocks with circumburst material generate the aforementioned afterglow (Kumar et al., 2015). In France, GRBs lie at the core of the theoretical models developed by Frédéric Daigne, Robert Mochkovitch and their collaborators in the ASTHUP team but also by Guillaume Dubus, Benoît Cerutti, Guy Pelletier and the Sherpas group at IPAG and by Thierry Foglizzo and his collaborators at CEA/Irfu. They are the prime targets of the *SVOM* mission and many people in France are devoted to their observational study, at IRAP for instance. Furthermore, mid-January 2019, a rapid follow-up of the GRB *GRB-190114C* detected by Swift/BAT led to the first sub-TeV detection of a GRB from the ground thanks to the MAGIC Cherenkov telescopes. Although the origin and properties of this GRB are still unclear, it opens the possibility of ground-based gamma-ray Astronomy with the upcoming CTA (Cherenkov Telescope Array) France is involved in.

The accretion disc plays a key role in the accretion/ejection mechanism which connects the different components and eventually produces the electromagnetic counterpart we observe. Due to its connections with the jet responsible for the short GRB, I want to address the following main questions:

1. under which conditions a disc is formed and which are its initial properties?
2. how do disc outflows develop and to what extent do they constrain the lateral expansion of the jet?

1.1 Accretion discs formed by NS tidal disruption

When two NSs merge, a fraction of the material is tidally disrupted and can form a disc (Baiotti et al., 2017), while magnetic field rearrangement occurs (Crinquand et al., 2018). When a NS merges with a BH, the situation is different: a disc can only be formed provided the tidal disruption of the NS occurs before the innermost stable circular orbit (ISCO), a critical distance below which the amount of angular momentum is too low to maintain a circular orbit. The constrain set by the presence of the ISCO has been shown to be very stringent. In Figure 2, I represented in fully opaque green the zone where the tidal disruption of a $1.4M_\odot$ NS would lead to the formation of a disc (based on arguments inspired from Foucart, 2012). This preliminary approach seems to indicate that only mergers of NSs with low mass BHs ($\lesssim 5M_\odot$) could lead to the formation of a disc but the result depends strongly on the BH spin and the redistribution of angular momentum between the ejected material and the inspiralling NS. Numerical simulations are required to evaluate the disc properties and its dependencies on the different parameters.

I will make use of the angular momentum preserving scheme I developed for `MPI-AMRVAC` to monitor the disc formation in NS-NS/BH-NS mergers with numerical simulations. To avoid any non-physical variations of the total angular momentum, I implemented a new way to solve the conservation of linear momentum which guarantees angular momentum conservation to machine precision (El Mellah et al., 2018a). It assures that the obtained discs have radial extensions physically accurate. I would be able to make use of the post-Newtonian formalism developed by Luc Blanchet, Guillaume Faye and their collaborators in the GreCo team at IAP to significantly speed up the simulations. Indeed, the full general relativistic treatment of the dynamics requires costly root-finding algorithms we could bypass thanks to a post-Newtonian formulation of the equations. Because computationally-demanding three-dimensional simulations will be required to evaluate the impact of the line-of-sight on the observables, such a speed-up is of prime importance.

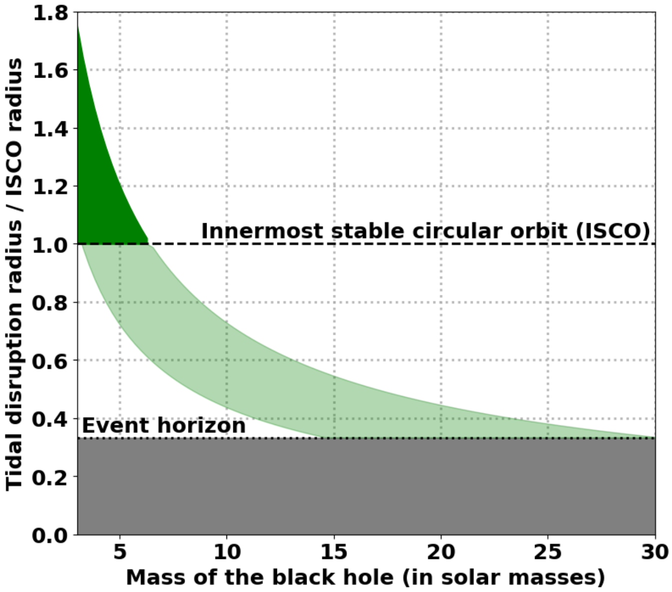

Figure 2: Ratio of the tidal disruption radius of a $1.4M_\odot$ NS by the radius of the ISCO of a non-rotating BH, as a function of the mass of the BH. The green shaded region shows the estimated tidal disruption radius for a NS radius between 9km (lower limit, high compacity, soft equation-of-state) and 15km (upper limit, low compacity, stiff equation-of-state). The tidal disruption radius needs to be larger than the ISCO radius to form a disc (fully opaque green shaded region).

1.2 Disc accretion / ejection and jet collimation

Beyond the question of the structure of the disc, it is necessary to understand how the surroundings (kilonova and jet) can be impacted by the disc, both through disc outflow and radiation. Since the heating rate of the kilonova due to fall-back accretion (Rosswog, 2007) can be of the same orders of magnitude as radioactive decay or magnetic heating (see sections 2.1 and 2.2 respectively), the interpretation of the kilonova light curves observed after a merger will require an accurate understanding of this connection .

During the first seconds following the merger, when the disc is a proficient source of neutrinos, disc outflows can rival or even dominate the dynamical ejecta i.e. the mass ejected from the contact interface between the colliding NS. Although physical differences exist between neutrinos and photons, the numerical treatment of neutrinos transport share many common points with the aforementioned radiative transfer problem. Simulations of neutrino-driven winds would quantify the amount of mass and energy reinjected in the kilonova by the disc outflow. As neutrino-cooling becomes inefficient, the disc transitions to a geometrically thick regime and the wind becomes richer in heavy elements such as lanthanides whose high opacity changes the emission properties. The hot surface of the disc acts like a stellar photosphere and the wind launching mechanism is similar to the one of line-driven winds of massive stars (Castor et al., 1975), a topic I extensively studied for the last three years, using numerical techniques such as periodic long characteristics in Cartesian slabs and effective acceleration inhibition distance (El Mellah et al., 2018b). I will extend these methods to model the specificities of this type of discs.

In such a highly optically thick disc, the coupling between matter and radiation must be accounted for. In order to do so, we developed an implicit multi-grid solver with Jannis Teunissen (CWI Amsterdam) and Nicolas Moens, a graduate student I co-supervise with Jon Sundqvist in KU Leuven. It is based on a flux-limited diffusion approach which represents a computationally-affordable method to solve the radiative transfer equation.

Finally, once the disc outflow has been constrained, its connection with the jet could be studied without prescribing ad hoc launching conditions. It has been suggested that the lateral expansion of the jet is initially limited by the denser disc wind (see Figure 3). Using `MPI-AMRVAC` with post-Newtonian prescriptions, I could study the modalities of this confinement in high-resolution three-dimensional simulations. On this occasion, I would actively collaborate with Martin Lemoine (IAP) whose work on collisionless relativistic shocks in the jet produced by non-stationary launching conditions (Pelletier et al., 2017) would benefit from these numerical simulations.

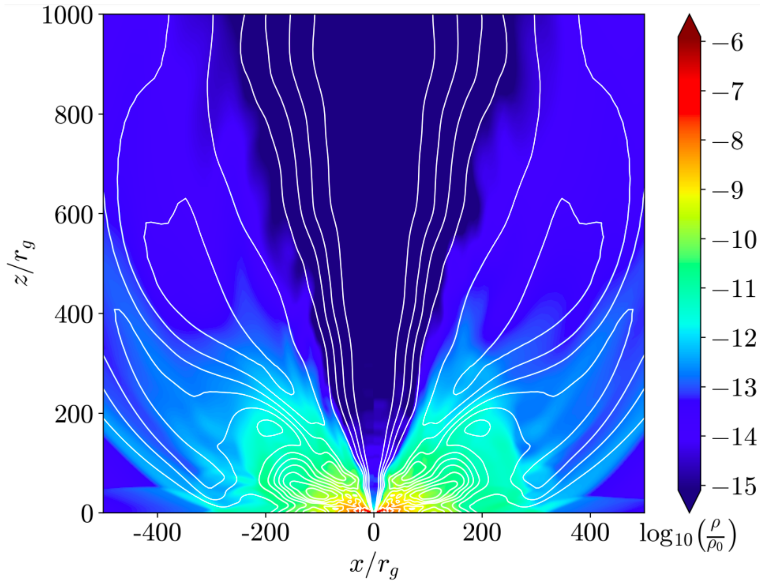

Figure 3: Density and magnetic field contours from a simulation by Kathirgamaraju et al. (2019) where a low-density relativistic jet is launched from the compact object at the origin. The lengths are scaled with gravitational radii and $\rho_0 \sim 7 \cdot 10^{16}\text{g}\cdot\text{cm}^{-3}$. These simulations were performed from a prescribed torus as initial conditions.

2 Kilonovae

Kilonovae are week-long supernovae-like transients found in association with short GRBs, with a spectral peak ranging from near infrared to optical and a peak luminosity at $10^{40-41}\text{erg}\cdot\text{s}^{-1}$ reached after a few days (Tanaka, 2016; Metzger, 2017). They are thought to be produced by neutron-rich material ejected during a NS-NS/BH-NS merger: as the mildly relativistic cocoon expands, it is heated by radioactive decay (Li et al., 1998) but also by fall-back accretion onto the central body (see section 1.2) and possibly by a millisecond magnetar formed by the merger (Yu et al., 2013).

The relative contribution of these mechanisms will be a central problem to interpret the kilonovae light curves observed in coincidence with GW signals from NS-NS mergers, which will lead the community to address the following questions:

1. How neutron-rich are the different components of the ejecta?
2. How can the rotational energy of a fastly rotating magnetar remnant be transferred to the ejecta?

2.1 A site for nucleosynthesis of neutron-rich elements

Kilonovae have long been suspected to be the main site for the nucleosynthesis of the heaviest elements (Lattimer et al., 1974), along with core-collapse supernovae (MacFadyen et al., 1999). Due to their dense neutron-rich content (i.e. low electron fraction), kilonovae can be the stage of rapid neutron-capture by seed nuclei like Iron, the so-called "r-process". The yield of this nucleosynthesis and the associated heating of the kilonova can be derived from nuclear reaction networks (Metzger et al., 2010) and the electron fraction, with higher yields for lower electron fractions. However, the electron fraction can only be deduced once we properly account for neutrino-irradiation: neutrino absorption reactions on nucleons increase the electron fraction of the material and might inhibit the formation of lanthanides. Since the opacity of lanthanides can quickly dominate and determine the properties of a kilonova light curve, we need to figure out how neutrinos interact with the different components during a NS-NS/BH-NS merger.

Computationally efficient methods to solve neutrino transport in the context of core-collapse supernovae have been developed by members of the LUTh in Meudon (Peres et al., 2011; Peres et al., 2014). I propose to extend this treatment to NS-NS/BH-NS mergers and implement it in a form suitable to be used in conjunction with `MPI-AMRVAC`. During my postdoctoral years, I have worked on different schemes to solve the radiative transfer equations: methods inspired from long characteristics with Jon Sundqvist, flux-limited diffusion and an alternating directional implicit scheme with Nicolas Moens and multi-grid solvers with Jannis Teunissen. I will adapt these methods to neutrino transport. Coupling the micro-Physics to the flow dynamics has become an absolute requirement to improve our understanding of these high-temperature environments.

2.2 Spinning down of a magnetar remnant

Extraction of the huge rotational energy contained in a millisecond magnetar (i.e. with a magnetic field strength above 10^{14}G) via electromagnetic torques might significantly enhance the electromagnetic emission from NS-NS mergers. It could be a major source of heating for the kilonova, provided it can sustain a high spinning down luminosity for long enough (see Figure 4). The modalities of the coupling between the plasma and the magnetosphere depend strongly on the relative extension of the magnetosphere with respect to the corotation radius, the radius at which the period of a Keplerian orbit matches the NS spin period (see e.g. the propeller effect described in Bozzo et al., 2008).

I am currently working, in collaboration with Zakaria Meliani (LUTh), on MHD setups to compute torques applied to NSs in X-ray binaries. Thanks to the radially stretched meshes I implemented during my PhD, we could adapt these setups to kilonovae and characterize the impact of the interaction with the spinning down magnetosphere on the dynamics of the flow.

This work would bring key information to shed unprecedented light on another topic of interest of contemporary Astrophysics: the internal structure of NSs and their equation-of-state (EOS). When a NS-NS merger occurs, three different types of remnants can be formed, from the lighter to the heavier: a stable NS, a supramassive NS sustained by its solid body rotation, or a body immediately collapsing into a BH (for simplicity, I include hypermassive NS in this last case). While a stable magnetar can participate indefinitely in the heating of the kilonova (although at lower levels as time goes by), a supramassive NS will collapse into a BH once it spins down below a certain threshold: in this case, only a fraction of the rotational energy can be extracted before the NS collapses. The possibility of a short or long-lived NS remnant could not be ruled out in the GW signal of the 2017 double NS merger.

In Figure 4 is represented the simplified spinning-down luminosity of an aligned rotating dipole (Spitkovsky, 2006; Philippov et al., 2015). Its plateau value scales as the square of the NS magnetic field but the spinning down time scales as the revert of the square of the magnetic field: a higher magnetic field starts at a higher luminosity level but quickly decreases below the plateau level a lower magnetic field can sustain for a longer period of time. The premature endings of the curves for a supramassive NS (green lines) indicates the collapse of the NS into a BH, assuming a NS EOS which leads to a collapse time similar to the spinning down time for a $2.4\mathrm{M}_{\odot}$ NS (based on Metzger et al., 2015).

These four illustrative limit cases could be explored in much more detail with full three-dimensional MHD numerical simulations. I am willing to make use of the extensive numerical expertise I have acquired in this domain over the last years to capture these different regimes and evaluate the impacts on the light curve of the kilonova. The effect of the collapse time, tidally linked to the EOS of the condensed matter in NS interior, could also be investigated. Once confronted to a large sample of observed double NS mergers, numerical results would set stringent constrains on the NS EOS.

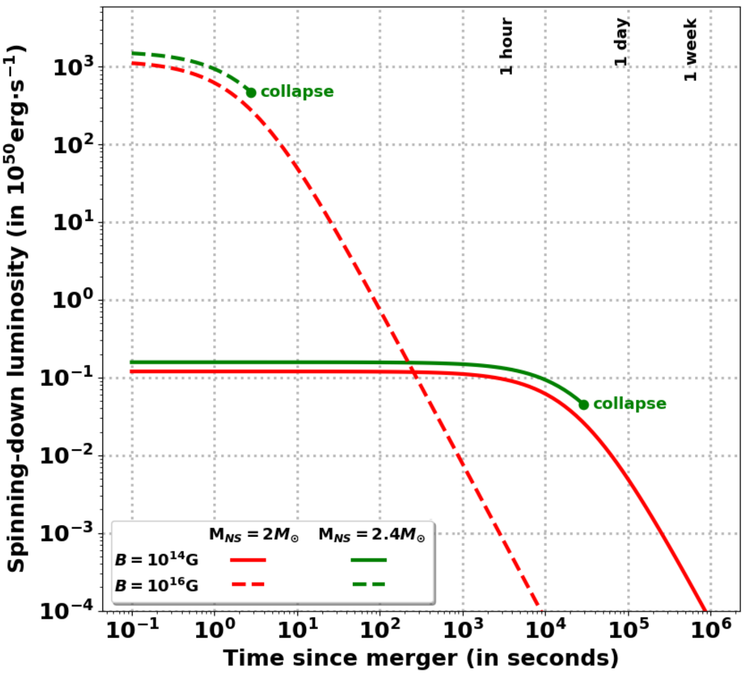

Figure 4: Rates of NS rotational energy decay as a function of time. Different NS magnetic field strengths and masses are considered, and standard parameters taken from Metzger (2017) are used. While a $2\mathrm{M}_{\odot}$ NS does not need centrifugal support to avoid collapsing into a BH, a $2.4\mathrm{M}_{\odot}$ NS might qualify as a supramassive NS (depending on the EOS) and collapse once it has evacuated too much rotational energy (green dots). See text for more details.

Conclusion

The properties of the electromagnetic counterparts detected with the GW signal of 2017 are still puzzling in many aspects. Was the blue color of the kilonova due to the formation of a long-lived NS whose flux of neutrinos could have inhibited lanthanide nucleosynthesis? Was its high luminosity due to the heating by fall-back accretion onto a BH formed by the merger of the two NSs? Or by magnetic heating from a strongly magnetized remnant NS? Was the short GRB intrinsically fainter due to the absence of BH formation (Murguia-Berthier et al., 2017)? Or was it an ultra-relativistic jet seen off-axis?

Many unanswered questions remain and more are to be expected in the next years. The interpretation of the plethora of kilonovae light curves and short GRBs to come requires a better understanding of the Physics at stake now that new constrains are set by the concomitant GW and GRB observations. I am willing to take part in this collective effort in the ASTHUP team at IAP. I have no doubt I can trigger new collaborations with the GreCo team to take advantage of their expertise in gravitational theory and foster renewed partnerships with the ASTHUP team, along with the neighboring LUTh at the Observatory of Meudon. On the long term, the X-IFU instrument aboard the Athena satellite will provide high-resolution X-ray spectra to characterize the ionization properties of the material surrounding the compact remnant after a NS-NS/BH-NS merger. It will bring new insights on the deposition of energy in the ejecta, of direct interest to be compared with predictions from numerical simulations.

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ENSEIGNEMENT

Résumé des enseignements dispensés

Après une première expérience d'enseignement au lycée Gustave Eiffel en 2010 dans le cadre de mes études à l'ENS de Cachan, j'ai été reçu second au concours de l'Agrégation de Physique en 2011. Durant la 1^{e} année de mon monitorat de thèse, ma mission d'enseignement s'est déroulée pour moitié en Première Année Commune aux Etudes de Santé (PACES) sous la direction d'Isabelle Grenier (AIM, Paris 7). J'y étais responsable de deux 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. J'encadrais ensuite les travaux pratiques du cours de M1 "Traitement du signal - Signaux déterministes" de Laurent Daudet (Institut Langevin, Paris 7), à hauteur de 32h TD (signaux discrets, analyse de Fourier, convolutions, spectre de puissance, filtrage, etc). En 2^{e} et 3^{e} année de thèse, j'ai rejoint l'équipe de Cécile Roucelle (APC, Paris 7) où j'ai encadré les TDs de Mécanique du point en L1. Durant les 128h qui m'ont été assignées, j'ai formé et évalué des étudiants néophytes aux spécificités du raisonnement physique.

En 1^{e} année de contrat postdoctoral à l'Université de Leuven, j'ai encadré des projets scientifiques de Master dans l'unité d'enseignement *Computational Methods for Astrophysical Applications* dirigée par Rony Keppens ($\sim$60h TD). En 2^{e} année, je me suis porté volontaire pour encadrer deux groupes de TD d'étudiants en 1^{e} année de Génie biologique, dans le cadre d'un cours d'Algèbre linéaire. Cette année, je remplace Rony Keppens comme co-responsable du cours de Master *Computational Methods for Astrophysical Applications* à l'occasion de son départ en année sabbatique ($\sim$40h de cours).

2018-19	Computational methods for Astrophysics	40h cours	M2	KU Leuven
2017-18	Algèbre linéaire	30h TD	L1	KU Leuven
2016-17	Computational methods for Astrophysics	60h TD	M2	KU Leuven
2014-16	Mécanique du point	128h TD	L1	Paris 7
2013	Physique pour les PACES	32h TD	L1	Paris 7
2013	Systèmes et signaux déterministes	32h TP	M1	Paris 7
2009-10	Cours en Seconde et Terminale	16h cours	Lycée Gustave Eiffel	

Insertion dans l'UFR de Physique de Sorbonne Université

Le remaniement des maquettes de Licence et de Master amènera l'UFR de Physique de Sorbonne Université à contribuer aux portails d'enseignement pluridisciplinaires MIPI (Mathématiques Informatique Physique Ingénierie) et PCGI (Physique Chimie Géosciences Ingénierie). A travers un système de majeur/mineur, les étudiants s'investiront dans le développement d'un profil personnel où un cursus majeur en Physique à partir de la deuxième année peut être associé à une mineure dans un autre domaine. Grâce à l'UE OIP (Orientation et Insertion Professionnelle), les étudiants pourront construire un projet de formation cohérent tout en explorant de nouvelles pistes. La diversification des profils exigera du corps enseignant une capacité accrue à adapter le cours à une audience aux connaissances variées. Grâce à la pluralité des cursus dans lesquels j'ai été amené à enseigner (études de santé, physique, mathématiques, biophysique, ingénierie), je pense pouvoir ancrer mon enseignement dès le L1 dans un socle commun où tout un chacun pourra se retrouver. En particulier, ma participation à l'équipe pédagogique pourra prendre les formes évoquées dans la suite de cette section.

Parce que la Physique est avant tout une science basée sur les observations et l'expérience, l'Agrégation fait la part belle à l'expérience avec l'épreuve du montage de Physique. Le vaste panel d'expériences illustratives que j'ai été amené à déployer à cette occasion, en partie disponible en ligne, témoigne de ma capacité à organiser les travaux pratiques en Licence et Master mais aussi au centre de préparation à l'Agrégation de Physique de Montrouge dirigé par Agnès Maître (INSP, Sorbonne Université) et dans lequel Sorbonne Université sera bientôt amenée à intensifier son activité. Sorbonne Université propose aussi un Master des métiers de l'enseignement, de l'education et de la formation où les séances en laboratoire sont nombreuses et préparent certains candidats au CAPES. Je pourrai également prendre une part active dans les enseignements de ce Master.

Si l'Agrégation a été l'occasion de faire l'examen de mes connaissances et de ma capacité à les transmettre à autrui, j'ai pu enrichir mes réflexions sur la méthode scientifique en elle-même grâce aux cours d'épistémologie de Nadine De Courtenay (SPHERE, Paris 7) durant ma première année de thèse. Pour initier à mon tour les étudiants de Licence à la méthode scientifique, je mettrai à profit cet enseignement en participant à l'organisation des ateliers de recherche encadrée ou bien d'autres séances d'apprentissage par projet comme celle de "boîte noire" déjà mise en œuvre par Stéphanie Bonneau (laboratoire Jean Perrin, Sorbonne Université).

Les cursus intégralement en anglais dans lesquels est impliquée l'UFR de Physique de Sorbonne Université se multiplient : le parcours international du Master en Physique des systèmes complexes (i-PCS, https://physics-complex-systems.fr/en/) et le Master de l'International Centre for Fundamental Physics en partenariat avec l'ENS PSL par exemple. Au sein du Master i-PCS, j'ai les compétences requises pour dispenser le cours de Physique non-linéaire et celui de simulations numériques qui se déroulent tout deux au premier semestre de M2, à Paris. Ma maîtrise de l'anglais, grâce notamment à un séjour d'un an au MIT et à mon activité de recherche depuis, sera un atout pour participer à ces enseignements.

L'expertise numérique que j'ai acquise dans mon activité de recherche ces six dernières années me permettra de contribuer aux cours de Physique numérique, que ce soit pour l'introduction aux langages de bas niveau (Méthodes numériques et informatiques par Jacques Lefrère du LATMOS, Sorbonne Université) ou bien des enseignements plus avancés comme la résolution numérique de systèmes d'équations aux dérivées partielles. L'organisation logistique de l'enseignement, en mettant en place un réseau de machines virtuelles accessibles aux étudiants par exemple, ne m'est pas étrangère puisqu'elle a représenté une composante importante de l'enseignement *Computational Methods for Astrophysical Applications* auquel j'ai participé en tant qu'assistant en 2016 puis en tant qu'enseignant en 2018.

Au fur et à mesure que les technologies relatives au calcul hautes performances et aux systèmes intelligents se développeront (big data, machine learning, deep learning, etc), l'outil numérique dans les formations scientifiques prendra une place croissante. C'est pourquoi je souhaite aussi soumettre aux étudiants dès la Licence une base de donnée de sujets numériques d'exercices pour encourager le déploiement de compétences telles que la mise en ligne d'exposés intéractifs de leurs réponses via la programmation d'applets.

Réflexions sur les méthodes pédagogiques

Au-delà des enseignements que j'ai dispensés depuis 2010, j'ai manifesté un intérêt certain envers les questions relatives aux méthodes pédagogiques et en particulier à l'enseignement de la Physique. Fasciné par l'enseignement immersif de Jean-Michel Courty (LKB, Sorbonne Université), je me suis porté volontaire dès 2009 pour participer à une expérience de didactique organisée par Cécile De Hosson (LDAR, Paris 7) et ses collaborateurs. Grâce à l'ANR EVEILS qui leur avait été allouée, ils avaient pu développer un module de réalité virtuelle pour illustrer in situ des effets de cinématique relativiste, un billard relativiste où la vitesse de la lumière avait été ramenée à une valeur de l'ordre du mètre par seconde. L'enjeu était de vérifier l'assimilation profonde des notions de Relativité restreinte qui avaient été enseignées (composition des vitesses, aberration, effet Doppler, etc) en plaçant les sujets en situation.

Plus généralement, je crois que les nouvelles technologies d'immersion nous apportent une occasion inédite de déployer une forme d'enseignement inductive en complément de l'approche déductive qui est employée à présent. De la force de Coriolis à la polarisation d'une onde, nombreux sont les concepts qui gagneraient à être compris non seulement dans un cadre théorique mais aussi au travers de mises en contexte. Nous pouvons désormais procurer aux étudiants une intuition physique étendue à des idées largement étrangères à l'expérience quotidienne. Leur regard critique sur leurs propres résultats s'en trouvera grandi, ainsi que leur capacité à se représenter le comportement des modèles qu'ils seront amenés à développer par la suite.

Maintenir un niveau élevé d'attention tout au long d'un cours peut relever d'une gageure dès lors que les outils déployés semblent anachroniques au public visé. Mieux intéragir avec les étudiants nécessite de s'adapter aux formes de communication qui leur sont familières, sans pour autant dénaturer le contenu de l'enseignement dispensé. A cette fin, la vérification en temps réel de la bonne acquisition des connaissances avec des mini-quiz auxquels les étudiants répondent via des boîtiers interactifs me semble être une piste envisageable.

Conclusion

Compte tenu de mon parcours et de mon expérience d'enseignement ininterrompue depuis 2012, je pense avoir les compétences adéquates pour répondre aux objectifs d'enseignement de Sorbonne Université. Tant par mon volontariat que par ma formation personnelle à l'enseignement, j'ai témoigné de mon souhait de rejoindre le milieu universitaire pour y transmettre les savoirs qui m'avaient été dispensés. J'espère avoir l'occasion de mener à bien cette aspiration au sein de l'UFR de Physique de Sorbonne Université.