Title

Formation, evolution and impact of stellar binaries

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Equipe d'accueil : AHE/Gravitation (APC)

Context :

Massive stars live in binaries...

Several revolutions occurred in recent years in the stellar realm. The first one is the realization that most (over 75%) of massive stars live in a stellar couple (Sana et al. 2012). This binarity has major consequences on stellar evolution, strongly influenced by the presence of a "*companion*", in particular via transfer of mass and angular momentum (Chaty 2013, Garcia, Fogantini, Chaty et al. 2021). The fate of these stellar couples is determined by the evolution of each component, the most massive star collapsing first during the supernova explosion, giving rise to a neutron star or a black hole (Tauris et al. al. 2017). This marks the birth of an accreting stellar couple, formed of a compact star orbiting its companion, among the most fascinating stars in the Universe. The companion star, massive, is characterized by a substantial ejection of wind, depending on its composition, and the compact star, bathing in this wind, attracts part of this matter, which, accreted, accumulates onto the surface, heated to temperatures of several million degrees, emitting mainly in the field of X-rays. These stars regularly give rise to extreme variations in luminosity, of several orders of magnitude over the entire electromagnetic spectrum, on timescales ranging from seconds to months.

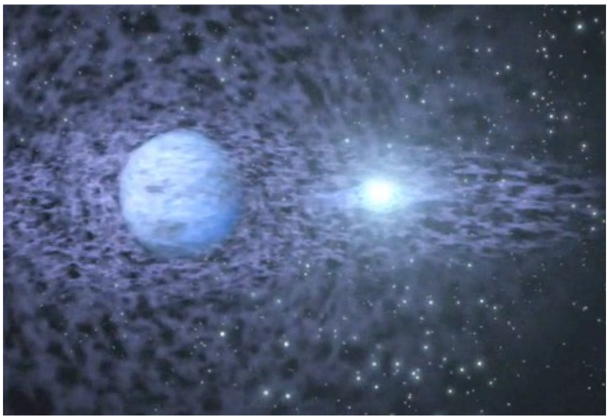
... until they merge…

The second revolution is the detection, by the interferometers of the LIGO/Virgo collaboration, of gravitational waves originating from the fusion of two black holes (first detection in 09/2015) then of two neutron stars (08/2017). This fusion occurs at the end of the evolution of stellar pairs, depending on their mass, their orbital separation, as well as several other parameters. The merging of two neutron stars is accompanied by an emission of electromagnetic waves, called *kilonova*, spectroscopic observations having detected for the first time, the creation of heavy atoms during this event, via the "*rapid process*" of nucleosynthesis (*r-process*).

…with an impact on their environment!

It is now established that the collapse of massive stars, in supernova, plays a key role in enriching the interstellar medium - from heavy atoms to complex molecules - as well as in triggering the formation of new stars. In contrast, the impact of the wind from these massive stars on their environment, throughout their lifetimes, has long been overlooked. However, this ejected matter disperses in the surrounding medium, until it collides with a dense interstellar medium, potentially at the origin of the triggering of new stellar formations, first suggested in the case of binaries, by observations with the *Herschel* satellite (Chaty et al. 2012, Servillat et al. 2014). Recent observations of r-process concomitant with the detection of a kilonova prove that the merging of two neutron stars is an important (if not major) contribution of nucleosynthesis in our Galaxy.

This PhD thesis, covering various fields of astrophysics, aims at studying the formation and evolution of these intriguing stellar couples, whose role is primordial within the cycle of matter, as well as their environmental impact, based on multi-wavelength observations from various ground and space observatories, including proprietary (ESO observatory) and public (*Gaia* satellite) data, and numerical simulations of stellar evolution, using the MESA code.



Objects of study:
Fig. 1: The objects of study are the stellar binaries, hosting compact objects (neutron stars and black holes, on the right) orbiting a massive star (on the left).

Description of the thesis work:

1. **The formation of massive stars** mainly depends on the characteristics of the surrounding interstellar medium at their birth - density, composition, rate of star formation - as well as on the mass and rotation of protostars. Observations, coupled with statistical studies, show that massive stellar binaries are born within stellar formation complexes, cradle of the most massive stars in our Galaxy (Coleiro & Chaty 2013, Fortin et al. subm.). These studies make it possible to follow the evolution of stellar pairs, in particular via parameters such as their age, speed, and migration distance from their place of birth. This part will be done mainly via multi-wavelength observations, using instruments at VLT observatory (such as wide-band X-shooter spectrograph), observational data released by astrometric *Gaia* satellite, and archival data from virtual observatories.
2. **The evolution of a massive star** within a stellar couple is determined by many factors, such as: mass ratio, orbital separation, and exchanges of matter and angular momentum. A large sample of compact binaries is now listed, which has grown considerably in recent years, consisting of stars at different stages of their evolution (Fortin et al 2018). We can thus compare the observational constraints on the spectral types, compositions, ages, *natal kicks*, and migration distances of these stars, with predictions of stellar evolution models. The fate of a couple of massive stars sometimes leads to the most energetic events in the Universe, when the two components collide and merge. This part will be performed via numerical 1D-hydrodynamical simulations of stellar evolution, using the public MESA code, installed on the DANTE cluster of APC.
3. **The environmental impact of massive stars** is a critical issue at all stages of stellar life. Indeed, throughout their life, massive stars eject an extremely powerful, dense and fast stellar wind, colliding with the interstellar medium. We have shown, from observations with the *Herschel* satellite, that the wind from a massive star could create a cavity in the surrounding interstellar medium, and even trigger stellar formation, as indicated by the presence of young stellar objects, around some massive stellar binaries. Finally, both supernova explosions and mergers of compact stars have a major impact on the surrounding interstellar environment, through the amount of ejected matter and released energy. This part will be done mainly using the 10 m - GTC (Gran Telescopio de Canarias) proprietary observations.

Description Group / lab / supervision :

This thesis, supervised by Sylvain Chaty, Professor at the University of Paris, will take place within the AHE (High Energy Astrophysics) and Gravitation group of APC (AstroParticule and Cosmology), an ideal laboratory for carrying out such a thesis, at the confluence of several fields of astrophysics —stellar formation, stellar binaries, interstellar medium, galaxies, gravitational waves, multi-messenger astrophysics…—. The PhD student will become member of the Virgo collaboration, via the APC Virgo group, especially within the Rates and Population working group.

Proposed work :

-Analysis of multi-wavelength observations: wide field photometry, spectroscopy, orbital parameters (ESO VLT/X-shooter, *Gaia* astrometric satellite…)
-Numerical 1D-hydrodynamical simulations of stellar evolution, using the public MESA code, installed on the DANTE cluster of APC.
-Writing of scientific articles
-Writing of telescope time proposals
-Oral presentations at national and international workshops/conferences

Training and skills required:

Master in Astronomy and Astrophysics

Acquired skills :

Several skills acquired and developed during this PhD thesis will be valuable and transferable to other fields: image analysis at different wavelengths (optical, infrared, radio), numerical simulations, data processing, writing of articles and proposals for telescope time, teamwork, oral presentations at national and international congresses.

Collaborations / Partnerships:

Various research collaborations (national/international) will be pursued and/or implemented during the PhD thesis.

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Bibliography :

Chaty et al., 2012, POS, 176, 92 ; **Chaty**, 2013, Advances in Space Research, 52, 2132 ; **Chaty** et al., Proc. IAU Symposium, 2019, 346, 161 ; **Coleiro** & Chaty, 2013, ApJ, 764, 185 ; **Fortin**, Chaty, Coleiro et al., 2018, A&A, 618, A150 ; **Sana** et al., 2012, Science, 337, 444 ; **Servillat**, Coleiro, Chaty et al., 2014, ApJ, 797, 114 ; **Tauris** et al. (including Chaty), 2017, ApJ, 846, 170