The leitmotiv for this thesis has been the understanding of the formation and the evolution of galaxies. To contribute pieces of the puzzle, we tackled this issue from a different point of view: we looked at all the stars that form a galaxy. To be sure, a galaxy is more than just billions of gravitationally-bound stars. It also consists of stellar remnants, interstellar gas and dust, and dark matter. The color of a galaxy is mainly due to the type of stars that compose the galaxy. Therefore, by comparing the spectrum of a galaxy with that of a star, it is possible to trace back the type of stars that prevalent within a galaxy. Recipes are used to model the spectral energy distribution (SED) of galaxies. We call this approach stellar population synthesis (SPS). The key ingredient, according to my – biased – point of view, is a set of libraries of stellar spectra. These libraries, either theoretical or empirical, are used to convert the outputs of stellar evolution calculations, such as surface gravity, effective temperature, into observable SEDs.

In this thesis, we chose to create a new empirical library. Besides the large number of existing libraries, empirical stellar libraries need improvements on the following points: better calibrations, more stars, higher spectral resolution and broader wavelength coverage. The technical progress made over the last decades leads to the emergence of new instruments, including the X-shooter spectrograph. This spectrograph, property of ESO (European Southern Observatory) and mounted at the Very Large Telescope (VLT) in Chile, offers the unique capability to produce in one shot a full spectrum from the ultra-violet wavelength range to the near-infrared (from 300 to 2480 nm), at a mean resolving power of 10 000.

During six semesters, we observed with X-shooter more than 700 stars from a variety of environments (from the nearby disc of the Milky Way to the Magellanic Clouds), with a variety of chemical compositions. All these stars are part of the X-shooter Spectral Library (XSL, P.I. S. C. Trager). Figure 5 shows an overview of our sample in a Hertzsprung-Russell diagram. The symbols represent the two phases of our survey: a Pilot survey (two first semesters) and the Large Programme (four semesters).

A large part of my thesis was devoted to the data reduction, in other words transforming the raw data into final one-dimensional spectra, ready for science application. To do so, we combined the tools provided by ESO with procedures of our own. One aspect of the data reduction process is shown in Chapter 4. This concerns the computation of the instrumental response curve, prior to the flux calibration. X-shooter is a ground-based instrument, consequently, the spectra are affected by the Earth’s atmosphere (also called telluric features). This is mainly seen in the near-infrared wavelength range, and to a lesser extent in the visible. Figure 6 shows an example of a near-infrared spectrum of a flux standard star, and the parts of the spectrum affected by the telluric absorption (in green) and
the instrumental features (in blue). Because of the intimate relation between these two effects, a procedure was developed to deal with both aspects at the same time.

Figure 5: The Hertzsprung-Russell diagram of XSL stars, taken from Chen et al. (2014b).

Figure 6: Near-infrared X-shooter spectrum of LTT 7987, taken from Moehler et al. (2014).
The X-shooter Spectral Library is an ambitious project with more than 700 (final) spectra of stars, which represents almost 10000 raw files. To deal with such an amount of data, a database was created, as described in Chapter 5. Furthermore, a dedicated website was created to release our data to the community.

A significant part of the stars within XSL are cool giants, either from the red giant branch (RGB) or the asymptotic giant branch (AGB). This is of course not a coincidence. Indeed, these stars have pulsating atmospheres, meaning that the stars actually increase and decrease in size periodically, which leads to changes in the brightness of the stars. This variability implies that two observations of the same star one in the optical wavelength range and the other in the near-infrared might give different results, if the times of observation are different. This issue will affect the construction of stellar population models. Thankfully with X-shooter, simultaneous observations over a broad wavelength range are now available. Furthermore, the (thermally pulsing) AGB is an important phase as stars at this stage are significant contributors to the near-infrared light of intermediate age stellar populations (1–3 Gyr).

Stars on the AGB have a double-shell burning structure: the carbon-oxygen core is surrounded by a helium (He) burning shell and a further hydrogen (H) burning shell, as shown in Figure 7. As the star evolves on the AGB, the helium shell runs out of fuel, and the star derives its energy from fusion of hydrogen. Periodically, the helium burning shell ignites violently (usually refers as helium shell flash or thermal pulse) and burns up the helium produced by the hydrogen shell since the last phase of helium activity. This creates a flash-driven convection zone which extends from the He shell almost up the H burning shell. Therefore, the products of helium burning (mainly carbon) are mixed throughout the intershell region. As the flash dies down, the energy deposited in the intershell causes the outer layers to expand and cool, and the H-burning shell is temporarily extinguished. The base of the convective envelope reaches inward and can penetrate beyond the H/He interface and into the region enriched in carbon. Carbon can thus be mixed to the surface, in the so-called “third dredge-up”.

With each dredge-up episode, the surface ratio of carbon over oxygen (C/O) increases. After a certain number of pulses, it may exceed unity and the star will then evolve from an oxygen-rich star (C/O < 1) to a carbon-rich star (C/O > 1). This means a change in the surface envelope: the oxides, such as TiO, VO, are replaced by carbon molecules, such as CN and C₂.

Neglecting the diversity of stars available in XSL, I focused during this thesis on one type of cool stars: carbon stars. Prior to XSL, only small collections of C-star spectra existed to represent their diversity.

Thanks to XSL, we doubled the number of carbon star spectra available across the optical and near-infrared spectral range, as shown in Chapter 2. Our sample includes stars from the Milky Way and the Magellanic Clouds. Some representative spectra of our sample are displayed in Figure 8.

The main characteristic of our sample is the bimodal behaviour of our stars when \((J – K)\) is larger than 1.6. At a given near-infrared color, in addition to the “classical” carbon stars, another family of spectra emerge, characterized by the presence of an absorption feature at 1.53 \(\mu\)m and a smoother appearance.
An example of such behaviour is seen when comparing the two orange spectra from Fig. 8.

To investigate the culprits of this behaviour, and to determine the fundamental parameters of our stars (such as the temperature, the metallicity), we compared our observed spectra with models. This analysis is summarized in Chapter 3. This comparison also aimed at validating and improving the models. We used state-of-the-art hydrostatic carbon-rich models, which means that the pulsation phenomenon and the dust effects are not part of the models. To redden our models, we did not use a standard extinction law, but we chose a polynomial correction, which takes into account the errors related to the flux calibration.

For rather blue carbon stars, we found good fits at intermediate resolution. Overall, the values of the fundamental parameters found in the visible and the near-infrared agree. However, the uncertainties for the estimated temperatures remain still high (more than 100 K) because of degeneracy between the parameters.

For the reddest stars, the hydrostatic models are not good anymore, which is expected. Indeed, those stars are more and more affected by the pulsation effect and by the effects of circumstellar material on the energy distribution (that a simple extinction law cannot reproduce). For those objects, the next step will be to compare them with dynamical models.
In this thesis, we have developed the X-shooter Spectral Library and some backstage processes. We have focused our analysis on one spectral type, the carbon stars. Until now, the small number of carbon stars in stellar libraries prevented the reproduction of their diversity in stellar population synthesis. With XSL, we go a step further: this collection extends the previous ones and even shows diversity. A comparison with hydrostatic carbon-rich models was done as a first pass, and the next step is now to turn to dynamical models, which take into account the pulsation properties. For now, we advise users to average our C-star spectra instead of using individual ones for stellar population synthesis applications. The X-shooter Spectral Library is full of stars from various spectral types, and more analysis like that in this thesis need to be done, before reaching for the galaxies.

Figure 8: Representative spectra from our sample of carbon stars, from Gonneau et al. (2015).