Research report

Antoine Chamballu

The aim of this report is to describe the activities I have been involved in since my arrival at the Service d'Astrophysique (SAp; CEA-Saclay) on March 19 2012 as a postdoc funded by P2IO. In this context, I have been involved in activities at SAp as well as the Service de Physique des Particules (SPP; CEA-Saclay) and the Institut d'Astrophysique Spatiale (IAS; Université Paris-Sud).

My work during the two years of my P2IO post-doc (nearly over) falls in with the overall effort of the *Planck* Collaboration to allow constraining cosmological parameters from galaxy cluster studies. *Planck* has performed an all-sky survey in the sub-millimeter range. Its main purpose is to perform the observation of the Cosmic Microwave Background (CMB). Nonetheless, it allows the observation (and the discovery) of galaxy clusters thanks to the imprint that the electrons constituting the hot intra-cluster medium leave on the black-body spectrum of the CMB, through their interaction with the CMB photons. This effect is known as the Sunyaev-Zel'dovich (SZ) effect.

Project Goals

My general goal was two-fold: take part of the definition and building of the *Planck* cluster catalog, of which the cosmological sample would be a sub-sample, and develop tools to use this catalog as a precise cosmological probe via the constraint of the cluster abundance as a function of their mass and redshift.

Among all the aspects that the first part of this project entailed, I focused on improving the relation between our signal and the mass of the clusters, i.e. the single most important parameter for the clusters' description. At the time of my arrival, one of the limitation towards this goal was the relative inability to produce a precise and unbiased mass estimate for the *Planck* clusters, especially the newly discovered ones. Firstly, estimates from *Planck* only are limited by the degeneracy between cluster size and flux resulting from its relatively low resolution (as detailed below); secondly, as a consequence of the large number of clusters discovered by *Planck*, the follow-up of the new *Planck* clusters with higher resolution instruments (in particular, X-ray telescopes) would demand unrealistically large programs. Realising this led to the definition of the first part of the project: the exhaustive test and investigation of the limitations of a new mass estimate (see below) obtained solely from *Planck* data and redshift measurements (needed for cosmological studies in any case).

The first cosmological results produced by the *Planck* collaboration using galaxy clusters were done using only the redshift information. Following this, the second part of the project consisted in evaluating the gain obtained when including the mass information to our cluster counts in order to derive tighter cosmological constraints and break some of the observed degeneracies.

Work Achieved

Linking our signal to the mass

Using the galaxy clusters observed by *Planck* and, more precisely, their abundance, as cosmological probes requires a proper characterisation of several ingredients. Firstly, one needs to understand the relation between observed cluster counts and clusters' effective abundance, i.e. determine the selection function of the survey. The link between this inferred abundance and the underlying cosmological model is then made through the use of the so-called mass function (numerous versions of this have been proposed in the literature) which, given a certain cosmological model, allows to predict the number of clusters in the sky as a function of their mass and redshift. Those two parameters are the most fundamental ones when describing a galaxy cluster. This is true for both cosmology and astrophysics, as all the other parameters that can be used to describe a cluster (e.g. temperature, X-ray luminosity, number of galaxies, etc.) can be related to them. This is even more true for the mass, the redshift being involved in the evolution of the relations between the mass and the other parameters.

Therefore, the precise estimate of the mass and the redshift of each cluster is critical. The redshift has to be measured thanks to independent observations (either optical or X-ray, the SZ effect being independent of the redshift). As for the mass, until now, it could only be done precisely using *Planck* data by including ancillary information from X-rays for known clusters (but there only is a limited number of them) or by performing a detailed follow-up with an X-ray telescope (e.g. *XMM-Newton*) of newly discovered clusters (which cannot be done for the whole *Planck* cluster catalog). This is due to the relatively poor angular resolution of the *Planck* detectors, resulting in a strong degeneracy between the size of the cluster and its SZ flux (which are necessarily required to estimate the cluster mass) and hence a weak constraint of the sizes and fluxes. A great part of my work has been devoted to solving this issue and testing newly derived clusters masses for cosmological constraints.

A new method to estimate the mass of clusters had been designed by Monique Arnaud before my arrival at SAp. The first part of my work consisted in exhaustively testing this new method. Its goal is to break the degeneracy between size and flux, and thus circumvent the intrinsic limitations of the *Planck* satellite. Combining several scaling laws (i.e. simple relations between parameters used to describe cluster properties, either observable or not) calibrated either from X-ray information solely or from combinations of SZ and X-ray information, one can derive the scaling law binding size, flux and redshift, effectively allowing to break the aforementioned degeneracy.

Firstly, I have been testing this method on several sub-samples of known clusters in *Planck*, with different quality and available ancillary information. Our new estimate was then shown to be comparable to the best estimates available from *Planck* data, i.e. obtained by breaking the size-flux degeneracy by extracting the cluster flux at the X-ray position and size, exhibiting a negligible bias and little scatter, thus showing an undeniable gain when compared to blind estimates. In particular, the cluster size is particularly well recovered by our method – which incidentally is what it was designed for – leaving most of the scatter due to differences between true and blindly recovered positions. Going further, comparisons with estimates coming from X-ray measurements solely (X-ray mass estimates coming from the measurement of the X-ray analogous to the SZ flux are known to be unbiased with low scatter) exhibited no or little biased with low scatter (the individual quality of our estimate being directly linked to the quality of the SZ data themselves). Finally, I tested our method on realistic multi-component all-sky simulations, processed with the same cluster extraction algorithm than for the data. This test was essential as it offered a way to compare our estimates, not only to other SZ or X-ray estimates, but also to the true (i.e. input) cluster flux or mass. It was again showed that our method allow a precise estimate of the cluster mass (with low bias and scatter) and that we can then get reliable mass estimates solely from SZ data (apart from redshift measurements, which are, first, needed for any kind of powerful cosmological studies and, second, much less time-costly to obtained than X-ray information). Moreover, the effect of an error on the position estimate was further investigated and proven to be the only limitation of our method (it should be noted that it isn't meant to solve this issue).

To sum up, it was shown from *Planck* data and simulations that our estimate of the cluster mass is close to as powerful as any estimate that would require an unrealistically large X-ray follow-up program (given the number of clusters discovered by *Planck*); the gain obtained when using our method is crucial. I could also investigate the errors on our estimate, in particular coming from a misestimate of the cluster's redshift. It was shown to be negligible compared to the dispersion coming from the extraction itself, even when considering a relatively conservative precision on the redshift, as provided by the SDSS observations.

These results are to be reported in an article from the *Planck* Collaboration soon to be concluded. Moreover, this method has been used to produce mass estimates for clusters with known redshifts, published in "*Planck 2013 results. XXIX. Planck catalogue of Sunyaev-Zeldovich sources*" (arXiv:1303.5089).

Including the mass in cosmological constraints

Moving on from those tests, I developed several codes to estimate the capabilities of our new mass estimate to provide tight cosmological constraints, i.e. one of its several applications. Prior to this, cosmological constraints were derived from the *Planck* clusters counts using only the redshift information (arXiv:1303.5080). Those results, although already very significant, were limited by the existence of various degeneracies between, for instance, σ_8, the normalisation of the matter power spectrum, and Ω_m, the matter density of the Universe, or the hydrostatic bias arising between the observed mass (either from SZ or X-ray observations) and the true mass of the cluster. The basic idea was that the inclusion of the mass information, with masses derived thanks to the method I tested, would allow to break this degeneracies and pave the way to tighter cosmological constraints.

I first looked at the degeneracy between σ_8 and the hydrostatic bias. I then showed that including the mass information doesn't help in this very case and that, consequently, direct measurements of the hydrostatic bias are needed. (Recent results from the *Planck* collaboration (A&A, 2013, 550, A129) and the *Weighting the Giants* project (arXiv:1402.2670) give us a usable direct measurement of this bias. Taking those measurements into account will be one of the important steps to come.) Doing this, I have investigated the effects of using catalogs with different signal to noise ratio (SNR) limits, varying the bin sizes for our counts and a different parameterisation where, instead of the mass, the SNR information is added to the redshift. Other parameters are being included in the analyses currently done; the gain on the σ_8-Ω_m degeneracy thanks to the use of our new mass estimates, especially when including direct measurements of the hydrostatic bias, is expected to be much more significant.

The definition of this project collectively involved SAp, SPP and IAS. The first part of the project was performed in close collaboration between SAp and SPP, with M. Arnaud and J.-B. Melin respectively. Both their supervision was crucial: at SAp in terms of understanding cluster physics related to this study, defining the tests to be performed and interpreting them; at SPP in the understanding of the extraction algorithm (developed there) and the use of its products. The second part of the project involved both IAS with N. Aghanim and M. Douspis in its early stages (the first versions of the codes

I use today were developed and tested there) and SPP, where J.-B. Melin, who I have been closely working with on this issue, has been coordinating the effort made within the *Planck* collaboration.

Relevance within P2IO

Galaxy clusters are one of the few existing cosmological probes, along with the Cosmic Microwave Background (CMB), baryonic oscillations and weak lensing. Among the others, they find their strength in being sensitive to both the cosmic expansion history predicted by the ΛCDM model and the cosmic growth of structures predicted by general relativity. As a consequence, the study of either clusters alone or combined with other cosmological probes provides a unique joint insight to those two pillars of our description of the Universe, and naturally falls within the scope of P2IO activities and should remain one of the main field to focus on.

As it was written above, in order to allow their exploitation, one need to access reliable information on the most fundamental observables used to link observations and cosmology dependent predictions: their mass and redshift. As my work was done in the frame of the *Planck* satellite observations, where clusters are detected thanks to the redshift independent SZ effect, measuring the redshift is out of our hands. This is not the case for the more critical mass measurements. Overcoming the problems related to mass estimation using *Planck* data is crucial in order to enable precise cosmological constraints.

Resolving this issue has been the principal goal of my work as part of my P2IO postdoc. There are two aspects of this: firstly, testing our new mass estimate and understanding its limitations has allowed its use in place of the highly dispersed and biased blind estimates; secondly, the introduction of the mass information obtained thanks to our method in our parameter estimation has been a useful step towards tighter cosmological constraints with clusters, at the very least regarding the code development that was needed.

Future after P2IO contract

I am not going to apply for any research position and am still reviewing the different options available to me.