 DOI: 10.18727/0722-6691/5037

# ALLSMOG, the APEX Low-redshift Legacy Survey for MOlecular Gas


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**We report the completion of the APEX Low-redshift Legacy Survey for MOlecular Gas (ALLSMOG), an ESO Large Programme, carried out with the Atacama Pathfinder EXperiment (APEX) between 2013 and 2016. With a total of 327 hours of APEX observing time, we observed the $^{12}CO(2–1)$ line in 88 nearby low-mass star-forming galaxies. We briefly outline the ALLSMOG goals and design, and describe a few science highlights that have emerged from the survey so far. We outline future work that will ensure that the ALLSMOG dataset continues to provide scientific value in the coming years. ALLSMOG was designed to be a reference legacy survey and as such all reduced data products are publicly available through the ESO Science Archive Phase 3 interface.**


## Background: observing molecular gas

The assembly of galaxies, over the past 13.8 billion years of cosmic time, is a complex process governed in large part by the behaviour of gas. From gas inflows pouring into dark matter halos (triggering waves of star formation), and the molecular clouds within galaxies (providing the fuel for future galaxy growth), to galactic outflows (which remove fuel and may suppress future star formation), gas regulates many of the physical processes governing the lives of galaxies. If we want to better understand how galaxies grow and evolve, we need to gain a better understanding of their cold gas content.

Observing this cold gas is challenging, however. While modern optical galaxy surveys boast sample sizes into the millions, there are no more than a few thousand galaxies with measured total gas masses (atomic + molecular). In addition the majority of the galaxies with measured gas masses are massive and metal-rich spirals — fairly unrepresentative of the galaxy population as a whole. This deficit arises from a simple physical problem: direct observations of hydrogen molecules are impractical, since molecular hydrogen ($H_2$) lacks a permanent dipole moment, and the quadrupole lines have excitation temperatures far higher than those in molecular clouds; and also carbon monoxide (the most commonly used molecular gas tracer molecule) cannot survive in the interstellar medium of galaxies without a dust screen to protect it from the dissociating ultraviolet photons. Low-metallicity environments, such as those in the interstellar medium (ISM) of lower-mass galaxies which lack significant dust content, can therefore contain plenty of invisible $H_2$, while being deficient in the visible tracer molecule (CO).

There are therefore two significant hurdles to clear if a better understanding of gas in galaxies is to be achieved. Firstly, a significant sample of low-mass galaxies must be assembled, and their gas contents studied. Secondly, the gas-phase metallicity of these galaxies should be well constrained, in order to reliably convert from a CO flux into a mass of molecular hydrogen (via the CO-to-$H_2$ conversion factor, $\alpha_{CO}$).

In order to begin to overcome these hurdles, we designed and carried out the ALLSMOG survey. Completed in 2016, ALLSMOG was an ESO Large Programme (awarded 300 hours on APEX over four semesters) designed to observe the CO(2–1) emission line in a sample of local ($z < 0.03$), low mass ($M_* < 10^{10}\ M_\odot$) galaxies. The sample was constructed to have a wide range of available ancillary data (including stellar mass, star formation rate and metallicity). The parent sample, based on the Sloan Digital Sky Survey (SDSS) data release 7 (DR7), provides spectra with the strong optical lines needed to estimate gas-phase metallicity, along with stellar masses and star formation rates. For inclusion in the ALLSMOG survey we also required an archival H I observation, enabling us to measure total (i.e., atomic + molecular) gas masses.

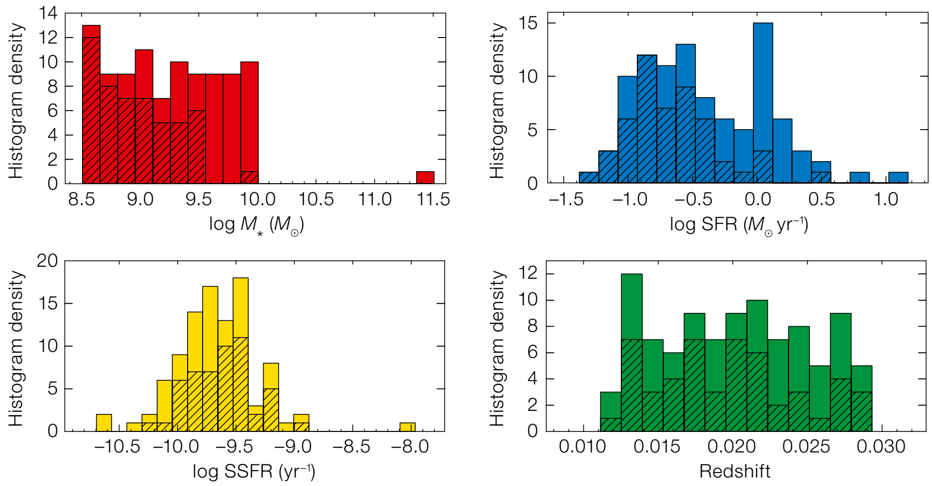


Figure 1. Histograms showing the distribution of parameters in the ALLSMOG sample. Clockwise from top left, the panels show: the distribution of log stellar mass; log star formation rate; redshift; and log specific star formation rate.

The final ALLSMOG survey, completed in 2016, consists of 88 low-mass local galaxies observed in CO(2–1). Histograms of the ALLSMOG parent sample, showing the distribution of various parameters (including stellar mass and redshift), are shown in Figure 1. A halfway-point survey paper was published by Bothwell et al. (2014), in which half of the final sample was made available (and some preliminary analysis was carried out). The full survey paper has now been published (Cicone et al., 2017). We briefly describe some details of the survey design, before giving a selection of scientific results that have emerged so far from the ALLSMOG survey.

## Survey details

The ALLSMOG sample is drawn entirely from the Max-Planck-Insitut für Astrophysik – Johns Hopkins University (MPA-JHU) catalogue of spectral measurements and galaxy parameters for the SDSS DR7 (Abazajian et al., 2009). The targets were selected according to the following criteria:

1. Classified as star-forming galaxies (i.e., no evidence of an active galactic nucleus, AGN) according to their location on the diagnostic diagram of Baldwin, Phillips & Terlevich (1981).
2. Stellar masses in the range $8.5 < \log(M_*/M_\odot) < 10$.
3. Redshifts in the range $0.01 < z < 0.03$. The upper bound is due to sensitivity; the lower bound ensures that targets fit within the 27 arcsecond APEX beam.
4. Declinations $\delta < 15$ degrees.
5. Gas-phase metallicity, $12 + \log(O/H) \lesssim 8.5$, according to the calibration by Tremonti et al. (2004). This is intended to exclude sources with very high CO-to-$H_2$ conversion values for which a detection with APEX would be unfeasible.

The project was initially allocated 300 hours of ESO observing time over the course of four semesters, corresponding to 75 hours per semester throughout periods P92–P95 (October 2013–September 2015). However, during P94 and P95 there was a slowdown in ALLSMOG observations, mainly due to the installation of the APEX visitor instrument Supercam, in combination with better-than-average weather conditions. Due to the resulting ~ 50 % time loss for ALLSMOG during these two semesters, the ESO Observing Programmes Committee (OPC) granted a one-semester extension of the project, hence allowing us to complete the survey in Period 96 (March 2016). The final total APEX observing time dedicated to ALLSMOG amounts to 327 hours.

ALLSMOG is intended to be a CO flux-limited survey, and is also (to first order) a CO luminosity-limited survey, thanks to the narrow redshift distribution of the sample ($0.01 < z < 0.03$). We aimed to reach a line peak-to-rms (root mean square) signal-to-noise (SNR) ratio of ≥ 3 for the detections and a uniform rms for the non-detections, corresponding to rms = 0.8 mK (31.2 mJy) per 50 km $s^{-1}$ channel for the APEX 230 GHz observations.

The ALLSMOG data were processed in the Grenoble Image and Line Data Analysis – Continuum and Line Analysis Single-dish Software (GILDAS-CLASS), using a series of customised scripts based on the statistics of the data, which included a by-eye check of each individual subscan (designed to eliminate scans with baseline ripples or non-Gaussian noise). Examples of final ALLSMOG spectra (presented with archival H I spectra), including non-detections, are shown in Figure 2.

## Results (I) — molecular gas scaling relations

Several of the earliest results to come from the ALLSMOG survey concern

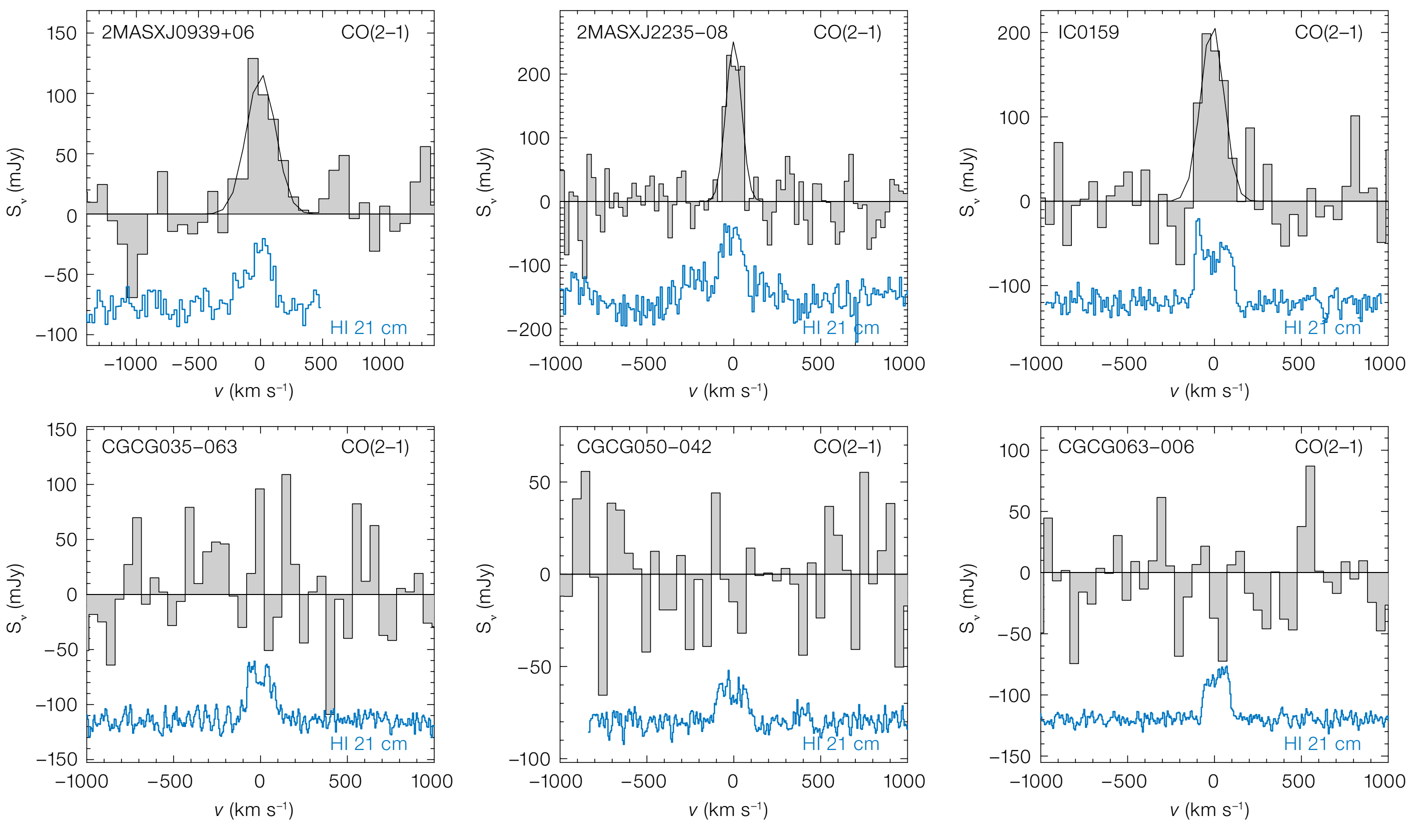


**Figure 2.** Six example spectra from the ALLSMOG survey, showing CO detections (top row) and non-detections (bottom row). In all panels, the grey upper spectrum is the APEX CO data, and the blue lower one is an archival H I spectrum. Figure adapted from Cicone et al. (2017).

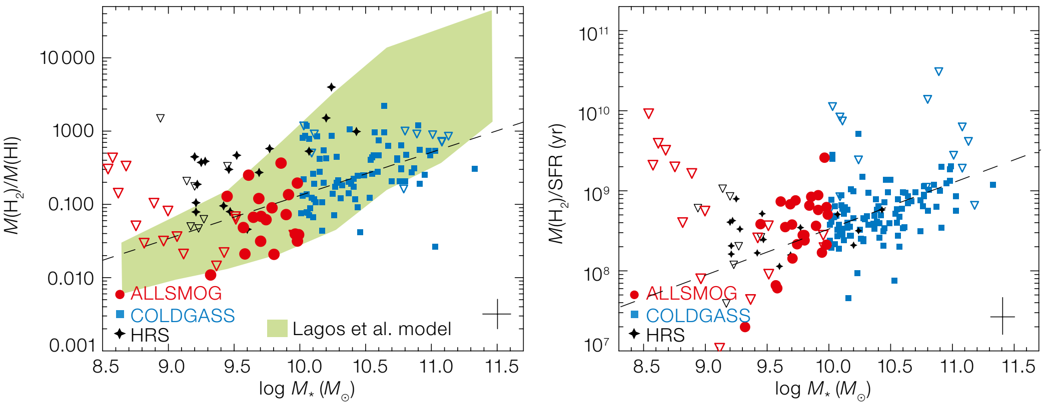


Figure 3. Left panel: $H_2$/H I ratios for the ALLSMOG sample plotted against stellar mass. Also plotted are the galaxies from the COLDGASS and HRS surveys. The green shaded region shows the semi-analytic model prediction from Lagos et al. (2011); the upper and lower bounds of the coloured region mark the 90th and 10th percentiles of the model distribution. Right panel: gas consumption timescales, plotted against stellar mass, for the ALLSMOG sample. Also plotted are the galaxies from the COLDGASS and HRS surveys. Both panels adapted from Bothwell et al. (2014).

molecular gas scaling relations — the strong trends between the molecular gas masses of galaxies and other large-scale properties (including stellar mass, star formation rate and metallicity). These scaling relations allow insight into the mechanisms underlying galaxy formation by providing simple, quantitative tests that models — both analytical and numerical — are required to match. Indeed, the ability (or otherwise) of a model to reproduce a variety of observed scaling relations has become a critical metric by which a model's success is judged.

### The $H_2$/H I ratio

One scaling relation explored in our first release (Bothwell et al., 2014) is the ratio between the molecular and atomic components of the ISM. The ratio of molecular to atomic gas mass in galaxies is dependent on a range of physical processes, including the interstellar radiation field, the pressure of the ISM, and the abundance of dust (which aids the formation of molecules). Figure 3 (left panel) shows the $H_2$/H I mass ratio, plotted against stellar mass for the ALLSMOG galaxies and our two comparison samples, the CO Legacy Database for GASS (COLDGASS) and the Herschel Reference Survey (HRS). We overplot in Figure 3 (left panel) the theoretically predicted $H_2$/H I ratio from Lagos et al. (2011). Our data (which use a Wolfire et al. (2010) CO-to-$H_2$ conversion factor, which scales with metallicity) produce an $H_2$/H I ratio distribution in very close accordance with the semi-analytic model data.

### Molecular gas consumption times

Another scaling relation explored in Bothwell et al. (2014) was the relationship between molecular gas mass and star formation rate. The ratio between these two quantities is often referred to as the gas consumption timescale, and can be interpreted as the time a galaxy can continue forming stars in the absence of a gas inflow or outflow (i.e., in a closed box). Figure 3 (right panel) shows the gas consumption timescale for ALLSMOG galaxies, and our two comparison samples COLDGASS and HRS, plotted against stellar mass. As above, we have used a Wolfire et al. (2010) CO-to-$H_2$ conversion factor to calculate molecular gas masses. We confirmed the trend found previously by both Saintonge et al. (2011) and Boselli et al. (2014): that the molecular gas consumption timescale is not constant, but increases with stellar mass over the full mass range of the detected samples (log $M_*/M_\odot > 9$). Molecular gas depletion timescales vary from ~ 2 Gyr at the most massive end of the distribution inhabited by COLDGASS galaxies (log $M_*/M_\odot > 11$), to ~ 100 Myr for the lowest-mass detected galaxies (log $M_*/M_\odot$ ~ 9).

## Results (II) — fundamental metallicity relations

In recent years, the well-known scaling relations between stellar mass and metallicity (the mass-metallicity relation), and stellar mass and star formation rate (SFR; the main sequence of galaxy evolution) have been extended into a three-dimensional relation, known as the fundamental metallicity relation (FMR; Lara-Lopez et al., 2010; Mannucci et al., 2010). Galaxies out to at least $z$ ~ 2.5 lie on the surface defined by the FMR, on which, (a) more massive galaxies have higher metallicities, and (b) at a given stellar mass, galaxies with higher SFRs have systematically lower metallicities. Based on this relation, Bothwell et al. (2013) conducted a study of 4253 local galaxies, finding that the mass-metallicity relation also exhibited a significant secondary dependence on mass of atomic hydrogen (H I), to the extent that the H I-FMR was potentially more fundamental than the correlation with SFR.

Using data from a variety of sources (including the ALLSMOG survey, which provided data on molecular gas masses, along with stellar masses and metallicities), our team was able to demonstrate a strong relationship between gas-phase metallicity and molecular gas content (Bothwell et al., 2016a; 2016b). Using Principle Component Analysis (PCA), we showed that the well-known FMR, describing a close and tight relationship between metallicity and SFR at fixed stellar mass, is entirely a by-product of the underlying physical relationship with molecular gas (see Figure 4).

## Summary and future plans

ALLSMOG was an ESO Large Programme, carried out with APEX between 2013 and 2016, which aimed to measure the molecular gas properties of a large sample of low-mass, low-metallicity galaxies in the local Universe. ALLSMOG was designed to be a reference legacy survey, and all reduced data products are publicly available through the ESO Phase 3 archive[1]. In addition, we intend to continue exploiting the ALLSMOG sample in the coming years.

One future project will use the ArTéMiS (*Architectures de bolomètres pour des Télescopes à grand champ de vue dans le domaine sub-Millimétrique au Sol*) bolometer camera on APEX to observe ALLSMOG galaxies at 350 and 450 μm, allowing their dust masses to be constrained via spectral energy distribution (SED) modelling. The ALLSMOG legacy dataset (which provides CO luminosities and metallicities, along with a suite of ancillary parameters), combined with submillimetre-derived dust masses, represents the ideal dataset for launching an investigation into the behaviour of the gas-to-dust ratio as a function of galaxy properties. A small pilot programme has been approved, and will be observed with APEX in late 2017 (principal investigator: Bothwell). The results from this initial study will serve as a proof of concept, guiding the design of future larger ALLSMOG follow-up programmes for far-infrared photometry.

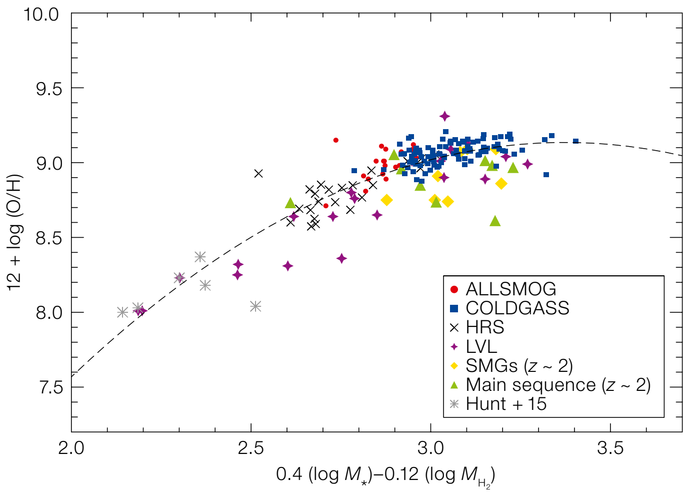


**Figure 4.** Gas-phase metallicity (12 + log (O/H)) *vs.* the optimum linear combination of stellar mass and molecular gas mass, for a variety of galaxy samples including ALLSMOG. Figure taken from Bothwell et al. (2016a) where further details of the combination of observed parameters can be found.

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## Links

[1] ESO Science Archive Facility Phase 3 access to ALLSMOG: http://archive.eso.org/wdb/wdb/adp/phase3_main/form?collection_name=ALLSMOG



The Atacama Pathfinder EXplorer (APEX) antenna against a backdrop of peaks above the Chajnantor plateau.