z-GAL – A Comprehensive Redshift Survey of the Brightest Herschel Galaxies

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Abstract. We here introduce *z*-GAL, a Large Program using NOEMA, aimed at a comprehensive 3 and 2-mm spectroscopic redshift survey of a large sample of 137 bright ($S_{500\mu m} > 80$mJy) *Herschel*-selected high-*z* dusty star forming galaxies, probing the peak of cosmic evolution. The results highlight the nature of the sources, including lenses and rare hyper-luminous infrared galaxies, as well as, in some cases, their multiplicity and will serve as a foundation for future detailed follow-up observations.

1 Introduction

Over the last two decades, surveys in the far-infrared and sub-millimeter wavebands have opened up a new window to our understanding of the formation and evolution of galaxies, revealing a population of massive, dust-enshrouded galaxies forming stars at enormous rates in the early Universe [1–3]. In particular, the extragalactic imaging surveys done with the *Herschel Space Observatory* have increased the number of dust-obscured star-forming galaxies (DSFGs) from hundreds to several hundreds of thousands [4, 5]. Including the all-sky Planck-HFI [6] and the South Pole Telescope (SPT) surveys [7], today we have vast samples of luminous DSFGs that are among the brightest in the Universe, including numerous examples of strongly lensed systems [8] and rare cases of extreme galaxies such as Hyper-Luminous InfraRed Galaxies (HyLIRGS) with $L_{\rm IR} > 10^{13}\,L_{\odot}$ [9, 10].

Detailed follow-up studies of these galaxies require robust estimates of their distances to investigate their physical properties. Measuring CO emission lines via sub-millimeter spectroscopy has proved to be the most reliable method to derive redshifts for high-*z* DSFGs. Recently completed redshift surveys have provided crucial information that enable targeted studies to explore the nature of DSFGs in the early Universe (e.g., [11], [12]).

We here present the NOEMA *z*-GAL project, which is to date the largest of these coordinated efforts (project M18AB - PI: P. Cox, T. Bakx & H. Dannerbauer; see [13] for first results), a comprehensive redshift survey of 137 of the brightest ($S_{500\mu m} \geq 80$mJy) DSFGs with photometric redshifts $z_{\rm phot} \geq 2$ selected from the *Herschel* surveys in the northern and equatorial fields (H-ATLAS, HerMES and HeRS) [14, 15].

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2 Main results

The main goal of the z-GAL project has been achieved by measuring for the entire sample of 137 sources robust spectroscopic redshifts based on the detection of at least two emission lines. The targets span the redshift range $0.8 < z < 6.0$ and are centered around the peak of cosmic evolution at $z \sim 2.5$. The sources display an exceptionally wide range of velocity widths, extending to full width half-maximum of $600\,\mathrm{km\,s^{-1}} < \Delta V < 1500\,\mathrm{km\,s^{-1}}$ for $\sim$ 60% of the sources, with many sources revealing double-peaked profiles indicative of merger systems and/or rotating disks (Fig. 1). The sources also reveal a remarkable diversity of morphologies in their dust and molecular gas emission, including evidence for gravitational amplification and binary/multiple systems. This variety is illustrated in Fig. 2 showing a lensed galaxy (HerBS-89a), a binary system (HerBS-70) at $z = 2.3$ which is at the center of a proto-cluster (Bakx et al. in prep.), and a case where two sources were detected at different redshifts in the same field (HerBS-43a at $z = 3.21$ and HerBS-43b at $z = 4.05$).

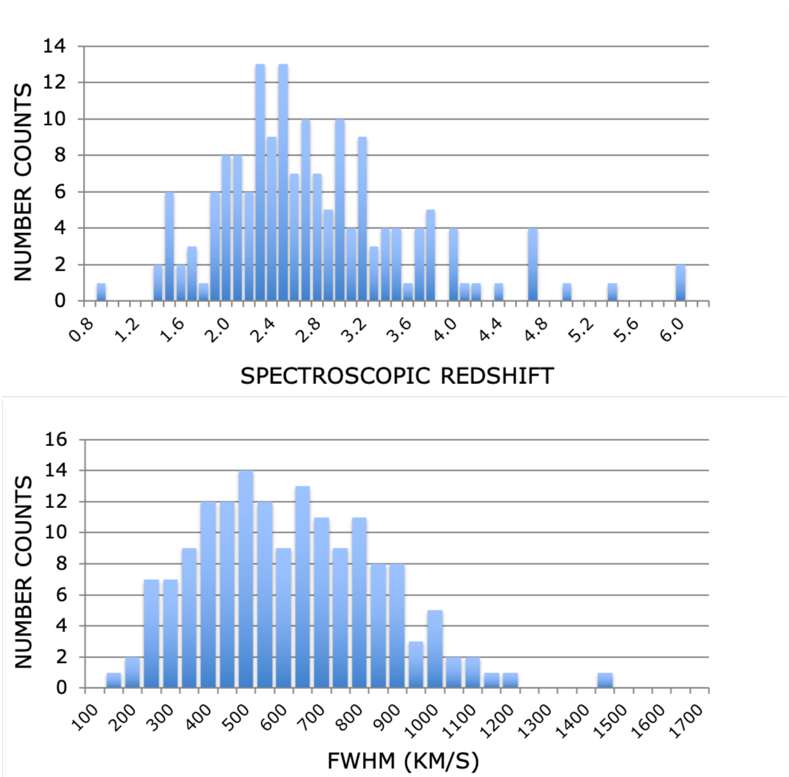

Figure 1. *Top panel*: Spectroscopic redshift distribution for the 137 bright *Herschel* sources from the z-GAL project. The spectroscopic redshifts are in the range $0.8 < z < 6.0$ with a median value of $z = 2.5 \pm 0.3$. *Lower panel*: Distribution of the full width at half maximum (FWHM) for the entire sample. The linewidths of the sources are large with a median value for the Full Width Half Maximum (FWHM) of $650 \pm 150\,\mathrm{kms^{-1}}$.

In addition to the detailed information obtained on their structure and kinematics (mainly through emission from mid-J CO transitions), the large instantaneous bandwidth of NOEMA ($\sim$16 GHz) provides, for each source, an exquisite sampling of the underlying dust continuum emission in the 3 and 2 mm bands. Together with the *Herschel* flux densities and, where available, data at 850 μm (from SCUBA-2) and 1 mm (from NOEMA or ALMA), the dust spectral energy distributions (SEDs) of the z-GAL sources are very well constrained.

Based on the successful measurements of z-GAL, the following remarks can be made regarding the derivation of robust redshifts: (i) Reliable spectroscopic redshift need the detection of *at least* two emission lines and one emission line is rarely enough; (ii) Photometric redshifts are only indicative and sometimes ambiguous. Their values depend on the adopted photometry and the available SED coverage used in the analysis and are found to be, on average, within 20% of the $z_{\rm spec}$ values; (iii) Most emission lines detected are from CO (from J=2-1 to 9-8), with some sources seen in H_2O and [CI] emission lines; for one source at z = 0.85, the two detected lines are HCN(3-2) and HCO^+(3-2); (iv) Some targets required a third line to lift any ambiguity, i.e., different redshift solutions were compatible with the available photometry. In many of those cases, the relative intensities of the CO emission lines do provide additional useful constraints.

With all the 137 *Herschel*-selected sources detected in the continuum and in at least two emission lines at 3 and 2 mm, the results of the z-GAL Large Program demonstrate the ability to efficiently derive redshifts and global properties of high-z galaxies using the new correlator Polyfix and the broad bandwidth receivers on NOEMA. In addition to the redshifts, the NOEMA data provide a richness of information on the sources' morphology, revealing in many cases sources that are complex and multiple, spanning the range from lensed galaxies to genuine binary or triple systems, and providing useful additional information on their properties. For the gravitationally amplified sources, ancillary data from the Hubble Space Telescope and the Keck provide additional information on both the foregound lensing galaxies and, in some cases, the backgound high-z system. Precise measurements of the amplification factors and the derivation of the properties of these sources will require higher resolution follow-up observations in the sub-millimeter and at optical/near-infrared wavelengths to study the characteristics of the foreground amplifying galaxy, as demonstrated in the case of HerBS-89a (see Sect. 3).

3 Infall activity in HerBS-89a

HerBS-89a belongs to the sample of 13 *Herschel*-selected galaxies observed by [13]. At z=2.94, HerBs-89a is the brightest galaxy of this sample, displaying the broadest CO emission line (FWHM $\sim$ 1100 km s^{-1}). HerBS-89a was further investigated using NOEMA and the VLA by [16], revealing a wealth of spectral features, including: two ^{12}CO line transitions (J =9-8 and 1-0) in addition to those reported by [13] (i.e., J=5-4 and 3-2); the three ground-state transitions of the molecular ion OH^+ (1_1-0_1, 1_2-0_1, and 1_0-0_1) and CH^+(1−0), all seen in absorption; and transitions of other molecular species including water and tracers of very dense gas (HCN and NH_2) - see Fig. 3. The combined continuum measurements available for HerBS-89a provide one of the most exquisite sampling to date of the far-infrared and sub/millimeter SED of a high-z galaxy, with a total of 16 broad-band measurements covering the range from 250 μm to 3 mm in the observed frame.

This uniquely rich collection of information has allowed a detailed study of HerBS-89a. The NOEMA data reach a spatial resolution of 0.55 × 0.33 arcsec at 254 GHz, revealing a partial Einstein ring (Fig. 3). Thanks to the very high S/N of the continuum emission, a detailed model of the gravitational lens was built, resulting in a picture of the galaxy in the image plane, prior to any beam convolution, and allowing the object reconstruction in the source plane. HerBS-89a is a powerful star forming galaxy, whose flux is magnified by a factor ∼ 5 by a foreground spiral galaxy at $z_{\rm phot} = 0.6 - 0.9$. Its intrinsic infrared luminosity is $L_{\rm IR} = (4.6 \pm 0.4) \times 10^{12}\,L_\odot$, its rate of star formation SFR $> 600\,{\rm M_\odot/yr}$, and its depletion timescale $\tau_{\rm depl} = (3.4 \pm 1.0) \times 10^8$ years. These values potentially position HerBS-89a in the

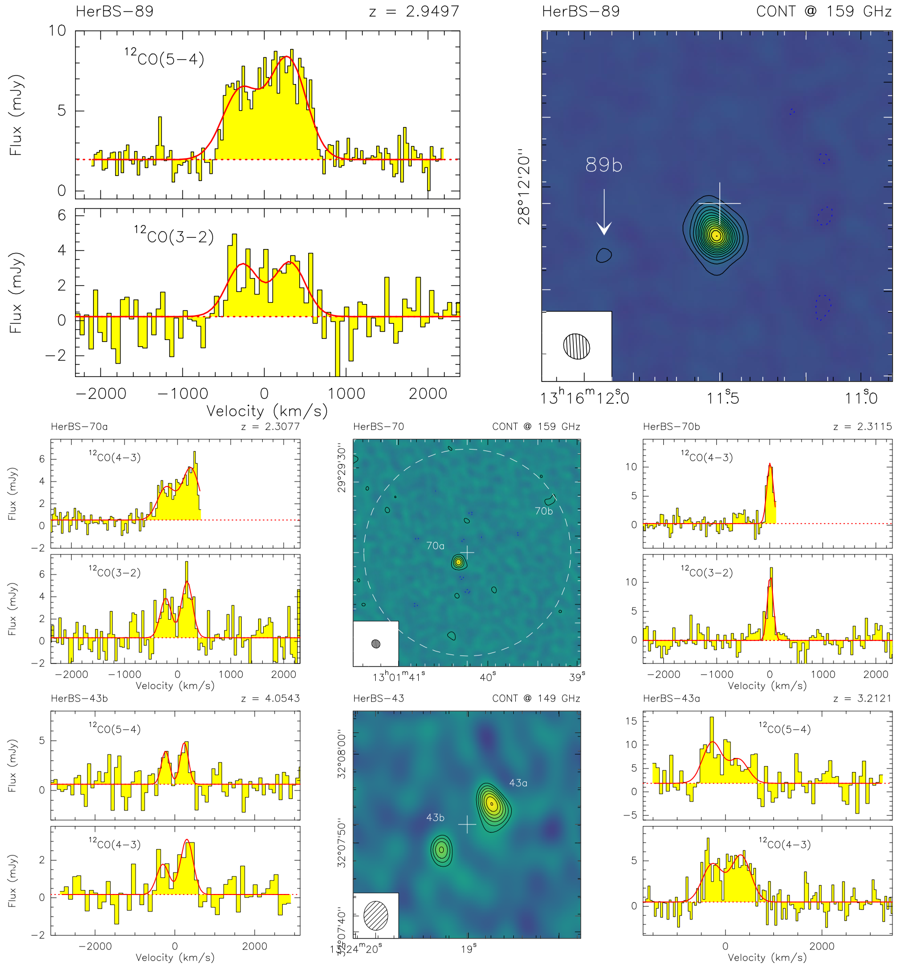

Figure 2. Continuum images at 2-mm and spectra from the 2 (top) and 3-mm (bottom) bands for the *Herschel* bright galaxies HerBS-89a, HerBS-70, and HerBS-43, representing, respectively, cases of a gravitationally amplified galaxy, a binary system with projected distance of ∼140 kpc, and a field with two galaxies with different redshifts, illustrating the diversity of the *z*-GAL sample. The source name, the continuum frequency, and the derived spectroscopic redshift are indicated along the top of each panel. The emission lines are identified in the upper left corner of each spectrum. The spectra are displayed with the continuum and each emission line is centered at the zero velocity corresponding to its rest frequency. Fits to the continuum and the emission line profiles are shown as dotted and solid red lines, respectively. The primary beam at 50% is shown with a dashed circle. The synthesized beam is shown in the lower left corner of each continuum image. Adapted from [13].

region between the so called "main sequence" of star forming galaxies at $z \sim 3$ and the locus of starburst outliers.

The ^{12}CO lines detected by NOEMA have a double profile, which can be explained either by a single rotating galaxy or by a system of two interacting objects. In addition to the broad ^{12}CO emission lines, the NOEMA spectra show deep absorption features of the molecular ions OH^+ and CH^+ redshifted by $\sim$ 100 km s^{-1} with respect to the galaxy's systemic velocity, revealing a rare example of gas inflow (see Fig. 2).

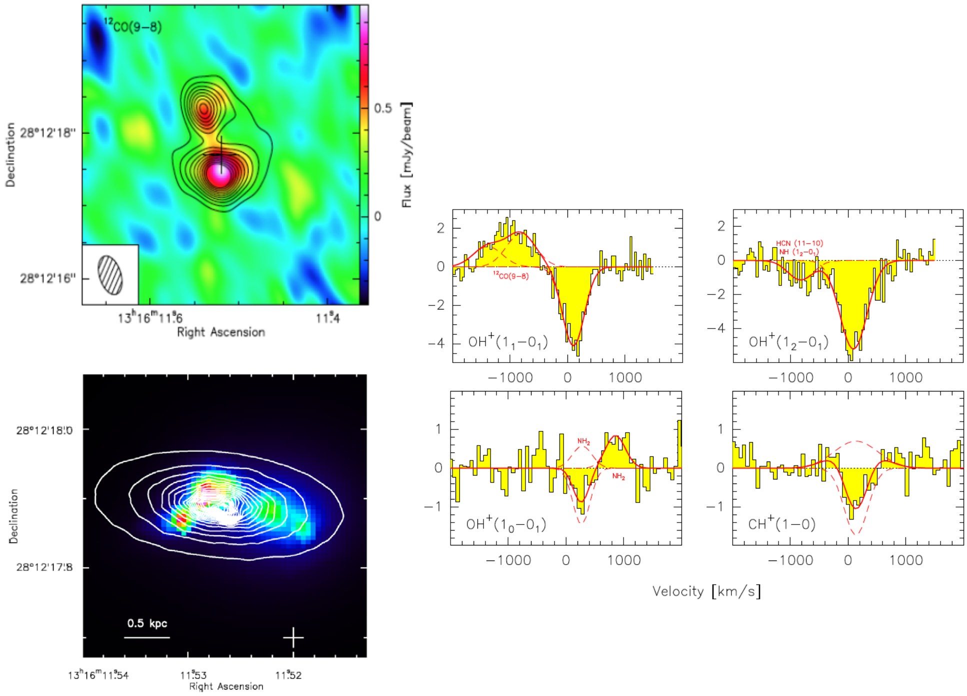

Figure 3. *Left panel*: (*Top*) Image of the ^{12}CO$(9-8)$ emission in HerBS-89a, compared to the underlying continuum. The synthesized beam (0.55"$\times$0.33") is shown in the lower left corner. (*Bottom*) Zeroth moment map of the ^{12}CO$(9-8)$ emission in the source plane of HerBS-89a, possibly indicating a merging system. The contours show the dust continuum emission. The cross at the lower right corner marks the phase center of the NOEMA observations and the linear scale is indicated in the left corner. *Right panel*: Spectra of the molecular absorption and emission lines detected in HerBS-89a. Each molecular line is identified in the lower corner of each panel (labeled in black) and, in the case of a line overlap, as ^{12}CO$(9-8)$/OH$^+(1_1-0_1)$, OH$^+(1_2-0_1)$/HCN$(11-10)$ and OH$^+(1_0-0_1)$/o$-$NH$_2(2_{02}-1_{11})(5/2-3/2)$, the second molecular line is labeled in red. The spectra are displayed with the continuum subtracted and, in each panel, the molecular line (labeled in black) is plotted relative to the zero velocity corresponding to its rest frequency. The main red-shifted absorption lines (Δ(V) $\sim +100$kms^{-1} clearly reveal infall activity in HerBS-89a. Adapted from [16]).

The gravitational lensing model mentioned above was applied to the NOEMA spectral cubes of HerBS-89a, with the aim to reconstruct its velocity field and study the inflow in the source plane. The limited angular resolution and S/N ratio per spectral element of the NOEMA data does not lead to a consensus picture of the kinematics of the system and with the data in hand, it is not possible to be conclusive on whether HerBS-89a is a single rotating galaxy or a merging pair. Consequently, different interpretations of the gas inflow could hold. In the least likely scenario, NOEMA might have detected a flow channeling gas from the intergalactic medium onto the galaxy. While such flow would in principle consist of pristine gas, the detected OH$^+$ and CH$^+$ transitions testify to the presence of enriched material. Enrichment in such kind of flow could happen, for example, in case of an accretion shock as the gas enters the halo of the galaxy. Alternatively, the flow could be part of a galactic fountain, in which a fraction of the gas expelled by the star formation winds falls back onto the galaxy.

In this case, an outflow should also be detected, but no evidence of any outflow feature was found in the NOEMA spectra of HerBS-89a. Finally, if HerBS-89a is in fact a merging pair or a multiple source, a third possibility is that the red-shifted OH^+ and CH^+ lines originate in a stream of matter between the two components, which would naturally explain the enriched composition of the flow.

4 Conclusions and Perspectives

Using NOEMA, the z-GAL survey has enabled the first systematic measurements of redshifts of a large and complete sample of high-z galaxies selected from the *Herschel* northern and equatorial surveys. These data provide a unique database for exploring, through dedicated follow-up observations, the properties of these sources, from the gas and dust properties to the feedback and fueling activity, down to linear scales of 100 pc in the case of gravitational amplification. The results of the z-GAL comprehensive redshift survey will be reported in a forthcoming first series of papers that will cover the following aspects: (i) Overview of the z-GAL survey (Cox et al.); (ii) The dust continuum and the evolution of dust properties with redshift (Ismail et al.); (iii) The molecular gas properties (Berta et al); (iv) The nature of the sources – extended/lensed/companions/HyLIRGs (Bakx et al.). Finally, the z-GAL survey will provide, together with other available redshift measurements, a sizeable and homogeneous sample of about ~300 bright *Herschel* selected galaxies with reliable redshifts, increasing significantly the number of known lensed galaxies at the peak of cosmic evolution and providing the largest sample of HyLIRGs and additional rare objects.

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