Astro2020 Science White Paper
Measuring the Metallicity of Low-Mass, Low-Metallicity Galaxies in the Early Universe and the Galactic Habitability.

Thematic Areas: X Planetary Systems,   ~~Star and Planet Formation~~,
  ~~Formation and Evolution of Compact Objects~~, X Cosmology and Fundamental Physics,
  Stars and Stellar Evolution,   ~~Resolved Stellar Populations and their Environments~~,
X Galaxy Evolution,   ~~Multi-Messenger Astronomy and Astrophysics~~

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1. Introduction:

About 380,000 years after the big bang, the universe saw the creation of the first neutral atoms, mainly H and He from the recombination of electrons onto heavier nuclei of protons and neutrons. This phase of the evolution of the universe transformed the previously opaque universe where the mean free path of photons of photons was short compared to cosmological distance scales to the transparent universe we live in today. This change in the phase happened at an estimated redshift $z = 1100$ when the universe temperature was about 4000K. The universe kept on cooling and molecules formed that eventually led to the formation of the first stars. This major event in the universe's lifetime, the cosmic dawn, probably happened 200 – 400 million years (Myrs) after the big bang at about $z = 20 - 16$ (e.g. Bromm et al. 2013). It marked the development of the main factories that produced the rest of the heavy elements (metals) contained in the universe until today. This is called the metallicity, hereafter.

Why is the metallicity of interest? Metallicity traces the building of the elements. Of course, the metallicity Z is a summary of all the element abundances (O/H, Fe/H, etc.) that bring a more specific information. These single-element abundances are much more difficult to estimate because we obviously need an excellent-quality spectroscopy. Unfortunately, when trying to detect and analyze galaxies before the End of Reionization, this detailed objective might be out of reach, even for the largest telescopes.

The metallic content in galaxies provide an information not only on the integrated star formation rate in galaxies (through nucleo-synthesis) but also on the fraction of metals exchanged with the Inter-Galactic Medium (IGM). Metals are unique tracers of galaxy evolution and of the past history of feedback because the physical processes that shape galaxies and determine their evolution leave imprints on metal distribution and relative abundance of different elements. The mass-metallicity relation is a strong correlation between these two physical parameters. The original interpretation of the shape of this relation (Tremonti et al. 2004) is that the saturation appears because galactic outflows regulate the metal content and an equilibrium metallicity is reached when the metals ejected by outflows are balanced by those produced by star-formation. The crucial parameters are therefore the metallicity and the stellar mass (and the SFR). In this paper, we will see how to best measure them in the young universe when galaxies are small (low stellar mass) and at low metallicity.

2. Open questions:

2.1. What do we know about the rise of metals?

The universe did not contain any metals (metallicity $Z = 0$) during the first 200 – 400 Myrs of its lifetime. In the subsequent history of the universe, stars enriched galaxies and the IGM (through galactic outflows) in metals (Safranek-Shrader, 2016). The rate of this enrichment is badly known (Schneider 2012). It is likely that this enrichment was not spatially homogeneous. Dense regions probably underwent a faster enrichment than less ones (Cooper et al. 2008). For instance, since the formation of the Milky Way, the ISM in the solar neighborhood has seen an increase in the metal abundance from near zero to about 2% by mass. The estimated solar metallicity is $Z_\odot = 0.014 - 0.020$ (e.g. Vagnozzi et al. 2017).

What is the present status on our knowledge on the rise of metals? Collecting a coherent information on the metallicity over various environments and redshifts is a difficult task for at least two reasons: a) in the local or low-redshift universe, several metallicity tracers co-exist that are not fully cross-calibrated (Kewley & Ellison 2008) and b) the same metallicity tracers used at low-redshift are not available for the higher redshift universe because we do not always have telescopes covering the necessary wavelength ranges. For instance, the widely used R23 metallicity tracer used at low-redshift involves several of the bright optical lines (Hα, Hβ, [OIII]4363, 4959, 5007, [NII]6548, 6584) easily detectable from ground-based or space telescopes in the optical frame. When observing objects to $z > 2.5$, Hα will move beyond λ_{obs}=2.3μm which makes it much more difficult to detect from the ground. To get coherent metallicities, the best method is to use the same tracer over the widest redshift range. Following up the bright optical

lines at z > 2.5 means that we need a space-borne near- to mid-infrared (IR) spectrograph, sensitive enough to detect galaxies in the early universe. There is not such an available today. We will see in Sect. 3 what are the prospects to have one in the mid- to long-term.
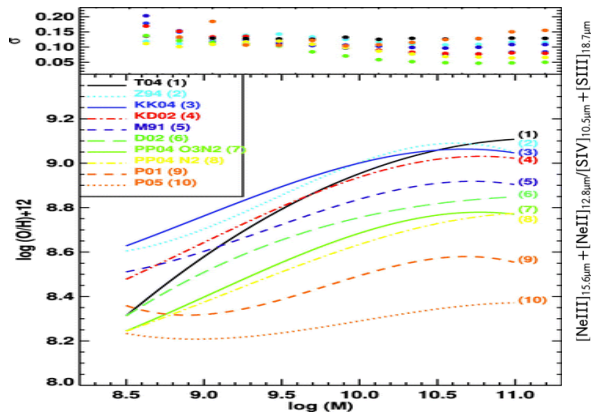

Figure 1: extracted from Figure 2 in Kewley & Ellison (2008). The top panel shows the rms scatter in metallicity about the best-fit relation for each calibration in 0.1 dex bins of stellar mass. The y-axis offset, shape, and scatter of the masse-metallicity relation differs substantially, depending on which metallicity calibration is used. The metallicity is estimated for ten optical O/H indicators.
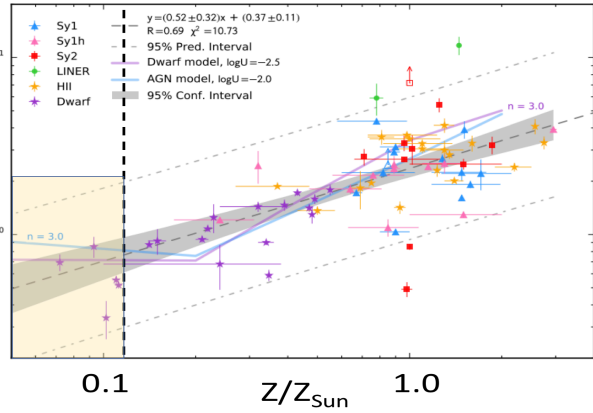

Figure 2: extracted from Fernandez-Ontiveros et al. (2017) and other similar ones shows that the fine structure infrared line are excellent metallicity tracers down to about 0.1 – 0.2 Z / Z$_\odot$. At lower metallicities (yellow region), the IR index saturates, and we must look for another metallicity tracer. The PAH3.3μm will be an excellent vector to measure the metallicity over a very wide range of redshifts, using the same metallicity indicator (see Sect. 3).
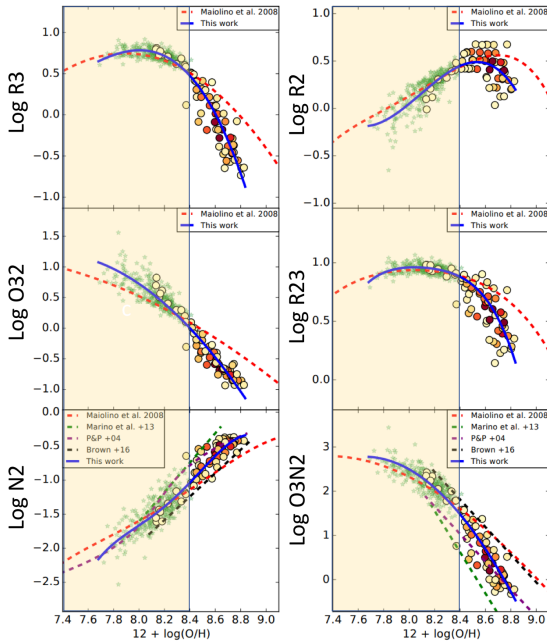

Figure 3: This plot extracted from Curti et al. (2017) shows the diagnosis using strong optical lines as a function of the oxygen abundance. Using these lines, a mid-IR spectrograph would be able to measure the metallicity of galaxies with the same tracer from z = 0 to z = 10.
Some of the tracers show degeneracies while other, involving Hα do not. The preferred tracers for the low-mass, low-metallicity galaxies (yellow region) would be O32 ([OIII] λ5007/[OII] λ3727), N2 ([NII] λ6584/Hα) and O3N2 (([OIII] λ5007/Hβ)/([NII] λ6584/Hα).
This means that we need to be able to observe enough galaxies (mapping efficiency) in the good wavelength range, accounting for the redshift.

2.2. When and where did the rise of metals happen?

Stellar mass and metallicity are two fundamental physical properties of galaxies. Both are metrics of the galaxy evolution process. The first one traces the mass of gas locked up into stars and metallicity traces the gas reprocessed by stars. Understanding galaxy evolution means that we should follow the evolution the co-evolution of these parameters with cosmic time (Tremonti et al. 2004). We need to have facilities capable of measuring the two parameters, in addition to the redshift.
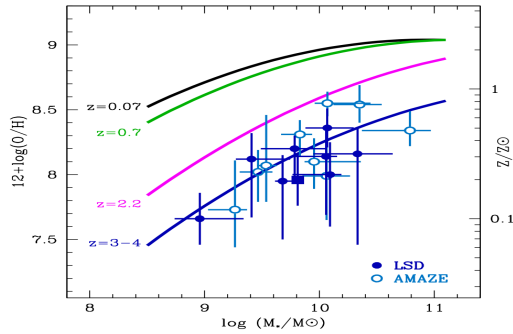
Figure 4: an example of the evolution of evolution of the mass-metallicity relation from Mannucci et al. (2009) at various redshifts. The mass-metallicity relation evolves from high-redshift (bottom) to low-redshift (top). In addition to this trend, more massive galaxies show some kind of saturation. The data are calibrated to the same metallicity scale and Chabrier IMF.

2.3. When did the rise of metals meet the origin of life?

Life, or at least life as we know it, is related to the rise of metals in several ways. First, life needs to be in a habitable zone. A habitable zone has been defined as a region of the universe with sufficiently high abundances of metals to form terrestrial planets that would host and sustain life (Spitoni et al. 2017). There is quite a large debate and a large variety of results, and, this is just the beginning of a story that would like to understand when life was (at least theoretically) able to appear.

A number of studies have tried to estimate the minimum metallicity in a galaxy at which planets with Earth-like characteristics could form (Gonzalez et al. 2001, Prantzos et al. 2008, Johnson & Li 2012). The consensus metallicity is 0.1 $Z_\odot$. More recently, several works tried to tackle this same question in a cosmological context (ΛCDM), e.g. by Forgan et al. (2017), Gobat & Hong (2016), Zackrisson et al. (2016) and Vukotic et al. (2016) tried to define the conditions in which halos can produce galactic structures capable to form habitable planets. Prantzos (2008) estimated the Probability of forming Earth-like planets (PFE) is PFE = 0.4 when the metallicity is above a threshold [Fe/H] ≥ -1 dex. For metallicities below the threshold, the probability PFE = 0. Lineweaver et al. (2001) suggested that the probability of forming Earth-like planets linearly correlates with metallicity. In other terms, PFE ∝ Z. But, Zinnecker (2004) found a threshold in metallicity Z ≥ 1/2 $Z_\odot$ for the formation of Earth-sized planets. PFE=0.4 was needed to reproduce the metallicity integrated probability of Lineweaver et al. (2001). Observationally, we can try to see whether the frequency of Earth-like-sized planets is related to the metallicity of the star. Using results from the Kepler mission, Buchhave et al. (2012) concluded that the frequency of such planets is almost independent of the metallicity of the host star.

3. Prospects for Moving Forward in the Next Decade and Beyond

3.1. We need to find methods valid and adapted to our goals.

The fine structure lines in the mid-IR and far-IR (Fig. 2) are very powerful to measure the metallicity of massive and metallic galaxies (e.g., Fernandez-Ontiveros et al. 2017). They do not suffer from the dust extinction and from the degeneracy observed for metallic galaxies when using rest-frame optical lines. But galaxies are expected to have lower masses and low metallicities at z > 5 (Fig. 5). If we want to focus on the rise of metals in the universe at z > 5, these IR fine structure lines are not good tracers for low-metallicity galaxies. This is a direct implication of the galaxy formation process in the ΛCDM cosmology:

- Galaxies build stellar mass with time
- Higher redshift galaxies have lower mass (M < $10^{10.5}$ $M_\odot$)
- We know there is a mass – metallicity relation (Sect. 2.2)
- Lower mass galaxies have lower metallicities (Z < 0.2 $Z_\odot$ or 12+log(O/H) < 8.4)
- Higher redshift galaxies have lower metallicities

If we cannot use the fine structure line, what are the options? We can utilize the strong power of the bright rest-frame optical lines and make use of the 3.3μm PAH feature. We detail these two options below.
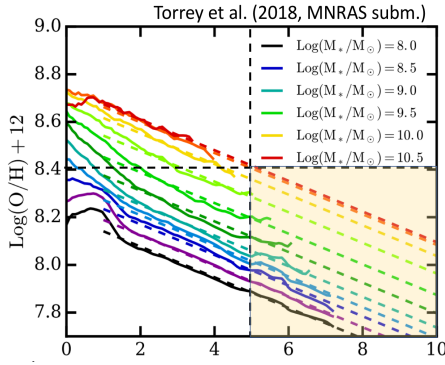
Figure 5: The metallicity of galaxies as a function of the redshift from Torrey al. (2018). At z > 5, galaxies with stellar masses below log $(M/M_\odot)$ = 10.5 will be at low metallicity.
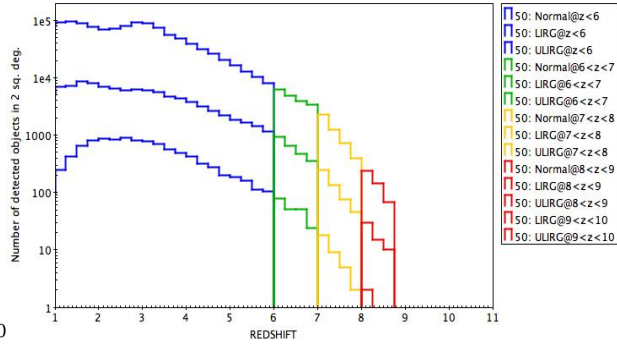

Figure 6: Number of detectable galaxies through the PAH3.3μm feature vs redshift for the Origins Space Telescope. This is estimated using Béthermin et al. (2017) and converting from the IR luminosity.

3.2. <u>Option 1: Bright optical lines:</u> For low-metallicity galaxies at z > 5 (Z < 0.1 $Z/Z_\odot$, Torrey et al. 2018), several metallicity optical tracers can be used (Fig. 3 or Dopita et al. 2016). But the previously mentioned degeneracy is an issue we would like to get rid of. The R2, R3 and R23 tracers show this degeneracy. Introducing the Hα line rise this degeneracy and the N2, O32 and O3N2 tracers provide a good metallicity response in the range we expect for high redshift galaxies at Z < 0.2 $Z/Z_\odot$ or 12+log(O/H) < 8.4. Because of the redshifts, these lines move to the range 3 < λ_{obs} (μm) < 9 at z > 6. This is the best option to carry out the rise of metals science case at z > 6. Two projects are adapted to this wavelength range: JWST/NIRSpec + MIRI and OST/uMISC. The former is well adapted and will certainly be used to this goal during its lifetime. But, JWST (https://jwst.nasa.gov/faq_scientists.html#lifetime) is designed to have a "*mission lifetime of not less than 5-1/2 years after launch, with the goal of having a lifetime greater than 10 years*" This means that no mission will be able to measure the metallicity and follow-up exotic and early universe galaxies and AGNs discovered by WFIRST, the ELT, ATHENA, SPICA in the rest-frame UV-Optical-NIR? So, it seems that we need the spectroscopic capabilities of uMISC to detect these lines. For instance, a survey with individual exposures of 10^4 sec (SNR = 10, 10^{-21} W/m^2 for OST/uMISC per field for 100 hours over about 30 uMISC fields (i.e., 300 arcmin^2) would open the universe up to z = 10 – 12 (Fig. 6). Note that at low-z, Hα/[OIII]$\sim$1.0. But, at z > 5, it might increase by a factor of a few (e.g. Faisst et al. 2016). Complementarity with ELTs+JWST in space will allow to use the same metallicity indicator over most of the lifetime of the universe.

3.3. <u>Option 2: 3.3μm PAH feature</u>: Fig. 7 shows a strong and linear decrease of q_{PAH}, the mass fraction of PAH that seems to be correlated to the metallicity of the observed galaxies. Several interpretations for this effect exist. But the leading one is that PAHs are destroyed in low-Z environment by the UV radiation field, which propagates more easily due to the lower dust content for galaxies with lower metallicities (Galliano et al. 2003; Boselli, Lequeux & Gavazii, 2004; Engelbracht et al. 2008; Gordon et al. 2008). What projects are adapted to this science case? JWST/MIRI, SPICA/SMI and the Origins Space Telescope (OST) upscaled imaging Mid-Infrared Spectroscope (uMISC). However, JWST is relatively hot and the performances decrease beyond 10 – 15μm (https://jwst-docs.stsci.edu/display/JPP/JWST+Background+Model). SPICA/SMI on the other hand is cooled to <8K and provide an excellent mapping speed, even better than JWST. But the limited size of the primary mirror is now the limit to access these very distant galaxies (http://www.spica-mission.org/). The present baseline version of OST/MISC does not provide the needed characteristics. However, an upscaled version (uMISC, see http://exoplanets.astron.s.u-tokyo.ac.jp/OST/MISC/index_misc_case_A.html) is perfectly adapted to this objective. So, this last option seems the only way to carry out the crucial programmes linked to the metallicity of low-mass, low-metallicity galaxies at z > 5 – 6.
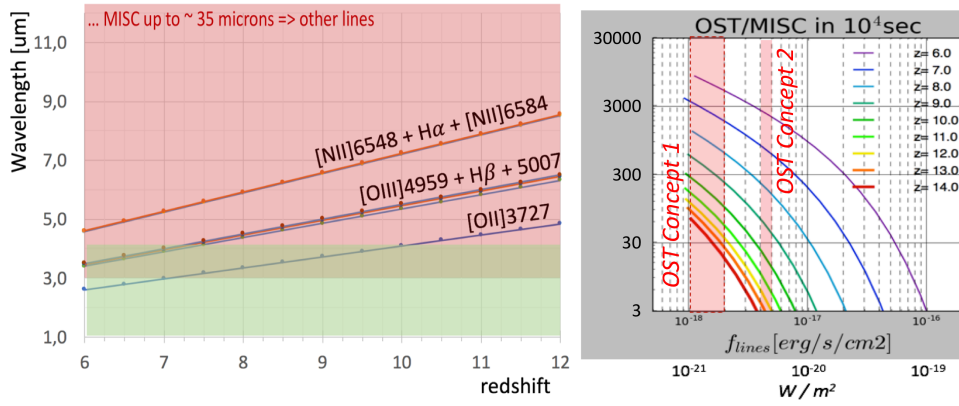
Figure 6: Left – Wavelength range where the bright optical lines needed to estimate the metallicity. Right – Estimated number of objects detected in 10,000 sec by OST/uMISC over 300 arcmin^2 for the two OST concepts and OST/uMISC.
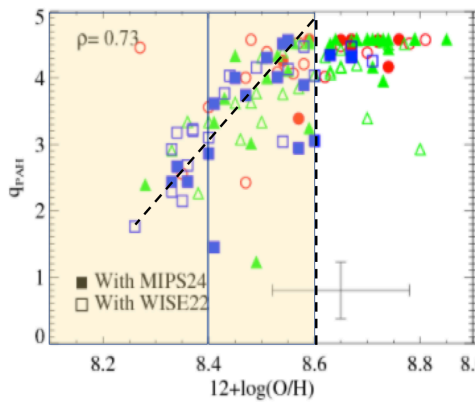

Figure 7: extracted and adapted from Ciesla et al. (2014). The mass fraction in the PAH, measured by the q_{PAH} parameter shows a linear decrease at 12 + log(O/H) < 8.6. The PAH3.3um feature could be used to measure the metallicity for these low-metallicity galaxies expected to lie in the universe at z > 5. However, this effect needs to be further calibrated and JWST will be very useful to meet this goal, but not at very high redshifts because of the loss in sensitivity caused by the strong thermal background beyond 10-15μm.

3.4. Measuring the stellar mass: WFIRST will provide a huge sample of galaxies in the two WFIRST Wide (mAB ≤ 27) and Deep (mAB ≥ 28) surveys at 5 < z < 6 - 10. To build the mass – metallicity relation (and the associated SFM - $M_\star$), we propose to measure $M_\star$ and SFR for a sample of at least 10 galaxies per bin for WFIRST-detected objects to z = 6 and try to complete this analysis to z $\approx$ 9 using the metallicity provided by either the fine structure line for the massive galaxies of the PAH3.3um for the less massive one. For instance, we would obtain two rest-frame NIR data points (1 for WFI-S and 1 for WFI-L) for a grand total of >120 galaxies that will give us an excellent basis for $M_\star$ (see Table 1). The rest-frame UV will be available from WFIRST. The rest-frame far-IR from OST-FIP. Again, JWST/MIRI, SPICA/SMI and the Origins Space Telescope (OST) upscaled imaging Mid-Infrared Spectroscope (uMISC) can theoretically perform this measure. But the same limits (mission lifetime and thermal background for JWST, size of primary mirror for SPICA) makes OST/uMISC the best candidate to fully cover the requirements for this case, especially after JWST.

z\mAB	25	26	27	28	29
5	6741	257674	2.8E+06	20084	73187
6	54	12773	307300	3873	20241
7	0	325	23164	532	4282
8	0	4	1165	55	730
9	0	0	44	5	96
10	0	0	1	0	13

Table 1: From Ma, Hopkins & Garrison-Kimmel (2018) rest-frame UV (with dust attenuation accounted) luminosity functions to estimate the number of objects in each of the two WFIRST surveys, i.e. Wide: m_{lim}=27 over 2200 deg^2 and DEEP: m_{lim}=29 over 3 deg^2 at 5 < z < 6 - 10. OST/uMISC will be able to estimate $M_\star$ and SFR for a sample of at least 10 galaxies per bin for WFIRST- detected for a grand total of >120 galaxies with SNR > 5 in 280 hours.

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