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Conference summary

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Abstract In the process of reading all the papers that appear in this voulume, we decided to provide a summary of the conference, that may help the reader in navigating through the volume. A shorter version of this summary has been published on the ESO Messenger (Saviane et al.) and it has considerable overlap with this one. Since there was not enough space on the ESO Messenger to fit all the details we decided to provide the full summary paper as the last paper of the volume.

Key words. Galaxies: abundances – Galaxies: evolution – Galaxies: fundamental parameters – Galaxies: ISM – Galaxies: star formation

1. Introduction

The conference started with an introductory talk by Anatoly Klypin, who updated the audience with the latest ΛCDM simulations of the evolution of the universe. The talk underlined one of the recurrent themes of the conference, i.e. that modeling gas processes and SF feedback is exceedingly difficult, so critical constraints to theory must be placed by measuring abundances at all redshifts and for different cosmic structures. After the primordial nucleosynthesis, chemical elements are produced in stars (either in quiescent or explosive ways) so a review of stellar nucleosynthesis was given by Paolo Ventura. He recalled how stars of different mass pollute the ISM with different elements, and at different times. Stars initially more massive than $\sim 8M_{\odot}$ undergo core–collapse, and contaminate their surroundings mainly with material exposed to advanced $\alpha-$ capture nucleosynthesis. The yields exhibit a characteristic odd–even effects, and are also modulated by the degree of stellar rotation. Intermediate mass stars pollute the interstellar medium via stellar winds during the AGB phase, especially with CNO elements. The yields of stars with mass below $\sim 3M_{\odot}$ are dominated by the Third Dredge–Up, and are extremely enriched in carbon. Higher masses undergo Hot Bottom Burning: their yields show up the signature of p–capture nucleosynthesis, thus being enriched in nitrogen, and depleted in their carbon and oxygen content. Both groups of stars are efficient dust producers, mainly under the form of carbonaceous dust, silicates and corundum.

In the rest of this article, summaries of invited and contributed talks are arranged in order of decreasing redshift. Table 1 provides an overview chronology of events

Table 1. Chronology of main events discussed in the article. The conversion from redshift to time was done via http://www.astro.ucla.edu/∼wright/CosmoCalc.html, assuming $H_0 = 71$, $\Omega_M = 0.270$, $\Omega_{\rm vac} = 0.730$.

time from BB	redshift z	event	Abundance
~ 1 to $\sim 10^3$ sec	$> 150 \times 10^6$	BBN	Observed: D/H=$(2.53 \pm 0.04) \times 10^{-5}$; Y=$0.254 \pm 0.003$; Predicted: $A(^7\mathrm{Li})$ = 2.7
After 0.1 Myr	$\sim 2,000$	CMB	
$\simeq 0.2 - 0.1$ Gyr	$\simeq 20 - 30$	First SF	When $H_2 \gtrsim 10^{-4} \Rightarrow$ SF starts; pollution depends on IMF (PISNe or not) and stellar rotation
		most metal-poor MW stars	SMSS J031300.36-670839.3 has [Fe/H]< -7.1 and A(C) = 6.0 (Keller et al. 2014), SDSS J102915+172827 has [Fe/H] = -5.0 and A(C)< 4.0 (Caffau et al. 2012); two populations of very metal poor stars in terms of carbon abundance (Norris et al., 2013; Spite et al., 2013)
$0.2 < t < 0.48$ Gyr	$20 > z > 10$	dwarf galaxies in Ricotti's simulations (progenitors of UFD?);	MDF peaked at [Fe/H]~ -1
$0.27 < t < 0.48$ Gyr	$15 \gtrsim z \gtrsim 10$	Pop III galaxies in low-density regions; candidates found @ $6.3 < z < 8.8$ behind lensing clusters (Rydberg in proceedings)	
~ 0.4 Gyr	~ 11	Lensed galaxy of 10^8-$10^9 M_\odot$ (Coe et al. 2013)	
~ 0.4 Gyr	~ 11	First galaxy candidates, LMC mass or larger (Oesch et al. 2013)	
$t > 0.48$ Gyr	< 10	reionization completed	
0.71 Gyr	7.51	Farthest galaxy redshift confirmed by Ly α (Finkelstein et al. 2013)	
0.97Gyr	5.9	GRB 130606A (Chornock et al. 2013)	[Si/H] $\gtrsim -1.7$ and [S/H] $\lesssim -0.5$
$t < 1.2$ Gyr	> 5	High density clumps ("disks") from DLA measurements	Enrichment by supernovae type-II from population-II stars and prompt type-I supernovae
1.2Gyr	5.0	GRB 111008A (Sparre in proceedings)	$\log N(\mathrm{HI})/\mathrm{cm}^{-2} = 22.30 \pm 0.06$; [M/H]$\simeq -1.7 \pm 0.1$ for S, Cr, Fe, Ni
1.3 Gyr	4.7	GRB 100219A (Thöne et al. 2013)	[S/H] $= -1.1 \pm 0.2$,
~ 2.19 Gyr	~ 3	IGM measurements from Lyα forest	[C/H] ~ -3.5
~ 2.19 Gyr	~ 3	Galaxy halo measurements from Lyman limit systems	[M/H] from pristine to $\sim +0.7$
$1.2 \rightarrow 12.38$ Gyr	$5 \rightarrow 0.1$	average "disk" metallicity from DLA measurements	[m/H] $= -0.22\,z - 0.65$; [α/Fe] $\sim +0.3$
1.8 Gyr	3.5	SF galaxies in Maiolino et al. (2008)	[m/H]~ -0.5 for galaxies of $\sim 10^{10} M_\odot$
3.34 Gyr	2	MZR from H II regions (Cullen in proceedings); highest-mass galaxies ($3 \times 10^{10} M_\odot$)	[O/H]~ -0.5
3.34 Gyr	2	First detected clusters of galaxies	
	1.49	Negative metallicity gradient for lensed galaxy (Yuan et al. 2011); "inside-out" formation?	-0.16 dex kpc^{-1}
4.6 Gyr	1.4	end of thick disk formation, Haywood in proceedings (start at 1.2 Gyr)	
7.7 Gyr	< 0.65	Galaxies with $9.8 < \log M_*/M_\odot < 11.5$ start to evolve as closed boxes (Rodrigues in proceedings)	

and observational data together with the abundances (where measured) at particular epochs.

2. z = ∞

Naturally, the first measurements are those of elements produced in the in the initial $\sim$ 15 min in the life of the universe: D, ^{3}He, ^{4}He and ^{7}Li are the products of the so-called big-bang nucleosynthesis. Ryan Cooke and Yuri Izotov presented their most recent estimates: from absorption spectra of DLAs $(D/H)_p = (2.53 \pm 0.04) \times 10^{-5}$ (Cooke et al. 2014); extrapolating from abundances measured from the emission spectra of HII regions in metal-poor galaxies, $Y_p = 0.254 \pm 0.003$ (Izotov et al. 2013); and from spectra of very metal poor stars the upper limit of lithium abundance is $A(^7\mathrm{Li}) \equiv 12 + \log(^7\mathrm{Li/H}) = 2.2$ (e.g Asplund et al. 2006), in the presence of many stars observed with a lower Li abundance at extremely low metallicities, the "meltdown" of the lithium plateau (Aoki et al. 2009; Sbordone et al. 2010). Because ^{3}He is also produced in low-mass MS stars, it cannot constrain cosmological models. Gary Steigman then pointed out that when inserted in the models, the abundances of D and ^{4}He can constrain the baryon-to-photon ratio (η_{10} or, $\Omega_B h^2$) and the number of equivalent neutrinos (ΔN_ν) to be added to the three standard ones. In addition, because the Hubble parameter is $H \propto \rho_R^{1/2}$, a finite ΔN_ν implies an additional contribution to the energy density ρ_R on top of the photon and neutrino ones, and therefore a non standard expansion rate. Given the quoted abundances, this indeed seems to be the case: a joint BBN + CMB analysis yields $\eta_{10} = 6.13 \pm 0.07$ ($\Omega_B h^2 = 0.0224 \pm 0.0003$) and $N_{\rm eff} = 3.46 \pm 0.17$ ($\Delta N_\nu = 0.40 \pm 0.17$). It was then recalled that one of the possible solutions to the dark matter problem is the introduction of a "weakly interacting massive particle". Depending on the nature of this WIMP, the lower bound to m_χ ranges from $\sim m_e$ to $\sim 10\,m_e$, while the best fit WIMP masses lie in the range $\sim 5 - 10$ MeV. Interestingly, the presence of an additional, free parameter relaxes the constraints on ΔN_ν so in this case a sterile neutrino is permitted at $\lesssim 68\%$ confidence. It should also be noted that the abundance of lithium is $\sim$ 3 times less than the BBN value, with or without a light WIMP, thus the "lithium problem" persists.

3. z = 2000

After $\sim 10^5$ yr ($z \sim 2,000$) the universe recombines and the cosmic background radiation is freed. At the same time structures keep growing under the gravitational influence of DM, and dense nodes form at the intersections of filamentary structures. Gas trapped in these nodes forms H_2 via the H^- chain, and when the abundance of H_2 reaches $\sim 10^{-4}$ cooling is sufficient to trigger star formation.

4. z = 30 -> 20

In his review, Volker Bromm thus recalled that the first stars form at redshifts $z \simeq 20 - 30$ ($\simeq 0.2 - 0.1$ Gyr after the big bang) inside $\sim 10^5 - 10^6 M_\odot$ 'mini-halos'. The subsequent evolution of both metallicity and cosmic structures depends on the mass function of these Pop III stars, i.e. whether it is limited to a few tens of solar masses, or it can reach $\sim 140 - 260 M_\odot$. In the latter case there will be pair instability SNe together with core-collapse SNe: PISNe transform half of their mass into metals, while only a few percent of the mass is converted into metals by CC SNe. In addition the energy output of PISNe is larger than that of CCSNe, which increases cooling times of the ejecta that eventually reassemble into a more massive DM halo. In any case, due to the faintness of the mini-halos, the first detectable objects by JWST should show above-primordial enrichment.

At the current early stage, simulations cannot fully constrain the Pop III IMF, so observations must come to rescue. Observations of the most metal poor stars in the Galactic bulge seem to indicate that they were formed in gas enriched by CC SNe, and that their Pop III progenitors were rapidly rotating (Chiappini et al. 2011), in agreement with recent models (Stacy et al. 2013). However searches for metal-free, Pop III, surviving low-mass stars are on-going, and their outcome will certainly lead to revisions of the current scenario.

Three such surveys were illustrated by Elisabetta Caffau, Heather Jacobson, and Katia Cunha. The first survey starts with SDSS-DR9 spectra and identifies TO stars with metallicities [Fe/H]< -3 to be followed up with UVES or X-Shooter at the VLT and has detected the most metal–poor star currently known: SDSS J102915+172827 (Caffau et al. 2012). The second survey uses the multi band photometry of SkyMapper to search for candidate EMP stars, which are then scrutinized with low-resolution spectra obtained with the Australian facilities, and the best candidates are then observed with high-resolution spectrographs obtained at Magellan, Keck, and the VLT. Heather gave us a preview of SMSS J031300.36-670839.3, later published in Keller et al. (2014). The null detection of iron lines puts its iron abundance at a record breaker [Fe/H]< -7.1, yet its high carbon abundance implies a global metallicity similar to that of metal-poor globular clusters. Its abundance pattern implies formation in gas enriched by a single $60\,M_{\odot}$ star that exploded as low-energy SN. These results are in line with the discussion of Pop III IMF, and early galaxy formation, outlined above. An earlier result of EMP surveys is that there seem to be two populations of very metal poor stars in terms of carbon abundance (Norris et al. 2013; Spite et al. 2013): the carbon-enhanced stars, like SMSS J031300.36-670839.3 and the carbon-normal stars, like SDSS J102915+172827. While not explicitly targeted to metal-poor stars, the SDSS3/APOGEE survey described by Katia Cunha is an example of many on-going or planned large-scale surveys of Milky Way stellar abundances.

5. z = 11 -> 9

While the first Star Formation (SF) is beyond the reach of current facilities, galaxy candidates at ever increasing redshifts are being found. Rychard Bouwens updated us on the most recent results of these searches, which are typically carried out with the HST. They show the early and fast assembly of galaxies, for example based on the UV luminosity density contributed by star forming systems, which increased by two orders of magnitude in ~ 1.5 Gyr, between redshift 10 and 3. Redshifts of the earliest galaxies are estimated based on SED fits to photometric points: for example Oesch et al. (2013) using WFC3/IR data and the Lyman break technique found seven $z \sim 9$ galaxy candidates, and one each at $z \sim 10$ and $z \sim 11$. If only galaxies with spectroscopic determinations of redshifts are considered, an object at $z = 7.51$ is the current record holder (Finkelstein et al. 2013), with only a handful more at $z > 7$. Spectrographs at 10m-class telescopes have been used to detect Lyman α emission from these galaxies, but measuring their metallicities is still not feasible.

At redshift 10 and beyond, current surveys can only detect galaxies with at least 10^8-$10^9 M_{\odot}$ in stellar mass, but lower mass objects must have formed even earlier. Indeed this is what Massimo Ricotti has been finding through simulations: interestingly, if evolved into the present-day universe, his objects would have properties comparable to the faintest dwarf spheroidal galaxies in the Local Group.

6. z = 15 -> 9

The chain of events outlined so far will work for the densest regions of the primordial universe, but Stiavelli & Trenti (2010) pointed out that chemically pristine galaxies in halos with mass $M \sim 10^8\ M_{\odot}$ may form at $z < 20$ in relatively underdense regions of the universe. They expect that such galaxies in the range $10 \lesssim z \lesssim 15$ could be found if magnified by lensing clusters, so Claes-Erik Rydberg went out to see whether this is true. And indeed by fitting Pop III model SED to multiband photometry data from the CLASH survey, he has found candidate Pop III galaxies with redshifts between 6.3 and 8.8, lensed by four galaxy clusters.

7. z = 6 -> 5

In order to find galaxies for which metallicity can be measured, lower redshifts must be considered. The first galaxies to be encountered along this route are GRB host galaxies, as it was explained by Martin Sparre. A fraction of GRBs have host galaxies that gives rise to damped Lyman-α absorption, which permits the measurement of their metallicity, currently up to redshift almost 6. For example Chornock et al. (2013) constrain the metallicity of GRB 130606A at $z = 5.913$ to be [Si/H] $\gtrsim -1.7$ and [S/H] $\lesssim -0.5$, and Thöne et al. (2013) observed GRB 100219A at $z = 4.7$ and measured a metallicity of [S/H] $= -1.1 \pm 0.2$, with an abundance pattern affected by either strong dust depletion or over-abundance of α-elements. Martin presented his own VLT/X-shooter spectroscopy of the optical afterglow of GRB 111008A at $z = 5.0$, which yielded an HI-content of $\log N(\mathrm{HI})/\mathrm{cm}^{-2} = 22.30 \pm 0.06$ and and a metallicity [M/H]$\simeq -1.7 \pm 0.1$ for several elements (S, Cr, Fe, Ni).

8. z = 5 -> 2

The way metallicities are measured for GRB hosts is shared by studies of the intergalactic medium (based on absorption line systems that are detected in front of $z \gtrsim 2$ quasars), so it is perhaps no coincidence that metallicity measurements of the IGM start to be available at redshifts similar to those of the GRB hosts quoted above. A review of this topic was given by Michele Fumagalli who showed us that below $z \sim 5$ IGM pollution is already widespread. Based on H I column densities converted into volume densities, it can be shown that absorption systems correspond to the IGM (i.e., cosmic web and voids), to galaxy halos, and to galactic disks or neutral gas clumps. In the IGM, measured carbon abundances between $z \sim 2-4$ depend on redshift and gas density, but typical values are [C/H] ~ -3.5 at $z \sim 3$, and an increase by a factor of $\sim 2-3$ from $z \sim 4.3$ to $z \sim 2.4$. This means that the enrichment of the IGM starts already in the first 1.2 Gyr of cosmic history. Considerable substructure is observed in the IGM, so Michele formulated the hypotheses that a significant fraction of the metals seen in the IGM has been carried from galaxies in the form of compact and enriched clumps that subsequently mix with the surrounding hydrogen. In galaxy halos, a large metallicity spread is observed, reaching supersolar ([M/H] $\sim +0.7$) values. Interestingly, some halos are completely unenriched (Fumagalli et al. 2011; Simcoe et al. 2012), so apparently pre-galactic metal enrichment was incomplete, and probably confined to the highest-density regions. Another explanation offered by Michele is that in galactic halos, chemically-pristine inflows coexist with metal-enriched outflows or galactic fountains. Turning to the highest density systems, their median metallicity is [M/H] ~ -1.5 with a 0.6 dex scatter, but if a "cosmological metallicity" is computed as an average over DLAs, this depends on redshift as $[\mathrm{m/H}]_c = (-0.22 \pm 0.03)z - (0.65 \pm 0.09)$ from $z = 0.1$ to $z = 5$. If this were treated as the Age-Metallicity Relation (AMR) of a real galaxy, and considering the mass dependence of AMRs, the galaxy would have a mass intermediate between the SMC and the LMC. Interestingly, DLAs are found to be α–enhanced with a median [α/Fe] $\sim +0.3$, and the [M/H] and [α/Fe] distributions in $z > 2$ DLAs with [M/H] $\lesssim -1$ agree with those observed for Galactic halo stars. Similar abundance patterns between DLAs and halo stars are also found in the most metal-poor DLAs at [M/H] $\lesssim -2$, hinting that there exists a connection between DLA gas and the sites where Galactic halo stars form. Abundance ratios of candidate DLAs at $z > 5$ point to enrichment by supernovae type-II from Pop II stars and prompt type-I supernovae, and because ratios do not change with redshift, DLAs must be enriched by young stellar populations.

More insight into IGM enrichment processes was offered by the presentations of Michael Rauch and Evan Scannapieco. Michael has an on-going investigation of high redshift galactic halos in which Lyα emission indicates the presence of young stellar populations and signs of tidal and/or ram pressure stripping characteristic of interacting galaxies. The release of metal-enriched gas during these interactions, possibly facilitated by a combination of stellar feedback and stripping, and enhanced by interaction rates increasing with redshift, may provide a mechanism for enriching the IGM as widely as observed. On the contrary, observed outflows do not appear to reach the distances required to explain the widespread metal enrichment, nor does the low density, metal-enriched IGM show any conspicuous signs of recent outflows.

These ideas are directly supported by the simulations presented by Evan Scannapieco. He finds that long-range outflows are excluded also by the fact that by $z \approx 2$, intergalactic enrichment appears to be concentrated around large galaxies and due primarily to metals from similarly-biased higher-redshift sources. The ejection of metals from galaxies appears to be more efficient at high-redshift than today, not only because of the smaller gravitational potential wells of galaxies, but also because of their more compact sizes, spatial distribution, and the overall expansion of the universe.

9. z = 3 -> 0

As we move down in redshift, metallicities for larger galaxy samples can be obtained, which show that a mass-metallicity relation (MZR) is in place already at $z \sim 3.5$ (Maiolino et al. 2008) A discussion of the MZR based on spectra of lensed galaxies was presented by Lisa Kewley. She showed some results from Yuan et al. (2013), highlighting how good SNR spectra of lensed galaxies can be used to estimate metallicities using the same methods applied for local galaxies. The redshift evolution of [O/H] can thus be better constrained. In addition it is possible to explore how the MZR extends to low-mass galaxies (down to $3 \times 10^7 M_\odot$).

10. z = 2

Metallicities for high-redshift galaxies are obtained with calibrations of emission line ratios versus metallicity obtained with local fiducial H II regions. However, earlier in the cosmic history physical conditions in the same regions might have been different, as postulated by Fergus Cullen. He finds that his MZR is offset by ~ 0.3 dex to lower values compared to that of Erb et al. (2006); for example his highest-mass galaxies ($3 \times 10^{10} M_\odot$) have [O/H]~ -0.5 instead of ~ -0.2. However the two datasets can be reconciled if the effect of a higher ionization parameter is applied to the Erb et al. (2006) sample.

11. z = 1.49

For distant unresolved objects metallicity estimates are averaged over the entire galaxy, so metallicity gradients can add scatter and spurious trends with redshift. Lisa Kewley then showed the case of a lensed galaxy at $z = 1.49$ (from Yuan et al. 2011) where a -0.16 dex kpc^{-1} gradient was found, which is significantly steeper than the gradient of late-type or early-type galaxies in the local universe. A gradient that flattens in time would support a disk formation scenario in which early infall/collapse in the galaxy center builds a chemically enriched nucleus, followed by slow enrichment of the disk (”inside-out” formation).

12. z = 0.6 -> 0

Throughout cosmic history, interactions between galaxies and gas exchanges with the environment play a big role in their evolution, an aspect of galaxy evolution that is being investigated by the IMAGES survey. The first presentation based on these data was by François Hammer, who examined mergers between gas-rich disk galaxies in the last 6 Gyr of cosmic history (i.e., starting at $z \sim 0.6$). The survey includes spatially-resolved kinematics, detailed morphologies and photometry from UV to mid-IR, which let François discover that at that redshift 50% of spiral progenitors were experiencing major mergers: therefore a high fraction of present day disks are the end products of rebuilds, a fact confirmed, e.g., by the high degree of substructure observed in NGC5907 and M31. In the future, it will be interesting to see how metallicities and abundance patterns are modified by major mergers, and if abundance studies can be used to uncover mergers through the "fossil record". In the second presentation Myriam Rodrigues investigated the role of gas exchanges during the past 6 Gyrs in the life of intermediate mass ($9.8 < \log M_*/M_\odot < 11.5$) disk galaxies. She considered the run of gas fraction with redshift, and found that galaxies in her sample evolved as closed systems since redshift ~ 0.6; however looking at gas fractions from the literature, it appears that at higher redshifts ($z \sim 2$ and $z \sim 3$) gas exchanges with the environment become more and more important.

13. z = 0+

Byproducts of mergers are various types of debris, of which the most conspicuous are tidal dwarf galaxies (TDGs). These are potential contributors to the enrichment of the IGM, so we asked Pierre-Alain Duc to review the status of this research field. His conclusion is that the case is still open. Some studies claim that TDGs are very fragile and do not survive internal and external processes, so they will pollute the IGM. But other models indicate that TDGs are robust and somehow manage to keep their material, despite the lack of dark matter. The answer could come from a census of TDGs: as Pierre-Alain said, the more numerous they are, the less they will play a role in the enrichment of the intergalactic medium. One step toward the census was illustrated by Sarah Sweet, who searched for TDGs in galaxy groups identified in the HIPASS survey (which they call "Choir" groups). She identified three (16% of dwarfs) strong TDG candidates based on their position in the luminosity-metallicity plane: they are above the relation defined by SDSS galaxies, probably because they were formed pre-enriched disk material ejected during galaxy encounters.

14. z = 0

At the end of the cosmic chemical evolution outlined so far are the objects that we observe in the local universe. Several sessions of the conference were therefore dedicated to reviewing abundance determinations for the Milky Way and associated structures. To summarize this broad section, we can start from the solar neighborhood. Because the solar system is immersed in the galactic disk, our observations suffer from extinction caused by gas and dust confined in the disk itself. Therefore a proper interpretation of observations needs to take into account the ISM distribution around the Sun. The status of such knowledge was the subject of a very interesting talk by Rosine Lallement, who presented us the latest maps of gas geometry within 500 pc from us.

14.1. MWG disk

Moving to the large scale structures of the Milky Way, Thomas Bensby started with a review of abundances of stars in different Galactic subsystems, especially the think/thick disk and the bulge. He recalled that in the [Mg/Fe]-[Fe/H] plane thin and thick disk stars in the solar neighborhood show distinct abundance trends, and this can be interpreted as an age difference, the thick disk being older. By collecting abundances for more distant stars, Thomas has found that the ratio of thick-to-thin disk stars changes with distance in a way that shows that the thick disk is more centrally concentrated than the think disk. In the solar neighborhood the thick disk represents 10% of disk stars.

New results on the chemical evolution of the MWG disk were also presented, based on the large set of spectra being collected by the HARPS GTO program (Adibekyan et al. 2012). Sara Bertran de Lis confirmed the α element enhancement of thick disk stars with oxygen abundances, and Garik Israelian found that thick and thin disk populations are different also when looking at [Cu/Fe], [Y/Fe] and [Ba/Fe] abundance ratios. Afterwards, after a general introduction on the principles of galactic chemical evolution by Nicolas Prantzos, Misha Haywood reported on new results based on Si abundances from the same HARPS database. After estimating the age of each star, a custom chemical evolution model is fit to the data, which allows them to reconstruct the Star Formation History (SFH) of the MW disk. It is then found that the thick disk formed between 12.5 and 9 Gyr ago, and that equal mass should be found in the thick and thin disks. Large amounts of gas were available early in the Galaxy to sustain the formation of the thick disk, adding support to the choice of adopting a closed-box model to approximate its chemical evolution.

Success in reproducing the [Fe/H] and [O/Fe] distribution functions of the MW disk was also achieved by Rob Yates with his semi-analytic model of galaxy formation, within the standard ΛCDM framework. The model has the added advantage of simultaneously reproducing the chemical properties of local elliptical galaxies (M_*-[O/Fe] relation) and the mass-metallicity relation of local star forming galaxies. Other simulations were presented by Noelia Jimenez who discussed how in her implementation, the so-called "single degenerate" scenario for SN Ia is able to reproduce the [α/Fe] ratios for bulge-dominated type galaxies, the observed SNIa rates and the observed correlation between the the star formation and the SN Ia rates in galaxies.

14.2. MWG bulge

The same [α/Fe]-[Fe/H] sequence of thick disk stars is shown by the bulge, but Thomas showed that age information can be also added by using microlensed turnoff stars. The AMR for these stars revelas that at [Fe/H]$\sim$ 0.4 an age spread is present. According to Thomas, all this evidence indicates that the bulge could have been formed from disk material, i.e. it could be a pseudo-bulge. However in her review, Melissa Ness used results from the ARGOS survey to show that, while the majority of stars in the bulge belong to the boxy/peanut shape, which indeed is a signature of formation from the disk, there remains a metal poor population which is not part of the boxy/peanut, whose origin is still unclear. It could be a classical bulge or a thick disk, or a mix of these two populations. On-going large-scale spectroscopic surveys will hopefully clarify this issue. Support to a secular formation of the bulge was given by Paola di Matteo with her dissipationless, N-body simulations. They show that, following bar formation, the whole stellar disk can feed stars into the central regions of the Galaxy, with final radial distribution that matches the original one. Based on the observed kinematics, Paola suggested that populations A, B and C, as defined by the ARGOS survey, can be associated, respectively, to the inner thin disk, to the young thick and to the old thick disk. In this bulge formation picture, Davide Massari illustrated how Terzan 5 could be one of its pristine fragments. The hypotheses rests on the fact that it hosts at least three stellar populations with different iron abundances (with a total spread of Δ[Fe/H]> 1 dex), and that its stars have chemical patterns that are similar to those of its surrounding environment (including α−element enrichment).

14.3. Galactic globular clusters

While the formation epoch of the bulge might be debated, there is no question that globular clusters are survivors from the first phases of galactic evolution, so they provide essential clues on the formation of the Galaxy. A review of the chemical properties of these stellar systems was given by Alessio Mucciarelli, who illustrated how advances in spectroscopic facilities led to a revision of the conventional view of these clusters. In particular, clusters with extended star formation histories have been revealed, which are possible remnants of dwarf galaxies being disrupted by the Milky Way.

While abundances offer the best way to investigate the origin of globular clusters, high-resolution spectroscopy is very time-consuming, so Javier Alonso Garcia showed how, in many cases, Strömgren photometry (and in particular, the $u - y$ vs. $v - y$ two-color diagram) can help uncover multiple stellar populations in a faster way. For that purpose, a survey using the SOI@SOAR camera is on-going, and the feasibility of the project was demonstrated by showing how in NGC 288 the RGB splits in two branches that belong populations with different metallicity.

Abundance investigations can help also to discriminate between competing scenarios for the formation of so-called blue-straggler stars. Using FLAMES@VLT Loredana Lovisi showed that C and O depletion for some BSSs in 47 Tucanae, M30 and ω Centauri points to a mass transfer origin for these BSSs.

When coupled with accurate ages, GC metallicities can offer good insight into the formation of the Milky Way. One such exercise was done by Ryan Leaman, who illustrated the main results published in Leaman et al. (2013). He showed that the age-metallicity relation (AMR) can be divided into two distinct, parallel sequences, and that clusters belonging to the more metal poor AMR should have been generated in hosts with stellar masses $\sim 10^7$-$10^8 M_\odot$. The metal-rich AMR clusters would have been formed in situ in the disc.

Studies like the one of Ryan benefit from homogeneous metallicity databases, but this is true for only a fraction of GGCs. This is why efforts like the one illustrated by Bruno Dias are important: he is trying to obtain iron and magnesium abundances using low resolution spectroscopy, in order to both expand GGC homogeneous metallicity sample, and to be able in the future to use the same method to collect abundances for large samples of stars inside Galactic satellites.

14.4. MWG halo + dwarf galaxies

Turning to the Galactic halo, our understanding of this MW component also changed recently thanks to the availability of large abundance data sets. It appears that it was partly formed in-situ and partly through the accretion of satellites that were disrupted and gave origin to the spherical and metal poor component. Therefore the two review talks that tackled abundances of the halo and of dwarf galaxies in the Local Group had many points in common. Andreea Font recalled the lines of evidence that support the dual nature of the halo, when they are compared to simulations: for instance the break in luminosity profile that separates the de Vaucouleurs profile of the in-situ component from the power-law profile of the accreted component. She also pointed out that the in-situ component must have been formed in a proto disk that was later disrupted, because pressure in galaxy halos is too low to trigger SF. Giuseppina Battaglia then expanded the view on dwarf galaxies, both in general terms and as possible contributors to the accreted component of the MW halo. She remarked as some dwarf galaxies might be the very first long-lasting systems that form in the universe. Abundances and kinematics of their stars are thus fundamental to test cosmological simulations of galaxy formation. In addition, comparing chemical patterns of halo stars to those in the satellite galaxies offers a way to test the ΛCDM framework of structure formation. In particular, MWG halo stars have constant [α/Fe] at all metallicities, while early type dwarfs always show a decline of [α/Fe] above some iron abundance. If the (outer) halo is made of accreted dwarfs, they must have had an initial SF different than the one seen in present-day dwarfs. Another interesting point touched by Giuseppina is the discovery of very metal-poor stars in dwarf galaxies; the current record is set at [Fe/H]$\simeq -4$ but even lower metallicity stars may be discovered, which in principle leaves open the possibility that these galaxies formed out of a pristine medium. Thus they would offer another way to constrain the properties of Pop III stars.

One issue with the comparison of present-day dwarf galaxies with possible progenitors, is that many of them orbit around massive hosts, so when simulating their evolution, care must be taken to explore the effects of tidal forces. One such study applied to Sextans was illustrated by Pascale Jablonka, who could reproduce the observed chemical and structural properties of the galaxy by dedicated SPH simulations which include detailed modeling of the gas physics and star-formation.

15. z = 0

No discussion of the importance of metallicity studies to understand cosmic evolution would be complete without a review of the intracluster medium (ICM) in the largest present-day structures of the universe, clusters of galaxies. This review was committed to Hans Boehringer, who showed how metallicities offer great insight in gas physics and its modeling. He recalled that ICM is heated to several 10^6 K, and so it is best studied with X-ray spectrographs on-board of satellites. Most of the baryonic mass is in fact in the ICM (12%) while only about 4% is in stars within galaxies (the rest is dark matter). Hans showed that clues on the origin of the ICM can be obtained by studying the relative abundances of C and N that come primarily from winds of AGB stars, of O and Mg that come primarily from core collapse supernovae, and of Fe and Ni that are primary products of SN Ia. For a simple stellar population, these phenomena happen at different times, so changes in the spatial distribution of relative abundances offer also clues to the SF history of cluster members. Furthermore, outside clusters the IGM is not readily visible, so the metal budget is not well constrained, while instead the ICM permits to better constrain abundance yields. Hans recalled that this research field is in its infancy, so future missions like ASTRO-H should bring much progress.

Finally, regarding the estimation of oxygen abundances in the circum-galactic medium based on O VI, Evgenii Vasiliev warned us that, based on his new ionization models, current metallicities might be over estimated by factors of two to three.

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