Report on the Workshop

Metal Production and Distribution in a Hierarchical Universe

held at Observatoire de Paris Meudon, France, 21–25 October 2013

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The workshop aimed at taking a global view of the evolution of metal abundances from the Big Bang to the present day, considering both observations and simulations. Abundance studies in stars and galaxies, and the variety of interstellar and intergalactic media, were covered. A summary of the workshop topics in order of decreasing redshift is presented, with considerable attention given to abundance studies of the Milky Way.

Almost a hundred researchers convened to discuss how metal abundances across cosmic time can help us to understand the evolution of the Universe and its main structures. The conference was hosted in the beautiful Pavillon Bellevue palace owned by the Centre national de la recherche scientifique (CNRS) and located in Meudon. As the title of the conference suggests, it tried to bridge often-separated research topics, in the hope of obtaining a global view of abundance studies, and of fostering cross-field collaborations. To reach these goals, the review talks were ordered to follow the metallicity evolution of the Universe from the very beginning to the present day, and to show how this evolution can be understood using the latest computer simulations and theories. In addition, contributed talks and posters enriched the programme with an exciting diversity of topics.

Two highlights of the conference were also the conference dinner in the grandiose Cassini Hall at the Paris Observatory, and an organ concert by Dominique Proust in Meudon-Bellevue Church. The dinner was preceded by a guided tour of the Observatory and the vista of the Paris landscape, and the concert was accompanied by a visual show of images related to music and astronomy.

Figure 1. The participants on the steps outside the Espace Isadora Duncan, Pavillon Bellevue where the workshop was held.

It would be impossible, in this limited space, to give a full account of the whole programme, so we extract the highlights to give an idea of the range of topics that were covered. More details can be gathered from the conference proceedings that will be published in the Memorie della Società Astronomica Italiana, and we hope that the fruits of the five-day discussion will appear in the literature in the coming months.

Introductory talks

The conference started with a talk by Anatoly Klypin updating the audience on the latest Lambda Cold Dark Matter (ΛCDM) simulations of the evolution of the Universe. The talk underlined one of the recurrent themes of the conference, i.e., that modelling gas processes and star formation feedback is exceedingly difficult, so critical constraints to theory must be placed by measuring abundances at all redshifts and for different cosmic structures. After primordial nucleosynthesis, chemical elements are produced in stars (either quiescent or explosive) so a review of stellar nucleosynthesis was given by Paolo Ventura. He recalled how stars of different mass pollute the interstellar medium (ISM) with different elements, and at different times. 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 and observational data together with the abundances (where measured) at particular epochs.

$z = \infty$

Naturally, the first measurements are those of elements produced in the initial ~ 15 min in the life of the Universe, during Big Bang nucleosynthesis (BBN): D, ^{3}He, ^{4}He and ^{7}Li. Yuri Izotov and Ryan Cooke presented their most recent estimates: from absorption spectra of damped Lyman-α absorbers, for deuterium $(D/H)_p = 2.53 \pm 0.04 \times 10^{-5}$ (Cooke et al., 2014); extrapolating from abundances measured from emission spectra of H II regions in metal-poor galaxies, the helium mass fraction $Y_p = 0.254 \pm 0.003$ (Izotov et al., 2013); and from spectra of very metal-poor stars the upper limit on the lithium abundance is $A(^7\mathrm{Li}) \equiv 12 + \log(^7\mathrm{Li/H}) = 2.2$ (Asplund et al., 2006; Sbordone et al., 2010). 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.

Time since Big Bang	Redshift z	Event	Abundance
~ 1 to ~ 10^3 sec	> 150 × 10^6	BBN	Observed: $(D/H)_p = 2.53 \pm 0.04 \times 10^{-5}$; $Y_p = 0.254 \pm 0.003$; Predicted: $A(^7Li) = 2.7$
After 0.1 Myr	~ 2000	Cosmic Microwave Background (CMB)	
~ 0.2–0.1 Gyr	~ 20–30	First star formation (SF)	When $H_2 \lesssim 10^{-4}$ ⇒ SF starts; pollution depends on mass function (pair instability SNe or not) and stellar rotation
		Most metal-poor MW stars	SMSS J031300.36-670839.3 has [Fe/H] < −7.1 (Keller+14); two populations of very metal poor stars (in terms of C abundance) (Norris+13; Spite+13)
$0.2 < t < 0.48$ Gyr	$20 > z > 10$	Dwarf galaxies in Ricotti's simulations (progenitors of ultra-faint dwarfs?)	Mass density function (MDF) peaked at [Fe/H] ~ −1
$0.27 < t < 0.48$ Gyr	$15 > z > 10$	Pop III galaxies in low-density regions; candidates at $6.3 < z < 8.8$ behind lensing clusters	
~ 0.4 Gyr	~ 11	Lensed galaxy of 10^8–10^9 $M_\odot$ (Coe+13);first galaxy candidates, Large Magellanic Cloud (LMC) mass or larger (Oesch+13)	
$t > 0.48$ Gyr	< 10	Reionisation completed	
0.71 Gyr	7.51	Furthest galaxy redshift confirmed by Ly-α (Finkelstein+13)	
0.97 Gyr	5.9	GRB 130606A (Chornock+13)	[Si/H] $\lesssim$ −1.7 and [S/H] $\lesssim$ −0.5
$t < 1.2$ Gyr	> 5	High density clumps ("discs") from DLA measurements	Enrichment by SN II from Pop II stars and prompt SN I
1.2 Gyr	5.0	GRB 111008A (Sparre+14)	$\log N(\mathrm{H\,I})/\mathrm{cm}^{-2} = 22.30 \pm 0.06$; $[M/H] \simeq -1.7 \pm 0.1$ for S, Cr, Fe, Ni
1.3 Gyr	4.7	GRB 100219A (Thoene+13)	$[S/H] = -1.1 \pm 0.2$
~ 2.19 Gyr	~ 3	IGM measurements from Ly-α forest	[C/H] ~ −3.5
~ 2.19 Gyr	~ 3	Galaxy halo measurements from Lyman limit systems	[M/H] from pristine to ~ +0.7
1.2 → 12.38 Gyr	5 → 0.1	Average "disc" metallicity from DLA measurements	[M/H] = −0.22; z ~ 0.65; [α/Fe] ~ +0.3
1.8 Gyr	3.5	SF galaxies in Maiolino+08	[M/H] ~ −0.5 for galaxies of ~ 10^{10} $M_\odot$
3.34 Gyr	2	MZR from H II regions (Cullen+14); highest-mass galaxies (3 × 10^{10} $M_\odot$)	[O/H] ~ −0.5
3.34 Gyr	2	First detected galaxy clusters	
	1.49	Negative metallicity gradient for lensed galaxy (Yuan+11); "inside-out" formation?	−0.16 dex kpc^{-1}
4.6 Gyr	1.4	End of Milky Way (MW) thick Disc formation, began at 1.2 Gyr (Haywood+13)	
7.7 Gyr	< 0.65	Galaxies with $9.8 < \log M_*/M_\odot < 11.5$ start to evolve as closed boxes (Rodrigues)	

Table 1. Chronology of main events discussed in the article. The conversion from redshift to time was done using CosmicCalc[1], assuming $H_0 = 71$, $\Omega_M = 0.270$, $\Omega_{vac} = 0.730$.

$20 \leq z \leq 30$

In his review, Volker Bromm recalled that the first stars form at redshifts z ≈ 20–30 (≈ 0.2 – 0.1 Gyr after the Big Bang) inside ~ 10^5–10^6 $M_\odot$ mini-haloes. The subsequent evolution of both metallicity and cosmic structures depends on whether the mass function of these Population III (Pop III) stars is limited to a few tens of solar masses, or it can reach ~ 140–260 $M_\odot$. In the latter case there will be pair-instability supernovae (SNe) together with core-collapse SNe, which will inject more metals, and will delay the reassembly of gas into long-surviving systems. At the current early stage, simulations cannot fully constrain the Pop III mass function, so observations must come to the rescue. Searches for surviving metal-free, Pop III, low-mass stars are ongoing, 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 the Sloan Digital Sky Survey (SDSS) Data Release 9 (DR9) spectra and identifies main sequence turn-off stars with metallicities [Fe/H] < −3 to be followed up with the UVES or X-shooter spectrographs at the Very Large Telescope (VLT). The second survey uses the multi-band photometry of SkyMapper to search for candidate extremely metal-poor stars, which are then confirmed with low- and high-resolution spectroscopy obtained with Magellan, Keck, and VLT. Heather gave us a preview of SMSS J031300.36-670839.3 (Keller et al., 2014) which has a record-breaking [Fe/H] < −7.1, and an abundance pattern consistent with gas enriched by a single 60 $M_\odot$ star that exploded as a low-energy supernova. While not explicitly targeted to metal-poor stars, the SDSS3 APO Galactic Evolution Experiment (APOGEE) survey, described by Katia Cunha, is an example of one of the many ongoing or planned large-scale surveys of Milky Way stellar abundances.

$9 \leq z \leq 11$

While the first star formation episode 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 Hubble Space Telescope (HST). For example, Oesch et al. (2013) using Wide Field Camera 3 near-infrared data and the Lyman-break technique found seven $z \sim 9$ galaxy candidates, and one each at $z \sim 10$ and $z \sim 11$. The data show the early and fast assembly of galaxies, for example based on the ultraviolet (UV) luminosity density contributed by star-forming systems, which increased by two orders of magnitude in ~ 1.5 Gyr, between redshifts 10 and 3. With current facilities primordial galaxies smaller than 10^8–10^9 $M_\odot$ in stellar mass are below detection, but they are predicted by Massimo Ricotti through simulations; interestingly, if evolved to the present-day Universe, his objects would have properties comparable to the faintest dwarf spheroidal galaxies in the Local Group.

$9 \leq z \leq 15$

Chemically pristine galaxies in haloes with mass $M \sim 10^8$ $M_\odot$ may form at $z < 20$ in relatively underdense regions of the Universe. Stiavelli & Trenti (2010) 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 check whether this is true. By fitting Pop III model spectral energy distributions (SEDs) to multiband photometry from the CLASH (Cluster Lensing And Supernova survey with Hubble) survey, he found candidate Pop III galaxies with redshifts between 6.3 and 8.8, lensed by four galaxy clusters.

$5 \leq z \leq 6$

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 gamma-ray burst (GRB) host galaxies, as explained by Martin Sparre. A fraction of GRBs have host galaxies that give rise to damped Lyman-α absorption, which permits the measurement of their metallicity, currently up to redshifts of almost 6. Martin presented his X-shooter spectroscopy of the optical afterglow of GRB 111008A at $z = 5.0$, which yielded an H I-content of log N(H I)/cm^{-2} = 22.30 ± 0.06 and a metallicity [M/H] ≈ −1.7 ± 0.1 for several elements (S, Cr, Fe, Ni).

$2 \leq z \leq 5$

A review of intergalactic medium (IGM) metallicities in regions of different density was given by Michele Fumagalli who showed us that below $z \sim 5$, IGM pollution is already widespread. In the IGM, measured carbon abundances are [C/H] ~ −3.5 at z ~ 3, and they increase by a factor of ~ 2–3 from $z \sim 4.3$ to $z \sim 2.4$. Considerable substructure is observed in the IGM, so Michele formulated the hypothesis that a significant fraction of the metals seen in the IGM escaped from galaxies as clumps that subsequently mixed with the surrounding hydrogen. In galaxy haloes, a large metallicity spread is observed, from pristine to super-Solar values, while in higher density systems, damped Lyman-α absorbers (DLAs), the average metallicity depends on redshift and reaches about 1/10 Solar at $z = 0.1$. Interestingly, DLAs are found to be α-element enhanced with a median [α/Fe] ~ +0.3. The [M/H] and [α/Fe] distributions in $z > 2$ DLAs with [M/H] $\lesssim -1$ agree with those observed for stars in the Galactic Halo.

More insight into IGM enrichment processes was offered by the presentations of Michael Rauch and Evan Scannapieco. Michael has an ongoing investigation of high-redshift Lyα galactic haloes, where young stellar populations and signs of tidal and/or ram-pressure stripping were found. The release of metal-enriched gas during interactions, which increases with redshift, may provide a mechanism for enriching the IGM as widely as observed. These ideas are directly supported by the simulations presented by Evan Scannapieco. He finds that long-range outflows are excluded, also because, by $z \approx 2$, intergalactic enrichment appears to be concentrated around large galaxies and due primarily to metals from similarly-biased higher-redshift sources.

$0 \leq z \leq 3$

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 ~ 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 signal-to-noise 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 3×10^7 $M_\odot$).

$z = 2$

Metallicities for high-redshift galaxies are obtained with calibrations of emission line ratios versus metallicity obtained from local fiducial H II regions. However, earlier in cosmic history the physical conditions in H II 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 (3×10^{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 ionisation parameter is applied to the Erb et al. (2006) sample.

$0 \leq z \leq 0.6$

Throughout cosmic history, galaxies are shaped by interactions and gas exchanges with the environment, an aspect of galaxy evolution that is being investigated by the IMAGES survey. François Hammer examined mergers between gas-rich disc galaxies in the last 6 Gyr of cosmic history, and, thanks to spatially-resolved kinematics, morphologies and multi-band photometry, he discovered that 50% of spiral progenitors were experiencing major mergers by z ~ 0.6. Therefore a high fraction of present-day discs are the end products of rebuilt discs. In the second presentation of IMAGES, Myriam Rodrigues investigated the role of gas exchanges in the life of intermediate mass ($9.8 < \log M_*/M_\odot < 11.5$) disc galaxies. She considered the run of gas fraction with redshift, and found that galaxies in her sample had evolved as closed systems since $z \sim 0.6$; however literature data show that at higher redshifts ($z \sim 2$–3) exchanges with the environment become more and more important.

$z = 0+$

Byproducts of mergers are various types of debris, of which the most conspicuous are tidal dwarf galaxies (TDGs), which were reviewed by Pierre-Alain Duc. The first step in understanding TDG role in IGM pollution would be a census: if they were found to be very numerous, it would mean that they manage to keep their material, despite the lack of dark matter, and therefore they would play a minor role in the enrichment of the intergalactic medium. One step toward this census was illustrated by Sarah Sweet, who searched for TDGs in “Choir” galaxy groups identified in the H I Parkes All Sky Survey (HIPASS) survey: 16 % of dwarfs were identified as strong TDG candidates based on their position in the luminosity–metallicity plane.

$z = 0$

At the end of the cosmic chemical evolution outlined so far are the objects that we observe in the local Universe. Clusters of galaxies and the intracluster medium (ICM) were discussed by Hans Boehringer. He showed that clues to the origin of the ICM can be obtained by studying the relative abundances of C and N that come primarily from winds of asymptotic giant branch (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. Hans recalled that this research field is in its infancy, so future missions like ASTRO-H should bring much progress. Later, Evgenii Vasiliev warned us that, based on his new ionisation models, current metallicities of the circumgalactic medium based on O VI might be over-estimated by factors of 2 to 3.

Abundances in the Milky Way

Several sessions of the conference were dedicated to reviewing abundance determinations for the Milky Way and associated structures. To summarise this broad section, we can start from the Solar Neighbourhood. Because the Solar System is immersed in the Galactic Disc, our observations suffer from extinction caused by gas and dust confined to the disc itself. Therefore a proper interpretation of the 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 her latest maps of gas geometry within 2.5 kpc.

Milky Way Disc

Thomas Bensby started with a review of abundances of stars in different Galactic subsystems, especially the thin/thick Disc and the Bulge. By collecting abundances for distant stars, Thomas has found that the ratio of thick-to-thin Disc stars changes with distance in a way that shows that the thick Disc is more centrally concentrated than the thin Disc.

New results on the chemical evolution of the Disc were also presented, based on the large set of spectra collected by the HARPS Guaranteed Time Observing programme (Adibekyan et al., 2012). Sara Bertran de Lis confirmed the α-element enhancement of thick Disc stars with O abundances, and Garik Israelian found that thick and thin Disc populations are different also when looking at [Cu/Fe], [Y/Fe] and [Ba/Fe] abundance ratios. Afterwards, after a general introduction to the principles of galactic chemical evolution by Nicolas Prantzos, Misha Haywood presented evidence (based on Si abundances from the same HARPS database) that the thick Disc formed between 12.5 and 9 Gyr ago from large amounts of gas, and evolved as a closed-box model.

Success in reproducing the [Fe/H] and [O/Fe] distribution functions of the Milky Way Disc was also achieved by Rob Yates with his semi-analytic model of galaxy formation, which simultaneously reproduces the chemical properties of local elliptical galaxies and the mass-metallicity relation of local star-forming galaxies. Other simulations were presented by Noelia Jimenez who discussed how in her implementation, the “single degenerate” scenario for SN Ia is able to reproduce, amongst others, the [α/Fe] ratios for bulge-dominated galaxies.

Milky Way Bulge

In her review, Melissa Ness used results from the Abundances and Radial velocity Galactic Origins Survey (ARGOS) to show that, while the majority of stars in the Bulge belong to a boxy/peanut shape, which is a signature of formation from the Disc, there remains a metal-poor population which is not part of the boxy/peanut, whose origin is still unclear (either a classical bulge or a thick disc). Support for a secular formation of the Bulge was given by Paola di Matteo with her dissipationless, N-body simulations, and Davide Massari illustrated how Terzan 5 could be a pristine fragment based on its large metallicity spread matching that of the Bulge itself.

Galactic globular clusters

While the formation epoch of the Bulge might be debated, there is no question that globular clusters (GCs) are survivors from the first phases of galactic evolution, so they provide essential clues on the formation of the Galaxy. Alessio Mucciarelli illustrated how advances in spectroscopic facilities have revealed clusters with extended star formation histories, which could be possible remnants of dwarf galaxies being disrupted by the Milky Way. Javier Alonso Garcia then showed how, in many cases, Strömgren photometry can help uncover multiple stellar populations in a faster way. Loredana Lovisi showed that C and O depletion (measured with the FLAMES spectrograph) for some blue-straggler stars in 47 Tucanae, M30 and ω Centauri points to a mass transfer origin for these stars.

When coupled with accurate ages, GC metallicities can offer good insight into the formation of the Milky Way, as shown by Ryan Leaman: he found that GCs define two age–metallicity relations (AMR), and that clusters belonging to the more metal-poor AMR should have been generated in hosts with stellar masses $\sim 10^7$–$10^8\,M_\odot$. Studies like Ryan’s benefit from homogeneous metallicity databases, which is why efforts like the one illustrated by Bruno Dias are important. He is trying to obtain Fe and Mg abundances using low-resolution spectroscopy, in order to expand the homogeneous metallicity sample. In the future this will enable the same method to be used to collect abundances for large samples of stars inside Galactic satellites.

Milky Way Halo + dwarf galaxies

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. Giuseppina Battaglia then expanded the view on dwarf galaxies, both in general terms and as possible contributors to the accreted component of the Milky Way Halo. One of the interesting points touched on by Giuseppina is the discovery of very metal-poor stars in dwarf galaxies; the current record is set at [Fe/H] ≈ −4, but even lower metallicity stars may be discovered, thus offering 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, which was applied to Sextans, was illustrated by Pascale Jablonka, who could reproduce the observed chemical and structural properties of the galaxy by dedicated soft particle hydrodynamic simulations which include detailed modelling of the gas physics and star formation.

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References

Adibekyan, V. Z. et al. 2012, A&A, 545, 32
Asplund, M. et al. 2006, ApJ, 644, 229
Chornock, R. et al. 2013, ApJ, 774, 26
Coe, D. et al. 2013, ApJ, 762, 32
Cooke, R. et al. 2014, ApJ, 781, 31
Cullen, F. et al. 2014, MNRAS, 440, 2300
Erb, D. K. et al. 2006, ApJ, 644, 813
Finkelstein, S. L. et al. 2013, Nature, 502, 524
Haywood, M. et al. 2013, A&A, 560, A109
Izotov, Y. et al. 2013, A&A, 558, 57
Keller, S. C. et al. 2014, Nature, 506, 463
Maiolino, R. et al. 2008, A&A, 488, 463
Norris, J. E. et al. 2013, ApJ, 762, 28
Oesch, P. A. et al. 2013, ApJ, 786, 108
Sbordone, L. et al. 2010, A&A, 522, 26
Sparre, M. et al. 2014, ApJ, 785, 150
Spite, M. et al. 2013, A&A, 552A, 107
Stiavelli, M. & Trenti, M. 2010, ApJ, 716, 190
Thöne, C. C. et al. 2013, MNRAS, 428, 3590
Yuan, T.-T. et al. 2013, ApJ, 763, 9

Links

[1] Cosmology Calculator: http://www.astro.ucla.edu/~wright/CosmoCalc.html

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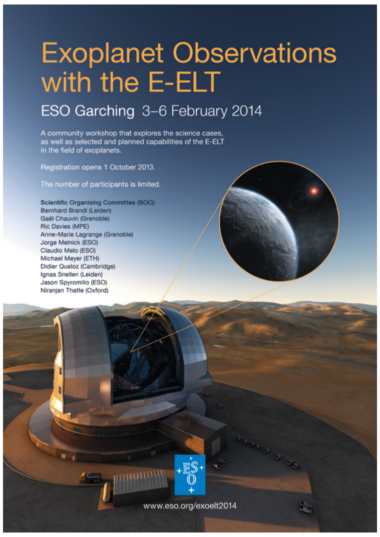
Report on the Workshop

Exoplanet Observations with the E-ELT

held at ESO Headquarters, Garching, Germany, 3–6 February 2014



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A brief summary of the presentations and discussions at the workshop on exoplanet science with extremely large telescopes is sketched. A broad range of topics covering the lifecycle of planets and the instrumentation landscape were presented.

Over 140 participants from the Member States of ESO and beyond attended the first ExoELT2014 workshop. The programme included significant time for discussions (45 minutes at the end of each morning and afternoon session and a whole session on the last day). As a result the programme was short on presentations (typically five per session) and long on debate and conversation. This report does not aim to summarise in detail the entire workshop as all the presentations are available on the workshop website[1]. A wiki page, linked from the conference programme[2], will be set up where we hope to continue the discussion that started at the meeting.

In such a rapidly changing field as exoplanet science, it would be folly to try to establish any ground truths. The workshop took place just after the Gemini