EUROPEAN SOUTHERN OBSERVATORY

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

VISITING ASTRONOMERS SECTION • Karl-Schwarzschild-Straße 2 • D-85748 Garching bei München • e-mail: visas@eso.org • Tel.: +49-89-32 00 64 73

APPLICATION FOR OBSERVING TIME — PERIOD: **78A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of COIs and the agreement to act according to the ESO policy and regulations, should observing time be granted

1. Title — Category: **A–8**

Is the low density IGM at $z \sim$ 2-3 metal-enriched?

2. Abstract

At the epoch of peak activity of galaxy and quasar formation (redshift $z \sim$ 2-3), over 90% of the baryons are in the IGM, but only about half of the metals produced by star formation in high-redshift UV-selected galaxies have been measured (the galaxies themselves, the IGM and the damped Ly-α absorbers). The missing metals could reside in regions with temperatures $T{>}2\times10^4$ K and HI column densities N(HI)$\lesssim10^{14}$ cm^{-2}, as suggested by hydrodynamic simulations with galactic superwinds. In these models, underdense regions of the IGM could be metal-enriched with mean abundances up to 10^{-2} solar. Our goal is to determine the metallicity level of the low density IGM. This requires detecting CIV column densities at least 10 times smaller than currently achieved, thus selecting as background targets the very brightest quasars and possibly GRBs. This will constrain the occurence and strength of galactic superwinds at $z \sim$ 2-3 and help solving the problem of missing metals.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	79	UVES	270h	any	d	$\leq 0.8''$	CLR	s

4. Number of nights/hours — Telescope(s) — Amount of time

a) already awarded to this project:

b) still required to complete this project:

5. Special remarks:

6. Principal Investigator: Jacqueline Bergeron (IAP, F, bergeron@iap.fr)

CoI(s): The ELT-SWG (Elsewhere, ESO)

7. Is this proposal linked to a PhD thesis preparation? State role of PhD student in this project

8. Description of the proposed programme

A) Scientific Rationale: The level of metal-enrichement of the IGM strongly depends on (1) the number and spatial distribution of sources ejecting metals during the reionization epoch (SN explosions, stellar winds, galactic outflows), (2) galactic winds at later times ($z < 5$).

The IGM is highly ionized by the metagalactic UV radiation flux (e.g. Sargent et al., 1980, ApJS, 42, 41) and its metal content is best traced by the CIV($\lambda\lambda$1548.2,1550.8) doublet. The other high-ionization metal lines are in the far-UV, thus blended with the numerous absorption lines of the Ly-α forest (this is also the case for the NV($\lambda\lambda$1238.8,1242.8) doublet except for absorbers possibly associated with the quasar environments, i.e. with a velocity relative to that of the quasar $\Delta v < 5000$ km s^{-1}). The IGM metal-enrichment is very inhomogeneous and the relative contribution to the cosmic metals of the true IGM versus metal-rich sites around starburst galaxies is not yet well known. Nevertheless, the lack of redshift evolution of the CIV cosmic density at $2 < z < 5$, $\Omega_{\rm b}({\rm C\,IV}) \sim 5 \times 10^{-8}$, suggests an early pollution of the universe by the first stars and galaxies (Songaila, 2001, ApJ, 561, L153 & 2005, AJ, 130, 1996; Pettini et al., 2003, ApJ, 594, 695). This lack of evolution appears to extend to even higher redshift, $5.5 < z < 6$ (Ryan-Weber et al., 2006, MNRAS, 371, L78). This is surprising since metal production should increase with cosmic time, although this might be compensated by an evolution in the global ionization fraction C IV/C. Alternatively, the CIV absorbers may be associated with outflowing interstellar gas, and the IGM is only traced by the absorbers of lowest CIV column densities. At $1.8 < z < 4.1$, the mean cosmic carbon abundance, $[{\rm C/H}] \equiv \log\left(({\rm C/H})/({\rm C/H})_\odot\right) = \log\left(\Omega_{\rm b}({\rm C})/\Omega_{\rm b}({\rm C}_\odot)\right)$ has been derived from HI-CIV absorption line samples analyzed using the pixel optical depth method (linking HI and CIV optical depths: Cowie & Songaila, 1998, Nature, 394, 44), and its value is $[{\rm C/H}] = -2.8$ (Schaye et al., 2003, ApJ, 596, 768). In these surveys, the HI column densities associated with the CIV absorbers are not small enough to probe underdense regions of the IGM gas (see e.g. Davé et al., 1999, ApJ, 511, 521).

At the epoch of the peak activity of galaxy and quasar formation ($z \sim$ 2-3), over 90% of the baryons are still in the IGM (e.g. Fukugita et al., 1998, ApJ, 503, 518). However, only about 40% of the metals produced by star formation activity in detected high-redshift UV-selected galaxies (with extinction correction) were measured in various sites: the galaxies themselves, the IGM and the damped Ly-α absorbers, N(HI) $> 10^{20.3}$ cm^{-2} (Pettini, 1999, astro-ph/9902173 & 2006, astro-ph/0603066). This is known as the *missing metals problem*. Feedback from galactic superwinds has been invoked to solve this shortfall of detected metals (Cen et al., 2005, ApJ, 635, 86; Bertone et al., 2005, MNRAS, 359,1201; Oppenheimer & Davé, 2006, MNRAS, 373, 1265). The missing metals would then reside in warm-hot regions with temperatures $T > 3 \times 10^4$ K. The fraction of missing metals may be lower than 60% if the metal census in high-z galaxies and sub-damped ($10^{19.0} <$ N(HI) $< 10^{20.3}$ cm^{-2})/damped absorbers is incomplete (Pettini, 2006) and/or if the metal content of the IGM diffuse phase at $T < 3 \times 10^4$ K is underestimated (Davé & Oppenheimer, 2007, MNRAS, 374, 427). The estimated total metal production is also a key parameter to derive the amount of missing metals, from a comparison with available observations of metallicity in various baryonic phases, and it substantially differs between different authors.

The metallicity of IGM gas with overdensity $\delta \equiv (\rho/\overline{\rho}) \sim 1$ is unknown and could be smaller than 10^{-3} solar. In hydrodynamic simulations of the IGM without galactic winds, the mean metallicity strongly decreases with decreasing gas density: for $\delta = 1$, the abundance relative to solar is $[{\rm Z/H}] \simeq -3.7$ (Cen et al., 2005). However, including galactic superwinds leads to substantial metal enrichment of the low density IGM, $\langle[{\rm Z/H}]\rangle \sim -2.0$ for $0.1 < \delta < 10$. The filling factor of metal-rich regions is a strong function of the strength of the galactic winds. The different models yield estimates of this volume filling factor in the range from a few per cent to a few tenths of per cent at $z \sim 2.5$ (Cen et al., 2005; Bertone et al., 2005; Oppenheimer & Davé, 2006). The affected regions have N(HI) $\lesssim 10^{14}$ cm^{-2} and about 90% of the IGM metal mass could have a temperature in the range (4-10)$\times 10^4$ K, corresponding to a doppler parameter b(CIV) = 7.4-11.7 km s^{-1}.

To determine the metallicity of the low N(HI) regions of the IGM, one cannot use the pixel optical depth method. This statistical approach is powerful for deriving the mean metallicity of the IGM (Songaila, 2001), but it only provides median opacities in bins of τ(HI), with the associated mean τ(CIV), thus an average over a range of metallicities for each bin of τ(HI). Study of individual absorption systems is thus necessary to constrain the metallicity and volume filling factor of the low N(HI) regions of the IGM. These regions trace either the true intergalactic metals or those associated with outflows from massive star-forming galaxies. The highly ionized gas, metal-enriched IGM is well probed by the OVI($\lambda\lambda$1031.9,1037.6) doublet when the blending of OVI lines with the Ly-α forest is not too severe, thus at $z_{\rm abs} \lesssim 2.5$. Preliminary results have been obtained from the analysis of a VLT-UVES quasar absorption line sample (Bergeron & Herbert-Fort, 2005, IAU 199 Conference Proceedings, p. 265, astro-ph/0506700). The main outcome is the existence of a bimodal distribution of the oxygen abundance as presented in Fig. 1 (Bergeron, unpublished: the observational classification of the two classes of absorbers, metal-poor and metal-rich, is confirmed by the analysis of their ionization level, thus abundance). Although the contribution of the OVI absorbers to the cosmic metal density is larger by a factor three than that derived from CIV (Songaila, 2001), it still does not solve the problem of the missing metals.

The detection of much weaker CIV (and OVI) lines than achieved with this VLT-UVES survey, i.e. reaching signal-to-noise ratio S/N $\gg$ 100 in the CIV wavelength range, is required to get a more complete metal census at $z \sim 2.5$. This is the goal of the proposed programme.

8. Description of the proposed programme (continued)

B) Immediate Objective: The metallicity of IGM regions with low N(HI) will be determined by a survey of the CIV doublet at high spectral resolution ($R \simeq 5 \times 10^4$) and very high S/N ($\gtrsim 1000$) of $z \sim 2.5$-3 bright quasars and GRBs. This will constrain the level of metal-enrichment of the low density IGM, thus the occurence and strength of galactic superwinds at $z \sim 2$-3.
This programme alone will yield the CIV cosmic density, Ω_b(CIV), that could directly be compared with the results obtained at lower S/N by Pettini et al. (2003) and Songaila (2005). It will also allow an estimate of the clustering of the metal-enriched sites. Observations of a large number of sightlines is then needed to overcome sample variance. The accessible CIV redshift range is $1.9 \lesssim z \lesssim 3.3$ (CODEX wavelength range: Pasquini et al., 2005, The Messenger, 122, 10). Some rough estimates (or limits) on the ionization level can be obtained from the simultaneous observations of the CII line (λ1334.5), the SiII lines ($\lambda\lambda\lambda$1260.4,1304.4,1526.7,1808.0) and the SiIV doublet ($\lambda\lambda$1393.8,1402.8). These low-ionization metal lines arise in gas with high overdensities, $\delta \gtrsim 100$, thus not the IGM, but in interstellar and halo gas of intervening galaxies. Abundances can be estimated when Ly-α is in the observing range, i.e. for $z \gtrsim 2.7$. This project should thus be complemented by a VLT-UVES survey of the same background targets to get the lower z (1.9-2.7) associated HI in order to derive the carbon abundance; observations of the associated NV and OVI doublets would also yield more reliable estimates of the ionization level.
Using the results of the hydrodynamic simulations with and without galactic superwinds, described in sect. 8A, yields expected CIV column densities at $\delta \sim 1$ of $10^{10.4}$ and $10^{8.8}$ cm^{-2}, respectively (assuming that photoionization by the metagalactic radiation flux is the dominant process which is roughly the case at $T < 10^5$ K). The smallest CIV column densities detected with 8-10 m class telescopes are N(CIV)$\sim 10^{11.5}$ cm^{-2} (spectroscopy of bright quasars at high resolution $R \sim 5 \times 10^4$ and high S/N ~ 100). Probing the low density regions of the IGM at $z \sim 2$-3 implies a gain in the detection limit of individual CIV doublets by at least a factor 10. This is also mandatory in order to constrain the occurence of weak, broadish ($b \sim 12$-20 km s^{-1}) CIV systems which trace gas at temperatures $T =$ (1-3) $\times 10^5$ K (see Fig. 2 for the b distribution of detected CIV and OVI absorbers).

Sample selection
The minimum number of background targets should be similar than those of the VLT-UVES large programme (thus ~15) that revealed the existence of the highly ionized OVI phase. The targets must be brighter than V=17 in order to reach a signal-to-noise of at least 1000 for exposure times of about 10-20 hr (see sect. 9). The number of known bright quasars in the southern sky is small; indeed all-sky surveys of bright objects are only complete in the northern sky (see sect. 12). The sample of quasars at $2.5 < z < 4.0$, brighter than V = 16.5 and accessible from the north (dec > -10 deg: 10 targets) is 5 times larger than that accessible from the south (dec $< +10$ deg: 2 targets). This is a severe problem for the proposed IGM project and even more so for the one that aims at measuring the expansion of the universe (the number of 25 quasars given in Pasquini et al. refers to objects at $2.0 < z < 4.0$ with V < 16.5, and most of them are at $z < 2.5$).
The planned photometric surveys with VST and VISTA should ease this problem. These photometric surveys should be complemented by spectroscopic idendification of the quasar candidates. Moreover, **extending the wavelength range of the CODEX facility down to 4130(3890) Å** would enable observations of the Ly-α forest down to $z = 2.4(2.2)$.

There are 17, currently known, bright (V < 17) quasars at $2.4 < z < 4.0$ observable from the southern sky (dec $< +20$ deg), of which 5 at $z > 3.0$. Thus an adequate sample of 15 targets implies a total observing time of about 270 hr for a 42 m ELT.
Very rare, bright GRBs (V $<$ 15-16) at $z \gtrsim 2.5$ are also possible targets.

C) Telescope Justification: An ELT is needed in order to achieve the required, very high S/N at high spectral resolution.

D) Observing Mode Justification (visitor or service): Bright single targets, thus service mode is best. Furthermore, targetting GRBs will require very prompt responses (~ 1 hr: see sect. 12).

E) Strategy for Data Reduction and Analysis: We will use standard data reduction tools, as already available for UVES data. The most complex part will be to correct for the order response since it will be necessary to get an extremely well defined continuum level. This is mandatory in order to detect very weak, broadish CIV systems, $b \sim 12$ km s^{-1}, as well as narrow ones.
For the weakest absorptions, the analysis will make use of the pixel optical depth method applied solely to the 2 CIV lines by searching for regions where the optical depths of the relative wavelengths of the doublet approximate the expected 2 : 1 ratio. These automated searches will enable a good estimate of the incompleteness due to noise and line overlap by adding artificial absorption lines to the spectra.

8. Attachments (Figures)

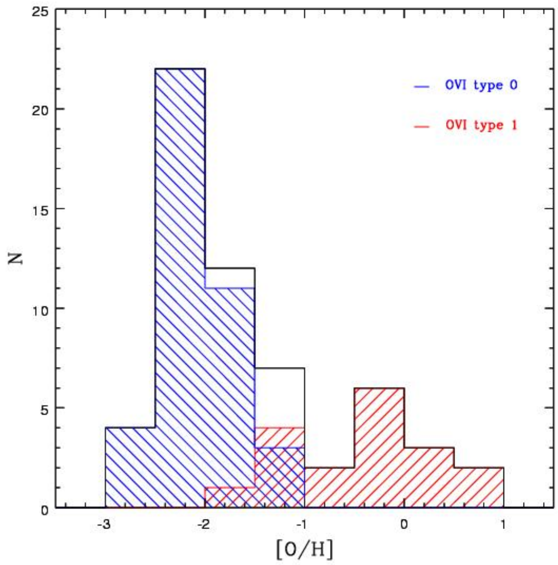

Fig. 1: Abundances of OVI absorbers derived from the analysis of 12 quasar sightlines: the distribution of [O/H] is clearly bimodal, which confirm the existence of two populations among the OVI absorbers. The median value of [O/H] is -2.06 and -0.35 for the type 0 and type 1 populations (observational selection criterium), respectively. The HI associated with the metal-rich absorbers has $10^{12.5} < N(HI) < 10^{15.0}$ cm $^{-2}$ or $0.1 < \tau(\mathrm{H\,I}) < 30$. The metal-rich population contributes to the cosmic oxygen density, $\Omega_b(O)$, at a level of $\sim$40%.

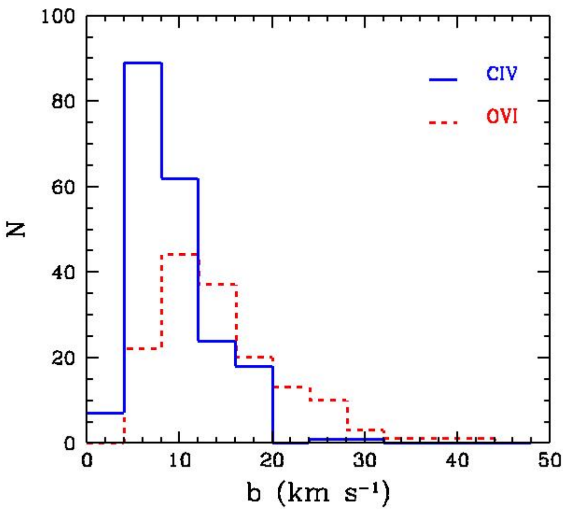

Fig. 2: CIV and OVI line width distributions at $\langle z \rangle \sim 2.3$. The high b ($> 30$ km s^{-1}) tail of the OVI absorbers is very uncertain due to the weakness of these absorbers and the low S/N (blending effects), thus there are no unambiguously very broad absorbers OVI in current data sets.

9. Justification of requested observing time and lunar phase

Lunar Phase Justification: We require the maximum sensitivity and photometric accuracy possible which means dark time.

Time Justification: (including seeing overhead) Using the ELT- Experimental ETC (Version 2.5WG)
Bright quasars at $z \sim 3$, V=17
CIV absorption at z = 2-3, $\Delta\lambda$ = 4640-6210 Å, observable in a single setting.
42 m diameter telescope
spectral resolution R=50000 - A(px) = 2(spectral)x3(spatial) with 100 mas/pixel
S/N = 1000 - Laser-Tomography AO
thus exposure time = 18 hr
if the signal is summed over the spatial profile, there will be a small gain in exposure time (or S/N) which is function of the **currently undefined** slit widths. Since the proposed project is more constraining in S/N than spectral resolution (detection of CIV systems with column densities as small as possible and line widths $b \gtrsim 6$ km s^{-1}), it would benefit of the possibility of **reasonnably large slit widths of 0.6″ or more**.

note - the above resolution and S/N yield N(CIV) $\sim 10^{10.3}$ cm^{-2} for a 5σ detection of CIV(λ1548). With this limit, one can probe IGM regions with overdensities close to unity and metallicities down to 10^{-2} solar, thus can constrain the volumic fraction of the IGM affected by superwinds.

Calibration Request: Special Calibration - Regular observations of standard star fields (!)

10. Report on the use of ESO facilities during the last 2 years

Report on the use of the ESO facilities during the last 2 years (4 observing periods). Describe the status of the data obtained and the scientific output generated.

11. Applicant's publications related to the subject of this application during the last 2 years

12. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	name	RA	DEC	time(hrs)	mag	DM	ang diam(')	note
A	B0001-2340	00 03 45	-23 23 55	20	16.7		QSO	z=2.280
A	B0100+1300	01 03 11	+13 16 18	10	16.57		QSO	z=2.686
A	B0109-3518	01 11 43	-35 03 00	20	16.9		QSO	z=2.406
A	B0123-527	01 25 06	-52 32 21	20	16.7		QSO	z=2.320
A	B0151-4326	01 53 27	-43 11 38	20	16.8		QSO	z=2.740
A	[B015815.2-373151	02 00 23	-37 17 21	20	16.92		QSO	z=2.25
A	HE 0320-1045	03 22 24	-10 35 12	20	17.0		QSO	z=2.282
A	B0410-430	04 11 45	-42 54 43	20	16.7		QSO	z=2.400
A	B0420-3850	04 22 14	-38 44 52	20	16.9		QSO	z=3.123
A	B0450-1310B	04 53 12	-13 05 46	10	16.5		QSO	z=2.300
A	J055445.7-330517	05 54 45	-33 05 17	20	16.7		QSO	z=2.360
A	J0939-1832	09 39 51	-18 32 15	10	16.2		QSO	z=2.400
A	J0942-1104	09 42 53	-11 04 25	10	16.6		QSO	z=3.054
A	HE 1104-1805A	11 06 33	18 21 24	10	16.2		Lense	z=2.319
A	J1124-1705	11 24 42	-17 05 17	10	16.5		QSO	z=2.400
A	J1200-1859	12 00 44	-18 59 45	20	16.9		QSO	z=2.453
A	B1246-057	12 49 13	-05 59 18.	20	16.7		QSO	z=2.226
A	B1317-0507	13 20 29	-05 23 35.	10	16.54		QSO	z=3.700
A	J1350-2512	13 50 38	-25 12 16	10	16.3		QSO	z=2.534
A	B1448-2317	14 51 02	-23 29 31	10	16.96		QSO	z=2.208
A	BWE 1653+1953	16 55 43	+19 48 47	10	16.60		QSO	z=3.260
A	J2106+1855	21 06 08	+18 55 49	20	16.8		QSO	z=2.21
A	B2120-0103	21 23 29	-00 50 52	10	16.67		QSO	z=2.261
A	LBQS 2139-4434	21 42 25	-44 20 17	10	16.64		QSO	z=3.23
A	B2204-5722	22 07 54	-57 07 36	10	16.6		QSO	z=2.725
A	B2217-2818	22 20 06	-28 03 23	10	16.0		QSO	z=2.406
A	J2313+0034	23 13 24	+00 34 44	20	16.7		QSO	z=2.20
A	J2350-4325	23 50 34	-43 25 59	10	16.3		QSO	z=2.90
A	J2351-1427	23 51 29	-14 27 48	20	16.9		QSO	z=2.940
A	B2355-463	23 58 09	-46 04 59	20	16.9		QSO	z=2.370

Target Notes: There are few, very bright quasars at $2.2 < z < 4$. Query of the SIMBAD data base (combined with NED for doubious cases) gives 17 quasars in this z range and with V < 16.5 (brightest V = 15.6) in the northern sky (dec > -10 deg), of which 10 at $z > 2.5$, and only 6 in the southern sky (dec $< +10$ deg), of which 2 at $z > 2.5$.
Extending the southern search to V < 17.0 and dec $< +20$ deg yields 30 targets (list given above), of which 17 at $z > 2.4$ and only 5 at $z > 3.0$.

If a very prompt response to the discovery of bright (V < 16) GBRs at $z \sim 2.5$-3 was possible, exposure times shorter by a factor 3 than those for quasars would then be required. Does such bright GRBs exist?
A GRB similar to GRB 050904, $z = 6.295$ (Kawai et al., 2006, Nature, 440, 184), with J=190 μJy ($J_{AB} = 18.2$) 3.1 hr after the burst (Haislip et al., 2006, Nature, 440, 181) would have at $z = 2.5$ a AB magnitude of 15.8 at 6000 Å, 1.5 hr after the burst. The $z = 6.295$ afterglow was fading in $t^{-1.36}$ up to 12 hr after the burst. For our hypothetical $z = 2.5$ GRB, this yields AB(6000 Å) = 15.3 and 17.0 at 1.0 and 3.2 hr after the burst, respectively, thus too short a time span to reach a S/N of 1000.

The expected number of weak CIV absorbers is given by integrating the observed CIV column density distribution per unit redshift path (in comoving space) and unit column density (the redshift path is defined as $dX/dz \equiv (1+z)^2\{0.7+0.3(1+z)^3\}^{-0.5} \cong \{(1+z)/0.3\}^{0.5}$ when $z > 1$, and for $\Omega_\Lambda, \Omega_m = 0.7, 0.3$). Using the N(CIV) distribution determined by Songaila (2005) and extrapolated down to N(CIV) $\simeq 10^{10.3}$ cm^{-2}, yields $dn/dX = 35$ for $10^{10.3} <$ N(CIV) $< 10^{12.0}$ cm^{-2} at a mean redshift $z = 2.7$. This leads to an expected number of weak CIV absorbers per sightline $N \sim 60$ in the interval $2.5 < z < 3.0$.

12b. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If yes, explain why the need for new data.

13. Scheduling requirements

14. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
79	UVES	A	DIC-1	Standard setting: 390+564