Reionizing the Universe

The Epoch of Reionization

and the Physics of the IGM

Groningen, The Netherlands, June $27^{\rm th}$ – July $1^{\rm st}$ 2005

Abstracts for Oral Presentations

1. **First Structure Formation**

   Tom Abel (Invited Talk)

   I will discuss how ab initio calculations of the formation of the very first objects in the universe can help to constrain models of re-ionization and will make detailed predictions to be tested with upcoming redshifted 21cm observations. I will also address physical aspects for the formation of mini-quasars as well as early super-massive black holes as sources for re-ionization.

2. **Transforming 21cm fluctuations into a great cosmological probe**

   Rennan Barkana

   We show that 21cm observations can be used to measure three separate power spectra at every redshift. This permits an unambiguous determination of the primordial baryonic power spectrum, and of the detailed properties of all astrophysical sources of 21cm fluctuations. In particular, the first galaxies can be detected and studied at redshift 20, based on fluctuations in stellar Lyα radiation. At higher redshifts, the evolution of gas density and temperature perturbations can be probed during the era of early baryonic infall.

3. **Luminosity Functions and Star Formation Rates at $z \sim 6-10$: Galaxy Buildup in the Reionization Epoch**

   Rychard Bouwens & Garth Illigworth

   HST ACS and NICMOS data are now of sufficient depth and areal coverage that we can place strong constraints on the formation and evolution of galaxies during the first 1-2 Gyrs of the universe. We have published limits on the bright end of the luminosity function (LF) at $z \sim 10$ (from 'J'-dropouts), published the first non-lensed detections of $z \sim 7-8$ galaxies ('z'-dropouts) in the UDF, and have assembled a deep, robust sample of 347 $z \sim 6$ objects ('i'-dropouts) with low contamination ($<\sim 5\%$) from all the deepest wide-area HST ACS data (UDF, UDF-Parallel, and GOODS fields). We use a sophisticated analysis that corrects for the dramatic changes in detectability of sources over this wide redshift range to establish statistically-robust samples with

minimal systematics. Key observables, such as the observed evolution in UV color and sizes, necessary for the interpretation of these dropout samples, have been determined. We have constructed an optimal determination of the rest-frame continuum UV LF at $z \sim 6$. Our LF extends to over 3 magnitudes below L^*, fainter than has been done at $z \sim 3$. Over the interval $z \sim 6$ to $z \sim 3$, we find strong evidence for evolution in the UV LF. Either (i) M^* has significantly brightened or (ii) the faint-end slope alpha has flattened from approximately -1.8 at $z \sim 6$ to -1.6 at $z \sim 3$. Scenarios, such as density evolution (ϕ^*), which do not include this evolution in M^* or alpha are now ruled out at 99.7% confidence - demonstrating the significance of this shift toward lower luminosities at higher redshifts. Remarkably, this shift to lower luminosities extends to even higher redshifts. Using all deep J+H NICMOS observations (800 orbits in total), we have been able to demonstrate that the bright end of the LF ($> 0.3L^*$) is at least 6 times lower at $z \sim 10$ than at $z \sim 4$, with a similar deficit being established for the $z \sim 7-8$ detections from our UDF NICMOS data. In this presentation, we discuss the evolution of the UV LF, the UV luminosity density and the star formation history of the universe in the reionization epoch at $z \sim 6 - 10$ relative to that at $z \sim 3$.

4. **The star formation histories of the earliest galaxies**

   Bremer, Lehnert, Forster Schreiber, Douglas, Verma

   I present results from a ground and spaced-based study of $5 < z < 6.5$ galaxies in two deep fields. With combined VLT, HST and SPITZER data we are able to determine many of the key properties of the sources including their star formation histories, star formation rates, ability to ionize their local volume, masses, metallicities and how they may enrich the surrounding IGM. These results are drawn from a large statistically significant sample of $z > 5$ sources, many with clearly determined spectroscopic redshifts. We show that a small minority of these sources underwent significant star formation as far back as $z \sim 10$, but the majority are extremely young and vigorous starbursts, contributing little to the ionization of the IGM at higher redshifts than those they are observed at.

5. **The Square Kilometer Array and the EoR**

   Frank Briggs (Invited Talk)

   Observing the Epoch of Reionization and the end of the Dark Age is one of five key science projects that will define the design of the SKA. In fact, the EoR studies pull the specifications in extreme directions, since the studies of diffuse emission from neutral hydogen push the low end of the frequency coverage to 100MHz (and perhaps below), while the observtion of CO from the earliest compact objects provides incentive to close the gap to reach ALMA's lower limit. Results from the pioneering experiments taking place at present will focus the SKA design, with the goal of following the development of structure and the earliest collapsed objects, and providing synergy

with the other great observatories of the coming decades.

6. **The foregrounds for EOR 21cm signals**

A.G. de Bruyn (Invited Review)

I will review what we know about the astronomical foregrounds for EoR observations and how they will effect the signals. Foregrounds can be separated in discrete, diffuse, continuum and spectral line foregrounds. The most important are the discrete sources and the diffuse Galactic synchrotron foreground. The contamination of discrete sources can probably be removed through observations with sufficiently long baselines. The biggest problem to deal with will be the diffuse Galactic continuum. Its fluctuation spectrum, at the relevant frequency and angular scale, is still poorly known. Spectral and spatial fluctuation levels at 350 MHz and 150 MHz can be estimated from WSRT observations in hand. Some results will be shown. The time-variable (through ionospheric Fraday rotation) polarization of the foreground, coupled to the highly polarized response of low frequency phased arrays, will require novel and complicated calibration procedures.

Low frequency astronomy is all-sky imaging because of the high station sidelobe levels, the intense Galactic and extragalactic emission, and the strong and time variable ionospheric refraction effects. This means that also foregrounds in directions away from the targeted Galactic 'EoR windows' are important as their chromatic sidelobes seriously contaminate the milliKelvin signal levels.

The sky noise, instrumental problems and foreground contamination levels are all strong functions of frequency. EoR observations at z=15 may well be an order of magnitude tougher than at z=9.

7. **The Star Formation Rate of the Universe at** $z \sim 6$

Andrew Bunker (Invited Talk)

We have used deep HST imaging with the ACS camera to identify a population of star-forming galaxies at $z \sim 6$ through their large i-z colors (due to absorption from the intervening Ly-alpha forest). We have spectroscopically confirmed some of these "i-drops" with Keck and Gemini. The number densities imply a much lower comoving star formation density than in the more recent past ($z \sim 3$), and the production of ionizing UV photons at $z \sim 6$ is probably insufficient to reionize the universe. New Spitzer/IRAC data indicates star formation may have started at $z \gg 6$ in some of these galaxies.

8. **Obervational Constraints on Self-consistent Reionization Models**

T. Roy Choudhury and A. Ferrara

A self-consistent formalism to jointly study cosmic reionization and thermal history of the IGM is presented. The model implements most of the relevant physics governing these processes, such as the inhomogeneous IGM density distribution, three different sources of ionizing photons (PopIII stars, PopII stars and QSOs), and radiative feedback. By constraining the free parameters with available data on redshift evolution of Lyman-limit systems, Gunn-Peterson and electron scattering optical depths, Near InfraRed Background (NIRB), and cosmic star formation history, we select a fiducial model, whose main predictions are: (i) H was completely reionized at $z \sim 14$, while at least 90% of HeII must have been reionized by $z \sim 11$. At $z \sim 8$, HeIII suffered an almost complete recombination as a result of the extinction of PopIII stars, as required by the interpretation of the NIRB. (ii) A QSO-induced complete HeII reionization occurs at $z = 3.5$ a similar double H reionization does not take place due to the large number of photons above 1 Ryd from PopII stars and QSOs, even after PopIII stars have disappeared. (iii) Following reionization, the temperature of the IGM corresponding to the mean gas density is boosted to 20000 K. Observations are consistent with the temperature of the HII regions around $z > 3.5$, while they are consistent with the temperature of the HeIII regions around $z < 3.5$. This might be interpreted as a signature of (second) HeII reionization. (iv) Only 0.2% of the stars produced by $z = 2$ need to be PopIII stars in order to achieve the hydrogen reionization. Such model not only relieves the tension between the Gunn-Peterson optical depth and WMAP observations, but also accounts self-consistently for all known observational constraints

9. **Element abundances in the first stars**

Leonid Chuzhoy

We show that element abundances of the first stars are likely to be significantly different from the primordial values due to the processes of gravitational sedimentation and ambipolar diffusion. The gravitational sedimentation, which is efficient until the end of reionization epoch at $z \sim 6$, produces many helium rich gas clouds with mass up to $10^3 M_\odot$ that subsequently serve as preferential sites for the formation of Pop III stars. The ambipolar diffusion, besides reducing the magnetic flux, results in depletion of elements with low ionization potential from the metal poor protostellar clouds. The latter process explains the discrepancy between WMAP findings and measured lithium abundance.

10. **Simulating Radiative Processes During Reionization**

Benedetta Ciardi (Invited Talk)

While the radiation produced by the first luminous objects propagates into the intergalactic medium, the neutral hydrogen which survives cosmic reionization is likely to emit radiation at 21cm. In this talk I will discuss simulations of these two main radiative processes that take place during reionization.

11. **Simulations of Galaxy Formation in the Reionization Epoch**

Romeel Dave

I will present results outlining the detectability of high-redshift ($z > 7$) sources from cosmological hydrodynamic simulations. Emission line objects are possibly easier to detect but more difficult to interpret, while broad band techniques will likely require next generation space-based instruments. I will present initial results from our $z = 8.2$ survey for Ly-α emitters with Gemini. I will also present initial results from a new technique for radiative transfer that is fast, rigorous, and unconditionally stable.

12. **Predictions for Lyman α Emission from Early Galaxy Formation**

Mark Dijkstra, Zoltan Haiman, Marco Spaans

When gas collapses inside dark matter halo's with $T_{vir} > 10^4$ K, the majority of its gravitational binding energy is released in the Lyman alpha line. Using Monte-Carlo computations, we predict surface brightness and spectral profiles of the Lyman alpha cooling radiation for simple infall models for the gas.

13. **WMAP and the EoR**

Olivier Dore

Abstract Not Provided

14. **FIRST STARS AND THE COSMIC DAWN**

Andrea Ferrara (Invited Review)

The appearence of the first stars when the universe was only 100 Myr old marked the Cosmic Dawn and the occurrence of a number of physical effects (cosmic reionization, intergalactic medium metal enrichment, black hole formation, magnetic field cosmogenesis and - obviously - galaxy formation) which are now entering the realm of the observability and are strongly governed by so-called 'feedback effects'. I will review these physical processes at high redshift ($z > 5$) and their detectable imprints, and propose a number of experiments which could yield the first observational signals from the Dark Ages of the universe.

15. **Pre-ionization via dark matter annihilation**

Douglas Finkbeiner, Nikhil Padmanabhan, & Avi Loeb

Annihilating WIMP dark matter (100 GeV particles, thermal relic density) can produce sufficient power to substantially ionize the baryons falling into halos at $z \approx 20$. Whether this power ionizes efficiently depends on the spectrum of e^+, e^-, and gammas produced by the annihilations. We explore a generic model parameter space and find that some models provide a "head start" on the reionization of the Universe that may have observable consequences in high-z HI surveys.

16. **Analytic Models of Inhomogeneous Reionization**

Steven Furlanetto (Invited Talk)

In the past few years, both detailed cosmological simulations and simple analytic arguments have shown that reionization is a strongly inhomogeneous process, at least if discrete sources are responsible for ionizing the intergalactic medium (IGM). The resulting topology depends upon the clustering properties of ionizing sources, substructure in the IGM, and the role of feedback in galaxy formation. Thus, measuring the scales over which inhomogeneities occur throughout reionization (with, for example, highly-redshifted 21 cm emission) allows us to constrain a number of key properties of galaxy formation. Here I will describe a simple analytic model for the topology of reionization and show how it robustly predicts large-scale fluctuations in the ionized fraction (on the scales of tens of Mpc). I will also describe some of the observational implications of this inhomogeneity.

17. **Outfitting the VLA for Study of the Epoch of Reionization**

L. Greenhill, R. Blundell, C. Carilli, A. Loeb, R. Perley, S. Furlanetto, M. Zaldarriaga

Mapping the structure of the universe during the cosmological epoch of reionization (EOR) is a new frontier of astrophysics. Little data exist to test models of the reionization. However, the early universe comprised mainly atomic hydrogen, and direct imaging of the HI shells around early quasars could be used to constrain critical parameters, such as the neutral fraction of the universe and the epoch at which these objects formed. Estimation of the statistical properties of angular fluctuations in HI line brightness temperature could also be used to test models of the reionization process.

The Smithsonian Astrophysical Observatory, in collaboration with NRAO, has embarked on a project to outfit the Very Large Array for operation at 190 MHz, with a planned start date for data acquisition before the end of 2005. I will discuss results of field testing prototype receivers and describe some of the challenges of working with the VLA at such low frequencies.

18. **The LOFAR-EoR Strategy**

M.P. van Haarlem

The design of the Low Frequency Array (LOFAR) is being driven by a number of different Key Projects, one of which is the Epoch of Reionization. The EOR plans have the greatest impact on the high band antenna's, their configuration in the core and the digital processing provided by beamformers plus the BlueGene/L based correlator.

The high band antenna's cover the frequency range from 120 to 240 MHz, corresponding to a redshift range from 11 to 5. These antenna's are arranged in 32 stations distributed over a core area that measures roughly 2x3 km. This talk summarizes the design of LOFAR, is sofar that it is relevant for EOR observations.We also discuss the observing strategy to be used in carrying out the observations.

19. **The matter power spectrum inferred from the Ly-alpha forest and its implication for the EoR.**

Martin G. Haehnelt (Invited Talk)

Abstract Not Provided

20. **Simulating Reionization: A New Photon-Conserving Method for Radiative Transfer**

Ilian T. Iliev, Garrelt Mellema, Marcelo Alvarez and Paul R. Shapiro

We present a new numerical method for transferring ionizing radiation which is explicitly photon-conserving, fast and efficient. The code accurately follows both fast and slow ionization fronts without need to adopt small time-steps, for any grid resolution, making it very appropriate for direct coupling with gasdynamic and N-body codes, on both fixed and adaptive grids. We tested the new method in detail in both one and three dimensions on various astrophysically-relevant problems, and compared the one- and three-dimensional solutions and to exact analytical solutions for I-front propagation (some of which we derived here for the first time) at various resolutions in time and space. The code results proved very robust, matching closely the analytical and 1-D solutions even at very low resolutions in space and time. We would also discuss the direct coupling of this code to gas-dynamic methods, with both fixed and adaptive grids, and N-body codes, as well as further testing of our radiative transfer method on problems involving gas dynamics. Finally, we would present the first applications of our code to simulations of the Epoch of Reionization and other astrophysical problems, including observational predictions for the 21-cm emission and absorption signals and the imprint of reionization on the CMB anisotropies.

21. **Upper limit on the Lyman continuum flux escaping from $z \sim 3$ galaxies**

Inoue, A.K., Iwata, I., Deharveng, J.-M., Buat, V., Burgarella, D.

We measured the Lyman continuum flux escaping from two $z \sim 3$ galaxies in the Hubble Deep Field South by using the narrow-band photometry with the Very Large Telescope. We did not find any significant Lyman continuum flux from the galaxies. The corresponding upper limit on the F_{900}/F_{1400} flux density (per Hz) ratio is about 0.1 (3-sigma confidence level). With the observed ultraviolet luminosity density of the universe, the upper limit on the flux ratio gives us an upper limit on the Lyman continuum luminosity density of the universe. We will discuss some implications for the cosmic reionization by extrapolating our result at $z \sim 3$ to higher redshift.

22. **HI at high redshift**

Nissim Kanekar, Jayaram N Chengalur

I will describe our recent HI 21-cm absorption studies of a large sample of damped Lyman-α systems (DLAs) at redshifts $0.09 < z < 3.5$, carried out with the GMRT and the GBT. 21cm absorption was clearly detected in 11 DLAs, with $0.09 \leq z_{abs} \leq 3.4$. We find that the typical spin temperature (T_s) of DLAs at all redshifts are far higher ($T_s \geq 1000$ K) than those in the Galaxy or nearby spirals ($T_s \leq 300$ K). The only exceptions are a few low z absorbers identified with spiral disks, which do indeed show low T_s. This implies that evolutionary effects are not

crucial in understanding the difference in spin temperatures between local spirals and high redshift DLAs. I will present new evidence for an anti-correlation between T_s and metallicity [Zn/H], which suggests that metallicity is the primary factor in determining the ISM temperature. The spin temperature appears to be a good secondary indicator of the nature of the absorbing galaxy, with high T_s values typical of small, low metallicity galaxies and low T_s found in late-type disks. We find that most of the HI in high z DLAs is in the warm phase, with very small fractions of the cold neutral medium.

23. **The physics of the Epoch of Reionization**

Avi Loeb (Invited Review)

The re-ionization history of cosmic hydrogen, left over from the big bang, provides crucial fossil evidence for when the first stars and black holes formed in the infant universe. Current observations provide a mixed message. The large-scale polarization anisotropies of the cosmic microwave background measured by WMAP imply a reionization redshift of 10-20. However, the extent of the ionized regions around the highest redshift quasars indicate a significantly neutral universe at a redshift of 6.4. I will summarize the status of current observational and theoretical studies, and address the possibility that the time evolution of the mean ionization fraction might have been non-monotonic. The truth will likely be revealed over the next decade through observations of the Lyman-alpha spectra of galaxies, quasars and gamma-ray bursts, and most importantly the detection of the 21 cm transition from diffuse hydrogen at redshifts above 6.

24. **The Mileura Widefield Array as an EOR machine**

Colin Lonsdale, David Barnes, Frank Briggs, Lincoln Greenhill, Jackie Hewitt, Miguel Morales, Rachel Webster

The Mileura Widefield Array (MWA) is a facility under development by a US-Australian collaboration, exploiting the extraordinarily radio-quiet environment in outback Western Australia. The goal is to enable very sensitive observations of extremely wide fields of view, at frequencies below about 1.5 GHz. In the 80-300 MHz range, we are pursuing the early implementation of a demonstrator array, specifically designed to enable robust detection and characterization of redshifted 21 cm structures from the epochs of reheating and reionization. The design of this EOR machine will be described, which is based on the principle of controlling systematic errors of various kinds, and enabling accurate foreground subtraction. Such foreground subtraction, which demands high precision polarimetric calibration and close attention to error propagation via spectral and spatial sidelobes, is the most difficult technical challenge of 21cm EOR measurements. The project status, including results from equipment on the ground at Mileura, will be presented.

25. **The Pre-reionisation state of the IGM**

Piero Madau (Invited Review)

Abstract Not Provided

26. **The Impact of Reionization on the IGM**

Avery Meiksin (Invited Review)

The impact of reionization on the formation of cosmic structures will be reviewed. Observational signatures arising from the Intergalactic Medium will be particularly emphasized as a means for diagnosing the epoch and nature of the reionizing sources. The current situation on the possibility of late He+ reionization will also be discussed, as well as the expected impact of reionization on the formation of galaxies.

27. **Lensing of 21 cm maps**

Brice Menard

21 cm surveys will provide us with ideal source planes for gravitational lensing studies, i.e. a distribution of high-redshift sources having some power down to very small angular scales. Moreover, a large number of independent source planes is accessible by observing at different frequencies. Using simulated maps of 21 cm emission by Ciardi et al., we will show how they are affected by foreground galaxy clusters and large-scale structures. We will then show that reconstructing the density field with the 21cm-lensing technique provides a much better accuracy than any cosmic shear surveys. We will finally apply our results to upcoming 21 cm surveys and investigate their potential to constrain cosmology.

28. **Probing Reionization and Early Structures with the Proximity Effect, SNe and GRBs**

Andrei Mesinger, Zoltan Haiman, Renyue Cen, Benjamin Johnson, Rosalba Perna

We develop and assess the potential of several powerful techniques, designed to investigate the details of reionization. First, we present a procedure to probe the neutral fraction using the Lyman alpha transmission statistics of high-redshift ($z > 6$) sources. A rudimentary application of such a technique on quasar SDSS J1030+0524 has yielded compelling evidence of a large neutral fraction

($x > 0.2$) at $z \sim 6$. We also quantify the prospects of detecting the suppression of star-formation in low-mass galaxies at reionization from high-redshift supernovae rates, specifically from those obtainable from the James Webb Space Telescope (JWST). Finally, we explore how the power spectrum of cosmological density perturbations on small scales, which determine the abundance of nonlinear structures at high redshifts, could be constrained with detections of high-redshift gamma-ray bursts by the Swift satellite.

29. **Statistical EOR detection and foreground subtraction: recent results and the implications for array design.**

Miguel F. Morales, Judd Bowman, Jacqueline Hewitt

Statistical EOR analyses extend the techniques developed for CMB observations to three dimensions, and have become the basis for EOR observations with the MWA, LOFAR, and PAST. Subtracting the strong astrophysical and instrumental foregrounds is the primary challenge for observing the 21 cm EOR signature, and several foreground removal techniques have been proposed in the literature. In this talk I will bring the previously proposed techniques together with new results to provide a comprehensive picture of foreground subtraction for the statistical EOR analyses. Using this complete foreground subtraction framework, I will also present the array performance characteristics needed to subtract the EOR foregrounds, and accurate sensitivity predictions.

30. **The Impact of ionized IGM on the CMB anisotropy by the Sunyaev-Zeldovich effect**

Fernando Atrio-Barandela, Jan P. Muecket

The upcoming PLANCK mission will considerably increase the sensitivity with respect to anisotropy contributions at high multipoles in the CMB power spectrum. We examine the impact of the highly ionized intergalactic medium via Sunyaev-Zeldovich effect at various redshifts and discuss it's dependence on the evolution of parameters characterizing the state of the intergalactic medium such as the mean temperature, the polytropic index of the equation of state and the evolution of the overall photo-ionizing UV background flux. Although on the edge of detectibility, the sensitivity of CMB anisotropies on small scales with respect to the evolution of the thermal state of IGM opens, in principle, the possibility to get independent information about the thermal history of the IGM.

31. **Cosmological tests with the 21 cm data**

Adi Nusser (Invited Talk)

Abstract Not Provided

32. **21cm tomography and foreground removal**

S. Peng Oh (Invited Talk)

Radio foregrounds in the 100-200 MHz range can be several orders of magnitude larger than the expected 21cm signal from high redshift. I present some simulations of 21cm signal recovery in the presence of foregrounds using trend-removal techiques, and discuss the prospects for 3D 21cm tomography.

33. **Searching for Reionization with 21CMA/PAST**

U. L. Pen, X. P. Wu, J. Peterson (Invited Talk)

we describe the current status of the Chinese 21CMA project, and preliminary scientific results. 21CMA has completed the first 20 hexagonal pods of 127 log periodic antennae, and construction is underway to complete 80 pods. The operating frequency range is 50-200 Mhz.

34. **Goals and Design of the Primeval Structure Telescope**

Jeffrey Peterson, Xiang Ping Wu, Ue Li Pen

The Primeval Structure Telescope, also called the 21cm Array, is under construction at Ulastai, Xin Jiang, China. The main goal of the project is to search for early ionzation of the universe, by mapping the 21 cm emission of neutral hydrogen at redshifts from about 6 to 25. This emission is expected to be seen as patchy on arcminute scales at the redshift of half ionization. We will attempt to detect that patchiness beneath much stronger foregrounds due to synchroton emission from the Galaxy and radio emission from extragalactic sources. The design, goals and progress of the project will be summarized.

35. **The origin of intergalactic metals around Lyman-break galaxies**

C. Porciani, P. Madau

Theoretical and observational arguments suggest that the intergalactic medium (IGM) might have been polluted with metals produced by early star formation. In this scenario, Lyman-break galaxies (LBGs) at redshift $z = 3$ are likely to be surrounded by old metal bubbles, relics of an era when the characteristic mass of galaxies was small and gas retainment more difficult. We find that pregalactic enrichment of the IGM from $10^8 - 10^{10} \odot$ dwarf galaxies at $6 < z < 12$ can quantitatively explain the high cross-correlation between CIV systems and LBGs observed at $z = 3$. The reason is twofold. First, both LBGs and high-z dwarfs are biased tracer of the mass distribution and form from exceptionally high density fluctuations which are strongly clustered. Second, the action of gravity tends to increase the spatial association between metal bubbles and LBGs. Our analysis shows that, in order to match the abundance of CIV systems observed at $z = 3$, the metal bubbles generated by high-z dwarfs must have comoving sizes of ~ 100 kpc. We conclude that the observed galaxy–CIV spatial association needs not to be generated by late "superwinds" from LBGs.

36. **Descending from on high: Lyman-series cascades and spin-kinetic temperature coupling in the 21cm line.**

Jonathan Pritchard, Steven Furlanetto, Marc Kamionkowski

One interesting source of brightness temperature fluctuations in high-redshift 21cm observations is the spin temperature, especially during the era of the first generation of sources. In this case, the fluctuations arise from variations in the radiation background near luminous sources. Previous work has shown that higher Lyman-series photons contribute a substantial fraction of the fluctuations. However, the spin-kinetic temperature coupling from these photons has not been considered in detail. We use the quantum mechanical transition rates to calculate the probability that a higher Lyman-series photon will form a Lyman-alpha photon as the end product of a decay cascade. Those cascades that do not end as Lyman-alpha photons instead produce two $2s \rightarrow 1s$ photons, resulting in much less efficient spin coupling. Further, we investigate the direct coupling through higher Lyman-series photons, and in particular Lyman-beta, which is decoupled from the Lyman-α transition by the quantum selection rules. Incorporating these features, we calculate the resulting fluctuations for some simple models of the first luminous sources.

37. **The Kinematics of the IGM at Redshifts 2-4**

Michael Rauch

Based on spectroscopy of QSO pairs and gravitationally lensed QSOs we describe the general motions of the intergalactic medium on scales from 100 pc to 300 kpc (physical) and discuss sources of kinetic energy, bulk motion and turbulence.

We present direct evidence for gravitational collapse in the low density cosmic web. Discussing various kinematic and spatial signatures of galactic feedback into the IGM we give quantitative limits on the extent of mechanical feedback the IGM has suffered.

38. **The First Generation of Star-Forming Halos**

Darren Reed, Richard Bower, Carlos Frenk, Liang Gao, Adrian Jenkins, Tom Theuns, Simon White

We model gas cooling in high-resolution N-body simulations in order to investigate the formation of the first generation of stars. We follow a region of a LCDM universe especially selected to contain a rich cluster by the present day. The properties of the dark halos that form in these sub-solar mass resolution simulations are presented in a companion paper by Gao et al. The first gas clouds able to cool by molecular hydrogen line emission collapse at extremely high redshift, $z \approx 47$, when the mass of the dark halo is $2.4 \times 10^5 M_{sun}/h$. By $z \approx 30$, a substantial population of halos are capable of undergoing molecular hydrogen cooling although their ability to form stars is dependent on the efficiency of feedback processes such as dissociating Lyman-Werner radiation. The mass of the main halo grows extremely rapidly and, by $z \approx 36$, its virial temperature has reached $10^4 K$, at which point gas cooling becomes dominated by more effective atomic line processes. By $z \approx 30$, a small "group" of galaxies will have formed unless prevented from doing so by feedback processes. By this redshift, massive population III stars are able to ionise gas well beyond their own host halo and neighbouring HII regions can percolate to form an ionized superbubble. Such patches would be too widely separated to contribute significantly to reionisation at this time. The large number density of early cooling halos in the pre-reionised universe raises the exciting prospect that this ultra-early generation of stars may be observable as gamma-ray bursts or supernovae.

39. **Probes of high-z structure and ionization**

Martin J. Rees (Invited Review)

This talk will address several interlinked issues: how and when the first gravitationally-bound structures form the nature of the first energy input into the IGM (UV or X-rays?) the scale of inhomogeneities in the HI distribution the hierarchical build-up of black holes. Most current mod-

els suggest that the transition from a neutral to a predominantly ionized medium is very gradual, starting at redshifts excceding 20. The special role of 21cm mesaurements will be emphasised.

40. **Black-holes and the (Pre-)reionization process**

Massimo Ricotti (Invited Talk)

Models of the early reionization of the intergalactic medium (IGM) by massive stars require a protracted epoch of zero-metallicity star formation in order to be consistent with WMAP. Although this is possible, we find it unlikely unless most population III stars collapse directly into black holes without polluting the IGM with metals.

We show that, in this scenario, the gas accretion onto "seed" black holes from population III stars produce X-ray radiation that may be more effective in ionizing the IGM than the primary radiation from the stars. The partial ionization produced by the X-ray background starts in low density regions of the IGM and proceeds into the denser filaments where the sources reside. Although X-rays cannot ionize the IGM above 10ionization rate from the redshifted X-ray background increases the fractional ionization of HI above the 10re-ionization of HeII and re-heating of the IGM at around redshift 3. At redshift z¿=6, complete re-ionization of the IGM by normal stellar populations is faster and easier to achieve as most of the intergalactic volume is already partially ionized.

41. **An exploration of the effects of HD cooling on primordial star formation**

Emanuele Ripamonti

It is well known that H_2 molecules are the main cooling agents in the small halos where primordial star formation takes place. However, there are indications that in some situations HD could become as least as important as H_2. By using simplified 1D models we explored the influence of HD cooling on the collapse of primordial halos in a large range of the $M_{halo} - z_{vir}$ parameter space, and found that HD has no influence on halo evolution up to virialization (e.g., the minimum mass of collapsing halos is unaffected by HD cooling), but it can change the thermal history of the gas in small halos, leading to a reduction of temperature, and possibly lowering the typical mass of stars.

42. **Reionizing the Large Scale Structure**

Jelle Ritzerveld & Vincent Icke

Incorporating radiative transfer processes into numerical simulations is, and has always been, an arduous task. Yet, it is essential to take into account radiative processes, especially when trying to do realistic simulations of the Epoch of Reionization. An important element for these simulations to be realistic is that the simulation box is large enough to be statistically representative. The (dark) matter herein has a highly inhomogeneous distribution, resulting in the fact that the first sources of ionizing photons also follow this inhomogeneity. Combining these two facts, we see that we need a radiative transfer solver, which can deal with highly inhomogeneous distribution of matter and sources, and is fast enough to solve the equations for a very large number of sources. Unfortunately, the standard ray-tracing and Monte Carlo methods scale with the number of sources. Our radiative transfer method, *SimpleX*, uses an Lagrangian, unstructured grid, which follows the medium distribution. This feature has as a result that the operation count of the method does *not* scale with the number of sources, by which we are able to do very fast simulations of the reionization of a large volume of the large scale structure.

43. **High Redshift Lyman-α Emitting Galaxies**

James Rhoads (Invited Talk)

Because Lyman alpha photons are scattered in a neutral universe, Lyman alpha emission from galaxies provides a test for reionization: such emission should be rare and/or faint in the early stages of reionization. This test is sensitive to neutral fractions around 30-50%, and complements the Gunn-Peterson test, which saturates at much smaller neutral fraction. To apply this test, we must identify and characterize a suitable source population. I will summarize our current understanding of high redshift Lyman alpha galaxies as a population of young objects whose prominent line emission is dominated by star formation (rather than accretion power). I will then present applications of the Lyman alpha reionization test to date, which show that most intergalactic hydrogen was already ionized before $z = 6.5$. Finally, I will outline future prospects in this field, including neutral fraction constraints at higher redshifts, and studies of reionization topology from spatial mapping of Lyman-alpha galaxy distributions. Both extensions will be possible with available technologies.

44. **Multifrequency analysis of the 21 cm fluctuations from the era of Reionization**

Mario G. Santos, Asantha Cooray, Lloyd Knox

Measurements of the 21 cm fluctuations are emerging as a powerful tool to explore the end of the cosmic dark ages and the reionization epoch. However, detection of this signal is complicated by

the huge foreground contamination. I will discuss the prospects for extracting detailed statistical properties of the neutral hydrogen distribution at several frequencies, taking into account the modelling of the foregrounds. In particular I will show how well the angular power spectra of the 21 cm fluctuations can be determined with upcoming experiments and how different assumptions about the foreground models will affect the signal extraction. This cleaned 21 cm signal can then be used to put constraints on the reionization model.

45. **Observational Summary**

Wallace Sargent (Invited Review)

I shall summarize the observations.

46. **Evolution of Low Luminosity Galaxies at High Redshift**

Marcin Sawicki & David Thompson

Sub-L* galaxies, while faint, are abundant and so make a highly significant contribution to the UV luminosity density of the Universe. However, constraints on the sub–L* population at high redshift have been poor to date because of the high cost of observing such faint objects. We use very deep Keck UGRI imaging ($R_{lim} = 27$, or SFR$\approx 1 M_{sun}$/yr) to study the evolution of the faint end of the UV-selected galaxy population from $z \sim 4$ to $z \sim 2$. We find that the number of sub-L* galaxies declines significantly with increasing redshift. In addition to implications for the evolution of high-z galaxies themselves, our observation of the declining number density of sub-L* galaxies places constraints on the likelihood that a population of abundant, low-luminosity galaxies is responsible for reionizing the early universe.

47. **What do the Intergalactic metals tell us about the EoR?**

Joop Schaye (Invited Talk)

The enrichment of the intergalactic medium with heavy elements provides us with an archaeological record of star formation at very high redshift and with a laboratory to study the interactions between galaxies and their environments. I will review recent results from observational and theoretical studies of intergalactic heavy elements and I will discuss what intergalactic metals can tell us about reionization.

48. **The extinction of the first massive stars**

Raffaella Schneider, Ruben Salvaterra, Andrea Ferrara & Benedetta Ciardi

In the last few years the universality of the stellar IMF has been questioned by the results of theoretical studies, which consistenly predict that the first stars were very massive. On the other hand, observations of present-day stellar populations show that stars form according to a Salpeter IMF. These findings imply that an IMF transition must have occurred affecting the properties of the stars during cosmic evolution. Here we review our current understanding of the physical processes responsible for this transition, as well as its implications for the cosmic star formation history and the history of reionization.

49. **The Impact of Small-Scale Structure on Cosmic Reionization and the End of the Dark Ages**

Paul Shapiro (Invited Talk)

The universe was reionized by redshift z 6 by a small fraction of the baryons in the universe, which released energy following their condensation out of a cold, dark, and neutral IGM into the earliest galaxies. The theory of this reionization is a critical missing link in the theory of galaxy formation. Recent work suggests that the photoevaporation of dwarf galaxy minihalos may have consumed a significant fraction of the photons required to reionize the currently-favored Lambda-CDM universe. The role of small-scale structure like minihalos and the clumping of the intergalactic gas outside of halos has generally been overlooked in the treatment of cosmic reionization, however. As the frontier of numerical cosmology moves now to respond to the difficult challenge of including radiative transfer in gas and N-body dynamics simulations, it is critical that these effects of small-scale structure be resolved. We will review recent developments in our understanding of this process, in the context of the discovery of angular fluctuations in the polarization of the CMB at large angles by the Wilkinson Microwave Anistropy Probe and the detection of the Gunn-Peterson effect in the spectra of high redshift quasars at z 6 discovered by the Sloan Digital Sky Survey. We will also discuss the possibility of observing redshifted 21-cm lines from these minihalos before and during reionization, the first baryonic structures to emerge in the universe.

50. **The Polytropic Equation of State of Primordial Gas Clouds**

M. Spaans & J. Silk

The polytropic equation of state (EOS) of primordial gas clouds with modest enrichment is computed, motivated by the recent observations of very Fe-deficient stars, [Fe/H]$\sim 10^{-3.5} - 10^{-5}$, such as HE 0107-5240 and CS 29498-043. These stars are overabundant, relative to Fe, in C and O. We assume that the observed abundances of species like C, O, Si and Fe are representative of the gas from which the currently observed metal-deficient stars formed. Under this assumption,

we find that this primordial metal abundance pattern has profound consequences for the thermal balance and chemical composition of the gas, and hence for the EOS of the parental cloud. The polytopic EOS is soft for low, [O/H]$< 10^{-3}$, oxygen abundances, but stiffens to a polytropic index γ large than unity for [O/H]$> 10^{-2}$ due to the large opacity in the CO and H_2O cooling lines. It is further found that a regulating role is played by the presence and temperature of the dust, even when the overall carbon abundance is only [C/H]$\sim 10^{-2}$. When the dust is warmer than the gas, a region with $\gamma \sim 1.2$ results around a density of $\sim 10^4$ cm^{-3}. When the dust is colder than the gas, a region with $\gamma \sim 0.8$ is found for a density of $\sim 10^6$ cm^{-3}.

51. **The High-redshift SDSS QSOs and their implication on the EoR**

Michael Strauss (Invited Talk)

The SDSS has now discovered 18 quasars with redshifts greater than 5.7. I will summarize the data available to date on the optical depth of the Lyman-alpha decrement in these quasars as a function of redshift. High signal-to-noise ratio spectra of two of the highest-redshift quasars tell conflicting stories: a quasar at $z = 6.3$ shows a complete absence of flux in the Lyman alpha forest, while the quasar at $z = 6.4$ shows measureable flux. Thus different lines of sight imply a complicated end to the epoch of reionization. I will conclude with a discussion of future prospects for studies of high-redshift quasars.

52. **ATNF Cosmological Re-ionization Experiment**

Ravi Subrahmanyan, Aaron Chippendale and Ron Ekers

We are building a low-frequency radio telescope to detect signatures from the epoch of re-ionization. The system is designed to operate in the 100 to 228 MHz band corresponding to the redshift range 5.2-13.2. The antenna element is pyramidal spiral and designed to give a sky response that is frequency independent. The observing modes include all-sky total power spectral measurements as well as large-angular-scale interferometer measurements using a pair of antennas. The back-end is a poly-phase digital spectrometer that computes auto and cross-power spectra with high spectral resolution for interference rejection. The experiment will be sited at a remote Australian site where ground conditions are appropriate and interference is low. The project is fully funded and first light is scheduled for June 2005. The design philosophy and observing strategies will be presented along with a status report.

53. **Constraining the EoR with High resolution CMB Data**

Naoshi Sugiyama (Invited Talk)

I discuss possible implications on CMB anisotropies and polarisation of the early reionisation. It is known that peculiar motion of the ionised medium generates secondary CMB anisotropies due to the Doppler effect, which is often referred as the Ostriker-Vishniac effect or the kinetic Sunyaev-Zeldovich effect. With these secondary temperature anisotropies and secondary polarisation of CMB on very large angular scales induced by late time scattering of photons, we can reveal the process of reionisation, i.e., when and how reionisation takes place.

54. **Lyman alpha halos around sources before cosmological reionization**

Argyro Tasitsiomi, Andrey V. Kravtsov, Nickolay Gnedin

I will present results of detailed Lyman alpha radiative transfer around sou rces produced in very high redshift state-of-the-art cosmological simulations with emphasis not only in the Lyman alpha flux, but also in the detailed s hape and structure of the Lyman alpha line and the information it conveys about the early evolutionary stages of the universe, such as galaxy formation and IGM evolution.

55. **Reionisation and the thermal history of the IGM**

Tom Theuns

Because the thermal time-scales are long, the low-density, photo-ionised intergalactic medium retains a memory of when it became reionised. I will discuss the constraints this places on the reionisation epoch and the sources of ionising photons.

56. **A Deep Search for Lyman-alpha Emitters at $z \sim 6.5$: New Results from the VLT**

Kim-Vy Tran, Simon Lilly

We present new results from our ongoing search for Lyman-alpha emitting galaxies (LAEs) at $z \sim 6.5$ using the multi-slit/narrow-band filter technique on the VLT/FORS2. Compared to first results presented in Tran et al. (2004), our new observations reach luminosities that are ~ 2 times fainter. This enables us to better constrain the shape of the luminosity function of LAEs at $z \sim 6.5$

and provides better overlap with studies of LAEs at lower redshift, e.g. $z \sim 3$. Determining the number density and luminosities of LAEs at $z \sim 6.5$ directly tests whether stars generated enough photons to reionize the universe. Comparing the $z \sim 6.5$ LAE luminosity function to those at lower redshift also provides a useful constraint on how galaxy populations have evolved since high redshift.

57. **Measuring and Simulating the IGM at z=2-3**

David Tytler, Mike Norman, David Kirkman, Tridi Jena, Nao Suzuki

We are measuring the properties of the IGM redshifts 2 to 3 by comparing precise measurements of the Lyman alpha forest with a large suite of hydrodynamic simulations. Two statistics especially useful: the mean amount of absorption by HI and the distribution of the widths of the Ly-alpha lines, equivalent to the power spectrum on small scales. We have measured the mean amount of absorption from the low density IGM with an error of 1%. We have run over 50 large simulations to determine how these statistics depend on the input cosmological and astrophysical parameters of the IGM. We know the sets of parameters that agree with observations. We obtain the most accurate measurements of the intensity of the UVB, and of the IGM temperature.

58. **Early Reionization by Pop III Binaries**

Masayuki Umemura

The nature of ionizing sources that caused the early reionization is still under debate. Although Pop III stars or mini-quasars has been considered so far as ionizing sources, it has been recently revealed that a significant portion of Pop III stars can form in binary systems. The end product of the Pop III binaries could be massive star-massive black hole (BH) binaries, and they can be significant far UV sources via mass accretion from a companion star to a BH. In this paper, we consider the possibility of the early reionization by Pop III binaries, and also derive the constraints on the mass density of relic BHs in the universe to account for the early reionization.

Abstracts for Posters

1. **The Cosmological H II Region of the First Star**

   Marcelo Alvarez, Volker Bromm, Paul Shapiro

   Numerical simulations of the formation of the first stars predict that they formed at redshifts $z > 20$ in minihalos with masses of about $10^6 M_{sun}$. These first stars produced ionizing radiation that heated the surrounding gas and affected subsequent star formation, while at the same time contributing to the reionization of the universe. In order to understand these radiative feedback effects in detail, we have undertaken three-dimensional simulations of the propagation of an ionization front around massive Population III stars ($M \approx 100 - 200 M_{sun}$) that form at a redshift $z = 20$. We follow the evolution of the H II region created by the star within the density distribution resulting from a smoothed particle hydrodynamics (SPH) simulation of primordial star formation. A few hundred thousand years after the star's formation, the expanding ionization front escapes the halo and propagates into the surrounding intergalactic medium. We describe the structure and evolution of this H II region and discuss implications for reionization and subsequent star formation.

2. **Polarization of High Redshift 21-cm Radiation**

   Daniel Babich, Abraham Loeb

   We consider possible polarization mechanisms of the 21-cm line radiation. After discussing processes that could produce intrinsically polarized emission, we calculate the polarization due to Thomson scattering along the line-of-sight. In analogy to secondary polarization production of the CMB, the 21-cm brightness temperature correlations will produce a quadrupole moment incident on the scatterers which will become polarized.

3. **Parametrized EOR Power Spectrum Sensitivity of the MWA**

   Judd Bowman, Miguel F. Morales, Jacqueline Hewitt

   We present accurate sensitivity calculations for statistical EOR observations with the Mileura Widefield Array. To aid other researchers in determining the model separation power of upcoming statistical EOR observations, we parametrize the sensitivity of the MWA power spectrum observations. This sensitivity parametrization can be easily added to theoretical power spectra to show the capabilities and limitations of first generation EOR observations.

4. **Fluorescent Lyα emission from the high-redshift intergalactic medium**

   Sebastiano Cantalupo, Cristiano Porciani, Simon J. Lilly and Francesco Miniati

   We combine a high-resolution hydro-simulation of the ΛCDM cosmology with two radiative transfer schemes (for continuum and line radiation) to predict the properties, spectra and spatial distribution of fluorescent Lyα emission at $z \sim 3$. We focus on line radiation produced by recombinations in the dense intergalactic medium ionized by UV photons. In particular, we consider both a uniform background and the case where gas clouds are illuminated by a nearby quasar. We find that the emission from optically thick regions is substantially less than predicted from the widely used static, plane-parallel model. The effects induced by a realistic velocity field and by the complex geometric structure of the emitting regions are discussed in detail. We make predictions for the expected brightness and size distributions of the fluorescent sources. Our results account for recent null detections and can be used to plan new observational campaigns both in the field (to measure the intensity of the diffuse UV background) and in the proximity of bright quasars (to understand the origin of high colum-density absorbers).

5. **Near infra-red spectroscopic searches for magnified redshift 8 to 10 galaxies behind galaxy clusters**

   Davey J.N.G., Warren S.J. and Weatherley S.J.

   We have begun a search for serendipitous Lya emission from galaxies at very high redshift, magnified by intervening massive galaxy clusters. The data are archive VLT-ISAAC observations of specific targets, taken by others. We make a search for Lyα emission along the slit for galaxies $8 < z < 10$ fortuitously falling on the slit. We will provide a summary of the current status of this programme at the meeting. The detection limits between the sky lines are as faint as a few times $10^{-18} ergs/s/cm^2$. Since the sources will be highly magnified, the unlensed detection limits are substantially deeper.

6. **Populations of $z > 5$ Galaxies**

   Laura Douglas, Malcolm Bremer, Matt Lehnert

   I report on ongoing work studying populations of galaxies at $z > 5$ using very deep multiband imaging from the VLT, the NTT and the HST/ACS. These data were used to identify R-dropout Lyman Break galaxies and separate them from any lower redshift or galactic contaminants. From a initial list of two hundred good $z > 5$ candidates, identified in 10 separate fields, we have follow-up spectroscopy on more than 60 of them. Analysis of the number density of objects, over the ten fields, implies a lower comoving star formation density than at $z = 3$ suggesting a lack of UV photons from bright objects compared to that required to reionise the universe at these redshifts.

7. **Spitzer Imaging of i'-drop Galaxies: Old Stars at z=6**

L.Eyles, A. Bunker, E. Stanway, M. Lacy, R. Ellis, M. Doherty

We present new evidence for mature stellar populations with ages in massive galaxies seen at a time when the Universe was less than 1Gyr old. We analyse the prominent Spitzer/IRAC detections of two $z \sim 6$ star-forming galaxies selected through the "i-band dropout" technique (the Lyman-break technique at $z \sim 6$ with HST/ACS imaging). We had subsequently confirmed spectroscopically with the Keck telescope. The new Spitzer photometry reveals significant Balmer/4000Å discontinuities, indicative of dominant stellar populations with ages > 100Myr, and most likely ages of $250 - 650$Myr and implied formation redshifts $z \sim 7.5 - 13.5$. Remarkably, our sources have best-fit stellar masses of $2 - 4 \times 10^{10} M_{\odot}$. This indicates that at least some galaxies with stellar masses $> 20\%$ of those of a present-day L^* galaxy had already assembled within the first Gyr after the Big Bang. Our result lends support to the hypothesis advocated in our earlier analyses of the Ultra Deep Field and GOODS HST/ACS data. The declining global star formation density and presence of established systems at $z \sim 6$ suggests long-lived sources at earlier epochs ($z > 7$) played a key role in reionizing the Universe.

8. **Intergalactic HeII absorption towards QSO 1157+3143**

C. Fechner, D. Reimers, H.-J. Hagen, P. Jakobsen, D. Tytler, D. Kirkman

We report the discovery of a further line of sight allowing detection of HeII Lyα absorption by the intergalactic medium. A HST/STIS survey of 32 bright $z \sim 3$ quasars selected from the Hamburg Quasar Surveys yielded one detection toward QSO 1157+3143 ($z \sim 3, B \simeq 17$). A 10 orbit follow-up spectrum reveals a UV spectrum significantly supressed by two intervening Lyman limit systems at z=2.77 and 2.97, but with the continuum flux recovering sufficiently shortward of ~ 1700 Åto allow the study of the HeII absorption spectrum in the redshift range $2.75 \leq z \leq 2.97$. The absorption is characterized by alternating voids and dense filament structures seen in both HeII and HI. Attempts to model the HeII opacity in terms of HI Lyα forest absorption are not successful in the voids, suggesting that HeII reionization is not complete between z=2.77 and 2.97.

9. **Gamma ray bursts: towards the reionization era**

P. Filliatre & P. Goldoni

Gamma ray bursts (GRBs) are the most powerful events in the Universe, being able to release about 10^{52} ergs in few seconds, mainly in the gamma ray domain, most probably by the mean of shocks in a ultrarelativistic outflow coming from the collapse of a massive star. Their cosmological origin has been proven in 1997 by the observation of the afterglow, which appears after the burst and last a few days. The afterglow emission spans from the X-ray bande to the radio band. It is

thought to result from the interplay between the ejectae and the interstellar medium. The afterglow is indeed a very bright source, although transient, and have been already observed up to $z = 4.5$, a record for a stellar object. The absorption features on the afterglow spectrum probe the close environment of the object, and hence the physical conditions at those high redshifts. Moreover, simple extrapolations show that the afterglows may be observable up to $z \sim 16$, provided that fast enough near-infrared observations are done, and that population III stars are able to produce GRBs. The X-shooter spectrograph will be the first 2nd generation instrument of the VLT. One of its major goals is to make spectra of GRB afterglows with a high signal to noise. Having a very large spectral coverage including near-infrared, it will be able to deliver a detailed insight of the farthest stellar objects of the Universe.

10. **Is the Ly-alpha forest able to constrain the epoch of reionization?**

Simona Gallerani, Tirthankar Roy Choudhury, Andrea Ferrara

In this work we use a semianalytical approach to simulate the Ly-alpha forest flux distribution varying the ionizing radiation background. We consider two models: (i) the first is characterized by an highly ionized IGM after redshift 14, (ii) the second is based on a more traditional reionization history in which the overlapping of ionized regions is completed by redshift 6. In both models statistical analysis of the flux are performed. In the early reionization model the flux properties match the observed ones, as far as the mean transmitted flux evolution, the flux probability distribution function and the dark gap width (DGW) distribution are concerned. Interestingly, at high redshift, the DGW distribution appears to be an excellent statistical diagnostic to discriminate among different reionization models.

11. **Patchy He II reionization and the physical state of the IGM**

Liron Gleser, Adi Nusser, Andrew J. Benson, Hiroshi Ohno, Naoshi Sugiyama

We investigate the He II reionization by QSOs and its effect on the thermal state of the clumpy intergalactic medium (IGM). To do so, we use a Monte-Carlo model which assumes that patchy reionization develops as a result of the discrete distribution of QSOs. The model includes various recipes for the propagation of the ionizing photons, and treats photo-heating self-consistently. The model provides the fraction of He III, the mean temperature in the IGM, and the He II mean optical depth — all as a function of redshift. It also predicts the evolution of the local temperature versus density relation during reionization. Our findings are as follows: The fraction of He III increases gradually until it becomes close to unity at $z \sim 2.8 - 3.0$. The He II mean optical depth decreases from $\tau \sim 10$ at $z > 3.5$ to $\tau < 0.5$ at $z > 2.5$. The mean temperature rises gradually between $z \sim 4$ and $z \sim 3$ and declines slowly at lower redshifts. The model predicts a flattening of the temperature-density relation with significant increase in the scatter during reionization at

$z \sim 3$. Towards the end of reionization the scatter is reduced and a tight relation is re-established. This scatter should be incorporated in the analysis of the Lyα forest at $z < 3$. Comparison with observational results of the optical depth and the mean temperature at moderate redshifts constrains several key physical parameters.

12. **Cosmological implications of the uncertainty in astrochemical rate coefficients**

S. Glover, D. W. Savin, A.-K. Jappsen

The cooling of neutral gas of primordial composition, or with very low levels of metal enrichment, depends crucially on the formation of molecular coolants such H_2 and HD within the gas. Although the chemical reactions involved in the formation and destruction of these molecules are well known, the same cannot be said for the rate coefficients of these reactions, some of which are uncertain by an order of magnitude. In this presentation, we discuss two reactions for which large uncertainties exist – the formation of H_2 by the associative detachment of H^- with H, and the destruction of H^- by mutual neutralization with protons – and show that these uncertainties can have a dramatic impact on the effectiveness of cooling during protogalactic collapse.

13. **A Description of Ly-alpha forests as Spatial Poisson Point Distributions**

Christian Graf, Rainer Wehrse

This contribution presents an approach describing Lyα absorber systems as an inhomogenous poisson point distribution. In contrast to conventional methods, the forest of lines is treated as a distribution in the space spanned by the two parameters: line position and equivalent width. In this way, additional information not conveyed in a one-dimensional analysis of line-positions is obtained. Possible inferences on the IGM are discussed. As a demonstration, the method is applied to the Lyman-alpha forest of the QSO Q0055-269.

14. **Source Discriminant for Cosmic Reionization**

Kumiko Hiroi, Masayuki Umemura, Taishi Nakamoto

The spatial pattern of neutral hydrogen (HI) distributions during the cosmic reionization strongly depends upon the type of ionizing sources. So far, several theoretical models for ionizing sources have been proposed, which include Pop III stars, Pop III black hole accretion, or mini-quasars. If

the difference in HI pattern is detected, one possibly discriminate the ionizing sources responsible for the reionization. To derive the discriminant quantitatively, we simulate the cosmic reionization processes for various types of ionizing sources, by solving 6D radiative transfer. Based on numerical results, we analyze the dependence of HI pattern on the spectrum and luminosity of ionizing sources and discuss the applicability of this discriminant for 21cm tomography.

15. **Miliura Wide Field Array update**

C. Johnston, D. Barnes, S. Wyithe

Recent discoveries of sources with redshifts greater than z 6 have taken astronomy to the edge of the reionisation epoch. In the near future, with the introduction of low frequency arrays, the observational focus on the reionisation epoch is expected to shift from Ly-alpha absorption to 21cm emission. A substantially neutral IGM at z 6 should provide a detectable signal for these arrays, allowing direct observation of the boundaries of individual HII regions, as well as determination of the statistics of fluctuations in the neutral IGM. One such low frequency array is the Milieura Wide Field Array Low Frequency Demonstrator (MWA-LFD) which is to be located in the radio-quiet region of Western Australia.

In this talk we describe analysis of the feasability of detecting individual cosmological HII regions around high redshift quasars as well as simulations of telescope visibilities for the MWA, . Our analysis generates radio-interferometric data specific to the configuration of the MWA, and performes calibration and analysis of the resulting spectral cubes using AIPS++.

16. **The cooling finction of HD molecule and its role on the formation of the dwarf galaxies**

Ramona Nuez Lopez, Anton Lipovka, Vladimir Avila

We report new calculations of the cooling rate of primordial gas by the HD molecule, taking into account its ro-vibrational structure. The HD cooling function is calculated including radiative and collisional transitions for $J = 0, ..., 8$ rotational levels, and for the vibrational levels $v = 0, ..., 3$. We find that the inclusion of ro-vibrational transitions increases significantly the HD cooling efficiency at high densities ($n_H > 10^4 - 10^5 cm - 3$) and temperatures ($T_k > 3000$ K). We present also the HD cooling rate in the presence of CMBR for different values of T_r. We discuss about the relevance of including our results in models and simulations of formation of the first dwarf galaxies and globular clusters.

17. **Reconstruction of the large scale structure from weak lensing simulations of gas at the epoch of reionization**

Tingting Lu, Ue-Li Pen

The structures in the neutral hydrogen gas during and before the epoch of reionization are the potentially richest untapped sources of cosmological information. We show how these sources can be used as sources for weak gravitational lensing. Optimal estimators allow the simultaneous measurements of shear and magnfication. We present results applying these techniques to simulations.

18. **Primordial Black Hole Accretion and Reionization**

Katherine Mack, Jeremiah Ostriker

We present the results of an analytical and numerical study of possible mechanisms for the growth of primordial black holes (PBHs). We estimate the conditions under which PBHs existent at the time of matter-radiation equality could grow to become a cosmologically significant component of dark matter, seeds of supermassive black holes, or ultra-luminous x-ray sources. We also discuss the possible effects of PBHs on the reionization history of the universe, thus placing new limits on the present-day PBH population.

19. **STERILE NEUTRINOS AND BACKGROUND RADIATION**

M. MAPELLI, A. FERRARA

Sterile neutrinos represent one of the possible candidate of dark matter (Dolgov 2002 and reference therein). In principle, they can be detected through the effects of their decays. Radiative neutrino decays can contribute to the background radiation in different bands (Dolgov & Hansen 2001 Drees & Wright 2000). It has also been proposed that non-radiative neutrino decays, producing electrons which interact with CMB photons via inverse Compton scattering, can give a contribution to the Reionization of the Universe (Hansen & Haiman 2004). We discuss the possible role of both radiative and non-radiative sterile neutrino decays in producing the background radiation (in particular in the Infrared and X ranges) and in reionizing the Universe. In this way, we also try to put some constraint on the sterile neutrino mass, lifetime and density.

20. **3D Line Transfer Modeling and Application to Lyα Halos**

Erik Meinkoehn

The paper is to contribute to the understanding of the early universe, by studying models of three-dimensional radiation fields trapped in moving gas clouds, which are characterized by varying densities and velocities. As to the early universe, it is a well-known asumption that high-redshifted hydrogen clouds are the precursors of present-day galaxies. In observations of such high-redshift gas clouds, the Lyα line is usually found to be the only prominent emission line in the entire spectrum. The investigation of the Lyα line is therefore of central importance for the theory of galaxy formation and evolution, since it – or, to be more specific, its profile – contains all the information about the spatial distribution and the kinematics of the interstellar gas, and also about the nature of the photon source.

A typical Lyα halo is generally characterized by a heterogeneous density structure and considerable length scale discrepancies, if the source region and the halo extension are compared. For such a halo, thin regions of the spatial domain exist where the specific radiation intensity varies rapidly, whereas photon transport is smooth in the remaining parts which are much larger. Due to this, the implementation of very efficient numerical methods turns out to be indispensable for the generation of solutions of the complex line transfer problems, which need to be sufficiently accurate so as to permit a quantitative comparison with observational data. Because of the size of the resulting linear system of equations, use of parallelization techniques and local grid refinement strategies based on a-posteriori error estimators is imperative. Only the recent development of efficient preconditioning methods permits a systematic investigation of 3D radiation fields in Lyα halos with large column densities of the neutral hydrogen.

21. **A New Photon-Conserving Method for Transferring Ionizing Radiation**

Garrelt Mellema, Ilian T. Iliev, Marcelo Alvarez and Paul R. Shapiro

We give an overview of the capabilities of our new numerical method for transferring ionizing radiation on grids. We will illustrate its photon-conserving character, its behaviour in one and three spatial dimensions, the coupling to hydrodynamics, and how it can be used to study the problem of reionization.

22. **Growth of Linear Perturbations before the Era of the First Galaxies**

Smadar Naoz Rennan Barkana

We calculate the evolution of linear density and temperature perturbations in a universe with dark matter, baryons, and radiation, from cosmic recombination until the epoch of the first galaxies. In addition to gravity, the perturbations are affected by electron scattering with the radiation and by

gas pressure. We include the effect of spatial fluctuations in the baryonic sound speed and show that they induce around a 10small scales, and a larger change on all scales in the power spectrum of gas temperature fluctuations. We use these results to predict the modified mass function of halos at high redshift.

23. **Hybrid Characteristics: 3D radiative transfer for parallelized AMR hydrodynamics codes**

E.J. Rijkhorst, A. Dubey, T. Plewa, G. Mellema

We have created a new characteristics based radiative transfer method, called *Hybrid Characteristics*, which can handle multiple sources of ionizing radiation on an AMR hierarchy of grids. The algorithm is designed such that it runs effectively on a distributed memory type of parallel machine. It is fully integrated with the FLASH AMR hydrodynamics package and uses the DORIC routines to calculate the ionization. The parallel and AMR features of our hybrid characteristics method enable us to perform radiation hydrodynamical simulations in 3D at a very high resolution. Astrophysical applications range from photo-evaporative flows to calculations of dynamical Strmgren regions, and re-ionization computations for cosmological density fields.

24. **Probing the Warm-Hot IGM with Constellation-X and XEUS**

Bassem Sabra, Chadia Kanaan

It is generally agreed that an appreciable fraction of the baryons in the universe are locked up in a hot, ionized phase of the intergalactic medium (IGM). This IGM component is known as the warm-hot IGM or the WHIM. Future X-ray telescopes will allow to probe the WHIM in more detail. The aim of the present study is to characterize the limits and capabilities of future X-ray telescopes such as Constellation-X and XEUS in revealing the properties of the WHIM. We will present results of X-ray simulations of the effect of WHIM absorption on quasar spectra as "observed" with Constellation-X and XEUS.

25. **Location, Location, Location: Properties of 5 Submm Galaxies within 1 Arcmin of a Spectroscopically Confirmed Lyman-alpha Emitter at** $z \sim 6.5$

Kim-Vy Tran, Tracy Webb, Kentaro Motohara

From very deep 850 micron imaging with SCUBA, we have identified 5 submillimeter galaxies (SMGs) within 1 arcminute of the spectroscopically confirmed $z \sim 6.5$ Lyman-alpha emitter

SDF-1 (Kodaira et al.). The highly clustered nature of the SMGs indicate they lie in a protocluster environment, and the possibility that the SMGs are at $z \sim 6.5$ is particularly intriguing. We present first results from our multi-wavelength study of this unusual system and describe our ongoing program to obtain deep submm imaging of known $z \sim 6.5$ LAEs in the Subaru Deep Field.

26. **Primordial star formation triggered by UV photons from decaying particles**

Evgenii Vasiliev, Yuri Shchekinov

The presence of decaying particles in the universe in the pre-ionization epoch enhances significantly H_2 kinetics in virialized halos. It results in more efficient radiative cooling and decreases the lower mass limit of the first star-forming systems. Consequently, the fraction of baryons contained in the first luminous objects and their contribution to the reionization of the universe can significantly increase in comparison with the standard scenario.

27. **The UKIDSS LAS search for $z > 6.4$ quasars, to explore the epoch of reionisation**

Steve Weatherley, Steve Warren, Paul Hewett, Sandy Leggett

The UKIRT Infrared Deep Sky Survey (UKIDSS) commenced in April, and will use 1000 nights of UKIRT time over 7 years to undertake a set of surveys that overall will detect 100 times a many photons as 2MASS. The Large Area Survey element will cover 4000 sq degs within the SDSS footprint, in YJHK to $K = 18.4$ (Vega 5 sigma). One of the main goals is to extend the successful SDSS searches for very high-redshift quasars to beyond z=6.4 to explore the epoch of reionisation.

We provide details of the timetable for the observations, and estimated numbers of $z > 6.4$ quasars. We also present simulated colours with realistic surface densities of cool stars, and realistic photometric errors, in order to estimate the contamination and completeness of quasar samples. We aim to present some preliminary survey data by the time of the conference.

28. **Simulation of reionization observables**

Oliver Zahn

Arcminute cmb measurements and 21 cm experiments promise to constrain the morphology of first ionized regions and inform us about the underlying physics. Besides experimental challenges the usefulness of these observables will depend on the accuracy of their theoretical modelling.

29. **LOFAR as a Probe of the Sources of Cosmological Reionisation**

S. Zaroubi & J. Silk

We propose use of the thickness of the ionisation front as a discriminant between alternative modes of reionisation in the early universe, by stars or by miniquasars. Assuming a photoionisation-recombination balance, we find that for miniquasar sources the transition from neutral to ionised intergalactic medium is extended and has two features. The first is a sudden steep increase in the neutral fraction with a typical width of $5-10$ comoving megaparsecs, depending on the miniquasar power. The second feature is a long wing that represents a much slower transition from neutral fraction of ≈ 0.8 to 1. The angular resolution of LOFAR is expected to resolve these scales and will, therefore, play an important role in discriminating the hard sources of ionising photons from the stellar ones.

List of Participants

- **Tom Abel**
  KIPAC/Stanford
  2575 Sand Hill Road, MS29
  Menlo Park,
  United States
  Hi@TomAbel.com
- **Nabila Aghanim**
  Institut d'Astrophysique Spatiale
  Batiment 121, Universite Paris Sud
  91405 Orsay,
  France
  aghanim@ias.fr
- **Marcelo Alvarez**
  University of Texas at Austin
  1 University Station, C1400
  78712 Austin,
  USA
  marcelo@astro.as.utexas.edu
- **Alexandre Amblard**
  University of California, Berkeley
  601 Campbell Hall
  CA 94720 Berkeley,
  USA
  amblard@astro.berkeley.edu
- **Daniel Babich**
  Harvard University
  17 Oxford St.
  02138 Cambridge, MA,
  USA
  babich@fas.harvard.edu
- **Rennan Barkana**
  Tel Aviv University
  School of Physics and Astronomy
  69978 Tel Aviv,
  Israel
  barkana@wise.tau.ac.il
- **Matteo Barnabé**
  Kapteyn Astronomical Institute
  Postbus 800
  9700AV Groningen,
  The Netherlands
  M.Barnabe@astro.rug.nl
- **Rachel Bean**
  Princeton University
  Peyton Hall, Ivy Lane, NJ
  08544 Princeton,
  USA
  rbean@astro.princeton.edu
- **Milan Bogosavljevic**
  California Institute of Technology
  1200 East California Blvd
  91125 Pasadena,
  United States of America
  milan@astro.caltech.edu
- **James Stewart Bolton**
  Institute of Astronomy
  Madingely Road
  CB3 0HA Cambridge,
  UK
  jsb@ast.cam.ac.uk
- **Silvia Bonoli**
  University of Toronto
  60 St. George street Rm. 1403
  M5S3H8 Toronto,
  Canada
  bonoli@astro.utoronto.ca
- **Rychard Bouwens**
  Univeristy of California, Santa Cruz
  1156 High Street
  95060 Santa Cruz,
  United States of America
  bouwens@ucolick.org
- **Malcolm Bremer**
  University of Bristol
  Tyndall Avenue
  BS8 1TL Bristol,
  UK
  m.bremer@bristol.ac.uk
- **Michiel Brentjens**
  Kapteyn Institute / ASTRON
  Landleven 12
  9747AD Groningen,
  The Netherlands
  m.a.brentjens@astro.rug.nl
- **Frank Briggs**
  ANU/ATNF
  Mount Stromlo Observatory, Cotter Road
  2611 Weston Creek, ACT,
  Australia
  fbriggs@mso.anu.edu.au
- **Elias Brinks**
  Centre for Astrophysics Research
  School of Physics & Astronomy, Universiy of Hertfordshire, College Lane
  AL10 9AB Hatfield,
  United Kingdom
  ebrinks@star.herts.ac.uk
- **Willem N Brouw**
  Kapteyn
  Postbus 800
  9700AV Groningen,
  Netherlands
  Wim.Brouw@csiro.au

- **Ger de Bruyn**
  Kapteyn Institute & ASTRON
  Postbus 800
  9700 AV Groningen,
  The Netherlands
  ger@astron.nl
- **Andrew Bunker**
  University of Exeter
  School of Physics, Stocker Road
  EX44QL Exeter,
  United Kingdom
  bunker@astro.ex.ac.uk
- **Sebastiano Cantalupo**
  ETH Zurich
  Institute for Astronomy, ETH-Honggerbeg, HPF C9
  CH8093 Zurich,
  Switzerland
  cantalupo@phys.ethz.ch
- **Tzu-Ching Chang**
  UC Berkeley
  Astronomy Dept, 601 Campbell Hall, UC Berkeley UC Berkeley
  94720 Berkeley,
  USA
  tchang@astro.berkeley.edu
- **Tirthankar Roy Choudhury**
  SISSA - ISAS
  Via Beirut 2-4
  34014 Trieste,
  Italy
  chou@sissa.it
- **Leonid Chuzhoy**
  University of Texas at Austin
  Astronomy Dept., University of Texas, RLM 16.206
  78712 Austin, TX,
  USA
  chuzhoy@astro.as.utexas.edu
- **Benedetta Ciardi**
  Max Planck Institute for Astrophysics
  Karl-Schwarzschild-Str. 1
  85741 Garching,
  Germany
  ciardi@mpa-garching.mpg.de
- **Romeel Dave**
  Arizona
  933 N Cherry Ave
  95721 Tucson, AZ,
  USA
  rad@as.arizona.edu
- **Jeremy Davey**
  Imperial College
  Blackett Laboratory, Prince Consort Road
  SW7 2BW London,
  UK
  jdavey@imperial.ac.uk
- **Mark Dijkstra**
  Columbia University
  550 West 120th Street, Room 1328, Mailcode 5246
  10027 New York,
  U.S.A
  mark@astro.columbia.edu
- **Laura Douglas**
  University of Bristol
  H.H.Wills Physics Laboratory, University of Bristol, Tyndall Avenue
  BS8 1TL Bristol,
  UK
  L.Douglas@bristol.ac.uk
- **Marian Douspis**
  LATT - OMP
  14, avenue E. Belin
  F-31400 Toulouse,
  France
  douspis@ast.obs-mip.fr
- **Laurence P. Eyles**
  School of Physics, University of Exeter
  Stocker Road
  EX4 4QL Exeter,
  United Kingdom
  eyles@astro.ex.ac.uk
- **Heino Falcke**
  ASTRON
  P.O. Box 2
  7990 AA Dwingeloo,
  The Netherlands
  falcke@astron.nl
- **Cora Fechner**
  Hamburger Sternwarte
  Gojenbergsweg 112
  21029 Hamburg
  Germany
  cfechner@hs.uni-hamburg.de
- **Andrea Ferrara**
  SISSA/International School for Advanced Studies
  Via Beirut, 4
  34014 Trieste,
  Italy
  ferrara@sissa.it
- **Philippe Filliatre**
  Astroparticule et Cosmologie - CEA, Service d'Astrophysique
  Service d'Astrophysique, CE-Saclay, Orme des Merisiers, Batiment 709
  F-91191 Gif sur Yvette,
  France
  filliatr@cea.fr
- **Doug Finkbeiner**
  Princeton University
  Peyton Hall - Ivy Lane
  08544-1001 Princeton, NJ,
  USA
  dfink@astro.princeton.edu

- **Steven Furlanetto**
  Caltech
  Mail Code 130-33 California Institute of Technology
  91125 Pasadena,
  United States
  sfurlane@tapir.caltech.edu
- **Simona Gallerani**
  ISAS(International School of Advanced Studies)
  via Beirut 2-4
  34014 Trieste,
  Trieste
  galleran@sissa.it
- **Brad Gibson**
  Swinburne University
  Centre for Astrophysics & Supercomputing
  3128 Hawthorn,
  Australia
  bgibson@swin.edu.au
- **Stuart P.D. Gill**
  Columbia University
  Mail # H39, PO Box 218, Hawthorn
  3122 Melbourne,
  Australia
  sgill@astro.swin.edu.au
- **Liron Gleser**
  Technion - Israel Institute of Technology
  Physics Department, Technion city
  32000 Haifa,
  Israel
  lirong@techunix.technion.ac.il
- **Simon Glover**
  American Museum of Natural History
  Central Park West at 79th Street
  10024 New York,
  USA
  scog@amnh.org
- **Christian Alexander Graf**
  ITA
  Albert-Ueberle-Str. 2
  69120 Heidelberg,
  Germany
  graf@ita.uni-heidelberg.de
- **Lincoln Greenhill**
  Harvard-Smithsonian CfA
  Center for Astrophysics, 60 Garden St, Mail Stop 42
  02138 Cambridge,
  United States
  greenhill@cfa.harvard.edu
- **Michiel van Haarlem**
  ASTRON
  P.O. Box 2
  7990 AA Dwingeloo,
  Netherlands
  haarlem@astron.nl
- **Martin Gerhard Haehnelt**
  Institute of Astronomy
  Madingley Road
  CB3 0HA Cambridge,
  UK
  haehnelt@ast.cam.ac.uk
- **Peter John Dr Hall**
  International SKA Project Office
  C/- CSIRO (ATNF), PO Box 76
  1710 Epping,
  Australia
  hall@skatelescope.org
- **Marijke Haverkorn**
  Harvard University
  60 Garden Street MS-67
  02138 Cambridge,
  USA
  mhaverkorn@cfa.harvard.edu
- **Jacqueline Hewitt**
  MIT Kavli Institute for Astrophysics and Space Research
  Room 37-241
  02139 Cambridge, MA,
  USA
  jhewitt@mit.edu
- **Kumiko Hiroi**
  Center for Computational Sciences, University of Tsukuba
  1-1-1 Tennoudai
  305-8577 Tsukuba,
  Japan
  hiroi@rccp.tsukuba.ac.jp
- **Ilian T Iliev**
  CITA
  CITA, McLennan Labs, 60 St. George Street, University of Toronto, Toronto, Ontario
  M5S 3H8 Toronto,
  Canada
  Iliev@cita.utoronto.ca
- **Akio Inoue**
  Osaka Sangyo University
  3-1-1, Nakagaito
  574-8530 Daito,
  Japan
  akinoue@las.osaka-sandai.ac.jp
- **Chris Johnston**
  Melbourne University
  Parkville
  3010 Melbourne,
  Australia
  cjohnsto@ph.unimelb.edu.au
- **Nissim Kanekar**
  NRAO
  1008 Lopezville Road
  87801 Socorro, New Mexico,
  USA
  nkanekar@aoc.nrao.edu
- **Peter Katgert**
  Leiden Observatory
  P.O. Box 9513
  2300RA Leiden,
  Netherlands
  katgert@strw.leidenuniv.nl

- **Hennie Zondervan-Kimsma**
  Kapteyn Astronomical Institute
  Landleven 12
  9747 AD Groningen,
  the Netherlands
  h.zondervan@astro.rug.nl
- **L.V.E. Koopmans**
  Kapteyn Astronomical Institute
  P.O. Box 800
  9700AV Groningen,
  the Netherlands
  koopmans@astro.rug.nl
- **Katarina Kovac**
  Kapteyn Astronomical Institute
  P.O.Box 800
  9700AV Groningen,
  The Netherlands
  kovac@astro.rug.nl
- **Mathieu Langer**
  Astrophysics - Oxford University
  Keble Road
  OX1 3RH Oxford,
  United Kingdom
  mlanger@astro.ox.ac.uk
- **Adam Lidz**
  Harvard-Smithsonian Center for Astrophysics
  888 Massachusetts Avenue, Apt. 414
  02139 Cambridge,
  United States
  alidz@cfa.harvard.edu
- **Abraham Loeb**
  Harvard University
  CfA, MS 51, 60 Garden Street
  02138 Cambridge, MA,
  USA
  aloeb@cfa.harvard.edu
- **Colin Lonsdale**
  MIT Haystack Observatory
  Off route 40
  01886 Westford, MA,
  USA
  cjl@haystack.mit.edu
- **Tingting Lu**
  Univerisity of Toronto
  60 St. George street, Univeristy of Toronto
  M5S 3H8 Toronto,
  Canada
  ttlu@cita.utoronto.ca
- **Katherine Mack**
  Princeton University
  Peyton Hall - Ivy Lane
  08544 Princeton, NJ,
  USA
  mack@astro.princeton.edu
- **Piero Madau**
  University of California Santa Cruz
  1156 High Street
  95064 Santa Cruz,
  USA
  pmadau@ucolick.org
- **Manuela Magliocchetti**
  S.I.S.S.A.
  Via Beirut 2-4
  34100 Trieste,
  Italy
  maglio@sissa.it
- **Michela Mapelli**
  SISSA/ISAS
  Via Beirut 4
  34014 Trieste,
  Italy
  mapelli@sissa.it
- **Gerard Massacrier**
  Centre de Recherche Astronomique de Lyon
  ENS Lyon, 46 Allee d'Italie
  69007 Lyon,
  France
  gerard.massacrier@ens-lyon.fr
- **Avery Meiksin**
  Institute for Astronomy, University of Edinburgh
  Blackford Hill
  EH9 3HJ Edinburgh,
  United Kingdom
  A.Meiksin@roe.ac.uk
- **Erik Meinkoehn**
  Institute for Theoretical Astrophysics
  Albert-Ueberle-Strae 2
  69120 Heidelberg,
  Germany
  erik.meinkoehn@iwr.uni-heidelberg.de
- **Garrelt Mellema**
  ASTRON
  P.O. Box 2
  7990 AA Dwingeloo,
  The Netherlands
  gmellema@astron.nl
- **Brice Menard**
  Institute for Advanced Study
  Einstein Drive
  NJ 08540 Princeton,
  USA
  menard@ias.edu
- **Andrei Mesinger**
  Columbia University
  550 West 120th Street
  10027 New York,
  United States
  mesinger@astro.columbia.edu
- **George Miley**
  Sterrewacht Leiden
  Postbus 9513
  2300RA Leiden,
  NL
  miley@strw.leidenuniv.nl
- **Miguel Morales**
  MIT
  77 Massachusetts Ave., Building 37-664H
  02139 Cambridge,
  United States
  mmorales@space.mit.edu

- **Jan Muecket**
  Astrophysikalisches Institut Potsdam
  An der Sternwarte 16
  14482 Potsdam,
  Germany
  jpmuecket@aip.de
- **Volker Mueller**
  Astrophysical Institute Potsdam
  An der Sternwarte 16
  14482 Potsdam,
  Germany
  vmueller@aip.de
- **Smadar Naoz**
  Tel Aviv University School of Physics and Astronomy
  Tel Aviv, 69978, ISRAEL
  69978 Tel Aviv,
  Israel
  smadar@wise1.tau.ac.il
- **Ramona Nuez Lopez**
  Instituto de Astronomia, UNAM
  Circuito de la Investigacion Cientifica
  04510 Mexico, D.F.,
  Mexico
  ramona@astroscu.unam.mx
- **adi Nusser**
  Technion- Haifa
  Technion
  32000 Haifa,
  Israel
  adi@physics.technion.ac.il
- **Peng Oh**
  University of California, Santa Barbara
  Dept of Physics, University of California, Santa Barbara, CA 93106
  93106 Santa Barbara,
  USA
  peng@physics.ucsb.edu
- **Dore Olivier**
  Princeton University
  Dpt of Astrophysical Sciences / Peyton Hall / Princeton University
  08540 Princeton,
  USA
  olivier@astro.princeton.edu
- **Andreas Pawlik**
  Leiden Observatory
  PO Box 9513
  2300 RA Leiden,
  Netherlands
  Germany
  pawlik@strw.leidenuniv.nl
- **Ue-Li Pen**
  CITA
  60 St George St
  m5s3h8 toronto,
  canada
  pen@cita.utoronto.ca
- **Jeffrey Peterson**
  Dept. of Physics, Carnegie Mellon University
  5000 Forbes Ave
  15213 Pittsburgh, PA,
  Usa
  jbp@cmu.edu
- **Cristiano Porciani**
  ETH Zurich
  Institute for Astronomy, ETH Honggerberg HPF G3.1
  CH8093 Zurich,
  Switzerland
  porciani@phys.ethz.ch
- **Jonathan Pritchard**
  Caltech
  1200 E. California Blvd, MC 103-33
  CA 91125 Pasadena,
  United States
  jp@tapir.caltech.edu
- **Michael Rauch**
  Observatories of the Carnegie Institution of Washington
  813 Santa Barbara Street
  91001 Pasadena,
  USA
  mr@ociw.edu
- **Darren Reed**
  Institute of Computational Cosmology, Durham University
  Science Laboratories, South Road
  DH1 3LE Durham,
  United Kingdom
  Darren Reed <d.s.reed@durham.ac.uk>
- **Martin Rees**
  Institute of Astronomy
  Madingley Road
  CB3 0HA Cambridge,
  England
  mjr@ast.cam.ac.uk
- **James Rhoads**
  Space Telescope Science Institute
  3700 San Martin Drive
  MD 21218 Baltimore,
  U.S.A.
  rhoads@stsci.edu
- **Kirsty Joy Rhook**
  Institute of Astronomy, University of Cambridge
  Madingley Road
  CB3 OHA Cambridge,
  United Kingdom
  krhook@ast.cam.ac.uk
- **Massimo Ricotti**
  University of Maryland College Park
  Dept. of Astronomy, campus box 2421
  20742 College Park,
  USA
  ricotti@astro.umd.edu

- **Mattia Righi**
  Max Planck Institut fuer Astrophysik
  Karl Schwarzschild Str. 1
  D-85748 Garching,
  Germany
  righi@mpa-garching.mpg.de

- **Erik-Jan Rijkhorst**
  Steerewacht Leiden
  P.O. Box 9513
  2300 RA Leiden,
  The Netherlands
  rijkhors@strw.leidenuniv.nl

- **Emanuele Ripamonti**
  University of Groningen
  Postbus 800
  9700 AV Groningen,
  The Netherlands
  ripa@astro.rug.nl

- **Jelle Ritzerveld**
  Leiden Observatory
  Niels Bohrweg 2
  2333 CA Leiden,
  The Netherlands
  ritzervj@strw.leidenuniv.nl

- **Huub Rottgering**
  Sterrewacht Leiden
  P.O. Box 9513
  2300 RA Leiden,
  The Netherlands
  rottgeri@strw.leidenuniv.nl

- **Bassem Sabra**
  Notre Dame University
  Department of Sciences
  72 Zouk Mikael, Zouk Mosbeh,
  Lebanon
  bsabra@ndu.edu.lb

- **Renzo Sancisi**
  Bologna Observatory & Kapteyn Institute
  Via Ranzani, 1
  40127 Bologna,
  Italy
  sancisi@astro.rug.nl

- **Robert Sanders**
  Kapteyn Institute
  PO Box 800
  9700 AV Groningen,
  Nederland
  sanders@astro.rug.nl

- **Mario G. Santos**
  CENTRA - IST
  Departamento de Fisica, Instituto Superior Tecnico, Av. Rovisco Pais 1
  1049-001 Lisbon,
  Portugal
  mgrsantos@ist.utl.pt

- **Wallace Sargent**
  California Institute of Technology
  Astronomy Dept. 105-24
  91125 Pasadena, CA,
  USA
  wws@astro.caltech.edu

- **Marcin Sawicki**
  UCSB
  Physics Department, University of California
  93106 Santa Barbara,
  USA
  sawicki@physics.ucsb.edu

- **Joop Schaye**
  Leiden Observatory
  PO Box 9513
  2300 RA Leiden,
  Netherlands
  schaye@strw.leidenuniv.nl

- **Richard T. Schilizzi**
  International SKA Project Office
  ASTRON, Postbus 2
  7990 AA Dwingeloo,
  Netherlands
  schilizzi@skatelescope.org

- **Raffaella Schneider**
  Centro Enrico Fermi Roma - OAArcetri
  Largo E. Fermi, 5
  50125 Firenze,
  Italy
  raffa@arcetri.astro.it

- **Benoit Semelin**
  LERMA, Observatoire de Paris
  61 av de l'observatoire
  75014 Paris,
  France
  benoit.semelin@obspm.fr

- **Paul Shapiro**
  Department of Astronomy, The University of Texas at Austin
  Dept. of Astronomy,1 University Station, C1400
  78712-0259 Austin, TX,
  USA
  shapiro@astro.as.utexas.edu

- **Peter Shaver**
  ESO
  Karl-Schwarzschild-Str. 2
  85748 Garching bei Muenchen,
  Germany
  pshaver@eso.org

- **Marco Spaans**
  Kapteyn Astronomical Institute
  P.O.Box 800
  9700 AV Groningen,
  The Netherlands
  spaans@astro.rug.nl

- **Else Starkenburg**
  Kapteyn Astronomical Institute
  Landleven 12
  9747 AD Groningen,
  the Netherlands
  else@astro.rug.nl
- **Michael Strauss**
  Princeton University
  Dept. Astrophysical Sciences, Ivy Lane
  08544 Princeton, New Jersey,
  USA
  strauss@astro.princeton.edu
- **Ravi Subrahmanyan**
  CSIRO Australia Telescope
  Locked Bag 194
  2390 Narrabri NSW,
  Australia
  Ravi.Subrahmanyan@csiro.au
- **Naoshi Sugiyama**
  National Astronomical Observatory of Japan
  Osawa, Mitaka
  181-8588 Tokyo,
  Japan
  naohsi@th.nao.ac.jp
- **Argyro Tasitsiomi**
  KICP & Dept. of Astronomy and Astrophysics, University of Chicago
  5640 S. Ellis Ave
  60637 Chicago,
  USA
  iro@oddjob.uchicago.edu
- **Johannes P. Terlouw**
  Kapteyn Astronomical Institute
  P. O. Box 800
  9700 AV Groningen,
  Netherlands
  J.P.Terlouw@astro.rug.nl
- **Tom Theuns**
  Institute for Computational Cosmology
  Durham University
  dh1 3le Durham,
  UK
  tom.theuns@durham.ac.uk
- **Rajat Mani Thomas**
  University of Groningen
  Kapetyn Astronimcal Institute, Landleven 12
  9747 Groningen,
  The Netherlands
  thomasr@mps.mpg.de
- **Eline Tolstoy**
  Kapteyn Institute
  postbus 800
  9700AV Groningen,
  NL
  etolstoy@astro.rug.nl
- **Scott Trager**
  Kapteyn Astronomical Institute
  Postbus 800
  9700 AV Groningen,
  Netherlands
  sctrager@astro.rug.nl
- **Kim-Vy Tran**
  Institute for Astronomy
  ETH Zurich
  CH-8093 Zurich,
  Switzerland
  vy@phys.ethz.ch
- **David Tytler**
  UCSD
  SERF 0424, 9500 Gilman Dr
  92093-0424 La Jolla, CA 92093-0424,
  USA
  tytler@ucsd.edu
- **Masayuki Umemura**
  University of Tsukuba
  Tennodai 1-1-1
  305-8577 Tsukuba,
  Japan
  umemura@rccp.tsukuba.ac.jp
- **Marcos Valdes**
  SISSA
  Via Beirut 2
  34014 Trieste,
  Italy
  valdes@sissa.it
- **Evgenii Vasiliev**
  Physics Department, Rostov University
  Sorge 5
  344090 Rostov on Don,
  Russia
  eugstar@mail.ru
- **Marc Verheijen**
  Kapteyn Astronomical Institute
  Landleven 12
  9747 AD Groningen,
  The Netherlands
  verheyen@astro.rug.nl
- **Corina Vogt**
  ASTRON
  Oude Hoogeveensedijk 4
  7991 PD Dwingeloo,
  Netherlands
  vogt@astron.nl
- **Mark Walker**
  Kapteyn Instituut / ASTRON
  Postbus 800
  9700 AV Groningen,
  The Netherlands
  m.walker@astro.rug.nl
- **Steve Warren**
  Imperial College
  Astrophysics, Blackett Labs, Prince Consort Rd
  SW7 2BW London,
  UK
  sjw4@imperial.ac.uk

- **Stephen Weatherley**
  Imperial College London
  Astrophysics Group, Blackett Lab, Prince Consort Road
  SW7 2BW London,
  UK
  stephen.weatherley@imperial.ac.uk
- **Yevgen Zadorin**
  NBS
  Ukraine 02232 Kiev Visockogo, 4 #38
  02232 Kiev,
  Ukraine
  evgeniyzadorin@mail.ru
- **Oliver Zahn**
  Harvard University
  60 Garden Street
  02138 Cambridge,
  USA
  ozahn@cfa.harvard.edu
- **Saleem Zaroubi**
  Kapteyn Astronomical Institute
  Landleven 12
  9747 AD Groningen,
  Netherlands
  saleem@astro.rug.nl
- **Martin Zwaan**
  European Southern Observatory
  Karl-Schwarzschild Strasse 2
  85748 Garching b Muenchen,
  Germany
  mzwaan@eso.org
- **Jackie Zwegers**
  Kapteyn Astronomical Institute
  Landleven 12
  9747 AD Groningen,
  The Netherlands
  zwegers@astro.rug.nl