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Adaptive Optics Systems

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Editors

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Contents

Part One

xxix *Conference Committee*

xxxiii *High redshift galaxy surveys (Plenary Paper) [7016-500]*
Masanori Iye, National Astronomical Observatory of Japan (Japan)

ASTRONOMICAL SCIENCE WITH ADAPTIVE OPTICS

7015 03 **Adaptive optics and extrasolar planetary systems (Invited Paper) [7015-02]**
A.-M. Lagrange, J.-L. Beuzit, G. Chauvin, D. Mouillet, Lab. d'Astrophysique de l'Observatoire de Grenoble, Univ. J. Fournier (France)

7015 07 **The science case for the Next Generation AO system at W. M. Keck Observatory [7015-06]**
C. Max, E. McGrath, D. Gavel, Univ. of California, Santa Cruz (United States); D. Le Mignant, P. Wizinowich, W. M. Keck Observatory (United States); R. Dekany, Caltech Optical Observatories, California Institute of Technology (United States)

ASTRONOMICAL SCIENCE TECHNIQUES

7015 08 **LGS AO science impact: present and future perspectives (Invited Paper) [7015-07]**
M. C. Liu, Univ. of Hawai'i (United States)

7015 0A **Precision astrometry with adaptive optics (Invited Paper) [7015-09]**
P. B. Cameron, M. C. Britton, S. R. Kulkarni, California Institute of Technology (United States)

AO DEMONSTRATORS AND FIELD TESTS

7015 0C **Laboratory demonstrations of multi-object adaptive optics in the visible on a 10 meter telescope [7015-11]**
S. M. Ammons, L. Johnson, Univ. of California, Santa Cruz (United States); E. A. Laag, Univ. of California, Riverside (United States); R. Kupke, D. T. Gavel, Univ. of California, Santa Cruz (United States)

7015 0E **CANARY: the on-sky NGS/LGS MOAO demonstrator for EAGLE [7015-13]**
R. M. Myers, Durham Univ. (United Kingdom); Z. Hubert, Observatoire de Paris à Meudon (France); T. J. Morris, Durham Univ. (United Kingdom); E. Gendron, Observatoire de Paris à Meudon (France); N. A. Dipper, Durham Univ. (United Kingdom); A. Kellerer, Observatoire de Paris à Meudon (France); S. J. Goodsell, Durham Univ. (United Kingdom); G. Rousset, Observatoire de Paris à Meudon (France); E. Younger, Durham Univ. (United Kingdom); M. Marteaud, Observatoire de Paris à Meudon (France); A. G. Basden, Durham Univ. (United Kingdom); F. Chemla, Observatoire de Paris à Meudon (France); C. D. Guzman, Durham Univ. (United Kingdom); T. Fusco, ONERA (France); D. Geng, Durham Univ. (United Kingdom); B. Le Roux, Observatoire Astronomique de Marseille-Provence (France); M. A. Harrison, Durham Univ. (United Kingdom); A. J. Longmore, UK Astronomy Technology

Ctr. (United Kingdom); L. K. Young, Durham Univ. (United Kingdom); F. Vidal, Observatoire de Paris á Meudon (France); A. H. Greenaway, Heriot-Watt Univ. (United Kingdom)

- 7015 0F **MAD on sky results in star-oriented mode** [7015-14]
E. Marchetti, R. Brast, B. Delabre, R. Donaldson, E. Fedrigo, C. Frank, N. Hubin, J. Kolb, J.-L. Lizon, M. Marchesi, S. Oberti, R. Reiss, C. Soenke, S. Tordo, European Southern Observatory (Germany); A. Baruffolo, P. Bagnara, Osservatorio Astronomico di Padova (Italy); A. Amorim, J. Lima, Univ. de Lisboa (Portugal)
- 7015 0G **Visible light laser guidestar experimental system (Villages): on-sky tests of new technologies for visible wavelength all-sky coverage adaptive optics systems** [7015-15]
D. Gavel, M. Ammons, UCO/Lick Observatory, Univ. of California Santa Cruz (United States); B. Bauman, Lawrence Livermore National Lab. (United States); D. Dillon, E. Gates, B. Grigsby, J. Johnson, C. Lockwood, K. Morzinski, UCO/Lick Observatory, Univ. of California Santa Cruz (United States); D. Palmer, Lawrence Livermore National Lab. (United States); M. Reinig, UCO/Lick Observatory, Univ. of California Santa Cruz (United States); S. Severson, Sonoma State Univ. (United States)
- 7015 0H **VOLT: the Victoria Open Loop Testbed** [7015-16]
D. R. Andersen, M. Fischer, Herzberg Institute of Astrophysics, National Research Council Canada (Canada); R. Conan, Univ. of Victoria (Canada); M. Fletcher, J.-P. Véran, Herzberg Institute of Astrophysics, National Research Council Canada (Canada)
- 7015 0I **Layer oriented: science with MAD and beyond** [7015-17]
R. Ragazzoni, Y. Almomany, C. Arcidiacono, R. Falomo, J. Farinato, M. Gullieuszik, INAF – Astronomical Observatory of Padova (Italy); E. Diolaiti, M. Lombini, INAF – Astronomical Observatory of Bologna (Italy); A. Moretti, INAF – Astronomical Observatory of Padova (Italy); G. Piotto, Univ. degli Studi di Padova (Italy); E. Marchetti, R. Donaldson, European Southern Observatory (Germany); R. Tuolla, Univ. degli Studi di Padova (Italy)

LASER TECHNOLOGY DEVELOPMENT

- 7015 0J **Laser technology for astronomical adaptive optics (Invited Paper)** [7015-18]
D. Gavel, UCO/Lick Observatory, Univ. of California, Santa Cruz (United States)
- 7015 0K **A new guide star laser using optimized injection mode-locking** [7015-19]
J. Munch, T. P. Rutten, N. Simakov, M. Hamilton, The Univ. of Adelaide (Australia); C. d'Orgeville, Gemini Observatory (Chile); P. J. Veitch, The Univ. of Adelaide (Australia)
- 7015 0L **Simple model, including recoil, for the brightness of sodium guide stars created from CW single frequency fasors and comparison to measurements** [7015-20]
P. D. Hillman, J. D. Drummond, C. A. Denman, Air Force Research Labs. (United States); R. Q. Fugate, New Mexico Institute of Mining and Technology (United States)
- 7015 0M **Calculation of returns from sodium beacons for different types of laser** [7015-21]
E. Kibblewhite, The Univ. of Chicago (United States)
- 7015 0N **20 W and 50 W guidestar laser system update for the Keck I and Gemini South telescopes** [7015-22]
I. Lee, M. Jalali, N. Vanasse, Z. Prezkuta, K. Groff, J. Roush, N. Rogers, E. Andrews, G. Moule, B. Tiemann, A. K. Hankla, Lockheed Martin Coherent Technologies (United States);

S. M. Adkins, W. M. Keck Observatory (United States); C. d'Orgeville, Gemini/AURA Inc. (Chile)

ADAPTIVE OPTICS CORRECTORS

- 7015 0O **Deformable mirror technologies for astronomy at CILAS** [7015-23]
J.-C. Siquin, J.-M. Lurçon, C. Guillemard, CILAS (France)
- 7015 0Q **Validation of a new adaptive deformable mirror concept** [7015-25]
R. Hamelinck, Technische Univ. Eindhoven (Netherlands) and TNO Science and Industry (Netherlands); R. Ellenbroek, Delft Univ. of Technology (Netherlands); N. Rosielle, TNO Science and Industry (Netherlands); M. Steinbuch, Technische Univ. Eindhoven (Netherlands); M. Verhaegen, Delft Univ. of Technology (Netherlands); N. Doelman, TNO Science and Industry (Netherlands)

ADAPTIVE OPTICS FOR ELT

- 7015 0R **Progress toward developing the TMT adaptive optical systems and their components** [7015-26]
B. Ellerbroek, TMT Observatory Corp. (United States); S. Adkins, W. M. Keck Observatory (United States); D. Andersen, J. Atwood, Herzberg Institute of Astrophysics (Canada); C. Boyer, TMT Observatory Corp. (United States); P. Byrnes, Herzberg Institute of Astrophysics (Canada); R. Conan, Univ. of Victoria (Canada); L. Gilles, TMT Observatory Corp. (United States); G. Herriot, Herzberg Institute of Astrophysics (Canada); P. Hickson, Univ. of British Columbia (Canada); E. Hileman, D. Joyce, National Optical Astronomy Observatories (United States); B. Leckie, Herzberg Institute of Astrophysics (Canada); M. Liang, National Optical Astronomy Observatories (United States); T. Pfrommer, Univ. of British Columbia (Canada); J.-C. Siquin, CILAS (France); J.-P. Veran, Herzberg Institute of Astrophysics (Canada); L. Wang, TMT Observatory Corp. (United States); P. Welle, Herzberg Institute of Astrophysics (Canada)
- 7015 0S **The field stabilization and adaptive optics mirrors for the European Extremely Large Telescope** [7015-27]
E. Vernet, L. Jochum, P. La Penna, N. Hubin, R. Muradore, European Southern Observatory (Germany); J. M. Casalta, NTE S.A. (Spain); I. Kjelberg, CSEM (Switzerland); J.-C. Siquin, F. Locre, P. Morin, R. Cousty, J.-M. Lurçon, J.-J. Roland, B. Crepy, CILAS (France); E. Gabriel, AMOS (Belgium); R. Biasi, M. Andrighettoni, G. Angerer, Microgate (Italy); D. Gallieni, M. Mantegazza, M. Tintori, A.D.S. International (Italy); E. Molinari, D. Tresoldi, G. Toso, P. Spanó, M. Riva, G. Crimi, INAF Osservatorio Astrofisico di Brera (Italy); A. Riccardi, INAF Osservatorio Astrofisico di Arcetri (Italy); G. Marque, J.-L. Carel, E. Ruch, Sagem Défense Sécurité (France)
- 7015 0T **Concept study of a multi-object AO system for the EAGLE instrument on the European ELT** [7015-28]
T. Fusco, ONERA (France) and Groupement d'Intérêt Scientifique PHASE (France); G. Rousset, LESIA, Observatoire de Paris (France) and Groupement d'Intérêt Scientifique PHASE (France); F. Assémat, ONERA (France), LESIA, Observatoire de Paris (France), and Groupement d'Intérêt Scientifique PHASE (France); B. Neichel, ONERA (France), GEPI, Observatoire de Paris (France), and Groupement d'Intérêt Scientifique PHASE (France); E. Gendron, LESIA, Observatoire de Paris (France) and Groupement d'Intérêt Scientifique

PHASE (France); R. M. Myers, T. Morris, Durham Univ. (United Kingdom); F. Chemla, GEPI, Observatoire de Paris (France) and Groupement d'Intérêt Scientifique PHASE (France); C. Robert, ONERA (France) and Groupement d'Intérêt Scientifique PHASE (France); I. Bryson, UK Astronomy Technology Ctr., Royal Observatory (United Kingdom); J. G. Cuby, Lab. d'Astrophysique de Marseille (France)

7015 0U **A preliminary overview of the multiconjugate adaptive optics module for the E-ELT** [7015-29]

E. Diolaiti, INAF-Osservatorio Astronomico di Bologna (Italy); J.-M. Conan, ONERA (France); I. Foppiani, Univ. di Bologna (Italy); M. Lombini, INAF-Osservatorio Astronomico di Bologna (Italy); C. Petit, C. Robert, ONERA (France); L. Schreiber, Univ. di Bologna (Italy); P. Ciliegi, INAF-Osservatorio Astronomico di Bologna (Italy); E. Marchetti, European Southern Observatory (Germany); M. Bellazzini, INAF-Osservatorio Astronomico di Bologna (Italy); L. Busoni, S. Esposito, INAF – Osservatorio Astrofisico di Arcetri (Italy); T. Fusco, ONERA (France); N. Hubin, European Southern Observatory (Germany); F. Quiros-Pacheco, INAF – Osservatorio Astrofisico di Arcetri (Italy); A. Baruffolo, INAF – Osservatorio Astronomico di Padova (Italy); S. D'Odorico, European Southern Observatory (Germany); J. Farinato, INAF – Osservatorio Astronomico di Padova (Italy); B. Neichel, ONERA (France); R. Ragazzoni, C. Arcidiacono, INAF – Osservatorio Astronomico di Padova (Italy); V. Biliotti, INAF – Osservatorio Astrofisico di Arcetri (Italy); G. Bregoli, INAF-Osservatorio Astronomico di Bologna (Italy); G. Cosentino, Univ. di Bologna (Italy); G. Innocenti, INAF-Osservatorio Astronomico di Bologna (Italy)

MEDIUM FOV ADAPTIVE OPTICS (0.5-3')

7015 0X **GeMS: Gemini Mcao System: current status and commissioning plans** [7015-32]

M. Boccas, F. Rigaut, D. Gratadour, C. d'Orgeville, M. Bec, F. Daruich, G. Perez, G. Arriagada, Gemini Observatory (Chile); S. Bombino, C. Carter, C. Cavedoni, Gemini Observatory (United States); F. Collao, P. Collins, P. Diaz, Gemini Observatory (Chile); A. Ebbers, Gemini Observatory (United States); R. Galvez, G. Gausachs, Gemini Observatory (Chile); S. Hardash, E. James, S. Karewicz, Gemini Observatory (United States); M. Lazo, D. Maltes, R. Mouser, R. Rogers, R. Rojas, Gemini Observatory (Chile); M. Sheehan, Gemini Observatory (United States); G. Trancho, V. Vergara, T. Vucina, Gemini Observatory (Chile)

AO PROGRAMS AND FACILITIES FOR LARGE TELESCOPES

7015 0Y **The Magellan Telescope adaptive secondary AO system** [7015-33]

L. M. Close, V. Gasho, D. Kopon, P. M. Hinz, W. F. Hoffmann, CAAO, Steward Observatory, The Univ. of Arizona (United States); A. Uomoto, T. Hare, OCIW (United States)

7015 0Z **The PALM-3000 high-order adaptive optics system for Palomar Observatory** [7015-34]

A. H. Bouchez, R. G. Dekany, California Institute of Technology (United States); J. R. Angione, Jet Propulsion Lab. (United States); C. Baranec, M. C. Britton, K. Bui, Caltech Optical Observatories, California Institute of Technology (United States); R. S. Burruss, Jet Propulsion Lab. (United States); J. L. Cromer, California Institute of Technology (United States); S. R. Guiwits, Jet Propulsion Lab. (United States); J. R. Henning, J. Hickey, D. L. McKenna, Palomar Observatory (United States); A. M. Moore, California Institute of Technology (United States); J. E. Roberts, T. Q. Trinh, M. Troy, T. N. Truong, Jet Propulsion Lab. (United States); V. Velur, Caltech Optical Observatories, California Institute of Technology

(United States)

- 7015 10 **Current status of the laser guide star adaptive optic system for Subaru Telescope** [7015-35]
Y. Hayano, H. Takami, O. Guyon, S. Oya, M. Hattori, Y. Saito, M. Watanabe, National Astronomical Observatory of Japan/Subaru Telescope (United States); N. Murakami, National Astronomical Observatory of Japan (Japan); Y. Minowa, M. Ito, S. Colley, M. Eldred, T. Golota, M. Dinkins, National Astronomical Observatory of Japan/Subaru Telescope (United States); N. Kashikawa, M. Iye, National Astronomical Observatory of Japan (Japan)
- 7015 11 **W. M. Keck Observatory's next-generation adaptive optics facility** [7015-36]
P. Wizinowich, W.M. Keck Observatory (United States); R. Dekany, Caltech Optical Observatories, California Institute of Technology (United States); D. Gavel, C. Max, Univ. of California Observatory (United States); S. Adkins, W.M. Keck Observatory (United States); B. Bauman, Univ. of California Observatory (United States); J. Bell, W.M. Keck Observatory (United States); A. Bouchez, M. Britton, Caltech Optical Observatories, California Institute of Technology (United States); J. Chin, R. Flicker, E. Johansson, W.M. Keck Observatory (United States); R. Kupke, Univ. of California Observatory (United States); D. Le Mignant, W.M. Keck Observatory (United States); C. Lockwood, Univ. of California Observatory (United States); D. Medeiros, W.M. Keck Observatory (United States); E. McGrath, Univ. of California Observatory (United States); A. Moore, Caltech Optical Observatories, California Institute of Technology (United States); C. Neyman, W.M. Keck Observatory (United States); M. Reinig, Univ. of California Observatory (United States); V. Velur, Caltech Optical Observatories, California Institute of Technology (United States)
- 7015 12 **The adaptive secondary mirror for the Large Binocular Telescope: results of acceptance laboratory test** [7015-37]
A. Riccardi, M. Xompero, D. Zanotti, L. Busoni, C. Del Vecchio, P. Salinari, P. Ranfagni, Osservatorio Astrofisico di Arcetri (Italy); G. Brusa Zappellini, Large Binocular Telescope Observatory, Univ. of Arizona (United States); R. Biasi, M. Andrighttoni, Microgate s.r.l. (Italy); D. Gallieni, E. Anaclerio, A.D.S. International s.r.l. (Italy); H. M. Martin, S. M. Miller, Steward Observatory, Univ. of Arizona (United States)

LASER GUIDE STAR FACILITIES

- 7015 15 **The laser guide star program for the LBT** [7015-40]
S. Rabien, N. Ageorges, Max Planck Institut für extraterrestrische Physik (Germany); R. Angel, Steward Observatory, Univ. of Arizona (United States); G. Brusa, J. Brynnel, Large Binocular Telescope Observatory (United States); L. Busoni, Osservatorio Astrofisico di Arcetri (Italy);
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Stalcup, Steward Observatory, Univ. of Arizona (United States); J. Storm, Astrophysikalisches Institut Potsdam (Germany); L. Strüder, Max Planck Institut Semiconductor Lab. (Germany); M. Thiel, Max Planck Institut für extraterrestrische Physik (Germany); G. Weigelt, Max Planck Institut für Radioastronomie (Germany); J. Ziegler, Max Planck Institut für extraterrestrische Physik (Germany)

7015 16 **CAMERA: a compact, automated, laser adaptive optics system for small aperture telescopes** [7015-41]

M. Britton, V. Velur, N. Law, California Institute of Technology (United States); P. Choi, B. E. Penprase, Pomona College (United States)

7015 17 **ELP-OA : status report of the setup of the demonstrator of the polychromatic laser guide star at Observatoire de Haute Provence** [7015-42]

R. Foy, Univ. de Lyon (France) and Observatoire de Haute-Provence (France); P.-É. Blanc, Observatoire de Haute-Provence (France); T. Fusco, ONERA (France); A. Laloge, A. Le Van Suu, S. Perruchot, Observatoire de Haute-Provence (France); A. Petit, DEN/DANS/DPC, Commissariat à l'Energie Atomique Saclay (France); P. Richaud, Observatoire de Haute-Provence (France); M. Tallon, É. Thiébaud, Univ. de Lyon (France); M. Boër, Observatoire de Haute-Provence (France)

ADAPTIVE OPTICS FED INSTRUMENTATION AND HIGH CONTRAST IMAGING II

7015 18 **The Gemini Planet Imager: from science to design to construction** [7015-43]

B. A. Macintosh, NSF Ctr. for Adaptive Optics (United States) and Lawrence Livermore National Lab. (United States); J. R. Graham, NSF Ctr. for Adaptive Optics (United States) and Univ. of California, Berkeley (United States); D. W. Palmer, NSF Ctr. for Adaptive Optics (United States) and Lawrence Livermore National Lab. (United States); R. Doyon, Univ. de Montréal (Canada); J. Dunn, Herzberg Institute of Astrophysics (Canada); D. T. Gavel, NSF Ctr. for Adaptive Optics (United States) and Univ. of California, Santa Cruz (United States); J. Larkin, NSF Ctr. for Adaptive Optics (United States) and Univ. of California, Los Angeles (United States); B. Oppenheimer, American Museum of Natural History (United States); L. Saddlemyer, Herzberg Institute of Astrophysics (Canada); A. Sivaramakrishnan, NSF Ctr. for Adaptive Optics (United States) and American Museum of Natural History (United States); J. K. Wallace, NSF Ctr. for Adaptive Optics (United States) and Jet Propulsion Lab. (United States); B. Bauman, NSF Ctr. for Adaptive Optics (United States) and Lawrence Livermore National Lab. (United States); D. A. Erickson, Herzberg Institute of Astrophysics (Canada); C. Marois, NSF Ctr. for Adaptive Optics (United States), Lawrence Livermore National Lab. (United States), and Herzberg Institute of Astrophysics (Canada); L. A. Poyneer, NSF Ctr. for Adaptive Optics (United States) and Lawrence Livermore National Lab. (United States); R. Soummer, NSF Ctr. for Adaptive Optics (United States) and American Museum of Natural History (United States)

7015 19 **A new integral field spectrograph for exoplanetary science at Palomar** [7015-44]

S. Hinkley, Columbia Univ. (United States) and American Museum of Natural History (United States); B. R. Oppenheimer, D. Brenner, American Museum of Natural History (United States); I. R. Parry, Institute of Astronomy, Univ. of Cambridge (United Kingdom); A. Sivaramakrishnan, R. Soummer, American Museum of Natural History (United States); D. King, Institute of Astronomy, Univ. of Cambridge (United Kingdom)

- 7015 1A **High-contrast imaging with Keck adaptive optics and OSIRIS** [7015-45]
M. McElwain, Princeton Univ. (United States); J. Larkin, S. Metchev, B. Zuckerman, Univ. of California, Los Angeles (United States)
- 7015 1B **Prototyping coronagraphs for exoplanet characterization with SPHERE** [7015-46]
A. Boccaletti, LESIA, Observatoire de Paris (France); L. Abe, FIZEAU, Univ. de Nice-Sophia Antipolis (France); J. Baudrand, LESIA, Observatoire de Paris (France); J.-B. Daban, R. Douet, G. Guerri, S. Robbe-Dubois, P. Bendjoya, FIZEAU, Univ. de Nice-Sophia Antipolis (France); K. Dohlen, LAM, Observatoire de Marseille-Provence (France); D. Mawet, Jet Propulsion Lab. (United States)

REAL TIME CONTROL AND ALGORITHMS

- 7015 1D **The SPHERE XAO system: design and performance** [7015-48]
C. Petit, T. Fusco, ONERA (France); J. Charton, LAOG, Observatoire de Grenoble (France); D. Mouillet, Observatoire Midi-Pyrénées (France); P. Rabou, LAOG, Observatoire de Grenoble (France); T. Buey, G. Rousset, LESIA, Observatoire de Paris (France); J.-F. Sauvage, ONERA (France); P. Baudoz, P. Gigan, LESIA, Observatoire de Paris (France); M. Kasper, E. Fedrigo, N. Hubin, European Southern Observatory (Germany); P. Feautrier, J.-L. Beuzit, LAOG, Observatoire de Grenoble (France); P. Puget, LESIA, Observatoire de Paris (France)
- 7015 1E **Toward feasible and effective predictive wavefront control for adaptive optics** [7015-49]
L. A. Poyneer, Lawrence Livermore National Lab. (United States); J.-P. Véran, Herzberg Institute of Astrophysics (Canada)
- 7015 1F **Globally optimal minimum-variance control in adaptive optical systems with mirror dynamics** [7015-50]
C. Correia, ONERA (France); H.-F. Raynaud, C. Kulcsár, Lab. de Traitement et de Transport de l'Information, Univ. Paris XIII (France); J.-M. Conan, ONERA (France)
- 7015 1G **Minimum variance control in presence of actuator saturation in adaptive optics** [7015-51]
C. Kulcsár, H.-F. Raynaud, Lab. de Traitement et de Transport de l'Information, Univ. Paris XIII (France); C. Petit, J.-M. Conan, ONERA (France)
- 7015 1H **Performances of the fractal iterative method with an internal model control law on the ESO end-to-end ELT adaptive optics simulator** [7015-52]
C. Béchet, Univ. de Lyon (France), Univ. Lyon 1 (France), CNRS, UMR 5574, Ctr. de Recherche Astrophysique de Lyon (France), and Ecole Normale Supérieure de Lyon (France); M. Le Louarn, European Southern Observatory (Germany); M. Tallon, É. Thiébaud, Univ. de Lyon (France), Univ. Lyon 1 (France), CNRS, UMR 5574, Ctr. de Recherche Astrophysique de Lyon (France), and Ecole Normale Supérieure de Lyon (France)

WAVEFRONT SENSING

- 7015 1K **Ultra-high-sensitivity wavefront sensing for extreme-AO** [7015-55]
O. Guyon, Subaru Telescope, National Astronomical Observatory of Japan (NAOJ) (United States)

- 7015 1M **Concept for laser guide star dynamic refocusing using rotating phase plates** [7015-57]
B. J. Bauman, Lawrence Livermore National Lab. (United States); S. Ebstein, Lexitek, Inc. (United States)
- 7015 1N **Shack-Hartmann wavefront reconstruction with elongated sodium laser guide stars: improvements with priors and noise correlations** [7015-58]
M. Tallon, I. Tallon-Bosc, C. Béchet, E. Thiébaud, Univ. de Lyon (France), Univ. Lyon 1 (France), CNRS, UMR 5574, Ctr. de Recherche Astrophysique de Lyon (France), and Ecole Normale Supérieure de Lyon (France)
- 7015 1O **An optical solution to the LGS spot elongation problem** [7015-59]
L. Schreiber, Univ. di Bologna (Italy); M. Lombini, INAF-Osservatorio Astronomico di Bologna (Italy); I. Foppiani, Univ. di Bologna (Italy); E. Diolaiti, INAF-Osservatorio Astronomico di Bologna (Italy); J.-M. Conan, ONERA, DOTA-CC (France); E. Marchetti, European Southern Observatory (Germany)
- 7015 1P **LGS wavefront sensing using adaptive beam projectors** [7015-60]
S. Esposito, L. Busoni, Osservatorio Astrofisico di Arcetri (Italy)
- 7015 1R **Detectors for AO wavefront sensing (Invited Paper)** [7015-62]
M. Downing, G. Finger, D. Baade, N. Hubin, O. Iwert, J. Kolb, European Southern Observatory (Germany)

HIGH CONTRAST IMAGING

- 7015 1S **EPICS: the exoplanet imager for the E-ELT** [7015-63]
M. E. Kasper, European Southern Observatory (Germany); J.-L. Beuzit, C. Verinaud, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); N. Yatskova, European Southern Observatory (Germany); P. Baudoz, A. Boccaletti, LESIA, Observatoire de Paris à Meudon (France); R. G. Gratton, Osservatorio Astronomico di Padova (Italy); N. Hubin, F. Kerber, European Southern Observatory (Germany); R. Roelfsema, ASTRON (Netherlands) and NOVA, Univ. Utrecht (Netherlands); H. M. Schmid, ETH Zürich (Switzerland); N. A. Thatte, Univ. of Oxford (United Kingdom); K. Dohlen, LAM (France); M. Feldt, Max-Planck-Institut für Astronomie (Germany); L. Venema, ASTRON (Netherlands); S. Wolf, Christian-Albrechts-Univ. zu Kiel (Germany)
- 7015 1T **An end-to-end polychromatic Fresnel propagation model of GPI** [7015-64]
C. Marois, Herzberg Institute of Astrophysics (Canada) and Lawrence Livermore National Lab. (United States); B. Macintosh, Lawrence Livermore National Lab. (United States); R. Soummer, American Museum of Natural History (United States); L. Poyneer, B. Bauman, Lawrence Livermore National Lab. (United States)
- 7015 1U **The SPHERE XAO system: design and performance** [7015-65]
C. Petit, T. Fusco, ONERA (France); J. Charton, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); D. Mouillet, Observatoire Midi-Pyrénées (France); P. Rabou, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); T. Buey, G. Rousset, LESIA, Observatoire de Paris (France); J.-F. Sauvage, ONERA (France); P. Baudoz, P. Gigan, LESIA, Observatoire de Paris (France); M. Kasper, E. Fedrigo, N. Hubin, European Southern Observatory (Germany); P. Feautrier, J.-L. Beuzit, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); P. Puget, LESIA, Observatoire de Paris (France)

7015 1V **Performance of the near-infrared coronagraphic imager on Gemini-South** [7015-66]
M. Chun, Institute of Astronomy, Univ. of Hawaii (United States); D. Toomey, Mauna Kea Infra-Red LLC (United States); Z. Wahhaj, B. Biller, Institute of Astronomy, Univ. of Hawaii (United States); E. Artigau, T. Hayward, Gemini Observatory (Chile); M. Liu, Institute of Astronomy, Univ. of Hawaii (United States); L. Close, Univ. of Arizona (United States); M. Hartung, F. Rigaut, Gemini Observatory (Chile); C. Ftaclas, Institute of Astronomy, Univ. of Hawaii (United States)

7015 1W **Post-coronagraphic wave-front sensing for the exo-planet imaging camera and spectrograph, EPICS for the European ELT** [7015-67]
C. Véraud, R. Mollard, P. Kern, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); R. Galicher, P. Baudoz, Lab. d'Etudes Spatiales et d'Instrumentation en Astrophysique (France) and Groupement d'Intérêt Scientifique PHASE (France); J.-L. Beuzit, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); G. Rousset, Lab. d'Etudes Spatiales et d'Instrumentation en Astrophysique (France) and Groupement d'Intérêt Scientifique PHASE (France)

AO MODELING

7015 20 **Wavefront error budget development for the Thirty Meter Telescope laser guide star adaptive optics system** [7015-71]
L. Gilles, L. Wang, B. Ellerbroek, Thirty Meter Telescope Project Office (United States)

7015 21 **Physical optics modeling and optimization of laser guide star propagation** [7015-72]
R. Holzöhner, D. Bonaccini Calia, W. Hackenberg, European Southern Observatory (Germany)

WIDE FOV AO (5-10')

7015 22 **Commissioning the MMT ground-layer and laser tomography adaptive optics systems** [7015-73]
N. M. Milton, M. Lloyd-Hart, Univ. of Arizona/Steward Observatory (United States); C. Baranec, Caltech Optical Observatories, California Institute of Technology (United States); T. Stalcup, K. Powell, D. McCarthy, C. Kulesa, K. Hege, Univ. of Arizona/Steward Observatory (United States)

7015 23 **GLAS/NAOMI: ground-layer AO at the William Herschel Telescope** [7015-74]
C. Benn, D. Abrams, T. Agocs, D. Cano, T. Gregory, J. C. Guerra, O. Martin, Isaac Newton Group (Spain); T. Morris, R. Myers, Univ. of Durham (United Kingdom); S. Rix, R. Rutten, I. Skillen, J. Skvarč, S. Tulloch, Isaac Newton Group (Spain)

7015 24 **ESO adaptive optics facility** [7015-75]
R. Arsenault, P.-Y. Madec, N. Hubin, J. Paufigue, S. Stroebele, C. Soenke, R. Donaldson, E. Fedrigo, S. Oberti, S. Tordo, M. Downing, M. Kiekebusch, R. Conzelmann, M. Duchateau, A. Jost, W. Hackenberg, D. Bonaccini Calia, B. Delabre, European Southern Observatory (Germany); R. Stuik, Univ. of Leiden (Netherlands); R. Biasi, MicroGate S.r.l. (Italy); D. Gallieni, P. Lazzarini, ADS International s.r.l. (Italy); M. Lelouarn, A. Glindeman, European Southern Observatory (Germany)

- 7015 25 **Sharpening of natural guide stars for low-order wavefront sensing using patrolling laser guide stars** [7015-76]
R. Dekany, California Institute of Technology (United States); C. Neyman, R. Flicker, W. M. Keck Observatory (United States)
- 7015 26 **Performance and error budget of a GLAO system** [7015-77]
A. Tokovinin, Cerro Tololo Inter-American Observatory (Chile)
- 7015 27 **Field sampling adaptive optics: a new concept for multi-IFU spectrographs** [7015-78]
R. Content, R. Myers, T. Morris, Univ. of Durham (United Kingdom)

AO POSTPROCESSING

- 7015 29 **Tests of the PSF reconstruction algorithm for NACO/VLT** [7015-80]
Y. Clénet, LESIA/CNRS, Observatoire de Paris (France) and LESIA, Observatoire de Paris (France); C. Lidman, European Southern Observatory (Chile); E. Gendron, LESIA, Observatoire de Paris (France); G. Rousset, LESIA, Univ. Paris Diderot (France); T. Fusco, ONERA (France); N. Kornweibel, European Southern Observatory (Chile); M. Kasper, European Southern Observatory (Germany); N. Ageorges, European Southern Observatory (Chile)
- 7015 2B **Maximum likelihood-based method for angular differential imaging** [7015-82]
L. M. Mugnier, ONERA/DOTA (France) and Groupement d'Intérêt Scientifique PHASE (France); A. Cornia, ONERA/DOTA (France), LESIA, Observatoire de Paris (France), and Groupement d'Intérêt Scientifique PHASE (France); J.-F. Sauvage, N. Védrenne, T. Fusco, ONERA/DOTA (France) and Groupement d'Intérêt Scientifique PHASE (France); G. Rousset, LESIA, Observatoire de Paris (France) and Groupement d'Intérêt Scientifique PHASE (France)

Part Two

POSTERS: ASTRONOMICAL SCIENCE WITH AO

- 7015 2C **Imaging the dense stellar cluster R136 with VLT-MAD** [7015-83]
M. A. Campbell, Institute of Astronomy, The Univ. of Edinburgh, Royal Observatory (United Kingdom); C. J. Evans, UK Astronomy Technology Ctr., Royal Observatory (United Kingdom); J. Ascenso, Ctr. de Astrofísica, Univ. do Porto (Portugal); A. J. Longmore, UK Astronomy Technology Ctr., Royal Observatory (United Kingdom); J. Kolb, European Southern Observatory (Germany); M. Gieles, European Southern Observatory (Chile); J. Alves, Calar Alto Observatory - Ctr. Astronomico Hispano-Alemán (Spain)

POSTERS: POSTPROCESSING

- 7015 2D **Astronomical extended object image reconstruction after primary correction by Yunnan Observatory 1.2m adaptive optics system** [7015-84]
X. Chang, R. Li, National Astronomical Observatories (China) and Graduate School of the Chinese Academy of Sciences (China); Y. Xiong, National Astronomical Observatories (China)

- 7015 2E **Post-processing of adaptive optics images based on frame selection and multi-frame blind deconvolution** [7015-85]
Y. Tian, Institute of Optics and Electronics (China) and Graduate School of the Chinese Academy of Sciences (China); C. Rao, Institute of Optics and Electronics (China); K. Wei, Institute of Optics and Electronics (China) and Graduate School of the Chinese Academy of Sciences (China)
- 7015 2F **An iterative deconvolution algorithm using combined regularization for low-order corrected astronomical images** [7015-86]
H. Chen, National Astronomical Observatories/Nanjing Institute of Astronomical Optics & Technology (China) and Graduate School of the Chinese Academy of Sciences (China); X. Yuan, X. Cui, National Astronomical Observatories/Nanjing Institute of Astronomical Optics & Technology (China)
- 7015 2G **The space variant PSF for deconvolution of wide-field astronomical images** [7015-87]
M. Řeřábek, P. Páta, Czech Technical Univ. in Prague (Czech Republic)
- 7015 2H **Lucky imaging and speckle discrimination for the detection of faint companions with adaptive optics** [7015-88]
S. Gladysz, National Univ. of Ireland, Galway (Ireland); J. Christou, National Science Foundation (United States); N. Law, R. Dekany, Caltech Optical Observatories, California Institute of Technology (United States); M. Redfern, National Univ. of Ireland, Galway (Ireland); C. Mackay, Institute of Astronomy, Univ. of Cambridge (United Kingdom)
- 7015 2I **Getting lucky with adaptive optics: diffraction-limited resolution in the visible with current AO systems on large and small telescopes** [7015-89]
N. M. Law, California Institute of Technology (United States); R. G. Dekany, Caltech Optical Observatories, California Institute of Technology (United States); C. D. Mackay, Institute of Astronomy, Univ. of Cambridge (United Kingdom); A. M. Moore, M. C. Britton, V. Velur, Caltech Optical Observatories, California Institute of Technology (United States)
- 7015 2J **Optimal linear estimation of binary star parameters** [7015-90]
D. Burke, N. Devaney, S. Gladysz, National Univ. of Ireland, Galway (Ireland); H. H. Barrett, M. K. Whitaker, L. Caucci, College of Optical Sciences, Univ. of Arizona (United States) and Ctr. for Gamma Ray Imaging, Univ. of Arizona (United States)
- 7015 2K **Exploring the impact of PSF reconstruction errors on the reduction of astronomical adaptive optics based data** [7015-91]
L. Jolissaint, Univ. of Leiden (Netherlands); H. Carfantan, E. Anterrieu, Lab. d'Astrophysique de Toulouse-Tarbes, Univ. de Toulouse, CNRS (France)
- 7015 2L **Dynamic support region-based astronomical image deconvolution algorithm** [7015-92]
Z. Geng, Zhengzhou Institute of Surveying and Mapping (China); B. Chen, Guilin Air Force Academy (China); Q. Xu, B. Zhang, Z. Gong, Zhengzhou Institute of Surveying and Mapping (China)

POSTERS: LASER GUIDE STAR FACILITIES

- 7015 2N **Update on the TMT laser guide star facility design** [7015-94]
C. Boyer, B. Ellerbroek, TMT Observatory Corp. (United States); M. Gedig, Empire Dynamic Structures (Canada); E. Hileman, R. Joyce, M. Liang, National Optical Astronomy

Observatory (United States)

- 7015 2O **Operation of Laser Guide Star Facility at La Silla Paranal Observatory** [7015-95]
J. L. Alvarez, E. Bendek, J. Beltran, F. Gutierrez, I. Munoz, G. Valdes, N. Kornewibel,
European Southern Observatory (Chile)
- 7015 2P **The Gemini South MCAO laser guide star facility: getting ready for first light** [7015-96]
C. d'Orgeville, F. Daruich, G. Arriagada, M. Bec, M. Boccas, Gemini Observatory (Chile);
S. Bombino, C. Carter, C. Cavedoni, Gemini Observatory (United States); F. Collao,
P. Collins, Gemini Observatory (Chile); E. James, S. Karewicz, Gemini Observatory (United
States); M. Lazo, D. Maltres, R. Mouser, G. Perez, F. Rigaut, R. Rojas, Gemini Observatory
(Chile); M. Sheehan, Gemini Observatory (United States); G. Trancho, V. Vergara, T. Vucina,
Gemini Observatory (Chile)
- 7015 2S **Facilitizing the Palomar AO laser guide star system** [7015-99]
J. E. Roberts, Jet Propulsion Lab. (United States); A. H. Bouchez, California Institute of
Technology (United States); J. Angione, R. S. Burruss, Jet Propulsion Lab. (United States);
J. L. Cromer, R. G. Dekany, California Institute of Technology (United States); S. R. Guiwits,
Jet Propulsion Lab. (United States); J. R. Henning, J. Hickey, Palomar Observatory, California
Institute of Technology (United States); E. Kibblewhite, Univ. of Chicago (United States);
D. L. McKenna, Palomar Observatory, California Institute of Technology (United States);
A. M. Moore, California Institute of Technology (United States); H. L. Petrie, Palomar
Observatory, California Institute of Technology (United States); J. C. Shelton, Jet Propulsion
Lab. (United States); R. P. Thicksten, Palomar Observatory, California Institute of Technology
(United States); T. Trinh, Jet Propulsion Lab. (United States); R. Tripathi, Palomar Observatory,
California Institute of Technology (United States); M. Troy, T. Truong, Jet Propulsion Lab.
(United States); V. Velur, California Institute of Technology (United States)
- 7015 2T **Strategy for laser guide star operations without human aircraft spotters** [7015-100]
P. J. Stomski, B. Goodrich, S. Shimko, W. M. Keck Observatory (United States)
- 7015 2U **LGSF operational problems management at La Silla Paranal Observatory** [7015-101]
E. A. Bendek, J. L. Alvarez, J. Parra, European Southern Observatory (Chile)
- 7015 2V **AO with LGS and mesospheric layer sensing** [7015-102]
L. Bolbasova, Tomsk State Univ., Institute of Atmospheric Optics (Russia); D. Bonaccini Calia,
European Southern Observatory (Germany); A. V. Goncharov, National Univ. of Ireland,
Galway (Ireland); V. Lukin, Tomsk State Univ., Institute of Atmospheric Optics (Russia)
- 7015 2W **Effect of the geomagnetic field on the intensity of sodium laser guide stars** [7015-263]
N. Moussaoui, Univ. of Sciences and Technology Hourari Boumediene (Algeria);
R. Holzlohner, W. Hackenberg, D. Bonaccini Calia, European Southern Observatory
(Germany)

POSTERS: REAL TIME CONTROL AND ALGORITHMS

- 7015 2Y **Performance of the Fourier transform reconstructor for the European Extremely Large Telescope** [7015-104]
I. Montilla, M. Reyes, Instituto de Astrofísica de Canarias (Spain); M. Le Louarn, European
Southern Observatory (Germany); J. G. Marichal-Hernández, J. M. Rodríguez-Ramos, Univ.
de La Laguna (Spain); L. F. Rodríguez-Ramos, Instituto de Astrofísica de Canarias (Spain)

- 7015 2Z **Fixed-point vs. floating-point arithmetic comparison for adaptive optics real-time control computation** [7015-105]
Y. Martín-Hernando, L. F. Rodríguez-Ramos, M. R. García-Talavera, Institute of Astrophysics of the Canary Islands (Spain)
- 7015 30 **FPGA-based slope computation for ELTs adaptive optics wavefront sensors** [7015-106]
L. F. Rodríguez Ramos, J. J. Díaz García, J. J. Piqueras Meseguer, Y. Martín Hernando, Instituto de Astrofísica de Canarias (Spain); J. M. Rodríguez Ramos, Univ. of La Laguna (Spain)
- 7015 31 **Update on the TMT adaptive optics real time controller** [7015-107]
C. Boyer, L. Gilles, B. Ellerbroek, TMT Observatory Corp. (United States); G. Herriot, J. P. Véran, Herzberg Institute of Astrophysics (Canada)
- 7015 34 **Simple iterative method for open-loop control of MEMS deformable mirrors** [7015-111]
C. Blain, Univ. of Victoria (Canada); O. Guyon, Subaru Telescope, National Astronomical Observatory of Japan (United States); R. Conan, C. Bradley, Univ. of Victoria (Canada)
- 7015 35 **Timing characterization and analysis of the Linux-based, closed loop control computer for the Subaru Telescope laser guide star adaptive optics system** [7015-112]
M. Dinkins, S. Colley, National Astronomical Observatory of Japan/Subaru Telescope (United States)
- 7015 36 **Structure of a hybrid signal LQG controller for adaptive optics** [7015-113]
D. P. Looze, Univ. of Massachusetts (United States)
- 7015 37 **Optimization of controller parameters to minimize residual variance in adaptive optics systems** [7015-114]
D. P. Looze, Univ. of Massachusetts (United States)
- 7015 38 **Multirate LQG AO control** [7015-115]
H. F. Raynaud, C. Kulcsár, L2TI, Univ. Paris XIII (France); C. Correia da Silva, L2TI, Univ. Paris XIII (France) and ONERA, DOTA, Unité HRA (France); J. M. Conan, ONERA, DOTA, Unité HRA (France)
- 7015 39 **2D-FFT implementation on FPGA for wavefront phase recovery from the CAFADIS camera** [7015-116]
J. M. Rodríguez-Ramos, E. Magdaleno Castelló, C. Domínguez Conde, M. Rodríguez Valido, J. G. Marichal-Hernández, Univ. of La Laguna (Spain)
- 7015 3A **Sinusoidal calibration technique for Large Binocular Telescope system** [7015-117]
F. Pieralli, A. Puglisi, F. Quiros Pacheco, S. Esposito, INAF, Osservatorio Astrofisico di Arcetri (Italy)
- 7015 3B **Real-time phase slopes calculations by correlations using FPGAs** [7015-118]
J. Trujillo Sevilla, M. R. Valido, Univ. de La Laguna (Spain); L. F. Rodríguez Ramos, Instituto de Astrofísica de Canarias (Spain); E. Boemo, Univ. Autónoma de Madrid (Spain); F. Rosa, J. M. Rodríguez Ramos, Univ. de La Laguna (Spain)
- 7015 3E **Upgrading the Keck AO wavefront controllers** [7015-121]
E. M. Johansson, M. A. van Dam, P. J. Stomski, J. M. Bell, J. C. Chin, R. C. Sumner,

P. L. Wizinowich, W. M. Keck Observatory (United States); R. Biasi, M. Andrichettoni, D. Pescoller, Microgate S.r.l. (Italy)

7015 3F **Wind estimation and prediction for adaptive optics control systems** [7015-122]
L. C. Johnson, D. T. Gavel, M. Reinig, D. M. Wiberg, Univ. of California, Santa Cruz (United States)

7015 3G **Optimal control techniques for the adaptive optics system of the LBT** [7015-123]
G. Agapito, F. Quirós-Pacheco, Osservatorio Astrofisico di Arcetri (Italy); P. Tesi, Univ. degli Studi di Firenze (Italy); S. Esposito, M. Xompero, Osservatorio Astrofisico di Arcetri (Italy)

7015 3H **Reduced wavefront reconstruction mean square error using optimal priors: algebraic analysis and simulations** [7015-124]
C. Béchet, M. Tallon, E. Thiébaud, Univ. de Lyon (France), Univ. Lyon 1, Observatoire de Lyon (France), CNRS, UMR 5574, Ctr. de Recherche Astrophysique de Lyon (France), and Ecole Normale Supérieure de Lyon (France)

7015 3I **Real-time wavefront control for the PALM-3000 high order adaptive optics system** [7015-125]
T. N. Truong, Jet Propulsion Lab. (United States); A. H. Bouchez, R. G. Dekany, California Institute of Technology (United States); J. C. Shelton, M. Troy, J. R. Angione, R. S. Burruss, Jet Propulsion Lab. (United States); J. L. Cromer, California Institute of Technology (United States); S. R. Guiwits, J. E. Roberts, Jet Propulsion Lab. (United States)

POSTERS: AO CORRECTORS

7015 3J **Wavefront correction with a ferrofluid deformable mirror: experimental results and recent developments** [7015-128]
D. Brousseau, E. F. Borra, COPL, Univ. Laval (Canada); S. Thibault, Immervision (Canada); A. M. Ritcey, J. Parent, O. Seddiki, J.-P. Déry, L. Faucher, J. Vassallo, A. Naderian, COPL, Univ. Laval (Canada)

7015 3K **Integrated adaptive optics system for small telescopes** [7015-129]
M. Loktev, G. Vdovin, Flexible Optical B.V. (Netherlands) and Delft Univ. of Technology (Netherlands); O. Soloviev, Flexible Optical B.V. (Netherlands)

7015 3L **Progress on the development of a zonal bimorph deformable mirror** [7015-130]
M. S. Griffith, L. C. Laycock, N. Archer, BAE Systems (United Kingdom); R. Myers, Univ. of Durham (United Kingdom); P. Doel, Univ. College London (United Kingdom); R. Birch, BAE Systems (United Kingdom)

7015 3M **Combined optically addressable spatial light modulator for affordable adaptive optics** [7015-131]
L. Orzó, Computer and Automation Research Institute (Hungary); G. Mező, Heliophysical Observatory (Hungary); S. Tókes, A. Radványi, Computer and Automation Research Institute (Hungary)

7015 3N **Empirical measurement of MEMS stroke saturation, with implications for woofer-tweeter architectures** [7015-132]
K. M. Morzinski, National Science Foundation Ctr. for Adaptive Optics (United States) and UCO/Lick Observatory, Univ. of California, Santa Cruz (United States); B. A. Macintosh,

National Science Foundation Ctr. for Adaptive Optics (United States), UCO/Lick Observatory, Univ. of California, Santa Cruz (United States), and Lawrence Livermore National Lab. (United States); D. Dillon, D. Gavel, National Science Foundation Ctr. for Adaptive Optics (United States) and UCO/Lick Observatory, Univ. of California, Santa Cruz (United States); D. Palmer, National Science Foundation Ctr. for Adaptive Optics (United States) and Lawrence Livermore National Lab. (United States); A. Norton, National Science Foundation Ctr. for Adaptive Optics (United States) and UCO/Lick Observatory, Univ. of California, Santa Cruz (United States)

- 7015 3O **Radetzky: a new, large grazing incidence interferometer for large plane surface testing** [7015-133]
E. Molinari, P. Spanò, G. Toso, D. Tresoldi, INAF – Osservatorio di Brera (Italy); R. Biasi, Microgate (Italy); J.-L. Carel, Sagem (France); D. Gallieni, ADS International (Italy)
- 7015 3Q **Adaptive secondary mirror for LBT and its capacitive sensors: how can we calibrate them?** [7015-135]
M. Xompero, A. Riccardi, D. Zanotti, INAF, Osservatorio Astrofisico di Arcetri (Italy)
- 7015 3R **Characterization of vibrating shape of a bimorph deformable mirror** [7015-136]
S. Oya, Y. Minowa, M. Hattori, M. Watanabe, Y. Hayano, M. Itoh, Y. Saito, H. Takami, National Astronomical Observatory of Japan, Subaru Telescope (United States); M. Iye, National Astronomical Observatory of Japan (Japan); O. Guyon, S. Colley, M. Dinkins, M. Eldred, T. Golota, National Astronomical Observatory of Japan, Subaru Telescope (United States)
- 7015 3S **Lightweight optical segment prototype for adaptive optics manufactured by hot slumping** [7015-137]
R. Canestrari, INAF - Osservatorio Astronomico di Brera (Italy) and Univ. degli Studi dell'Insubria (Italy); M. Ghigo, S. Basso, D. Spiga, INAF - Osservatorio Astronomico di Brera (Italy); L. Proserpio, INAF - Osservatorio Astronomico di Brera (Italy) and Univ. degli Studi dell'Insubria (Italy)
- 7015 3U **Large lightweight segmented mirrors for adaptive optics** [7015-139]
G. Rodrigues, R. Bastais, Univ. Libre de Bruxelles (Belgium); S. Roose, Y. Stockman, Ctr. Spatiale de Liège (Belgium); S. Gebhardt, A. Schoenecker, Fraunhofer Institut für Keramische Technologien und Systeme (Germany); P. Villon, Univ. de Technologie de Compiègne (France); A. Preumont, Univ. Libre de Bruxelles (Belgium)
- 7015 3X **Deformable mirror controller for open-loop adaptive optics** [7015-142]
D. Guzmán, Durham Univ. (United Kingdom); A. Guesalaga, Pontificia Univ. Católica de Chile (Chile); R. Myers, R. Sharples, T. Morris, A. Basden, C. Saunter, N. Dipper, L. Young, Durham Univ. (United Kingdom); L. Rodríguez, M. Reyes, Y. Martín, Instituto de Astrofísica de Canarias (Spain)

POSTERS: AO DEMONSTRATOR AND FIELD TESTS

- 7015 3Y **EUV-imaging experiments of a normal incident telescope with an adaptive optics system** [7015-143]
S. Kitamoto, T. Ogita, T. Shibata, E. Takenaka, N. Gotoh, Y. Shishido, D. Takei, M. Yoshida, M. Morii, H. Murakami, Rikkyo Univ. (Japan)

- 7015 3Z **High order test bench for extreme adaptive optics system optimization** [7015-144]
E. Aller-Carpentier, M. Kasper, P. Martinez, E. Vernet, E. Fedrigo, C. Soenke, S. Tordo, N. Hubin, European Southern Observatory (Germany); C. Verinaud, Lab. d'Astrophysique de Grenoble (France); S. Esposito, E. Pinna, A. Puglisi, A. Tozzi, F. Quiros, INAF – Osservatorio Astrofisico di Arcetri (Italy); A. G. Basden, S. J. Goodsell, G. D. Love, R. M. Myers, Durham Univ. (United Kingdom)
- 7015 42 **Atmospheric simulator for testing adaptive optic systems** [7015-147]
C. C. Wilcox, T. Martinez, F. Santiago, J. R. Andrews, S. R. Restaino, Naval Research Lab. (United States); S. W. Teare, New Mexico Institute of Mining and Technology (United States); D. Payne, Narrascope (United States)
- 7015 43 **VASAO: visible all sky adaptive optics: a new adaptive optics concept for CFHT** [7015-148]
O. Lai, C. Veillet, D. Salmon, K. Ho, M. R. Baril, G. A. Barrick, J. Thomas, D. Teeple, T. Benedict, Canada-France-Hawaii Telescope (United States); J. P. Pique, H. Guillet de Chatellus, Univ. Joseph Fourier (France)
- 7015 44 **Progress with extreme adaptive optics test bench for ELT at LAM** [7015-149]
M. Langlois, C. Pasanau, B. Leroux, G. Moretto, K. El Hadi, Lab. d'Astrophysique de Marseille (France); D. Rabaud, Shaktiware (France)
- 7015 46 **Application of Hartmann linear calibrations to ViLLaGEs** [7015-151]
S. M. Ammons, D. T. Gavel, D. R. Dillon, M. Reinig, Univ. of California, Santa Cruz (United States); B. Grigsby, UCO/Lick Observatories, Univ. of California, Santa Cruz (United States); K. M. Morzinski, Univ. of California, Santa Cruz (United States)
- 7015 47 **Optimization of MCAO performances: experimental results on ONERA laboratory MCAO bench** [7015-152]
A. Costille, C. Petit, J.-M. Conan, T. Fusco, ONERA, DOTA, Unité HRA (France); C. Kulcsár, H.-F. Raynaud, L2TI, Univ. Paris XIII (France)

POSTERS: WIDE FOV AO (3-10')

- 7015 49 **Observations of ground-layer turbulence** [7015-154]
M. Goodwin, C. Jenkins, P. Conroy, The Australian National Univ. (Australia); A. Lambert, Univ. of New South Wales (Australia)
- 7015 4A **Numerical Fourier simulations of tip-tilt LGS indetermination for the EAGLE instrument of the European ELT** [7015-155]
F. Assémat, ONERA (France), LESIA, Observatoire de Paris, CNRS, Univ. Paris Diderot (France), and Groupement d'Intérêt Scientifique PHASE (France); T. Fusco, J.-M. Conan, ONERA (France) and Groupement d'Intérêt Scientifique PHASE (France); G. Rousset, E. Gendron, LESIA, Observatoire de Paris, CNRS, Univ. Paris Diderot (France) and Groupement d'Intérêt Scientifique PHASE (France); B. Neichel, ONERA (France), GEPI, Observatoire de Paris, CNRS, Univ. Paris Diderot (France), and Groupement d'Intérêt Scientifique PHASE (France)
- 7015 4B **On-sky performance of the tip-tilt correction system for GLAS using an EMCCD camera** [7015-156]
J. Skvarč, S. Tulloch, Isaac Newton Group of Telescopes (Spain)

- 7015 4C **SAM: a facility GLAO instrument** [7015-157]
A. Tokovinin, R. Tighe, P. Schurter, R. Cantarutti, N. van der Blik, M. Martinez, E. Mondaca, A. Montane, Cerro Tololo Inter-American Observatory (Chile)
- 7015 4E **Optimisation of the range gating and calibration processes on the GLAS Rayleigh Laser Guide Star at the WHT** [7015-159]
O. Martin, D. C. Abrams, T. Agócs, C. Benn, C. Bevil, D. Cano, Isaac Newton Group of Telescopes (Spain); N. Dipper, Univ. of Durham (United Kingdom); T. Gregory, J. C. Guerra, Isaac Newton Group of Telescopes (Spain); T. Morris, R. Myers, Univ. of Durham (United Kingdom); S. Picó, S. Rix, R. Rutten, J. Skvarc, S. Tulloch, Isaac Newton Group of Telescopes (Spain)
- 7015 4F **ASSIST: the test setup for the VLT AO facility** [7015-160]
R. Stuik, Leiden Observatory, Leiden Univ. (Netherlands); R. Arsenault, R. Conzelmann, European Southern Observatory (Germany); A. Deep, Leiden Observatory, Leiden Univ. (Netherlands); B. Delabre, European Southern Observatory (Germany); P. Hallibert, L. Jolissaint, Leiden Observatory, Leiden Univ. (Netherlands); N. Hubin, European Southern Observatory (Germany); S. Kendrew, Leiden Observatory, Leiden Univ. (Netherlands); P.-Y. Madec, F. Molster, J. Paufigue, E. Pauwels, S. Stroebele, European Southern Observatory (Germany); E. Wieggers, Leiden Observatory, Leiden Univ. (Netherlands)
- 7015 4G **Ground-layer AO for Dome C: the WHITE instrument** [7015-161]
B. Le Roux, Observatoire Astronomique de Marseille-Provence, Univ. de Aix-Marseille (France); M. Carbillet, Univ. de Nice Sophia Antipolis, CNRS, Observatoire de la Côte d'Azur (France); M. Langlois, Observatoire Astronomique de Marseille-Provence, Univ. de Aix-Marseille (France); H. Trinquet, Univ. de Nice Sophia Antipolis, CNRS, Observatoire de la Côte d'Azur (France); D. Burgarella, M. Ferrari, Observatoire Astronomique de Marseille-Provence, Univ. de Aix-Marseille (France); F.-X. Schmider, Univ. de Nice Sophia Antipolis, CNRS, Observatoire de la Côte d'Azur (France)
- 7015 4H **IMAKA: imaging from Mauna KeA with an atmosphere corrected 1 square degree optical imager** [7015-162]
O. Lai, Canada-France-Hawaii Telescope (United States); M. Chun, Institute for Astronomy, Univ. of Hawaii at Hilo (United States); J. C. Cuillandre, Canada-France-Hawaii Telescope (United States); R. Carlberg, Univ. of Toronto (Canada); H. Richer, The Univ. of British Columbia (Canada); D. Andersen, J. Pazder, Herzberg Institute for Astrophysics (Canada); J. Tonry, Institute for Astronomy, Univ. of Hawaii at Manoa (United States); R. Doyon, Groupe d'Astrophysique, Univ. de Montréal (Canada); S. Thibault, Immervision (Canada); J. Dunlop, The Univ. of British Columbia (Canada); C. Pritchett, Univ. of Victoria (Canada); J. P. Véran, Herzberg Institute for Astrophysics (Canada); C. Ftaclas, Institute for Astronomy, Univ. of Hawaii at Hilo (United States); P. Onaka, Institute for Astronomy, Univ. of Hawaii at Manoa (United States); K. W. Hodapp, Institute for Astronomy, Univ. of Hawaii at Hilo (United States); R. A. McLaren, Institute for Astronomy, Univ. of Hawaii at Manoa (United States); E. Bertin, Y. Mellier, Institut d'Astrophysique de Paris (France); P. Astier, R. Pain, IN2P3 (France)
- 7015 4K **SLODAR turbulence monitors for real-time support of astronomical adaptive optics** [7015-165]
R. Wilson, T. Butterley, Univ. of Durham (United Kingdom); M. Sarazin, G. Lombardi, European Southern Observatory (Germany); M. Chun, S. Benigni, D. Weir, Institute for Astronomy, Univ. of Hawaii (United States); R. Avila, J.-L. Aviles, Instituto de Astronomia,

UNAM (Mexico)

- 7015 4L **High-resolution SLODAR measurements on Mauna Kea** [7015-166]
T. Butterley, R. W. Wilson, Univ. of Durham (United Kingdom); M. R. Chun, Univ. of Hawai'i at Hilo (United States); R. Avila, J.-L. Aviles, Univ. Nacional Autónoma de México (Mexico)

Part Three

POSTERS: MEDIUM FOV AO (0.5-3')

- 7015 4N **Opto-mechanical commissioning of the GLAS Rayleigh laser guide star for the WHT** [7015-169]
O. Martin, T. Agócs, D. Cano, T. Gregory, M. van der Hoeven, Isaac Newton Group of Telescopes (Spain); P. Jolley, European Southern Observatory (Germany); C. Martín, Isaac Newton Group of Telescopes (Spain); T. Morris, Univ. of Durham (United Kingdom); S. Picó, R. Pit, J. Rey, Isaac Newton Group of Telescopes (Spain)
- 7015 4O **Turbulence characterization at the Nasmyth focal plane of the VLT Melipal** [7015-170]
J. Kolb, European Southern Observatory (Germany)

POSTERS: WAVEFRONT SENSING

- 7015 4P **An improved wavefront control algorithm for large space telescopes** [7015-171]
E. Sidick, S. A. Basinger, D. C. Redding, Jet Propulsion Lab. (United States)
- 7015 4Q **Optical misalignment sensing for optical aperture synthesis telescope by using phase diversity** [7015-172]
F. Cao, National Astronomical Observatories/Nanjing Institute of Astronomical Optics and Technology (China) and Graduate School of Chinese Academy of Sciences (China); Y. Zhu, Z. Wu, National Astronomical Observatories/Nanjing Institute of Astronomical Optics and Technology (China)
- 7015 4S **Modeling of the Thirty-Meter-Telescope matched-filter-based LGS wavefront sensing** [7015-174]
R. Conan, O. Lardière, C. Bradley, Univ. of Victoria (Canada); G. Herriot, NRC-Herzberg Institute of Astrophysics (Canada); K. Jackson, Univ. of Victoria (Canada)
- 7015 4T **Laser-guide-star wavefront sensing for TMT: experimental results of the matched filtering** [7015-175]
O. Lardière, R. Conan, C. Bradley, Univ. of Victoria (Canada); G. Herriot, NRC-Herzberg Institute of Astrophysics (Canada); K. Jackson, Univ. of Victoria (Canada)
- 7015 4U **Wavefront sensing and control for a segmented primary mirror** [7015-176]
B. Dong, X. Yu, X. Zhang, B. Guo, L. Zhao, Beijing Institute of Technology (China)
- 7015 4V **Telluric sodium layer temporal variations** [7015-177]
M. Chun, Univ. of Hawai'i (United States); T. Butterley, R. Wilson, Univ. of Durham (United Kingdom); R. Avila, J.-L. Aviles, Univ. Nacional Autónoma de México (Mexico); B. Ellerbroek, Thirty Meter Telescope Project (United States); F. Rigaut, Gemini Observatory (Chile)

- 7015 4W **Low-order wavefront sensing in tomographic multi-beacon adaptive optics systems** [7015-178]
V. Velur, Caltech Optical Observatories, California Institute of Technology (United States);
R. Flicker, W. M. Keck Observatory (United States); R. Dekany, G. Rahmer, R. Smith,
A. Moore, Caltech Optical Observatories, California Institute of Technology (United States)
- 7015 4X **Wavefront measurement error in a Hartmann-Shack-type wavefront sensor due to field anisoplanatism** [7015-179]
F. Wöger, T. Rimmele, National Solar Observatory (United States)
- 7015 4Y **High-resolution lidar experiment for the Thirty Meter Telescope** [7015-180]
T. Pfrommer, P. Hickson, Univ. of British Columbia (Canada); C.-Y. She, J. D. Vance,
Colorado State Univ. (United States)
- 7015 4Z **A kind of Shack-Hartmann wavefront sensor with extremely large number of subapertures for adaptive optics system of extremely large telescope** [7015-181]
A. Zhang, C. Rao, X. Zhang, Z. Liao, Institute of Optics and Electronics (China); K. Wei,
Institute of Optics and Electronics (China) and Graduate School, Chinese Academy of
Sciences (China); Y. Zhang, W. Jiang, Institute of Optics and Electronics (China)
- 7015 51 **Hartmann modelling in the discrete spatial-frequency domain: application to real-time reconstruction in adaptive optics** [7015-183]
C. Correia, ONERA (France); C. Kulcsár, Univ. Paris XIII (France); J.-M. Conan, ONERA
(France); H.-F. Raynaud, Univ. Paris XIII (France)
- 7015 52 **Alternative schemes for multi-reference wavefront sensing** [7015-184]
A. V. Goncharov, N. M. Devaney, T. Farrell, J. C. Dainty, National Univ. of Ireland, Galway
(Ireland)
- 7015 53 **Development of a correlation tracker system for the New Solar Telescope** [7015-185]
S. Choi, Korea Astronomy and Space Science Institute (South Korea) and Kyung-Hee Univ.
(South Korea); J. Nah, Korea Astronomy and Space Science Institute (South Korea);
Y.-J. Moon, Kyung-Hee Univ. (South Korea); H. Wang, New Jersey Institute of Technology
(United States); R. Coulter, Big Bear Solar Observatory (United States)
- 7015 54 **Applying sensitivity compensation for pyramid wavefront sensor in different conditions** [7015-186]
V. Korkiakoski, C. Vérinaud, Lab. d'Astrophysique, Observatoire de Grenoble (France);
M. Le Louarn, European Southern Observatory (Germany)
- 7015 55 **Near-infrared wavefront sensing for the VLT interferometer** [7015-187]
S. Hippler, W. Brandner, Max-Planck-Institut für Astronomie (Germany); Y. Clénet,
Observatoire de Paris à Meudon (France); F. Hormuth, Max-Planck-Institut für Astronomie
(Germany); E. Gendron, Observatoire de Paris à Meudon (France); T. Henning, R. Klein,
R. Lenzen, D. Meschke, V. Naranjo, U. Neumann, J. R. Ramos, R.-R. Rohloff, Max-Planck-
Institut für Astronomie (Germany); F. Eisenhauer, Max-Planck-Institut für Extraterrestrische
Physik (Germany)
- 7015 56 **Wavefront sensor for the Large Binocular Telescope laser guide star facility** [7015-188]
L. Busoni, S. Esposito, INAF-Osservatorio Astrofisico di Arcetri (Italy); S. Rabien, M. Haug,
J. Ziegler, G. Hölzl, Max-Planck-Institut für Extraterrestrische Physik (Germany)

- 7015 58 **The double pyramid wavefront sensor for LBT** [7015-190]
A. Tozzi, P. Stefanini, E. Pinna, S. Esposito, INAF - Osservatorio Astrofisico di Arcetri (Italy)
- 7015 59 **The pyramid wavefront sensor for the high order testbench (HOT)** [7015-191]
E. Pinna, A. T. Puglisi, F. Quiros-Pacheco, L. Busoni, A. Tozzi, S. Esposito, Osservatorio Astrofisico di Arcetri (Italy); E. Aller-Carpentier, M. Kasper, European Southern Observatory (Germany)
- 7015 5A **Integration of the mid-high wavefront sensor to the Linc-Nirvana post-focal relay** [7015-192]
L. Schreiber, Univ. di Bologna (Italy); M. Lombini, INAF, Osservatorio Astronomico di Bologna (Italy); I. Foppiani, Univ. di Bologna (Italy); D. Meschke, F. De Bonis, P. Bizenberger, Max-Planck-Institut fuer Astronomie (Germany); G. Bregoli, INAF, Osservatorio Astronomico di Bologna (Italy); G. Cosentino, Univ. di Bologna (Italy); E. Diolaiti, INAF, Osservatorio Astronomico di Bologna (Italy); S. Egner, Subaru Telescope, NAOJ (United States); J. Farinato, INAF, Osservatorio Astronomico di Padova (Italy); W. Gaessler, T. Herbst, Max-Planck-Institut für Astronomie (Germany); G. Innocenti, INAF, Osservatorio Astronomico di Bologna (Italy); F. Kittmann, L. Mohr, Max-Planck-Institut für Astronomie (Germany); R. Ragazzoni, INAF, Osservatorio Astronomico di Padova (Italy); R.-R. Rohloff, Max-Planck-Institut für Astronomie (Germany)
- 7015 5C **Results of a pnCCD detector system for high-speed optical imaging** [7015-194]
R. Hartmann, PNSensor GmbH (Germany) and MPI Halbleiterlabor (Germany); S. Deires, M. Downing, European Southern Observatory (Germany); H. Gorke, Forschungszentrum Jülich (Germany); S. Herrmann, Max-Planck-Institut für extraterrestrische Physik (Germany) and MPI Halbleiterlabor (Germany); S. Ihle, PNSensor GmbH (Germany) and MPI Halbleiterlabor (Germany); G. Kanbach, Max-Planck-Institut für extraterrestrische Physik (Germany); J. Papamastorakis, Univ. of Crete (Greece); H. Soltan, PNSensor GmbH (Germany) and MPI Halbleiterlabor (Germany); A. Stefanescu, Max-Planck-Institut für extraterrestrische Physik (Germany); L. Strüder, Max-Planck-Institut für extraterrestrische Physik (Germany) and MPI Halbleiterlabor (Germany)
- 7015 5D **A novel WFS technique for high-contrast imaging: Phase Sorting Interferometry (PSI)** [7015-196]
J. L. Codona, M. A. Kenworthy, M. Lloyd-Hart, The Univ. of Arizona/Steward Observatory (United States)
- 7015 5F **Correction of the wavefront using the irradiance transport equation** [7015-198]
M. García, F. Granados, A. Cornejo, National Institute of Astrophysics Optics and Electronics (INAOE) (Mexico)
- 7015 5H **Implementation of the pyramid wavefront sensor as a direct phase detector for large amplitude aberrations** [7015-200]
R. Kupke, D. Gavel, J. Johnson, M. Reinig, Laboratory for Adaptive Optics, UCSC (United States)

- 7015 5J **The Multiple Field of View Layer Oriented wavefront sensing system of LINC-NIRVANA: two arcminutes of corrected field using solely Natural Guide Stars** [7015-202]
J. Farinato, R. Ragazzoni, C. Arcidiacono, A. Brunelli, M. Dima, G. Gentile, V. Viotto, INAF - Osservatorio Astronomico di Padova (Italy); E. Diolaiti, I. Foppiani, M. Lombini, L. Schreiber, INAF - Osservatorio Astronomico di Bologna (Italy); P. Bizenberger, F. De Bonis, S. Egner, W. Gässler, T. Herbst, M. Kürster, L. Mohr, R.-R. Rohloff, Max-Planck-Institut für Astronomie (Germany)
- 7015 5K **Autonomous phase retrieval control for calibration of the Palomar Adaptive Optics system** [7015-203]
S. Bikkannavar, C. Ohara, M. Troy, Jet Propulsion Lab. (United States)
- 7015 5L **Analysis of on-sky sodium profile data and implications for LGS AO wavefront sensing** [7015-204]
S. J. Thomas, D. Gavel, Univ. of California, Santa Cruz (United States); S. Adkins, W. M. Keck Observatory (United States); B. Kibrick, Univ. of California, Santa Cruz (United States)
- 7015 5M **High-order wavefront sensing system for PALM-3000** [7015-206]
C. Baranec, Caltech Optical Observatories (United States)
- 7015 5N **Telescope interferometers: an alternative to classical wavefront sensors** [7015-207]
F. Hénault, UMR 6525 CNRS H. FIZEAU – UNS, OCA (France)
- 7015 5O **Turbulence profiling using wide field of view Hartmann-Shack wavefront sensors** [7015-208]
T. A. Waldmann, T. Berkefeld, O. von der Lühe, Kiepenheuer-Institut für Sonnenphysik (Germany)
- 7015 5P **Layer oriented wavefront sensor for MAD on sky operations** [7015-209]
C. Arcidiacono, INAF, Osservatorio Astronomico di Padova (Italy); M. Lombini, INAF, Osservatorio Astrofisico di Bologna (Italy); R. Ragazzoni, J. Farinato, INAF, Osservatorio Astronomico di Padova (Italy); E. Diolaiti, INAF, Osservatorio Astrofisico di Bologna (Italy); A. Baruffolo, P. Bagnara, G. Gentile, INAF, Osservatorio Astronomico di Padova (Italy); L. Schreiber, INAF, Osservatorio Astrofisico di Bologna (Italy); E. Marchetti, J. Kolb, S. Tordo, R. Donaldson, C. Soenke, S. Oberti, E. Fedrigo, E. Vernet, N. Hubin, European Southern Observatory (Germany)
- 7015 5Q **Wavefront and distance measurement using the CAFADIS camera** [7015-210]
J. M. Rodríguez-Ramos, Univ. of La Laguna (Spain); B. Femenía Castellá, Grantecan (Spain); F. Pérez Nava, S. Fumero, Univ. of La Laguna (Spain)
- 7015 5R **A CMOS camera for pyramid wavefront sensors** [7015-262]
K. N. Modha, I. M. Stockford, Univ. of Nottingham (United Kingdom); I. Kepiro, C. Paterson, Imperial College London (United Kingdom); R. A. Light, M. Clark, M. Pitter, B. Hayes-Gill, Univ. of Nottingham (United Kingdom)

POSTERS: AO FOR ELT

- 7015 5S **Present optical and mechanical design status of NFIRAOS for TMT** [7015-211]
J. Atwood, P. Byrnes, G. Herriot, P. Welle, National Research Council of Canada, Herzberg Institute of Astrophysics (Canada)

- 7015 5T **Atmospheric refractivity effects on mid-infrared ELT adaptive optics** [7015-212]
S. Kendrew, L. Jolissaint, R. J. Mathar, R. Stuik, Leiden Observatory, Univ. of Leiden (Netherlands); S. Hippler, Max Planck Institute for Astronomy (Germany); B. Brandl, Leiden Observatory, Univ. of Leiden (Netherlands)
- 7015 5U **Preliminary design of the post focal relay of the MCAO module for the E-ELT** [7015-213]
M. Lombini, E. Diolaiti, INAF - Osservatorio Astronomico di Bologna (Italy); I. Foppiani, L. Schreiber, Univ. di Bologna (Italy); E. Marchetti, B. Delabre, European Southern Observatory (Germany)
- 7015 5V **Negating effects from sodium profile variations for TMT: the MOR truth wavefront sensor of NFIRAOS** [7015-214]
D. R. Andersen, National Research Council Canada, Herzberg Institute of Astrophysics (Canada); R. Conan, Univ. of Victoria (Canada); B. Ellerbroek, TMT Observatory Corp. (United States); G. Herriot, J.-P. Véran, National Research Council Canada, Herzberg Institute of Astrophysics (Canada)
- 7015 5W **Sky coverage estimates for the natural guide star mode of the TMT facility AO system NFIRAOS** [7015-215]
B. Ellerbroek, TMT Observatory Corp. (United States); D. Andersen, Herzberg Institute of Astrophysics (Canada)
- 7015 5X **Evaluating sky coverage for the NFIRAOS tip/tilt control architecture** [7015-216]
L. Wang, B. Ellerbroek, California Institute of Technology (United States); J.-P. Véran, Herzberg Institute of Astrophysics (Canada); J.-C. Siquin, CILAS (France)

POSTERS: AO FACILITIES

- 7015 5Y **Progress on the 127-element adaptive optical system for 1.8m telescope** [7015-217]
C. Rao, W. Jiang, Y. Zhang, N. Ling, Institute of Optics and Electronics (China); X. Zhang, Institute of Optics and Electronics (China) and Graduate School of the Chinese Academy of Sciences (China); H. Xian, Institute of Optics and Electronics (China); K. Wei, Institute of Optics and Electronics (China) and Graduate School of the Chinese Academy of Sciences (China); Z. Liao, Institute of Optics and Electronics (China); L. Zhou, Institute of Optics and Electronics (China) and Graduate School of the Chinese Academy of Sciences (China); C. Guan, M. Li, D. Chen, A. Zhang, W. Ma, X. Gao, Institute of Optics and Electronics (China)
- 7015 60 **GUIELOA, the Mexican adaptive optics system: expected performance and operation** [7015-219]
J. H. V. Girard, Instituto de Astronomía, Univ. Nacional Autónoma de México (Mexico); A. M. Watson, Ctr. de Radioastronomía y Astrofísica, Univ. Nacional Autónoma de México (Mexico); L. C. Álvarez, O. Chapa, S. Cuevas, R. Flores, F. Garfías, A. Iriarte, L. A. Martínez, B. Sánchez, Instituto de Astronomía, Univ. Nacional Autónoma de México (Mexico)
- 7015 61 **Development of a dichroic beam splitter for Subaru AO188** [7015-220]
Y. Minowa, H. Takami, M. Watanabe, Y. Hayano, National Astronomical Observatory of Japan/Subaru Telescope (United States); M. Miyake, Optical Coatings Japan Co., Ltd. (Japan); M. Iye, National Astronomical Observatory of Japan (Japan); S. Oya, M. Hattori, National Astronomical Observatory of Japan/Subaru Telescope (United States); N. Murakami, National Astronomical Observatory of Japan (Japan); O. Guyon, Y. Saito,

M. Itoh, S. Colley, M. Dinkins, M. Eldred, T. Golota, National Astronomical Observatory of Japan/Subaru Telescope (United States)

- 7015 62 **An infrared test camera for LBT adaptive optics commissioning** [7015-221]
I. Foppiani, Univ. di Bologna (Italy); M. Lombini, G. Bregoli, INAF, Osservatorio Astronomico di Bologna (Italy); G. Cosentino, Univ. di Bologna (Italy); E. Diolaiti, G. Innocenti, INAF, Osservatorio Astronomico di Bologna (Italy); D. Meschke, R.-R. Rohloff, T. M. Herbst, Max-Planck-Institut für Astronomie (Germany); C. Ciattaglia, INAF, Osservatorio Astronomico di Bologna (Italy)
- 7015 63 **Adaptive optics for the SALT** [7015-222]
M. A. Kenworthy, The Univ. of Arizona/Steward Observatory (United States); A. Sheinis, Univ. of Wisconsin (United States); D. A. H. Buckley, South African Astronomical Observatory (South Africa)
- 7015 64 **Implementation of 188-element curvature-based wavefront sensor and calibration source unit for the Subaru LGSAO system** [7015-223]
M. Watanabe, S. Oya, Y. Hayano, H. Takami, M. Hattori, Y. Minowa, Y. Saito, M. Ito, National Astronomical Observatory of Japan/Subaru Telescope (United States); N. Murakami, M. Iye, National Astronomical Observatory of Japan (Japan); O. Guyon, S. Colley, M. Eldred, T. Golota, M. Dinkins, National Astronomical Observatory of Japan/Subaru Telescope (United States)
- 7015 65 **A test stand for the MMT Observatory adaptive secondary** [7015-224]
T. Stalcup, MMT Observatory (United States); P. Hinz, O. Durney, T. Connors, R. Mopidevi, The Univ. of Arizona/Steward Observatory (United States)
- 7015 66 **W. M. Keck Observatory next-generation adaptive optics facility: science operations** [7015-225]
D. Le Mignant, W. M. Keck Observatory (United States) and Univ. of California, Santa Cruz (United States); C. R. Neyman, W. M. Keck Observatory (United States); E. J. McGrath, Univ. of California, Santa Cruz (United States)
- 7015 67 **Concept for the Keck Next Generation Adaptive Optics system** [7015-226]
D. Gavel, UCO Lick Observatory, UC Santa Cruz (United States); R. Dekany, Caltech Optical Observatories, Caltech (United States); C. Max, UCO Lick Observatory, UC Santa Cruz (United States); P. Wizinowich, S. Adkins, Keck Observatory (United States); B. Bauman, Lawrence Livermore National Lab. (United States); J. Bell, E. Johansson, Keck Observatory (United States); R. Kupke, C. Lockwood, UCO Lick Observatory (United States); A. Moore, Caltech Optical Observatories, Caltech (United States); C. Neyman, Keck Observatory (United States); M. Reinig, UCO Lick Observatory (United States); V. Velur, Caltech Optical Observatories, Caltech (United States)
- 7015 68 **The Gemini MCAO bench: system overview and lab integration** [7015-228]
M. Bec, F. J. Rigaut, R. Galvez, G. Arriagada, M. Boccas, G. Gausachs, D. Gratadour, Gemini Observatory (Chile); E. James, Gemini Observatory (United States); R. Rojas, R. Rogers, Gemini Observatory (Chile); M. P. Sheehan, Gemini Observatory (United States); G. Trancho, T. Vucina, Gemini Observatory (Chile)

POSTERS: HIGH CONTRAST IMAGING WITH AO

- 7015 6A **Improvement of phase diversity algorithm for non-common path calibration in extreme AO context** [7015-230]
C. Robert, T. Fusco, J.-F. Sauvage, L. Mugnier, ONERA (France)
- 7015 6B **Phase and Lyot-type coronagraphs for the High Order Testbench: prototyping and first laboratory results** [7015-231]
P. Martinez, European Southern Observatory (Germany), Observatoire de Paris Meudon (LESIA) (France), and Groupement d'Intérêt Scientifique PHASE (France); E. Vernet, European Southern Observatory (Germany); C. Dorrer, Lab. for Laser Energetics-Univ. of Rochester (United States); E. Aller Carpentier, European Southern Observatory (Germany); A. Boccaletti, Observatoire de Paris (LESIA) (France) and Groupement d'Intérêt Scientifique PHASE (France); M. Kasper, European Southern Observatory (Germany); J. Baudrand, Observatoire de Paris (LESIA) (France) and Groupement d'Intérêt Scientifique PHASE (France); C. Chaumont, Observatoire de Paris Meudon (GEPI) (France) and Groupement d'Intérêt Scientifique PHASE (France)
- 7015 6C **Theory and laboratory tests of the multi-stage phase mask coronagraph** [7015-232]
P. Baudoz, R. Galicher, J. Baudrand, A. Boccaletti, LESIA, Observatoire de Paris, CNRS, UPMC, Univ. Paris Diderot (France) and Groupement d'Intérêt Scientifique PHASE (France)
- 7015 6E **End-to-end simulation of AO-assisted coronagraphic differential imaging: estimation of performance for SPHERE** [7015-234]
A. Boccaletti, LESIA, Observatoire de Paris (France); M. Carbillet, FIZEAU, Univ. de Nice Sophia Antipolis (France); T. Fusco, ONERA-DOTA (France); D. Mouillet, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); M. Langlois, C. Moutou, K. Dohlen, LAM, Observatoire de Marseille-Provence (France)
- 7015 6F **Simulation of moving exoplanets detection using the VLT instrument SPHERE/IRDIS** [7015-235]
I. Smith, M. Carbillet, A. Ferrari, UMR 6525, H. Fizeau, Univ. de Nice Sophia Antipolis, CNRS, Observatoire de la Côte d'Azur (France); D. Mouillet, UMR 5571 LAOG, Observatoire des Sciences de l'Univers de Grenoble, Univ. Joseph Fourier, CNRS (France); A. Boccaletti, UMR 8109 LESIA, Observatoire de Meudon, CNRS (France); K. Dohlen, UMR 6110 LAM, Observatoire Astronomique de Marseille Provence, Univ. de Provence, CNRS (France)
- 7015 6G **A high-Strehl low-resolution optical imager (BESSEL): a measurement of the inner scale of turbulence** [7015-236]
M. A. Peters, L. M. Close, T. Stalcup, M. Rademacher, Steward Observatory, Univ. of Arizona (United States); G. A. Swartzlander, Jr., E. L. Ford, R. S. Abdul-Malik, College of Optical Sciences, Univ. of Arizona (United States)
- 7015 6I **Testing the APLC on the LAO ExAO testbed** [7015-238]
S. J. Thomas, Univ. of California, Santa Cruz (United States); R. Soummer, American Museum of Natural History (United States); D. Dillon, Univ. of California, Santa Cruz (United States); B. Macintosh, Univ. of California, Santa Cruz (United States) and Lawrence Livermore National Lab. (United States); J. W. Evans, Lawrence Livermore National Lab. (United States); D. Gavel, Univ. of California, Santa Cruz (United States); A. Sivaramakrishnan, American Museum of Natural History (United States); C. Marois, Herzberg Institute of Astrophysics (Canada); B. R. Oppenheimer, American Museum of Natural History (United States)

- 7015 6K **Contrast analysis and stability on the ExAO testbed** [7015-240]
J. W. Evans, Lawrence Livermore National Lab. (United States); S. Thomas, D. Gavel, D. Dillon, UCO Lick Observatory, Univ. of California, Santa Cruz (United States); B. Macintosh, Lawrence Livermore National Lab. (United States) and UCO Lick Observatory, Univ. of California, Santa Cruz (United States)
- 7015 6M **An advanced atmospheric dispersion corrector: the Magellan visible AO camera** [7015-242]
D. Kopon, L. M. Close, V. Gasho, CAAO, Steward Observatory, Univ. of Arizona (United States)
- 7015 6N **Post-coronagraph wavefront sensor for Gemini Planet Imager** [7015-243]
J. K. Wallace, J. Angione, R. Bartos, P. Best, R. Burruss, F. Fregoso, B. M. Levine, B. Nemati, M. Shao, C. Shelton, Jet Propulsion Lab. (United States)
- 7015 6P **Self-Coherent Camera: active correction and post-processing for Earth-like planet detection** [7015-245]
R. Galicher, P. Baudoz, G. Rousset, LESIA, CNRS, Observatoire de Paris (France)
- 7015 6Q **Observing strategies for the NICI campaign to directly image extrasolar planets** [7015-246]
B. Biller, Institute for Astronomy, Univ. of Hawaii (United States); É. Artigau, Gemini Observatory (Chile); Z. Wahhaj, Institute for Astronomy, Univ. of Hawaii (United States); M. Hartung, Gemini Observatory (Chile); M. C. Liu, Institute for Astronomy, Univ. of Hawaii (United States); L. M. Close, Steward Observatory, Univ. of Arizona (United States); M. R. Chun, C. Ftaclas, Institute for Astronomy, Univ. of Hawaii (United States); D. W. Toomey, Mauna Kea Infrared LLC (United States); T. Hayward, Gemini Observatory (Chile)
- 7015 6R **Exploring high contrast limitations for image slicer-based integral field spectrographs** [7015-247]
G. Salter, N. Thatte, M. Tecza, F. Clarke, Univ. of Oxford (United Kingdom); C. Verinaud, LAOG (France); M. Kasper, R. Abuter, ESO (Germany)

POSTERS: SOLAR AO

- 7015 6T **Adaptive optics system application for solar telescope** [7015-248]
V. P. Lukin, Institute of Atmospheric Optics (Russia) and Tomsk State Univ. (Russia); V. M. Grigor'ev, Institute of Solar-Terrestrial Physics (Russia); L. V. Antoshkin, N. N. Botugina, O. N. Emaleev, P. A. Konyaev, Institute of Atmospheric Optics (Russia); P. G. Kovadlo, Institute of Solar-Terrestrial Physics (Russia); N. P. Krivolutskiy, L. N. Lavrionova, Institute of Atmospheric Optics (Russia); V. I. Skomorovski, Institute of Solar-Terrestrial Physics (Russia)
- 7015 6U **Solar adaptive optics system at the Hida Observatory** [7015-249]
N. Miura, Y. Noto, S. Kato, S. Kuwamura, Kitami Institute of Technology (Japan); N. Baba, Hokkaido Univ. (Japan); Y. Hanaoka, National Astronomical Observatory of Japan (Japan); S. Nagata, S. Ueno, R. Kitai, Hida Observatory, Kyoto Univ. (Japan); H. Takami, Subaru Telescope, National Astronomical Observatory of Japan (United States)

POSTERS: AO MODELLING

- 7015 6V **Disaggregation of Preisach hysteresis model and nonlinear function least-squares fit** [7015-252]
D. Maciucă, G. Vasudevan, Lockheed Martin Space Systems Co. (United States)
- 7015 6Y **Performance of Monte-Carlo simulation of adaptive optics systems of the EAGLE multi-IFU instrument for E-ELT** [7015-255]
A. G. Basden, T. Butterley, M. A. Harrison, T. J. Morris, R. M. Myers, R. W. Wilson, E. Younger, Durham Univ. (United Kingdom); T. Fusco, ONERA (France); B. Le Roux, Observatoire Astronomique de Marseille-Provence (France); B. Neichel, Observatoire de Paris à Meudon (France)
- 7015 6Z **The software package SPHERE: a CAOS-based numerical tool for end-to-end simulations of SPHERE/VLT** [7015-256]
M. Carbillet, UMR 6525 H. Fizeau, Univ. de Nice Sophia-Antipolis, CNRS, Observatoire de la Côte d'Azur (France); A. Boccaletti, UMR 8109 LESIA, Observatoire de Meudon, CNRS (France); C. Thalmann, Institute of Astronomy, ETH Zürich (Switzerland); T. Fusco, ONERA, DOTA/E, Unite OASO (France); A. Vigan, UMR 6110 LAM, Observatoire Astronomique de Marseille Provence, Univ. de Provence/CNRS (France); I. Smith, UMR 6525 H. Fizeau, Univ. de Nice Sophia-Antipolis, CNRS, Observatoire de la Côte d'Azur (France); D. Mouillet, Lab. d'Astrophysique de l'Observatoire de Grenoble (France); K. Dohlen, UMR 6110 LAM, Observatoire Astronomique de Marseille Provence, Univ. de Provence, CNRS (France); P. Bendjoya, A. Ferrari, UMR 6525 H. Fizeau, Univ. de Nice Sophia-Antipolis, CNRS, Observatoire de la Côte d'Azur (France) (France)
- 7015 71 **Off-axis point spread function reconstruction from a dual deformable mirror adaptive optics system** [7015-258]
O. Keskin, R. Conan, C. Bradley, C. Blain, Univ. of Victoria (Canada)
- 7015 72 **Adaptive optics simulations for the European Extremely Large Telescope** [7015-259]
R. M. Clare, M. Le Louarn, S. Oertel, A. Garcia-Rissmann, European Southern Observatory (Germany)
- 7015 73 **PSD-based simulation algorithm for Wide FoV AO design: application to ELT studies** [7015-260]
B. Neichel, T. Fusco, J.-M. Conan, C. Petit, ONERA (France) and Groupement d'Intérêt Scientifique PHASE (France); G. Rousset, LESIA, Observatoire de Paris, CNRS, UPMC, Univ. Paris Diderot (France) and Groupement d'Intérêt Scientifique PHASE (France)

Author Index

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- 1 Astronomical Science with Adaptive Optics
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 David Mouillet, Laboratoire d'Astrophysique de l'Observatoire de
 Grenoble (France)
- 2 Astronomical Science Techniques
 Frank Eisenhauer, Max-Planck-Institut für extraterrestrische Physik
 (Germany)
 Anne-Marie Lagrange, Laboratoire d'Astrophysique de l'Observatoire
 de Grenoble (France)
- 3 AO Demonstrators and Field Tests
 Donald T. Gavel, UCO/Lick Observatory, University of California, Santa
 Cruz (United States)
 Enrico Marchetti, European Southern Observatory (Germany)
- 4 Laser Technology Development
 Domenico Bonaccini Calia, European Southern Observatory
 (Germany)
 Yutaka Hayano, National Astronomical Observatory of Japan, Subaru
 Telescope (United States)
- 5 Adaptive Optics Correctors
 Armando Riccardi, Osservatorio Astrofisico di Arcetri (Italy)
 Norbert Hubin, European Southern Observatory (Germany)
- 6 Adaptive Optics for ELT
 Brent L. Ellerbroek, California Institute of Technology (United States)
 Norbert Hubin, European Southern Observatory (Germany)
- 7 Medium FoV Adaptive Optics (0.5-3')
 Thierry Fusco, ONERA (France)
 Peter L. Wizinowich, W. M. Keck Observatory (United States)
- 8 AO Programs and Facilities for Large Telescopes
 Hideki Takami, National Astronomical Observatory of Japan, Subaru
 Telescope (United States)
 Michael Lloyd-Hart, The University of Arizona, Steward Observatory
 (United States)

- 9 Laser Guide Star Facilities
Richard M. Myers, University of Durham (United Kingdom)
Yutaka Hayano, National Astronomical Observatory of Japan, Subaru Telescope (United States)
- 10 Adaptive Optics Fed Instrumentation and High Contrast Imaging I
Bruce A. Macintosh, Lawrence Livermore National Laboratory (United States)
- 11 Adaptive Optics Fed Instrumentation and High Contrast Imaging II
Douglas A. Simons, Gemini Observatory (United States)
- 12 Real time Control and Algorithms
Miska Le Louarn, European Southern Observatory (Germany)
Corinne Boyer, California Institute of Technology (United States)
- 13 Wavefront Sensing
Miska Le Louarn, European Southern Observatory (Germany)
Enrico Marchetti, European Southern Observatory (Germany)
- 14 High Contrast Imaging
Bruce A. Macintosh, Lawrence Livermore National Laboratory (United States)
Markus E. Kasper, European Southern Observatory (Germany)
- 15 Large Scale AO Initiatives
Peter L. Wizinowich, W. M. Keck Observatory (United States)
Jean-Pierre Véran, National Research Council Canada (Canada)
- 16 AO Modeling
Brent L. Ellerbroek, California Institute of Technology (United States)
Thierry Fusco, ONERA (France)
- 17 Wide FoV AO (5-10')
Donald T. Gavel, UCO/Lick Observatory, University of California, Santa Cruz (United States)
- 18 AO Postprocessing
David Le Mignant, W. M. Keck Observatory (United States)
Anne-Marie Lagrange, Laboratory d'Astrophysique de l'Observatoire de Grenoble (France)

High redshift galaxy surveys

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ABSTRACT

A brief overview on the current status of the census of the early universe population is given. Observational surveys of high redshift galaxies provide direct opportunities to witness the cosmic dawn and to have better understanding of how and when infant galaxies evolve into mature ones. It is a much more astronomical approach in contrast to the physical approach of to study the spatial fluctuation of cosmic microwave radiation. Recent findings in these two areas greatly advanced our understanding of the early Universe. I will describe the basic properties of several target objects we are looking for and the concrete methods astronomers are using to discover those objects in early Universe. My talk starts with Lyman α emitters and Lyman break galaxies, then introduces a clever approach to use gravitational lensing effect of clusters of galaxies to detect distant faint galaxies behind the clusters. Finally I will touch on the status and prospects of surveys for quasars and gamma-ray bursts.

Keywords: gamma ray burst, high redshift, Lyman α emitter, Lyman break galaxy, quasar, survey

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1. INTRODUCTION

Since the discovery of the expansion of the Universe by Edwin Hubble in 1929, astronomers with ever more powerful telescopes surveyed the sky to find more and more distant galaxies. By studying distant galaxies, one can look back the early history of the Universe. Partridge and Peebles¹, in their classical 1967 paper, predicted the properties of primordial galaxies and pointed out that these galaxies with redshifted Lyman α emission are the targets observational astronomers should look for. Many attempts followed using 4m class telescopes for next three decades. This was, however, not an easy task².

Astronomers of this decade developed various techniques to isolate distant objects; narrow band imaging surveys for Lyman α emitting galaxies³⁻²⁸, multi-band photometric surveys for Lyman break galaxies²⁹⁻³⁸, searches for amplified images of gravitationally lensed galaxies³⁹⁻⁴⁷, quasars⁴⁸⁻⁵⁴ and studies of sporadic gamma ray bursts⁵⁵⁻⁵⁷ in high redshift galaxies. Galaxies up to redshift $z=6.96$ ¹⁸ were spectroscopically confirmed and there are additional candidate galaxies that appear to be at redshift $z>7$ ^{34-37,41,44,45}.

The current picture of the big bang Universe indicates that the expanding universe cooled rapidly to form neutral hydrogen from protons and electrons at 380,000 years after the big bang. This is the epoch when the photons are decoupled from the matter. The density fluctuation of the dark matter and the matter grew by gravitational interaction and it is conceived that the first generation of stars were born at around 200 million years after the big bang. Initial set of formed stars contained wide range of mass spectrum. The absence of metal elements in the primordial gas helped to form massive stars. Due to the strong UV radiation from those newly formed massive hot stars, the surrounding intergalactic matter was gradually re-ionized. A kind of “Global Warming of the Universe”. When and how these re-ionization process took place is not observationally clarified yet but WMAP5 results⁵⁹ suggest $z\sim 11$ if the re-ionization was an instantaneous event. It is more likely that the cosmic re-ionization could have taken place in an extended period sometime during $6 < z < 17$.

Detailed observations deep into the era beyond $z=7$ is, therefore, crucial. Some of the recent number counts of galaxies at $5.7 < z < 7$ indicate significant decrease in the number density of Lyman α emitting galaxies¹⁶⁻¹⁸, which could either be

due to the evolution of galaxies possibly through merging processes or due to the increasing fraction of neutral hydrogen blocking Lyman α emitting galaxies at high redshift.

I will describe the target population of galaxies in the early Universe and the technique astronomers are employing to find those objects together with some recent results.

2. NARROW BAND SURVEY FOR LYMAN α EMITTERS

What are Lyman α emitters, that are often abbreviated as LAEs? They are thought to be star-forming young galaxies with star formation rate from 1 to 10 solar mass per year. Hot massive stars produce strong UV radiation field and ionize the interstellar gas. The ionized hydrogen recombines and cools by emitting a Lyman α photon to settle down to the lowest ground level. The amount of stars produced in these galaxies is not yet very large as the usual continuum radiation from stars is not necessarily conspicuous. The spectra of LAEs are therefore characterized by strong Lyman- α emission line as shown in Fig.1.

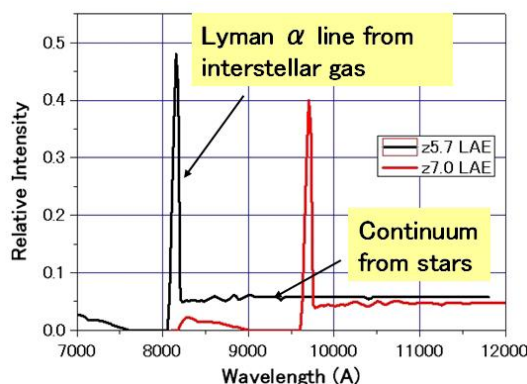


Fig. 1. Typical spectra of Lyman- α emitters showing conspicuous Lyman α emission lines.

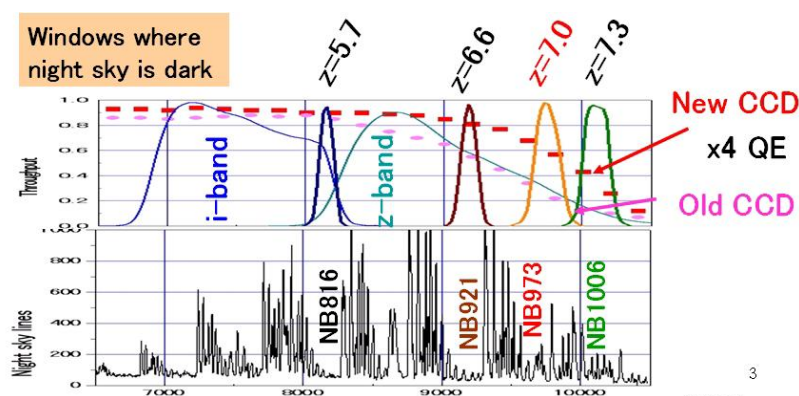


Fig. 2. OH night sky emission bands (lower panel) show a few gaps, which astronomers use as dark windows to study deep into the Universe. Narrow band filters whose transmission are matched to these dark windows are used to sample LAEs at $z=5.7$ (NB816), $z=6.6$ (NB921) and $z=7.0$ (NB973). The current CCD sensitivity falls rapidly toward 1000nm but recently developed high-resistivity, red-sensitive CCDs open a possibility to extend the accessible redshift limit up to $z=7.3$.

How to find those LAEs? It would be natural to catch the Lyman α emission line signal from these galaxies. Since these objects are so faint, one has to consider the properties of the sky background, actually foreground radiation from the Earth's atmosphere. The night sky glows ever brighter at longer wavelength. In the wavelength region below 1 micron, where Si-CCDs are sensitive, the night sky spectrum shows strong bands of OH emission lines as shown in the lowest panel of Fig.2. The gaps between these OH bands are nice dark windows to probe deep space.

Astronomers use narrow band filters whose transmittance bands are matched to one of these gaps to pick up light only in this gap to detect LAEs whose redshifted Lyman α emission enters in this gap. LAEs at appropriate redshift range are expected to show up brighter in the narrow band image than other broad band images. The narrow band (NB) survey is therefore trying to slice the universe in a narrow range of redshift. There are several such gaps, for instance, the narrow band filter NB816 that has the central wavelength at 816nm is suitable for isolating LAEs at redshift 5.7, NB921nm for redshift 6.6, etc. The most distant LAE at redshift 7.0 confirmed to date was also discovered using the narrow band imaging survey using a filter centered at 973nm. The sensitivity of current CCDs falls rapidly toward 1 micron but recent advent of red sensitive CCDs with thicker depletion layer will extend this redshift limit slightly up to about 7.3.

Let me talk on our discovery of the most distant galaxy. The red blob in the left panel of Fig. 3 shows the most distant galaxy, IOK-1¹⁸. This LAE was discovered among the 41,533 objects in the Subaru Deep Field through the narrow band filter NB973 for a total of 15 hours with SuprimeCam⁵⁸. All the objects were cross identified in images taken in other filters and only five photometric candidates for $z=7$ LAEs, which are visible only in this narrow band filter, were isolated (cf. Fig.4). Astronomers have a privilege to name their newly found objects and we took a liberty of naming them taking the initials of three main contributors to this survey, IOK-1 to IOK-5.

We have to be, however, careful as there are several types of possible contaminants in these 5-sigma photometric candidates. First, since the narrow band imaging observation was made 1-2 year after other broad band observations, some of the candidates may well be variable objects like AGNs or galaxies where supernovae added extra light when narrow band observation was made. Possibility for emission line objects at lower redshift is a common concern. To our surprise, simple statistics cautions us that there might be one or two 5 sigma noises as well, since there are millions of independent 2 arcsec apertures one can sample in the SuprimeCam field. Spectroscopic follow-up revealed that only one object, the brightest IOK-1, is a real LAE at redshift 6.96, with the characteristic asymmetric line profile as shown in the right panel of Fig.3.

Table 1 shows the top 10 list of high redshift galaxies with spectroscopic redshift measurement, to the best of my knowledge. You may notice that 9 out of 10 were discovered by Subaru/SuprimeCam survey in the single Subaru Deep Field. This is because Subaru/SuprimeCam enables observation of large survey volume with significant depth. Hubble Ultra Deep Field imaging survey with ACS probes much deeper than ground based observations, but has a much smaller survey volume. The wide field surveys to pick up scarce bright population and narrow field deep surveys to study fainter populations, are complementary to each other.

Subaru Deep Field surveys yielded several dozens of LAE candidates both at redshift 5.7 and 6.6 and about half of them are already confirmed spectroscopically to be LAEs. With this fair sample, one can derive the luminosity function of LAEs. The left panel of Fig.5 shows the UV continuum luminosity functions of LAEs at redshift 5.7 and 6.6 which are, more or less, identical. On the other hand, the right panel shows the Lyman α luminosity functions. We can see that the brighter population of LAEs at redshift 6.6 is significantly less abundant as compared to those at redshift 5.7.

This can be explained if the neutral hydrogen fraction of the intergalactic matter is increasing from redshift 5.7 to 6.6, as the neutral hydrogen selectively absorbs and scatters the Lyman α photons but not for UV continuum. The Ly- α luminosity functions, the UV luminosity functions, and the distribution of equivalent width of the LAEs can be reconciled with the presence of Pop III massive star formation followed by Pop II star formation to power Ly- α emission⁶⁰. Of course, the scarcity in LAEs at high redshift could also be due to the evolutionary history of those galaxies building from tiny proto galaxies. Cosmic variance could be another factor, if not significant to this level.

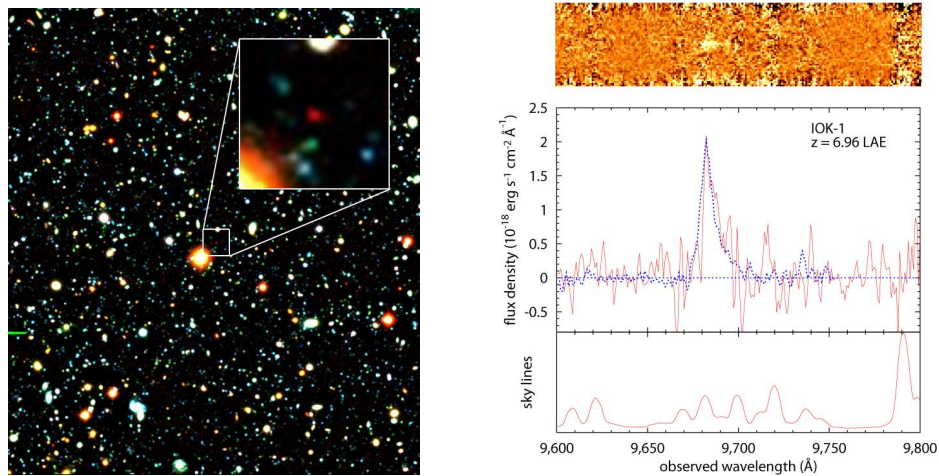


Fig. 3. (Left) The most distant galaxy IOK-1 is shown as a red blob in the inset panel. (Right) Spectrum of IOK-1 showing the characteristic Lyman α emission line with an asymmetric profile at 968nm indicating its redshift 6.96 (Right panel reproduced from Iye et al., 2006¹⁸).

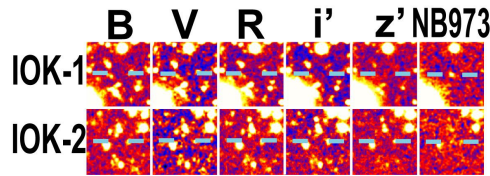


Fig. 4. Post stamp images of the NB973 objects IOK-1 and IOK-2. The latter was confirmed to be a 5-sigma noise (Edited from Ota et al., 2008²²).

Table 1: The most distant galaxies with measured redshift (as of June 6, 2008).

Rank	ID	Coordinates	z	Gyr [#]	Paper	Published date
1	IOK-1	J132359.8+272456	6.964	12.88	Iye et al.	Sep. 14, 2006
2	SDF ID1004	J132522.3+273520	6.597	12.82	Taniguchi et al.	Feb. 25, 2005
3	SDF ID1018	J132520.4+273459	6.596	12.82	Kashikawa et al.	Apr. 25, 2006
4	SDF ID1030	J132357.1+272448	6.589	12.82	Kashikawa et al.	Apr. 25, 2006
5	SDF ID1007	J132432.5+271647	6.580	12.82	Taniguchi et al.	Feb. 25, 2005
6	SDF ID1008	J132518.8+273043	6.578	12.82	Taniguchi et al.	Feb. 25, 2005
6	SDF ID1001	J132418.3+271455	6.578	12.82	Kodaira et al.	Apr. 25, 2003
8*	HCM-6A	J023954.7-013332	6.560	12.82	Hu et al.	Apr. 1, 2002
9	SDF ID1059	J132432.9+273124	6.557	12.82	Kashikawa et al.	Apr. 25, 2006
10	SDF ID1003	J132408.3+271543	6.554	12.82	Taniguchi et al.	Feb.25, 2005

Table 1. Top 10 list of the most distant galaxies. .

In order to identify LAEs at $z > 7$, quite a few projects to make narrow band imaging surveys with near infrared cameras are under way or planned²³⁻²⁸. The field of view of infrared cameras is still considerably smaller than that of, e.g., SuprimeCam and the increasing night sky background make the infrared imaging survey very challenging if the LAE luminosity function is further declining from $z=6.6$ to further redshift.

3. TWO COLOR DIAGNOSIS FOR LYMAN BREAK GALAXIES

Another population of galaxies searched for in the early Universe is called Lyman Break Galaxies, abbreviated as LBGs. LBGs are thought to be fairly massive galaxies with evolved stellar population. Stellar continuum is much stronger than LAEs. Lyman α emission is less conspicuous as compared with LAEs. The spectra of these galaxies show characteristic discontinuity at the blue side of Lyman α line caused by the intrinsic stellar atmospheric absorption and by the Intergalactic neutral hydrogen absorption. These galaxies, therefore, are visible at bands redward of Lyman α line but are not visible at bands blueward of the Lyman α line. One can select out LBG candidates at $z=6$ by i-band dropouts, $z=7$ by z' -band dropout, and $z=9$ by J-band dropouts.

Here again, one has to be careful for possible contaminants. Galactic T-dwarfs dwell in the similar region in two color diagram. One may be able to reject T-dwarfs by their point source images if the image quality is superb. Variable objects and 5 sigma noises are the common problems for this survey as well.

Hubble ACS and NICMOS imaging at Hubble Ultra Deep Field and GOODS field was used to identify faint z-dropouts at around $z=7.3$ and about 8 candidates were isolated, but similar attempt for J dropout didn't yield a candidate³⁷. Another group reported finding of 10 z-dropouts and 2 J-dropouts⁴⁶.

Unfortunately, many of these objects do not show strong Lyman α emission and spectroscopic confirmation of their genuine redshift is difficult.

4. SURVEY FOR STRONGLY LENSED GALAXIES

Let me turn to genius survey projects using the gravitational lensing effect of a massive cluster of galaxies to magnify and brighten the background faint galaxies. Cluster of galaxies are largest telescopes in the Universe with diameter about

1Mpc. They are nice telescopes for astronomers. You do not need to ask for funding agencies for construction budget and you do not need to ask engineers to design and build them. They are in situ and free of charge to use. Of course there are some drawbacks. You cannot point them to your favorite targets. Wavefront aberrations are bazaar. Although the images produced by cluster lensing are peculiarly deformed and enlarged, the largest advantage is the fact some of the lensed images are brightened considerably and when multiply lensed images are available they can be used to check for the consistency of their reconstructed source image.

Appropriate modeling of the gravitational field of the cluster enables the prediction of the location of critical lines for assumed source redshift slice where the magnification becomes infinity. Observers can look for lensed object along these critical lines and there are in fact several candidate galaxies found in this way³⁹⁻⁴⁷. For instance, a survey for strongly lensed LAEs in 9 clusters yielded six candidates⁴⁴. If any of these candidates are real, the number density of faint population of galaxies is much larger than previously considered and may well explain the necessary amount of re-ionizing source.

Fig.6 shows a promising z-dropout candidate at redshift 7.6 found behind the cluster Abel 1689 recently⁴⁵. Photometric results indicate better match to a galaxy at $z=7.6$, however, here again the possibility of galaxy at $z=1.7$ is hard to rule out just from imaging.

5. QUASARS AND GAMMA RAY BURSTERS

The last objects I am going to introduce are point sources, quasars and gamma ray bursts (GRBs), in the early Universe. The survey technique used to isolate high redshift quasar candidates is similar to that used for LBGs. Objects that match the expected spectral energy distribution of high redshift quasars are surveyed in the two color diagram or even a multi-dimension color manifold. Sloan Digital Sky Survey with its enormous data base is a nice test bed to apply this

approach. Many quasars beyond redshift 6 were found in this way⁴⁸⁻⁵². The most distant quasar to date is J1148+5251 at 6.42⁵¹. Gunn-Peterson test of quasars up to redshift 6 indicated strongly that the cosmic re-ionization ended by redshift 6.

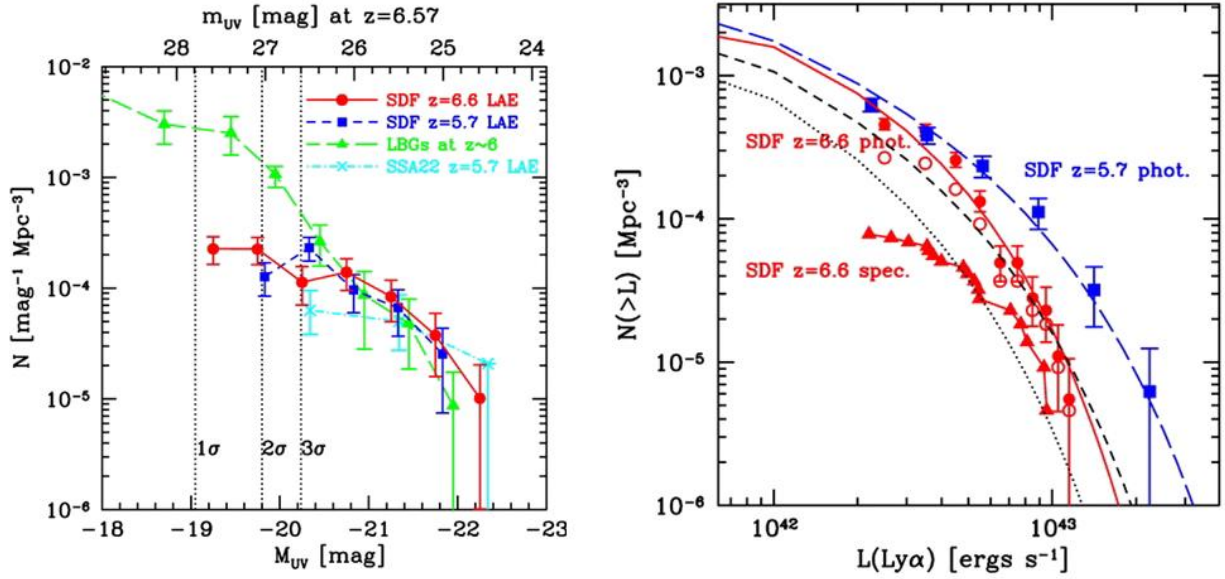


Fig. 5. (Left panel) UV continuum luminosity function of LAEs at $z=5.7$ (blue) and $z=6.6$ (red) which are more or less identical. (Right panel) Lyman α luminosity functions of LAEs at $z=5.7$ (blue) and $z=6.6$ (red). Note that the significant decrease in Lyman- α luminosity function at its bright end (Edited from Kashikawa et al., 2006¹⁷).

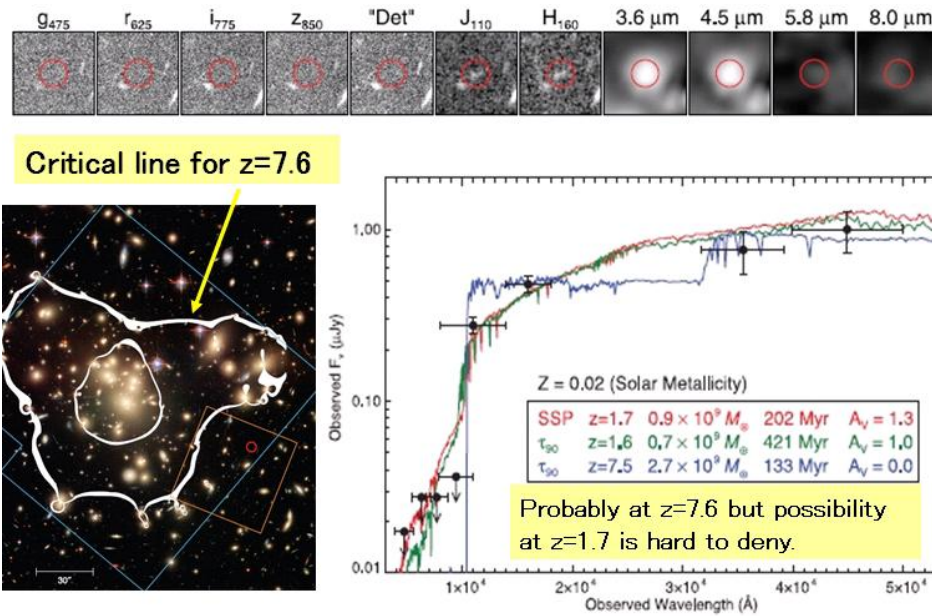


Fig.6. Lyman break galaxy candidate at $z \sim 7.6$ discovered behind the lensing cluster A1689 (Edited from Bradley et al. 2008⁴⁵).

The advent of the real time alert system of gamma ray burst increased the chance of optical and infrared astronomers to make prompt observations of these rapidly declining bursts. The most distant GRB observed to date is GRB050904 at $z=6.3$ ⁵⁵. GRBs at high redshift can be useful tools to probe the cosmic re-ionization through its Lyman- α damping wing⁵⁶.

GRB has a much simpler featureless continuum than the quasar spectra which has broad emission lines superposed on the non-thermal continuum. GRBs are, in a way, better probes to study the re-ionization history. Both quasars and GRBs are point sources, the advent of laser guide star adaptive optics makes the observation of fainter objects feasible and we expect many such observations if the observatories pay efforts for timely follow-up spectroscopy of long burst GRBs. GRBs may provide a new way to study even higher-redshift galaxies and first generation of stars.

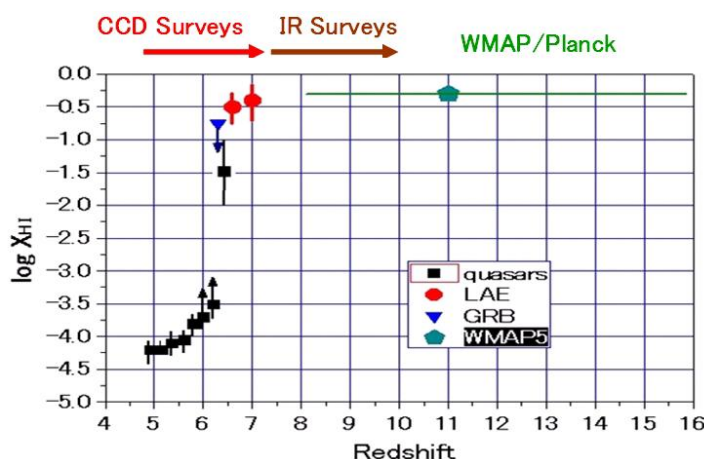


Fig. 7. Neutral hydrogen fraction of intergalactic matter as derived from Gunn-Peterson tests of $z>5$ quasars (black squares), damped Lyman- α wing profile (blue triangle), and Lyman α luminosity function (red circles). Also plotted is the WMAP 5 year result, which predict $z=11$ for instantaneous re-ionization. Note, however, that WMAP cannot constrain when re-ionization started and how long it took to complete.

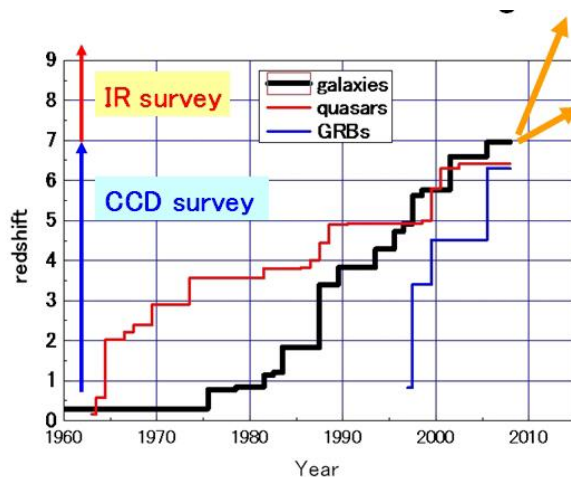


Fig.8. Growth history of largest redshift objects. Note that GRBs are catching up quickly (Based on Tanvir & Jakobsson, 2007⁵⁷)

Fig.7 shows the increase of the fraction of neutral hydrogen as measured from Gunn-Peterson tests⁵⁴ of quasars up to redshift 6.42 on the left hand. Our results from redshift 6.6 and 7.0 LAE is shown in red and an upper limit from redshift 6.3 GRB is shown in blue triangle. WMAP5 polarization study concludes that the cosmic re-ionization, if it took place instantaneously, would be at redshift around 11⁵⁹. However, WMAP results alone cannot pin down when the cosmic re-ionization started and how long it took to finish. Planck satellite may give more clue in 5 years time. Surveys for galaxies beyond redshift 7 up to 11 is, therefore, extremely important to elucidate what happened actually in this period and for that we need NIR deep surveys.

My last slide (Fig. 8) shows the annual growth of the records of highest redshift objects⁵⁷. The discovery of our $z=6.96$ galaxy was announced on Sep.14, 2006, 648 days ago. Simple statistical argument⁶¹ predicts that new record will come in, at 95% confidence level, at earliest in 17 days from today and at latest in 69 years. I am confident, however, that we do not need to wait so long as lots of new surveys are under way using near infrared cameras. Besides, observations of GRBs are catching up quickly, and considering the availability of innovated LGSAO, I would rather predict GRB will soon take over this race.

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