Draft version August 19, 2019
Preprint typeset using LaTeX style emulateapj v. 12/16/11

THE SIXTEENTH DATA RELEASE OF THE SLOAN DIGITAL SKY SURVEYS: FINAL RELEASE FROM THE EXTENDED BARYON OSCILLATION SPECTROSCOPIC SURVEY, AND FIRST RELEASE FROM APOGEE-2S

Víctor Silva Aguirre[1], Romina Ahumada[2], Carlos Allende Prieto[3,4], Andrés Almeida[5], Friedrich Anders[6,7], Scott F. Anderson[8], Brett H. Andrews[9], Borja Anguiano[10], Riccardo Arcodia[11], Marie Aubert[12], Santiago Avila[13,14], Vladimir Avila-Reese[15], Christophe Balland[16], Kat Barger[17], Sarbani Basu[18], Julian Bautista[19], Rachael L. Beaton[20], Timothy C. Beers[21], Chad F. Bender[22], Mariangela Bernardi[23], Matthew Bershady[24,25], Florian Beutler[19], Dmitry Bizyaev[26], Michael R. Blanton[27], Médéric Boquien[28], Jura Borissova[29,30], Jo Bovy[31,32], W.N. Brandt[33,34,35], Jonathan Brinkmann[26], Joel R. Brownstein[36], Kevin Bundy[37], Martin Bureau[38], Adam Burgasser[39], Mariana Cano-Díaz[15], Raffaella Capasso[40,41,42], Ricardo Carrera[43], Solène Chabanier[44], Brian Cherinka[45], Cristina Chiappini[6], Peter Doohyun Choi[46], Haeun Chung[47], Nicolas Clerc[48], Damien Coffey[11], Julia M. Comerford[49], Johan Comparat[11], Luiz da Costa[50,51], Marie-Claude Cousinou[12], Kevin Covey[52], Jeffrey D. Crane[20], Katia Cunha[51,22], Gabriele da Silva Ilha[53,50], Yu Sophia Dai[54], Sanna B. Damsted[55], Danny Horta Darrington[56], James W. Davidson Jr.[10], Kyle Dawson[36], Nikhil De[57,17], Axel de la Macorra[58], Nathan De Lee[59], Alice Deconto Machado[53,50], Sylvain de la Torre[60], Flavia Dell'Agli[3,4], Hélion du Mas des Bourboux[36], Aleksandar M. Diamond-Stanic[61], Sean Dillon[62,63], John Donor[17], Niv Drory[64], Chris Duckworth[65], Tom Dwelly[11], Garrett Ebelke[10], Arthur Davis Eigenbrot[24], Yvonne P. Elsworth[66], Mike Eracleous[33,34], Ghazaleh Erfanianfar[11], Stephanie Escoffier[12], Xiaohui Fan[22], Emily Farr[8], José G. Fernández-Trincado[67,68], Diane Feuillet[69], Alexis Finoguenov[55], Patricia Fofie[62,70], Amelia Fraser-McKelvie[71], Peter M. Frinchaboy[17], Sebastien Fromenteau[72], Hai Fu[73], Lluís Galbany[9], Rafael A. Garcia[44], D. A. García-Hernández[3,4], Luis Alberto Garma Oehmichen[15], Junqiang Ge[54], Marcio Antonio Geimba Maia[50,51], Doug Geisler[74,75,5], Joseph Gelfand[76], Julian Goddy[62], Jean-Marc Le Goff[44], Violeta Gonzalez-Perez[19], Kathleen Grabowski[26], Paul Green[77], Catherine J. Grier[22,33,34], Hong Guo[78], Julien Guy[79], Paul Harding[80], Sten Hasselquist[36,81], Adam James Hawken[12], Christian R. Hayes[10], Fred Hearty[33], S. Hekker[82,1], David W. Hogg[27], Jon Holtzman[83], Bau-Ching Hsieh[84], Daniel Huber[85], Jason A. S. Hunt[32], J. Ider Chitham[11], Julie Imig[83], Mariana Jaber[58], Camilo Eduardo Jimenez Angel[3,4], Jennifer A. Johnson[86], Amy Jones[87], Henrik Jönsson[88], Eric Jullo[60], Karen Kinemuchi[26], Charles C. Kirkpatrick IV[55], George W. Kite[19], Mark Klaene[26], Juna A. Kollmeier[20], Marina Kounkel[52], Dhanesh Krishnarao[24], Ivan Lacerna[67,89], Ting-Wen Lan[90], Richard R. Lane[91,30], David R. Law[45], Henry W. Leung[31], Hannah Lewis[10], Cheng Li[92], Jianhui Lian[19], Lihwai Lin (林俐暉)[84], Dan Long[26], Penélope Longa-Peña[28], Britt Lundgren[93], Brad W. Lyke[94], Steven R. Majewski[10], Arturo Manchado[3,4,95], Claudia Maraston[19], Paul Martini[86,96], Thomas Masseron[3,4], Karen L. Masters (何凱論)[62,19,97], Savita Mathur[3,4], Richard M. McDermid[98], Andrea Merloni[11], Michael Merrifield[71], Szabolcs Meszaros[99], Dante Minniti[100,30,101], Rebecca Minsley[61], Takamitsu Miyaji[102], Benoit Mosser[103], Eva-Maria Mueller[38,19],e Demitri Muna[86], Andrea Muñoz-Gutiérrez[58], Adam D. Myers[94], Preethi Nair[87], Rebecca Jean Nevin[49], Jeffrey A. Newman[9], David L. Nidever[104,105], Christian Nitschelm[28], Pasquier Noterdaeme[106], Julia E. O'Connell[74,17], Matthew D Olmstead[107], Daniel Oravetz[26], Yeisson Osorio[3,4], Zachary J. Pace[24], Nelson Padilla[91], Pedro A. Palicio[3,4], Hsi-An Pan[84], Kaike Pan[26], James Parker[26], Romain Paviot[60,12], Sebastien Peirani[106], Karla Peña Ramŕez[28], Samantha Penny[19], Will J. Percival[108,109], Ignasi Pérez-Ràfols[60], Patrick Petitjean[106], Matthew M. Pieri[60], Marc Pinsonneault[96], Vijith Jacob Poovelil[36], Adrian M. Price-Whelan[110,111], M. Jordan Raddick[112], Anand Raichoor[113], Amy Ray[17], Sandro Barboza Rembold[53,50], Rogemar A. Riffel[50,53], Rogério Riffel[114,50], Hans-Walter Rix[69], Annie C. Robin[68], A. Roman-Lopes[75], Carlos Román-Zúñiga[15], Benjamin Rose[45], Ashley J. Ross[96], Graziano Rossi[46], Kate Rowlands[112], Kate H. R. Rubin[115], Mara Salvato[11], Ariel G. Sánchez[11], Laura Sánchez-Menguiano[3,4], Alex Saro[116,117,42], Conor Sayres[8], Adam Schaefer[24], Ricardo P. Schiavon[56], Edward Schlafly[79], David Schlegel[79], Donald Schneider[34,33], Axel Schwope[6], Hee-Jong Seo[118], Aldo Serenelli[119,120], Shoaib Jamal Shamsi[62], Zhengyi Shao[78], Matthew Shetrone[64], Raphael Shirley[3,4], Joshua D. Simon[20], M. F. Skrutskie[10], Rebecca Smethurst[38], Jennifer Sobeck[8], Bernardo Cervantes Sodi[121], Diogo Souto[51,122], David V. Stark[90], Keivan G. Stassun[59], Dennis Stello[123], Julianna Stermer[16], Thaisa Storchi-Bergmann[114,50], Alina Streblyanska[3,4] Guy S. Stringfellow[49], Amelia Stutz[74], Genaro Suárez[102], Jing Sun[17], Manuchehr Taghizadeh-Popp[112], Michael S. Talbot[36], Jamie Tayar[85], Aniruddha R. Thakar[112], Daniel Thomas[19], Zak C. Thomas[19], Hector Hernandez Toledo[15], Christy A. Tremonti[24], Nicholas W. Troup[10], Sarah Tuttle[8], Marica Valentini[6], Jaime Vargas-González[124], Jose Antonio Vázquez-Mata[15], M. Vivek[33], David Wake[93], Yuting Wang[54], Benjamin Alan Weaver[105], Anne-Marie Weijmans[65], Vivienne Wild[65], John C. Wilson[10], Robert F. Wilson[10], Nathan Wolthuis[62], W. M. Wood-Vasey[9], Renbin Yan[125], Meng Yang[65], Christophe Yèche[44], Olga Zamora[3,4], Gail Zasowski[36], Kai Zhang[79], Cheng Zhao[113], Zheng Zheng[36], Zheng Zheng[54], Guangtun Zhu[112], Hu Zou[54]

Draft version August 19, 2019

Abstract

This paper documents the sixteenth data release (DR16) from the Sloan Digital Sky surveys overall, and the fourth from the fourth phase (SDSS-IV). This is the last data release which contains data (spectra and redshifts) from the Extended Baryon Oscillation Spectroscopic Survey (eBOSS). DR16 also includes the first data from the Apache Point Observatory Galactic Evolution Explorer 2 (APOGEE-2) Southern Observing, as well as more data from APOGEE-2 in the North. There is also the final data from the Time Domain Spectroscopic Survey (TDSS) and new data from the

SPectroscipic IDentification of ERosita (SPIDERS). There is no new data from the Mapping Nearby Galaxies at Apache Point Observatory (MaNGA) survey (or the MaNGA Stellar Library "MaStar") in this data release.

Subject headings: Atlases — Catalogs — Surveys

1. INTRODUCTION

The Sloan Digital Sky Surveys (SDSS) have been observing the skies from Apache Point Observatory (APO) since 1998 (using the Sloan 2.5m Telescope (Gunn et al.

spokesperson@sdss.org
[1] Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark
[2] Instituto de Astronomía, Universidad Católica del Norte, Av. Angamos 0610, Antofagasta, Chile
[3] Instituto de Astrofísica de Canarias (IAC), C/ Via Láctea s/n, E-38205 La Laguna, Tenerife, Spain
[4] Universidad de La Laguna (ULL), Departamento de Astrofísica, E-38206 La Laguna, Tenerife Spain
[5] Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, Universidad de La Serena. Avenida Raúl Bitrán S/N, La Serena, Chile
[6] Leibniz-Institut fur Astrophysik Potsdam (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany
[7] Institut de Ciències del Cosmos, Universitat de Barcelona (IEEC-UB), Carrer Martí i Franquès 1, 08028 Barcelona, Spain
[8] Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195, USA
[9] PITT PACC, Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA
[10] Department of Astronomy, University of Virginia, Charlottesville, VA 22904-4325, USA
[11] Max-Planck-Institut für extraterrestrische Physik, Gießenbachstraße 1, 85748 Garching, Germany
[12] Aix Marseille Université, CNRS/IN2P3, CPPM, Marseille, France
[13] Departamento de Física Teórica, Facultad de Ciencias, Universidad Autónoma de Madrid, 28049 Cantoblanco, Madrid, Spain
[14] Instituto de Física Teórica, UAM-CSIC, Universidad Autonoma de Madrid, 28049 Cantoblanco, Madrid, Spain
[15] Instituto de Astronomía, Universidad Nacional Autónoma de México, A.P. 70-264, 04510, Mexico, D.F., México
[16] Sorbonne Université, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), 4 Place Jussieu, F-75252 Paris, France
[17] Department of Physics & Astronomy, Texas Christian University, Fort Worth, TX 76129, USA
[18] Yale Center for Astronomy and Astrophysics, Yale University, New Haven, CT, 06520, USA
[19] Institute of Cosmology & Gravitation, University of Portsmouth, Dennis Sciama Building, Portsmouth, PO1 3FX, UK
[20] The Observatories of the Carnegie Institution for Science, 813 Santa Barbara Street, Pasadena, CA 91101, USA
[21] Department of Physics and JINA Center for the Evolution of the Elements, University of Notre Dame, Notre Dame, IN 46556, USA
[22] Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721-0065, USA
[23] Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA
[24] Department of Astronomy, University of Wisconsin-Madison, 475N. Charter St., Madison WI 53703, USA
[25] South African Astronomical Observatory, P.O. Box 9, Observatory 7935, Cape Town, South Africa
[26] Apache Point Observatory, P.O. Box 59, Sunspot, NM 88349
[27] Center for Cosmology and Particle Physics, Department of Physics, 726 Broadway, Room 1005, New York University, New York, NY 10003, USA
[28] Centro de Astronomía (CITEVA), Universidad de Antofagasta, Avenida Angamos 601, Antofagasta 1270300, Chile
[29] Instituto de Física y Astronomía, Universidad de Valparaíso, Av. Gran Bretaña 1111, Playa Ancha, Casilla 5030, Chile
[30] Millennium Institute of Astrophysics (MAS), Santiago, Chile
[31] Department of Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON, M5S 3H4, Canada
[32] Dunlap Institute for Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto, Ontario M5S 3H4, Canada
[33] Department of Astronomy and Astrophysics, Eberly College of Science, The Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802, USA
[34] Institute for Gravitation and the Cosmos, Pennsylvania State University, University Park, PA 16802, USA
[35] Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA
[36] Department of Physics and Astronomy, University of Utah, 115 S. 1400 E., Salt Lake City, UT 84112, USA
[37] UCO/Lick Observatory, University of California, Santa Cruz, 1156 High St. Santa Cruz, CA 95064, USA
[38] Sub-department of Astrophysics, Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH
[39] Center for Astrophysics and Space Science, University of California San Diego, La Jolla, CA 92093, USA
[40] Faculty of Physics, Ludwig-Maximilians-Universität, Scheinerstr. 1, 81679 Munich, Germany
[41] Excellence Cluster Universe, Boltzmannstr. 2, 85748 Garching, Germany
[42] INAF-Osservatorio Astronomico di Trieste, via G. B. Tiepolo 11, I-34143 Trieste, Italy
[43] Astronomical Observatory of Padova, National Institute of Astrophysics, Vicolo Osservatorio 5 - 35122 - Padova
[44] IRFU, CEA, Université Paris-Saclay, F91191 Gif-sur-Yvette, France
[45] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[46] Department of Physics and Astronomy, Sejong University, 209, Neungdong-ro, Gwangjin-gu, Seoul, South Korea
[47] Korean Institute for Advanced Study, 85 Hoegiro, Dongdaemun-gu, Seoul 130-722, Republic of Korea
[48] IRAP Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, CNRS, UPS, CNES, Toulouse, France
[49] Center for Astrophysics and Space Astronomy, Department of Astrophysical and Planetary Sciences, University of Colorado, 389 UCB, Boulder, CO 80309-0389, USA
[50] Laboratório Interinstitucional de e-Astronomia, 77 Rua General José Cristino, Rio de Janeiro, 20921-400, Brasil
[51] Observatório Nacional, Rio de Janeiro, Brasil
[52] Department of Physics and Astronomy, Western Washington University, 516 High Street, Bellingham, WA 98225, USA
[53] Departamento de Física, CCNE, Universidade Federal de Santa Maria, 97105-900, Santa Maria, RS, Brazil
[54] National Astronomical Observatories of China, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, China
[55] Department of Physics, University of Helsinki, Gustaf Hällströmin katu 2a, FI-00014 Helsinki, Finland
[56] Astrophysics Research Institute, Liverpool John Moores University, IC2, Liverpool Science Park, 146 Brownlow Hill, Liverpool L3 5RF, UK
[57] Fort Worth Country Day, Fort Worth, TX 76109
[58] Instituto de Física Universidad Nacional Autónoma de México, Apdo. Postal 20-364, México
[59] Department of Physics and Astronomy, Vanderbilt University, VU Station 1807, Nashville, TN 37235, USA
[60] Aix Marseille Université, CNRS, LAM, Laboratoire d'Astrophysique de Marseille, Marseille, France
[61] Department of Physics and Astronomy, Bates College, 44 Campus Avenue, Lewiston ME 04240, USA

2006)) and from Las Campanas Observatory (LCO) since 2017 (using the du Pont Telescope).

Now in its fourth phase (Blanton et al. 2017), SDSS-IV consists of three main surveys; the Extended Baryon Oscillation Spectroscopic Survey (eBOSS; Dawson et al. 2016), Mapping Nearby Galaxies at APO (MaNGA; Bundy et al. 2015), and the APO Galactic Evolution Explorer 2 (APOGEE-2; Majewski et al. 2017). Within eBOSS, SDSS-IV has also conducted two smaller programs: the SPectroscopic IDentification of ERosita Sources (SPIDERS; Clerc et al. 2016; Dwelly et al. 2017) and the Time Domain Spectroscopic Survey (TDSS; Morganson et al. 2015). These programs have investigated a broad range of cosmological scales, including large-scale cosmology in eBOSS, the population of quasars and variable or X-ray-emitting stars with TDSS

[62] Department of Physics and Astronomy, Haverford College, 370 Lancaster Ave, Haverford, PA 19041
[63] Department of Physics, Chico State University, 400 W 1st St, Chico, CA 95929, USA
[64] McDonald Observatory, The University of Texas at Austin, 1 University Station, Austin, TX 78712, USA
[65] School of Physics and Astronomy, University of St Andrews, North Haugh, St. Andrews KY16 9SS, UK
[66] School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
[67] Instituto de Astronomía y Ciencias Planetarias, Universidad de Atacama, Copayapu 485, Copiapó, Chile
[68] The Observatoire des sciences de l'Universit/'e de Besançon, 41 Avenue de l'Observatoire, 25000 Besançon, France
[69] Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
[70] Astronomy Department, Williams College, Williamstown, MA, 01267, USA
[71] School of Physics and Astronomy, University of Nottingham, University Park, Nottingham, NG7 2RD, UK
[72] Instituto de Ciencias Fśicas (ICF), Universidad Nacional Autónoma de México, Av. Universidad s/n, Col. Chamilpa, Cuernavaca, Morelos, 62210, México
[73] Department of Physics & Astronomy, University of Iowa, Iowa City, IA 52245, USA
[74] Departmento de Astronomía, Universidad de Concepción, Casilla 160-C, Concepción, Chile
[75] Departamento de Física y Astronomía, Facultad de Ciencias, Universidad de La Serena. Av. Juan Cisternas 1200, La Serena, Chile
[76] NYU Abu Dhabi, PO Box 129188, Abu Dhabi, UAE
[77] Harvard-Smithsonian Center for Astrophysics, 60 Garden St., MS 20, Cambridge, MA 02138, USA
[78] Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China
[79] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
[80] Department of Astronomy, Case Western Reserve University, Cleveland, OH 44106, USA
[81] NSF Astronomy and Astrophysics Postdoctoral Fellow, USA
[82] Max Planck Institute for Solar System Research, SAGE research group, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany
[83] Department of Astronomy, New Mexico State University, Las Cruces, NM 88003, USA
[84] Academia Sinica Institute of Astronomy and Astrophysics, P.O. Box 23-141, Taipei 10617, Taiwan
[85] Institute for Astronomy, University of Hawai'i, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
[86] Department of Physics and Center for Cosmology and AstroParticle Physics, The Ohio State University, Columbus, OH 43210, USA
[87] Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA
[88] Lund Observatory, Department of Astronomy and Theoretical Physics, Lund University, Box 43, SE-22100 Lund, Sweden
[89] Instituto Milenio de Astrofísica, Av. Vicuña Mackenna 4860, Macul, Santiago, Chile
[90] Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa 277-8583, Japan
[91] Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Av. Vicuna Mackenna 4860, 782-0436 Macul, Santiago, Chile
[92] Tsinghua Center of Astrophysics & Department of Physics, Tsinghua University, Beijing 100084, China
[93] Department of Physics, University of North Carolina Asheville, One University Heights, Asheville, NC 28804, USA
[94] Department of Physics and Astronomy, University of Wyoming, Laramie, WY 82071, USA
[95] CSIC, Spain
[96] Department of Astronomy, The Ohio State University, 140 W. 18th Ave., Columbus, OH 43210, USA
[97] SDSS-IV Spokesperson
[98] Department of Physics and Astronomy, Macquarie University, Sydney NSW 2109, Australia
[99] ELTE Gothard Astrophysical Observatory, H-9704 Szombathely, Szent Imre herceg st. 112, Hungary
[100] Departamento de Ciencias Fisicas, Facultad de Ciencias Exactas, Universidad Andres Bello, Av. Fernandez Concha 700, Las Condes, Santiago, Chile
[101] Vatican Observatory, V00120 Vatican City State, Italy
[102] Instituto de Astronomía, Universidad Nacional Autónoma de México, Ensenada, Baja California, México
[103] LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris, 5 place Jules Janssen, 92195 Meudon, France
[104] Department of Physics, Montana State University, P.O. Box 173840, Bozeman, MT 59717-3840, USA
[105] National Optical Astronomy Observatory, 950 North Cherry Avenue, Tucson, AZ 85719, USA
[106] Institut d'Astrophysique de Paris, UMR 7095, SU-CNRS, 98bis bd Arago, 75014 Paris, France
[107] King's College, 133 North River St, Wilkes Barre, PA 18711, USA
[108] Waterloo Centre for Astrophysics, Department of Physics and Astronomy, University of Waterloo, Waterloo, ON N2L 3G1, Canada
[109] Perimeter Institute for Theoretical Physics, Waterloo, ON N2L 2Y5, Canada
[110] Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA
[111] Center for Computational Astrophysics, Flatiron Institute, 162 Fifth Avenue, New York, NY, 10010
[112] Center for Astrophysical Sciences, Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218, USA
[113] Institute of Physics, Laboratory of Astrophysics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Observatoire de Sauverny, 1290 Versoix, Switzerland
[114] Departamento de Astronomia, Instituto de Física, Universidade Federal do Rio Grande do Sul. Av. Bento Goncalves 9500, 91501-970, Porto Alegre, RS, Brasil
[115] Department of Astronomy, San Diego State University, San Diego, CA 92182, USA
[116] Astronomy Unit, Department of Physics, University of Trieste, via Tiepolo 11, I-34131 Trieste, Italy
[117] IFPU - Institute for Fundamental Physics of the Universe, Via Beirut 2, 34014 Trieste, Italy
[118] Department of Physics and Astronomy, Ohio University, Clippinger Labs, Athens, OH 45701
[119] Institute of Space Sciences (ICE, CSIC), Carrer de Can Magrans S/N, Campus UAB, Barcelona, E-08193, Spain
[120] Institut d'Estudis Espacials de Catalunya, C/Gran Capita, 2-4, E-08034, Barcelona, Spain
[121] Instituto de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Campus Morelia, A.P. 3-72, C.P. 58089 Michoacán, México
[122] Departamento de Física, Universidade Federal de Sergipe, Av. Marechal Rondon, S/N, 49000-000 São Cristóvão, SE, Brazil
[123] School of Physics, UNSW Sydney, NSW 2052, Australia
[124] Centre for Astrophysics Research, School of Physics, Astronomy and Mathematics, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK
[125] Department of Physics and Astronomy, University of

and SPIDERS, nearby galaxies in MaNGA, and the Milky Way and its stars in APOGEE-2.

This paper documents the sixteenth data release from SDSS (DR16) in a series that began in 2001 (Stoughton et al. 2002). It is the fourth from SDSS-IV (following DR13: Albareti et al. 2017; DR14: Abolfathi et al. 2018 and DR15: Aguado et al. 2019). DR16 contains two important milestones:

- It contains the final data from eBOSS, completing that redshift survey. DR16 therefore marks the end of a twenty-year stretch during which SDSS was continuously performing a redshift survey of the universe, producing the largest catalog of spectroscopic galaxy redshifts by a factor of ten. DR16 has **DETERMINE THE NUMBER** redshifts of unique galaxies.

- It contains the first data from APOGEE-2S, which is mapping the Milky Way from the du Pont Telescope at LCO, in the southern hemisphere. The SDSS facilities are now operating in two hemispheres, yielding a view of all of the components of the Milky Way.

paragraph highlighting other smaller things, TBD from other sections

2. SCOPE OF DR16

DR16 is a cumulative data release, following the tradition of previous SDSS data releases. This means that all previous data releases are included in DR16, and data products and catalogs of these previous releases will remain accessible on our data servers. However, we strongly advise to always use the most recent SDSS data release, as data will have been reprocessed using updated data reduction pipelines, and catalogs may have been updated with new entries and/or improved analysis methods. Any of these changes between DR16 and previous data releases are documented in this paper and on the DR16 website `https://www.sdss.org/dr16`.

The content of DR16 is given by the following sets of data products:

1. eBOSS is releasing X new optical spectra of galaxies and quasars with respect to its previous SDSS data release. These targets were observed between MJD X and Y (real dates), and bring the total number of spectra observed by eBOSS to X. This number includes spectra observed as part of the TDSS and SPIDERS sub-surveys, as well as the spectra taken as part of the eBOSS reverberation mapping ancillary program. All spectra, whether released previously or for the first time in this data release have been processed using the latest version of the eBOSS data reduction pipeline X. In addition to the spectra, eBOSS is also releasing catalogs of redshifts, as well as various value-added catalogs. DR16 is the last SDSS data release that will contain new eBOSS spectra, as this survey has now finished.

2. APOGEE-2 is including X new infrared spectra of mostly stars in the Milky Way, as well as X. This includes X spectra observed with APOGEE-2South at Las Campanas Observatory in Chile, mostly covering targets X. These new spectra were taken between MJD X and Y (real dates) for APOGEE-2North (Apache Point Observatory), and MJD X and Y (real dates) for APOGEE-2South. DR16 also includes all previously released APOGEE and APOGEE-2 spectra, which have been re-reduced with the latest version of the APOGEE data reduction and analysis pipeline. In addition to the reduced spectra, element abundances and stellar parameters are included in this data release. APOGEE-2 is also releasing a number of value-added catalogs.

3. MaNGA and MaStar not releasing any new spectra in this data release, and the spectra and data products included in DR16 are therefore identical to the ones that were released in DR15. However, MaNGA is contributing a number of value-added catalogs in DR16, that are based on the DR15 sample and data products.

4. As mentioned before, since SDSS data releases are cumulative, DR16 also includes data from all previous SDSS data releases. The eBOSS **ALSO BOSS?, APOGEE and APOGEE-2 spectra that were previously released have all been reprocessed with the latest reduction and analysis pipelines. The MaNGA and MaStar data were last updated in DR15 (Aguado et al. 2019), and the SDSS-III MARVELS spectra were finalised in DR12 (?). SDSS Legacy Spectra were released in its final form in DR8 (?), and the SEGUE-1 and SEGUE-2 surveys had their final reductions released with DR9 (?). The SDSS imaging had its most recent release in DR13 (Albareti et al. 2017), when it was recalibrated for eBOSS imaging purposes. IS THIS TRUE?**

An overview of the total content of DR16, with number of spectra included, is given in Table 1 **QUESTION FROM KLM: Do we like the history - going from DR13 numbers to cumulative DR16, or want to cut this down? AMW: I kind of like to see the progression here. If possible, also include RM as I mention these above?**. An overview of the value-added catalogs that are new or updated in DR16 can be found in Table 2; adding these to the VACs previously released in SDSS, the total number of VACs in DR16 is X.

3. DATA ACCESS

Will contain links to SAS and CAS. Make clear how to see difference between APOGEE-2 North and South. Links to value added catalogs. Links to APOGEE-2 and eBOSS spectra in SAW, repeat that MaStar also available here. Marvin to access MaNGA data. Highlight that there will be some more MaNGA VACs included into Marvin. Although not data access as such, men-

Kentucky, 505 Rose St., Lexington, KY, 40506-0055, USA

TABLE 1
Reduced SDSS-IV spectroscopic data in DR16

Target Category	# DR13	# DR13+14	# DR13+14+15	# DR13+14+15+16
eBOSS				
LRG samples	32968	138777	138777	
ELG Pilot Survey	14459	35094	35094	
Main QSO Sample	33928	188277	188277	
Variability Selected QSOs	22756	87270	87270	
Other QSO samples	24840	43502	43502	
TDSS Targets	17927	57675	57675	
SPIDERS Targets	3133	16394	16394	
Standard Stars/White Dwarfs	53584	63880	63880	
APOGEE-2				
All Stars	164562	263444	263444	
NMSU 1-meter stars	894	1018	1018	
Telluric stars	17293	27127	27127	
APOGEE-N Commissioning stars	11917	12194	12194	
MaNGA Cubes	1390	2812	4824	4824
MaNGA main galaxy sample:				
`PRIMARY_v1_2`	600	1278	2126	2126
`SECONDARY_v1_2`	473	947	1665	1665
`COLOR-ENHANCED_v1_2`	216	447	710	710
MaStar (MaNGA Stellar Library)	0	0	3326	3326
Other MaNGA ancillary targets[1]	31	121	324	324

[1] Many MaNGA ancillary targets were also observed as part of the main galaxy sample, and are counted twice in this table; some ancillary targets are not galaxies.

TABLE 2
New or Updated Value Added Catalogs

Description	Section	Reference(s)
eBOSS ELG classification	§4.2.1	Zhang et al. (2019)
eBOSS Lyman-α VAC	§4.2.2	H. du Mas des Bourboux in prep.
SDSS Galaxy Single Fiber FIREFLY	§4.2.3	Comparat et al. (2017)
eBOSS QSO catalogs	§4.2.4	Lyke et al. in prep.
eBOSS lenses	§4.2.5	M. Talbot et al. in prep.
eBOSS ELG, LRG and QSO LSS catalogs	§4.2.6	eBOSS Team in prep.
SPIDERS X-ray clusters	§4.4.3	Kirkpatrick et al. in prep.
SPIDERS Rosat and XMM-Slew Sources	§4.5	Dwelly et al. (2017)
SPIDERS Multiwavelength Properties of RASS and XMMSL AGNs	§4.5.1	Dwelly et al. (2017); Salvato et al. (2018)
SPIDERS black hole masses	§4.5.2	Coffey et al. (2019)
APOGEE-2 red clumps	§5.8.1	Bovy et al. (2014)
APOGEE-2 `astroNN`	§5.8.2	Leung & Bovy (2019a)
APOGEE-2 *Joker*	§5.8.3	A. Price-Whelan et al., in prep
APOGEE-2 OCCAM	§5.8.4	Donor et al. (2018)
APOGEE-2 GravPot	§5.8.5	J. Fernández-Trincado et al. in prep.
MaNGA NSA images	§6.1	Blanton et al. (2011)
MaNGA PCA	§6.2	Pace et al. (2019a,b)
MaNGA DESI Morphology	§6.3	Vázquez-Mata et al. in prep.
APOGEE-2 StarHorse		Freidrich
MaNGA SEDMorph		Vivienne

tion Voyages if Britt and Rita are OK with advertising availability?

4. EBOSS: FINAL SAMPLE RELEASE

Need summary paragraph of the eBOSS experiment, with justification and references to survey and TS technical papers. Add summary sentence for science results, but depends on timing WRT final cosmology results. Opening paragraph for high-level legacy overview. Should include SPIDERS/TDSS as well if they are to be included in this section.

Make sure to cite SDSS/BOSS Spectrographs (Smee et al. 2013)

4.1. *Main eBOSS Section*

eBOSS is done, summarize legacy of cosmological surveys within SDSS, state years. eBOSS provides a spectroscopic sample over the redshift range $0.6 < z < 2$ using direct tracers (state why this is important) and supplements the Lyman-alpha forest sample of BOSS by adding XXX $z > 2$ new quasars per sqdeg and re-observations of XXX known lyman-alpha forest quasars per square degree that benefit from additional signal-to-noise. **KD to improve text**

4.1.1. *Scope and Summary*

Now eBOSS in specifics: Describe TS papers, target densities, redshift ranges, and successful redshift rates. Using successful redshifts as the metric, describe increment in data relative to DR14 (previous eBOSS release): The new release adds XXX sqdeg of spectroscopic coverage of luminous red galaxies and quasars, comprising XXX new LRG and YYY new quasars. New release also features the complete ELG program, covering XXX sqdeg and XXX spectroscopically confirmed ELG over the redshift interval $0.6 < z < 1.1$. With the completion of eBOSS, the BOSS and eBOSS samples provide six distinct target samples covering the redshift range $0.2 < z < 3.5$, as summarized in Table X. Show footprint for each target class from BOSS/eBOSS, with surface densities. -Julian Bautista or Ashley Ross to provide summary statistics

4.1.2. *Changes to the Spectral Reduction Algorithms*

The data in DR16 were processed with `v5_13_0` of the idl pipeline. This is the last version of the software that will be used for studies of large-scale structure with the SDSS telescope. Describe what is different between `v5_13_0` and the DR14 release. Provide some summary figures and statistics of how these algorithmic changes affect the spectral data quality. Add a table with short description of pipeline versions since DR9, include the following columns: data release, pipeline version, biggest algorithmic change. Julian Bautista to write.

4.1.3. *Anticipated Cosmology Results*

Describe plans for final studies. The DR16 paper is likely to come out before the eBOSS papers are posted to arXiv, but after the eBOSS papers are posted to the SDSS publications list. Do we reference the whole sequence of cosmology papers (in prep)? We could then provide direct references to these papers when we respond to the referee. Or do we just refer to published works and describe the overall plan to publish the final samples? KD to write.

4.2. *eBOSS Value Added Catalogs*

KD: should we divide VACs into those for final cosmology stuudy and those for galaxy/quasar science? We should make sure that we define the purpose of these catalogs and how we recommend that they be used.

4.2.1. *Classification of 0.32< z <0.8 eBOSS emission line galaxies*

This catalog gives the classification of $0.32 < z < 0.8$ eBOSS emission line galaxies into four types: star-forming galaxies, composites, AGNs and LINERs. It also contains the parameters: [OIII]/Hβ, [OII]/Hβ, [OIII] line velocity dispersion, stellar velocity dispersion, $u-g$, $g-r$, $r-i$, $i-z$ that are used for classification. The classification is based on a random forest model trained using $z < 0.32$ emission line galaxies labeled using standard optical diagnostic diagrams (Zhang et al. 2019). The codes, data and models are available at `https://github.com/zkdtc/MLC_ELGs`

4.2.2. *Lyman-α Forest Transmission VAC*

Cosmology Catalog This VAC contains the estimated fluctuations of transmitted flux fraction in the analysis pixels of the Lyman-α and Lyman-β spectra region of DR16Q quasars. In total, 211,375 line-of-sights contribute to the Lyman-α spectral regions and 70,626 to the Lyman-β one. This VAC contains everything needed to compute the 3D auto-correlation of Lyman-alpha absorption in two different spectral regions (e.g . du Mas des Bourboux 2019). When combined with the DR16Q quasar catalog, this VAC allows to also compute the 3D quasar x Lyman-alpha 3D cross-correlation. These two correlations are used to measure the Baryonic Acoustic Oscillations at $z \sim 2.33$.

4.2.3. *FIREFLY Stellar Population Models of SDSS Galaxy Spectra (single fiber)*

We determine the stellar population properties, age, metallicity, dust reddening, stellar mass, and star formation history for all single fiber spectra classified as galaxies that were published in this release (including those from SDSS-I, II, III and IV). This is an update of the calculation done by Comparat et al. (2017) on the galaxy spectra of the fourteenth data release. We perform full spectral fitting on individual galaxy spectra using the FIREFLY[126] code (Wilkinson et al. 2015; Goddard et al. 2017b,a; Wilkinson et al. 2017). We make use of high spectral resolution stellar population models from Maraston & Strömbäck (2011). Calculations are carried out using the Chabrier (2003) stellar initial mass function and two input stellar libraries MILES and ELODIE (Sánchez-Blázquez et al. 2006; Falcón-Barroso et al. 2011; Prugniel et al. 2007). We publish all catalogs of properties through the SDSS web interfaces (value added catalogue and sci-server) and hand out individual best-fit model spectra through the firefly website[127] This catalog contains the newly completed samples of eBOSS LRG and eBOSS ELG and will be useful for a variety of studies on galaxy evolution and cosmology Bates et al. (e.g. 2019).

4.2.4. *eBOSS Quasar Catalog*

Cosmology Catalog Beginning with SDSS-I, SDSS has maintained a tradition of releasing a visually-inspected quasar catalog alongside major data releases. The new SDSS-DR16Q catalog (DR16Q; Lyke et al. in prep) represents the most recent, and largest, catalog of known unique quasars within SDSS. To ensure completeness, quasars from previous catalog releases (DR7Q; Schneider et al. 2010, DR12Q; Pâris et al. 2017) have been combined with observations from eBOSS in SDSS-IV. The catalog will contain data for more than 750k unique quasars, including redshifts from visual inspections, principle component analysis (PCA), and the SDSS automated pipeline. For appropriate objects the catalog will also contain information about broad absorption line (BAL) troughs, damped Ly α (DLA) absorbers, and emission line redshifts (via PCA). As in previous releases, DR16Q will also contain data from GALEX (Martin et al. 2005), UKIDSS (Lawrence et al. 2007), WISE (Wright et al. 2010), FIRST (Becker et al. 1995), 2MASS (Skrutskie et al. 2006), ROSAT/2RXS (Boller et al. 2016a), XMM-Newton (Rosen et al. 2016), and Gaia (Gaia Collaboration et al. 2018). To facilitate analyses of pipeline accuracy and automated classification, a superset will be released containing ~ 1.4 million unique observations for objects targeted as quasars from SDSS-I/II/III/IV.

KD: this is a pretty important catalog as it is the last in the line of many QSO catalogs. It

[126] `https://github.com/FireflySpectra`
[127] `https://firefly.mpe.mpg.de/`

may be worth adding some statistics on the catalog and describing the evolution. For example, describe philosophy behind DR12Q, DR14Q, and DR16Q catalogs, with references. What algorithmic changes were implemented from one quasar catalog to the next? What redshift approach was used for DR16Q (refer back to redrock discussion for PCA approach). DLA, BAL approach, with references. Provide table of statistics on how DR16Q catalog is different from DR14Q.

4.2.5. *eBOSS Strong Gravitational Lens Detection Catalog*

We present a catalog of 700 probable and 400 likely candidate strong galaxy gravitational lens systems discovered by the presence of higher redshift background emission-lines in eBOSS galaxy spectra for Data Release 16. Our Spectroscopic Identification of Lensing Object (SILO) program extends the method of the BOSS Emission-Line Lens Survey (BELLS; Brownstein et al. 2012) and Sloan Lens ACS (SLACS; Bolton et al. 2006) survey to higher redshift, and has recently been applied to the spectroscopic discovery of strongly lensed galaxies in MaNGA (SILO; Talbot et al. 2018). Although these candidates have not been studied by a focussed followup imaging survey, we do provide an analysis of existing imaging from the SDSS Legacy Survey and the Dark Energy Spectroscopic Instrument (DESI) Legacy Surveys (Dey et al. 2019). This catalog includes the results of a manual inspection process, including grades and comments for each candidate, where we consider the effects of sky contamination, low signal-to-noise emission-lines, improper calibration, weak target emission-lines, systematic errors, gaussian modeling, and potential lensing features visually identified within the available imaging.

4.2.6. *eBOSS Large Scale Structure*

KLM: Is this in or out? DR16 includes full reductions of the completed set of observed eBOSS spectra. From these data large-scale structure (LSS) VACs are created, which, together map the 3D structure of the Universe from redshift 0.6 to redshift 2.2. These maps are carefully constructed so as to allow unbiased cosmological inference, the results of which are summarized in eBOSS science team (in prep. I). Three distinct samples were observed by SDSS-IV and used to produce LSS catalogs: luminous red galaxies (LRGs; Prakash et al. 2016); emission line galaxies (ELGs; Raichoor et al. 2017); and quasars (Myers et al. 2015). The details of their catalog construction are presented in eBOSS collaboration (in prep. II), with further details on the ELG sample presented in Raichoor et al. (in prep.). Some statement about what we learned about cosmology from these catalogs (?) Some statement about what public could do with these catalogs (?)

4.3. *SPIDERS*

SPIDERS (Spectroscopic IDEntification of EROSITA Sources) was originally designed as a multi-purpose follow-up program of the SRG/eROSITA all-sky survey (Merloni et al. 2012; Predehl et al. 2016), with the main focus on X-ray selected Active Galactic Nuclei (AGN) and clusters of galaxies. Given the delay in the launch of SRG (which took place in July 2019, i.e. after the end of the eBOSS survey) the program was re-purposed to target the bright X-ray sources from the ROSAT All-Sky Survey (RASS Voges et al. 1999, 2000) and XMM-Newton (X-ray Multi-mirror Mission; Jansen et al. 2001), which will be eventually better characterized by eROSITA.

All SPIDERS spectra taken since the beginning of SDSS-IV have targeted either point-like X-ray sources from the revised data reduction of ROSAT (2RXS Boller et al. 2016a) and XMM-Slew (Saxton et al. 2008) catalogs, or red-sequence galaxies in clusters detected by ROSAT (CODEX catalogue, Finoguenov et al. in prep.) or by XMM (XClass catalogue Clerc et al. 2012) samples.

In addition to the these programs, completed and fully released in DR16, the eROSITA Performance Verification survey (eFEDS) data set is currently planned to be available by November 2019 and should consist of 120 deg^2 observed to the final eROSITA all-sky survey depth over an equatorial field overlapping with the GAMA09 survey window. To address at least part of the original goals of SPIDERS (eROSITA follow-up) within SDSS-IV, we plan to dedicate a special set of 12 special plates for these targets, to be observed in Spring 2020, and released as part of the final SDSS-IV DR17. An extensive eROSITA follow-up program, instead, is planned for the next generation of the survey, SDSS-V (Kollmeier et al. 2017).

4.4. *Clusters of Galaxies*

With SPIDERS and in DR16, 2,740 X-ray selected clusters (out of a total of 4,114) were spectroscopically confirmed. It constitutes the largest cluster spectroscopic sample ever build.

4.4.1. *Target selection update*

A substantial fraction of SPIDERS fibers are targeting galaxies selected via the red-sequence technique around candidate X-ray galaxy clusters (Rykoff et al. 2012, 2014). The systems were found by filtering X-ray photons over-densities in the RASS with an optical cluster finder. The targeting strategy and the parent samples relevant to most of the targets are fully described in Clerc et al. (2016).

We added in chunk `eboss20` a few `SPIDERS_RASS_CLUS` targets obtained by extending the red-sequence search up to five times the cluster virial radius in CODEX clusters detected through their weak-lensing signature (Shan et al. 2014). Moreover, we introduced three new target subclasses, taking advantage of deeper optical datasets that enable cluster member measurements at higher redshifts:

- `SPIDERS_CODEX_CLUS_CFHT`: following the procedure described in Brimioulle et al. (2013), pointed CFHT/Megacam observations and CFHT-LS fields provide deep $(u)griz$ photometry. 54 spectra were acquired with the corresponding bit mask `EBOSS_TARGET2 = 6`;
- `SPIDERS_CODEX_CLUS_PS1`: 249 high-redshift ($z_\lambda > 0.5$) CODEX cluster candidates were searched for red-sequence counterparts in PanStarrs PS1 (Flewelling et al. 2016) using a custom algorithm.

129 spectra were acquired with the corresponding bit mask `EBOSS_TARGET2 = 7`;

- `SPIDERS_CODEX_CLUS_DECALS`: these targets are output of a custom red-sequence finder code applied to DeCALS photometric data[128] (Dey et al. 2019). 48 spectra were acquired with the corresponding bit mask `EBOSS_TARGET2 = 8`.

4.4.2. *Galaxies and redshifts*

The sky area covered by eBOSS/SPIDERS spectroscopic plates[129] amounts up to $5,350\,\mathrm{deg}^2$; it defines the area relevant to DR16 SPIDERS galaxy cluster science and catalogues (Clerc et al. in preparation). A total of 48,013 galaxy redshifts are matched to red-sequence galaxies, regardless of any actual membership determination. Of those, 26,527 are SPIDERS targets specifically. The additional redshifts were collected from past SDSS-I, II, III (including SEQUELS) and other eBOSS programs. The median i-band magnitudes of the acquired targets are $i_{\mathrm{fiber2}} = 20.0$ and $i_{\mathrm{cModel}} = 18.5$ and most of the spectra are typical of red, passive galaxies at $0.05 \lesssim z \lesssim 0.7$, displaying characteristic absorption features (Ca H+K, G-band, MgI, NaD, etc.) Such magnitude and redshift ranges and the purposely narrow spectral diversity make the automated galaxy redshift determination a straightforward task for the eBOSS pipeline, that is well-optimised in this area of the parameter space (Bolton et al. 2012). In total, 47,492 redshifts are successfully determined with a `ZWARNING_NOQSO = 0`. The remaining $\sim 1\%$ showing a non-zero flag are mainly due to non-existent data or insufficient signal to noise ratios; their small number allows a treatment on a case-by-case basis.

4.4.3. *VAC: SPIDERS X-ray clusters catalog for DR16*

Within the DR16 eBOSS area, 2,740 X-ray clusters showing a richness $\lambda_{\mathrm{OPT}} > 10$ were spectroscopically validated based on galaxy redshift data from SDSS-I to -IV in their red-sequence. A total of 32,326 valid redshifts were associated with these galaxy clusters, leading to a median number of 10 redshifts per red sequence. The process of this validation is a combination of automatic and manual evaluations (Kirkpatrick et al. in prep.). An automated algorithm performed a preliminary membership assignment and interloper removal based on standard iterative σ-clipping methods. The results of the algorithm were visually inspected by six experienced galaxy cluster observers (totalling eleven since the beginning of the survey), ensuring at least two independent inspectors per system. A Web-based interface was specifically developed for this purpose: using as a starting point the result of the automated algorithm, the tool allows each inspector to interactively assess membership based on high-level diagnostics and figures (see Figure 16 in Clerc et al. 2016). A final decision is made by each inspector whether to validate the system as a bonafide galaxy cluster or mark as "unvalidated" in cases where the data is lacking. Validation is in most cases a consequence of finding three or more red-sequence galaxies in a narrow redshift window all within the X-ray estimated viral radius, compatible with them all being galaxy cluster members. A robust weighted average of the cluster member redshifts, provides the cluster systemic redshift. A majority vote was required for each system to be finally "validated" or "unvalidated"; in the former case, an additional condition for agreement is the overlap of the cluster redshifts' 95% confidence intervals. For cases without a clear majority, additional inspectors were asked to evaluate, or else a discussion amongst inspectors was held in order to reach a new consensus.

4.5. *X-ray point like sources*

Throughout SDSS-IV, the SPIDERS program has been providing spectroscopic observations of ROSAT and XMMSL2 sources in the BOSS footprint (Dwelly et al. 2017). For ROSAT sources, the major difficulty lies in the identification of secure counterparts of the X-ray sources at optical wavelength, given the large positional uncertainties. To solve this problem, the Bayesian cross-matching algorithm NWAY (Salvato et al. 2018) was used, in combination with priors based ALLWISE (Cutri et al. 2013) infrared (IR) color-magnitude distributions which, at the depth of the 2RXS and XMMSL2 surveys, can distinguish be- tween X-ray emitting and field sources. WISE positions were matched to photometric counterparts in SDSS.

In addition to those targeted during eBOSS/SPIDERS, a large number of ROSAT and XMMSL1 sources (not always targeted as such) received spectra during the SDSS-I/II (2000–2008 York et al. 2000) and the SDSS- III (Eisenstein et al. 2011) BOSS (2009–2014 Dawson et al. 2013) surveys.

By combining these with SDSS-IV spectra, the spectroscopic completeness achieved by the SPIDERS survey as of SDSS DR16 in the $\sim 5,300\ \mathrm{deg}^2$ of the eBOSS footprint area is $\sim 53\%$ for the ROSAT sample as a whole (10,590 sources), raising to $\sim 63\%$ considering only high-confidence X-ray detections and to $\sim 87\%$ considering sources with high-confidence X-ray detections and optical counterparts with magnitudes in the nominal eBOSS survey limits ($17 \leq$ `mFiber2,i` ≤ 22.5). Outside the eBOSS area, the spectroscopic completeness of this sample is lower: $\sim 28\%$ for the sample as a whole, $\sim 39\%$ considering only high-confidence X-ray detections, and $\sim 57\%$ considering sources with high-confidence X-ray detections and optical counterparts with magnitudes in the nominal survey limits. **ALL NUMBERS TO BE VERIFIED ONCE MORE before submission**

Comparat et al. (in preparation) presents the SPIDERS spectroscopic survey of X-ray point-like sources, and a detailed description of the associated DR16 Value Added Catalogs, that we summarize below.

4.5.1. *VACs: Multiwavelength Properties of RASS and XMMSL AGNs*

We present the multiwavelength characterization over the area covered by the SEQUELS and eBOSS DR16 surveys ($\sim 5300\ \mathrm{deg}^2$ TBC) of two highly complete samples of X-ray sources:

1. The ROSAT All-Sky Survey (RASS) X-ray source catalog (2RXS Boller et al. 2016a)
2. The XMM-Newton Slew Survey point source catalog (XMMSL Saxton et al. 2008, version 1.6).

[128] http://legacysurvey.org/decamls/
[129] Chunks `eboss`1–5, 9, 16, 20, 24, 26, 27 and `boss`214, 217.

We provide information about the X-ray properties of the sources as well as of their counterparts at longer wavelengths (optical, IR, radio) identified first in the All-WISE IR catalog via a Bayesian cross-matching algorithm (Dwelly et al. 2017; Salvato et al. 2018). We complement this with dedicated visual inspection of all the SDSS spectra, providing accurate redshift estimates (with objective confidence levels) and source classification, beyond the standard eBOSS pipeline results. These two VACs supersede the two analogous ones published in DR14.

4.5.2. *VAC: Spectral Properties and Black Hole Mass Estimates for SPIDERS SDSS DR16 Type 1 AGN*

This VAC contains optical spectral properties and black hole mass estimates for the SDSS DR16 sample of X-ray selected SPIDERS type 1 AGN. This is the DR16 edition of an earlier SPIDERS VAC covering SPIDERS type 1 AGN up to SDSS DR14, which was presented by Coffey et al. (2019) and Aguado et al. (2019). As part of the SPIDERS programme (Dwelly et al. 2017), X-ray sources detected by both the Second ROSAT All-Sky Survey catalogue (2RXS; Boller et al. 2016b) and the second XMM-Newton Slew survey catalogue (XMMSL2; Saxton et al. 2008) were followed up with SDSS optical spectroscopy. The spectral regions around the MgII and Hβ emission lines were fit using a multicomponent model in order to derive optical spectroscopic properties as well as derived quantities such as black hole mass estimates and Eddington ratios. This resulted in a sample of 8867 X-ray selected type 1 AGN with optical spectral measurements. Visually confirmed redshifts and X-ray luminosity measurements are also included in this catalogue. For further details on the production of this VAC, see Coffey et al. (2019).

4.6. *TDSS*

[Draft update from SA] The Time Domain Spectroscopic Survey (TDSS), a subprogram of eBOSS in SDSS-IV, is providing the first large-scale, systematic follow-up spectroscopic survey to characterize photometric variables. The completion of eBOSS observations discussed above correspondingly marks the completion of TDSS observations, as TDSS also relies on the BOSS spectrographs, using a small fraction (about 5%) of the optical fibers piggybacking on eBOSS plates. TDSS observations thus effectively also concluded with eBOSS data collection in February of 2019, and with the full TDSS spectroscopic data included in DR16.

There are three main components of TDSS, each now with data collection complete:

(1) The primary TDSS spectroscopic targets are selected from their variability within Pan-STARRS1 (PS1_ multi-epoch imaging photometry, and/or from longer-term photometric variability between PS1 and SDSS imaging data (e.g., see Morganson et al. 2015). TDSS single epoch spectroscopy (SES; Ruan et al. 2016)) of these targets establish the nature (e.g., variable star vs. variable quasar, and subclass, etc) of the photometric variable, and in turn often then suggest the character of the underlying variability (e.g., pulsating RR Lyrae vs. flaring late-type star vs. cataclysmic variable, etc). Accounting for the relevant SDSS-IV (and a pilot program, known as SEQUELS, in SDSS-III) observations, new optical spectra have been collected for more than 108,000 such TDSS photometric variables through DR16. Also accounting for spectra of similar additional TDSS variables fortuitously already having spectra within the earlier SDSS archives, of order one-third of the TDSS variables are spectroscopically classified as variable stars, and most of the other two-thirds are variable quasars.

(2) Another 6,500 TDSS spectroscopic fibers in SDSS-IV are allotted to repeat spectra of known star and quasar subclasses of unusual and special interest, anticipated or suspected to exhibit spectroscopic variability in few epoch spectroscopy (FES; e.g., see MacLeod et al. 2018). A recent specific example of the latter, are TDSS spectra of nearly 250 dwarf Carbon stars that provide strong evidence of statistical radial velocity variations indicative of subclass binarity (e.g., Roulston et al, 2019).

(3) The more recently initiated TDSS Repeat Quasar Spectroscopy (RQS; also see MacLeod et al. 2018)program obtains multi-epoch spectra for 16,500 known quasars, sampling across a broad range of properties including redshift, luminosity, and quasar subclass type (i.e., with a larger sample size, but also a greater homogeneity and less a priori bias to specific quasar subclasses than the TDSS FES programs), all of which have at least one earlier epoch of SDSS spectroscopy already available in the SDSS archive. The RQS program especially addresses quasar spectral variability on multi-year timescales, and in addition to its own potential for new discoveries of phenomena such as changing-look quasars or broad absorption line (BAL) variability and others, also provides a valuable (and timely) resource for planning of yet larger scale multi-epoch quasar repeat spectral observations anticipated for the Black Hole Mapper program in the future SDSS-V (see below).

In total, TDSS has selected or co-selected (in the latter case, often with eBOSS quasar candidate selections) more than 131,000 spectra in SDSS-IV that probe spectroscopy in the time-domain. All such quality spectra are available in DR16.

Does this go here? QSO Reverb Mapping Overview (Shen et al. 2015)

5. APOGEE-2: FIRST RELEASE OF SOUTHERN HEMISPHERE DATA, AND MORE FROM THE NORTH

5.1. *Introduction*

General statements about APOGEE-2 Duration. Commencement of Southern Survey. Number of stars included in DR16. Scientific areas encompassed.

Make sure to cite APOGEE Data Proc Pipeline (Nidever et al. 2015), APOGEE-2 Target Selection (Zasowski et al. 2017).

5.2. *APOGEE-2 Southern Survey Overview*

Extended description of APOGEE-2S

- Southern instrument blip [publication from Wilson et al. highlighted]
- Southern commissioning
- Operations and current performance
- Description of scope and departures from Northern Survey

5.3. *General APOGEE-2 Targeting*

- AP-2N: inclusion of two ancillary program calls; no BTX as not a part of DR16

- AP-2S: core science observations only; extended description of External Programs

- AP-2S: Mention of Santana et al. (in prep)

- All APOGEE: Addition of relevant targeting flags

5.4. *APOGEE DR16 Data Products (DRP+ASPCAP)*

- Highlight DR16-related DRP changes; radial velocity data

- Highlight DR16-related ASPCAP changes; stellar atmospheric parameters and individual element abundances

    1. line list enhancements
    2. employment of only MARCS model atmospheres for entire synthetic spectral grid
    3. generation of Cerium abundances
    4. ASPCAP fitting in giants across new C and N dimensions

- Mention of Jonsson et al. (in prep)

5.5. *Data Quality*

- Anticipated gains in quality (modest).

- Brief nod to APOGEE-associated VACs for DR16

5.6. *Future*

Note from KLM - possibly move to the Future section

- AP-2N: BTX program inclusion

- AP-2N: Mention of Beaton et al. (in prep)

- AP-2S: Extension of Southern Survey to goal science areas of K2 fields and substellar companions

- Description of final APOGEE-2 data release

5.7. *Images/Plots/Graphics*

1. APOGEE-2 DR16 Scope/Field Coverage [plot]

2. AP-2S Instrument on duPont Telescope; Schematics [picture/image]

3. Figure 1 from Jonsson et al. [plot]

4. Demonstration of DR16 Quality (comparison with literature and prior data releases) [plot]

5.8. *APOGEE Value Added Catalogs*

A number of value added catalogs based on APOGEE data are included in DR15.

5.8.1. *APOGEE red-clump catalog*

DR16 contains the latest version of the APOGEE red-clump (APOGEE-RC) catalog. This catalog is created in the same way as the DR14 version of the catalog, with a more stringent log g cut compared to the original version of the catalog (Bovy et al. 2014). The catalog contains 39,675 unique stars, about 30% more than in DR14. We include proper motions by matching to the Gaia DR2 catalog (Gaia Collaboration et al. 2018).

5.8.2. *APOGEE-`astroNN`*

The APOGEE-`astroNN` value-added catalog contains the results from applying the `astroNN` deep-learning code to APOGEE spectra to determine stellar parameters, individual stellar abundances (Leung & Bovy 2019a), distances (Leung & Bovy 2019b), and ages (Mackereth et al. 2019). Full details of how all of these quantities are determined from the DR16 data are given in Section 2.1 of Bovy et al. (2019). In addition, properties of the orbits in the Milky Way (and their uncertainties) for all stars are computed using the fast method of Mackereth & Bovy (2018) assuming the `MWPotential2014` gravitational potential from Bovy (2015). Typical uncertainties in the parameters are 60 K in Teff, 0.2 dex in log g, 0.05 dex in elemental abundances, 5 % in distance, and 30 % in age. Orbital properties such as the eccentricity, maximum height above the mid-plane, radial, and vertical action are typically precise to 4 to 8 %.

5.8.3. *APOGEE-Joker*

The APOGEE-*Joker* VAC contains posterior samplings over binary star orbital parameters (i.e. Keplerian orbital elements) for 224,401 stars with 3 or more APOGEE visit spectra that pass a set of quality cuts (as described in Price-Whelan et al., in prep.). The samplings are generated using *The Joker*, a custom Monte Carlo sampler designed to handle the very multi-modal likelihood functions that are natural to sparsely-sampled or noisy radial velocity time series (Price-Whelan et al. 2017, 2018). For some stars, these samplings are unimodal in period, meaning that the data are very constraining and the orbital parameters can be uniquely summarized; In these cases, we provide summary information about the samplings such as the maximum *a posteriori* sample values. Based on some simple cuts comparing the maximum likelihood posterior sample to the likelihood of a model for each source in which the radial velocities are constant (both quantities are provided in the VAC metadata), we estimate that there are $\gtrsim 25,000$ binary star systems robustly detected by APOGEE. The vast majority of these systems have very poorly constrained orbital parameters, but these posterior samplings are still useful for performing hierarchical modeling of the binary star population paramters (e.g., period distribution and eccentricity parameters) as is demonstrated in Price-Whelan et al. (in prep.).

5.8.4. *APOGEE-Open Cluster Chemical Abundances and Mapping*

The goal of the Open Cluster Chemical Abundances and Mapping (OCCAM) survey is to create a uniform (same instrument, same analysis pipeline) open cluster dataset. We combine proper motion (PM) and radial velocity (RV) measurements from Gaia DR2 (Gaia Collaboration et al. 2018) with RV and metallicity measurements from APOGEE to establish membership probabilities for each star observed by APOGEE near an open cluster. In this second VAC from the OCCAM survey, we do not impose a minimum number of reliable member stars as in Donor et al. (2018), but we do enforce a visual quality cut based on each cluster's PM cleaned CMD. A detailed description of the updated methods will be provided in Donor et al. (in prep). The final VAC includes 126 open clusters and 10191 APOGEE stars in the vicinity of those clusters. Average RV, PM, and average abundances for reliable ASPCAP elements are provided for each cluster, along with the visual quality determination. Membership probabilities based individually upon RV, PM, and [Fe/H] are provided for each star.

5.8.5. *GravPot16-VAC: Stellar Orbits for APOGEE DR16*

We present a VAC that contains an entry for every source observed on both the northern and southern hemisphere by the SDSS-IV Apache Point Observatory Galactic Evolution Experiment (APOGEE-2) in common with Gaia DR2, giving information about each star and its derived quantities, in particular, precise Galactic Orbital Elements. The stellar orbits were integrated into both an axisymmetric model and a model including the Galactic bar potential through the galaxy modeling algorithm called`GravPot16`[130], which fits the structural and dynamical parameters to the best we know of the recent knowledge of our own Milky Way galaxy. We adopt a simple Monte Carlo scheme to construct the initial conditions for each object, taking into account the uncertainties in the radial velocities provided by the APOGEE-2 survey, the absolute proper motions provided by the European Space Agency's Gaia mission (*Gaia* DR2), and the Photo-astrometric distances provided by the `StarHorse` algorithm, in order of seeing how much the orbital properties change, considering the errors of the measurements, and at the same time, how the Galactic bar affects them. With this initial data, some parameters were obtained in each orbit, such as the angular momentum vector and the orbital energy per unit mass, E, in the axisymmetric case, and the orbital Jacobi constant, E_J, which is conserved in the reference frame where the bar is at rest. This unprecedented homogeneous dataset allows us to give a short overview of these quantities in this paper. For reference, the solar position $R_\odot = 8.3$ kpc, and $Z_\odot = 11$ pc, the local kinematic parameters $V_{LSR} = 239$ km/s (for the motion of the local standard of rest), and $[\mathrm{U,V,W}]_\odot = [-11.10, -12.24, +7.25]$ km/s, in line with Brunthaler et al. (2011), and a bar angle of 20 deg, and a bar mass of 1.1×10^{10} Solar mass, in line with Fernández Trincado (2017; PhD.-Thesis). We use a right-handed, Cartesian Galactocentric coordinate system, where the X axis is oriented toward l = 180 deg., and the Y axis is oriented toward l = 270 deg. (the disk rotates toward l $\sim$ 90 deg.). This VAC is described in greater detail in J. Fernández-Trincado et al. in prep.

6. MANGA: VALUE ADDED CATALOGUES ONLY

[130] `https://gravpot.utinam.cnrs.fr`

MaNGA continues to observe galaxies at APO as described in (Drory et al. 2015; Yan et al. 2016), and following the end of eBOSS observing, now uses all dark time at APO. For DR16 there is no new data release of MaNGA data cubes or analysis products; all remaining data will be released in DR17. However a number of MaNGA related VACs are provided which we document here.

6.1. *NASA Sloan Atlas Images and Image Analysis*

We are releasing the underlying image and image analysis for the NASA Sloan Atlas (NSA). The methods used are described in Blanton et al. (2011) and Wake et al. (2017). Briefly, for a set of nearby galaxies of known redshift ($z < 0.15$) within the SDSS imaging area, we have created and analysed GALEX and SDSS images. This analysis forms the basis for the MaNGA targeting, and resulted in the `v1_0_1` NSA catalog released originally with DR14. We are now releasing the images which were analyzed to create those parameters. The data set includes the original catalogs from which the NSA sample was drawn, the mosaic images and inverse variance images that were analyzed, the deblending results for each object, the curve-of-growth and aperture corrections for each object, and other intermediate outputs. We expect that this data set may be useful for reanalysis of the GALEX or SDSS imaging. The full data set is large (15 terabytes) and therefore any users interested in using a large fraction of it are encouraged to make special arrangements to transfer the data through Globus rather than through other methods.

6.2. *MaNGA Principle Component VAC*

The MaNGA-PCA VAC provides resolved and integrated (aperture-corrected) stellar masses for galaxies in MaNGA, building on DRP version `v2_5_3`, DAP version `2.3.0`, and using `PCAY` (`https://www.github.com/zpace/pcay`) version `1.0.0` (Pace et al. 2019a). A library of continuous stellar populations (CSPs) are used to train a principal component analysis (PCA) model. Both the CSP spectra and the resulting principal component (PC) basis set are included in the VAC.

The resolved masses are found by adopting the PC system as a basis set for fitting the stellar continuum regions of MaNGA spectra, and using the goodness-of-fit of each synthetic spectrum for a given observed spectrum, to define a marginalized posterior probability density function for the observed spectrum's i-band stellar mass-to-light ratio. The median of that distribution is adopted as the fiducial stellar mass-to-light ratio of a spaxel (line of sight in a galaxy), and multiplied by the i-band luminosity to get an estimate for the stellar mass. At this time, i-band stellar mass-to-light ratio and i-band luminosity maps (both in solar units) are released. Stellar mass-to-light ratios have been vetted against synthetic spectra, and found to be reliable at median signal-to-noise ratios between 2 and 20, across a wide range of dust attenuation conditions, and across the full range of realistic stellar metallicities. Typical "random" uncertainties are approximately 0.1 dex (including age-metallicity degeneracies and uncertainties induced by imperfect spectrophotometry), and systematic uncertainties induced by choice of training star formation histories could be as high as

0.3 dex, but are believed to be closer to 0.1 to 0.15 dex (Pace et al. 2019a).

In addition to resolved maps of stellar mass-to-light ratio and i-band luminosity, a catalog of total stellar-masses for MaNGA DR16 galaxies is provided. We provide the total mass inside the IFU (after interpolating over foreground stars and unreliable measurements). We also supply two possible exterior masses intended to correct for mass falling outside the spatial grasp of the IFU: the first adopts the median stellar mass-to-light ratio of the outermost 0.5 effective radii, and the second (recommended) adopts a mass-to-light ratio consistent with the (g - r) color of the NSA flux minus the flux in the IFU (Pace et al. 2019b).

6.3. *Visual Morphology from DESI Images*

A new morphology catalogue is presented, based on a pure visual morphological classification. From a new uniform treatment of the SDSS images in combination with deeper images from the DESI Legacy Imaging Surveys DECaLS, BASS and MzLS (DESI; Dey et al. 2019), it is plausible to identify various structural features for a more definite morphological classification following the method implemented in Hernández-Toledo et al. (2010). The visual morphological classification is carried out judging three-panel mosaic images, a gray logarithmic-scaled r-band image, a filter-enhanced r-band image and the corresponding gri colour composite image using SDSS and DESI images. This catalogue contains the T-Type morphology, visual attributes (barred, edge-on, tidal debris) and the CAS parameters (Concentration, Asymmetry and Clumpiness; Conselice 2003) from the DESI images. This new MaNGA Visual Morphology catalogue is described in more detail in Vázquez-Mata et al. (in prep.).

7. CONCLUSIONS AND FUTURE PLANS

This data release, which is the sixteenth over all from SDSS (DR16) is the last release of cosmological survey data from SDSS (as part of the eBOSS survey), and the first release of data from Southern hemisphere observing as part of APOGEE-2S. DR16 contains no new data from the MaNGA survey part of SDSS-IV.

SDSS-IV has one final year of operations remaining, and is planning a further one final public data release. That data release, which will be the seventeenth from SDSS overall (DR17), will comprise all remaining data taken by all surveys in SDSS-IV. What follows is a brief summary of the intended contents of DR17

- Due to an accelerated pace of observing in February 2018-2019, eBOSS has finished observing, and so DR16 is the final data release for the eBOSS survey (with the exception of plates in the SPIDERS (and TDSS?) programmes. The successful launch of the eROSITA satellite (Predehl et al. 2014) means there will be SPIDERS plates for followup of eROSITA targets).

- MaNGA is observing in all remaining dark time from APO (since March 2019), and is on schedule to meet, or slightly exceed its intended goal of 10,000 galaxies. In addition MaNGA has been (provisionally?) awarded time to observe a subset of galaxies at an exposure time four times deeper than the typical survey.

- APOGEE-2 continues to observe from both the Northern (APO) and Southern (LCO) hemisphere. DR16 is the first release of data from the Southern hemisphere.

7.1. *SDSS-V*

Starting in 2020, after SDSS-IV has ceased observations at APO and LCO, the next generation of SDSS — SDSS-V — will begin (Kollmeier et al. 2017). SDSS-V is a multi-epoch spectroscopic survey to observe nearly six million sources using the existing BOSS and APOGEE spectrographs, as well as very large swathes of ISM in the Local Group using new optical spectrographs and a suite of small telescopes. SDSS-V will operate at both APO and LCO, providing the first all-sky "panoptic" spectroscopic view of the sky, and will span a wide variety of target types and science goals.

The scienntific program is divided into three "Mappers". The *Milky Way Mapper* (MWM) is targeting millions of stars with the APOGEE and/or BOSS spectrographs, ranging from the immediate solar neighborhood to the far side of the Galactic disk and the MW's satellite companions. The MWM will probe the formation and evolution of the MW, the physics and life-cycles of its stars, and the architecture of multi-star and planetary systems. The *Black Hole Mapper* (BHM) is targeting nearly half a million SMBHs and other X-ray sources (including newly discovered systems from the *eROSITA* mission) with the BOSS spectrograph in order to characterize the X-ray sky, measure black hole masses, and trace black hole growth across cosmic time. Finally, the *Local Volume Mapper* (LVM) employs a wide-field optical IFU and new optical spectrographs (with $R \sim 4000$) to map $\sim$3000 deg^2 of sky, targeting the ISM and stellar populations in the MW and several local galaxies. These maps will reveal the physics of star formation and of the interplay between stellar populations and the surrounding ISM.

SDSS-V builds upon the operational infrastructure and data legacy of earlier SDSS programs, but it includes several key new developments. Among these are the retirement of the SDSS plug-plate system and the introduction of robotic fiber positioners in the focal planes of both 2.5 meter telescopes at APO and LCO. These focal plane systems (FPS) enable more efficient observing and larger target densities than achievable in previous SDSS surveys. In addition, the LVM is facilitated by the construction of [[HOW MANY]] $\leq$1 meter telescopes at both observatories, linked to six new optical spectrographs based on the DESI design [[cite?]]. SDSS-V continues the SDSS legacy of open data policies and convient, efficient public data access, with improved data distribution systems to serve its large, diverse, time-domain, multi-object and integral-field data set to the world.

8. ACKNOWLEDGEMENTS

Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS-IV acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS web site is www.sdss.org.

SDSS-IV is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS Collaboration including the Brazilian Participation Group, the Carnegie Institution for Science, Carnegie Mellon University, the Chilean Participation Group, the French Participation Group, Harvard-Smithsonian Center for Astrophysics, Instituto de Astrofísica de Canarias, The Johns Hopkins University, Kavli Institute for the Physics and Mathematics of the Universe (IPMU) / University of Tokyo, Korean Participation Group, Lawrence Berkeley National Laboratory, Leibniz Institut für Astrophysik Potsdam (AIP), Max-Planck-Institut für Astronomie (MPIA Heidelberg), Max-Planck-Institut für Astrophysik (MPA Garching), Max-Planck-Institut für Extraterrestrische Physik (MPE), National Astronomical Observatories of China, New Mexico State University, New York University, University of Notre Dame, Observatário Nacional / MCTI, The Ohio State University, Pennsylvania State University, Shanghai Astronomical Observatory, United Kingdom Participation Group, Universidad Nacional Autónoma de México, University of Arizona, University of Colorado Boulder, University of Oxford, University of Portsmouth, University of Utah, University of Virginia, University of Washington, University of Wisconsin, Vanderbilt University, and Yale University.

Co-authorship on SDSS-IV data papers is alphabetical by last name and offered to all collaboration members who have contributed at least 1 month FTE towards any of the surveys during the period up to the end of data collection; and any external collaboration who has contributed at least 1 month FTE to work critical to the data release.

This research made use of ASTROPY, a community-developed core PYTHON (`http://www.python.org`) package for Astronomy (Robitaille et al. 2013); IPYTHON (Pérez & Granger 2007); MATPLOTLIB (Hunter 2007); NUMPY (Walt et al. 2011); SCIPY (Jones et al. 2001); and TOPCAT (Taylor 2005).

REFERENCES

Abolfathi, B., Aguado, D. S., Aguilar, G., et al. 2018, ApJS, 235, 42
Aguado, D. S., Ahumada, R., Almeida, A., et al. 2019, ApJS, 240, 23
Albareti, F. D., Allende Prieto, C., Almeida, A., et al. 2017, ApJS, 233, 25
Bates, D. J., Tojeiro, R., Newman, J. A., et al. 2019, MNRAS, 486, 3059
Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559
Blanton, M. R., Kazin, E., Muna, D., Weaver, B. A., & Price-Whelan, A. 2011, AJ, 142, 31
Blanton, M. R., Bershady, M. A., Abolfathi, B., et al. 2017, AJ, 154, 28
Boller, T., Freyberg, M. J., Trümper, J., et al. 2016a, A&A, 588, A103
—. 2016b, A&A, 588, A103
Bolton, A. S., Burles, S., Koopmans, L. V. E., Treu, T., & Moustakas, L. A. 2006, ApJ, 638, 703
Bolton, A. S., Schlegel, D. J., Aubourg, É., et al. 2012, AJ, 144, 144
Bovy, J. 2015, ApJS, 216, 29
Bovy, J., Leung, H. W., Hunt, J. A. S., et al. 2019, arXiv e-prints, arXiv:1905.11404
Bovy, J., Nidever, D. L., Rix, H.-W., et al. 2014, ApJ, 790, 127
Brimioulle, F., Seitz, S., Lerchster, M., Bender, R., & Snigula, J. 2013, MNRAS, 432, 1046
Brownstein, J. R., Bolton, A. S., Schlegel, D. J., et al. 2012, ApJ, 744, 41
Bundy, K., Bershady, M. A., Law, D. R., et al. 2015, ApJ, 798, 7
Chabrier, G. 2003, PASP, 115, 763
Clerc, N., Sadibekova, T., Pierre, M., et al. 2012, MNRAS, 423, 3561
Clerc, N., Merloni, A., Zhang, Y. Y., et al. 2016, MNRAS, 463, 4490
Coffey, D., Salvato, M., Merloni, A., et al. 2019, A&A, 625, A123
Comparat, J., Maraston, C., Goddard, D., et al. 2017, arXiv e-prints, arXiv:1711.06575
Conselice, C. J. 2003, ApJS, 147, 1
Cutri, R. M., Wright, E. L., Conrow, T., et al. 2013, Explanatory Supplement to the AllWISE Data Release Products, Tech. rep.
Dawson, K. S., Schlegel, D. J., Ahn, C. P., et al. 2013, AJ, 145, 10
Dawson, K. S., Kneib, J.-P., Percival, W. J., et al. 2016, AJ, 151, 44
Dey, A., Schlegel, D. J., Lang, D., et al. 2019, AJ, 157, 168
Donor, J., Frinchaboy, P. M., Cunha, K., et al. 2018, ArXiv e-prints, arXiv:1807.09791
Drory, N., MacDonald, N., Bershady, M. A., et al. 2015, AJ, 149, 77
du Mas des Bourboux, H. e. a. 2019, in prep.
Dwelly, T., Salvato, M., Merloni, A., et al. 2017, MNRAS, 469, 1065
Eisenstein, D. J., Weinberg, D. H., Agol, E., et al. 2011, AJ, 142, 72
Falcón-Barroso, J., Sánchez-Blázquez, P., Vazdekis, A., et al. 2011, A&A, 532, A95
Flewelling, H. A., Magnier, E. A., Chambers, K. C., et al. 2016, arXiv e-prints, arXiv:1612.05243
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, ArXiv e-prints, arXiv:1804.09365
Goddard, D., Thomas, D., Maraston, C., et al. 2017a, MNRAS, 466, 4731
—. 2017b, MNRAS, 465, 688
Gunn, J. E., Siegmund, W. A., Mannery, E. J., et al. 2006, AJ, 131, 2332
Hernández-Toledo, H. M., Vázquez-Mata, J. A., Martínez-Vázquez, L. A., Choi, Y.-Y., & Park, C. 2010, AJ, 139, 2525
Hunter, J. D. 2007, Computing In Science & Engineering, 90
Jones, E., Oliphant, T., Peterson, P., & Others. 2001, SciPy: Open source scientific tools for Python, , , [Online; accessed 2016-01-15]
Kollmeier, J. A., Zasowski, G., Rix, H.-W., et al. 2017, ArXiv e-prints, arXiv:1711.03234
Lawrence, A., Warren, S. J., Almaini, O., et al. 2007, MNRAS, 379, 1599
Leung, H. W., & Bovy, J. 2019a, MNRAS, 483, 3255
—. 2019b, arXiv e-prints, arXiv:1902.08634
Lyke, B. W., Higley, A. N., McLane, J. N., et al. in prep, TBD
Mackereth, J. T., & Bovy, J. 2018, PASP, 130, 114501
Mackereth, J. T., Bovy, J., Leung, H. W., et al. 2019, arXiv e-prints, arXiv:1901.04502
MacLeod, C. L., Green, P. J., Anderson, S. F., et al. 2018, AJ, 155, 6
Majewski, S. R., Schiavon, R. P., Frinchaboy, P. M., et al. 2017, AJ, 154, 94
Maraston, C., & Strömbäck, G. 2011, MNRAS, 418, 2785
Martin, D. C., Fanson, J., Schiminovich, D., et al. 2005, ApJ, 619, L1
Merloni, A., Predehl, P., Becker, W., et al. 2012, ArXiv e-prints, arXiv:1209.3114
Morganson, E., Green, P. J., Anderson, S. F., et al. 2015, The Astrophysical Journal, 806, 244
Morganson, E., Green, P. J., Anderson, S. F., et al. 2015, ApJ, 806, 244
Nidever, D. L., Holtzman, J. A., Allende Prieto, C., et al. 2015, AJ, 150, 173
Pace, Z. J., Tremonti, C., Chen, Y., et al. 2019a, ApJ
—. 2019b, ApJ

Pâris, I., Petitjean, P., Ross, N. P., et al. 2017, A&A, 597, A79
Pérez, F., & Granger, B. E. 2007, Computing in Science and Engineering, 9
Predehl, P., Andritschke, R., Becker, W., et al. 2014, in Proc. SPIE, Vol. 9144, Space Telescopes and Instrumentation 2014: Ultraviolet to Gamma Ray, 91441T
Predehl, P., Andritschke, R., Babyshkin, V., et al. 2016, in Proc. SPIE, Vol. 9905, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 99051K
Price-Whelan, A. M., Hogg, D. W., Foreman-Mackey, D., & Rix, H.-W. 2017, ApJ, 837, 20
Price-Whelan, A. M., Hogg, D. W., Rix, H.-W., et al. 2018, AJ, 156, 18
Prugniel, P., Soubiran, C., Koleva, M., & Le Borgne, D. 2007, ArXiv Astrophysics e-prints, astro-ph/0703658
Robitaille, T. P., Tollerud, E. J., Greenfield, P., et al. 2013, A&A, 588, A33
Rosen, S. R., Webb, N. A., Watson, M. G., et al. 2016, A&A, 590, A1
Ruan, J. J., Anderson, S. F., Green, P. J., et al. 2016, ApJ, 825, 137
Rykoff, E. S., Koester, B. P., Rozo, E., et al. 2012, ApJ, 746, 178
Rykoff, E. S., Rozo, E., Busha, M. T., et al. 2014, ApJ, 785, 104
Salvato, M., Buchner, J., Budavári, T., et al. 2018, MNRAS, 473, 4937
Sánchez-Blázquez, P., Peletier, R. F., Jiménez-Vicente, J., et al. 2006, MNRAS, 371, 703
Saxton, R. D., Read, A. M., Esquej, P., et al. 2008, A&A, 480, 611
Schneider, D. P., Richards, G. T., Hall, P. B., et al. 2010, AJ, 139, 2360
Shan, H. Y., Kneib, J.-P., Comparat, J., et al. 2014, MNRAS, 442, 2534
Shen, Y., Brandt, W. N., Dawson, K. S., et al. 2015, ApJS, 216, 4
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Smee, S. A., Gunn, J. E., Uomoto, A., et al. 2013, AJ, 146, 32
Stoughton, C., Lupton, R. H., Bernardi, M., et al. 2002, AJ, 123, 485
Talbot, M. S., Brownstein, J. R., Bolton, A. S., et al. 2018, MNRAS, 477, 195
Taylor, M. B. 2005, in Astronomical Data Analysis Software and Systems XIV
Voges, W., Aschenbach, B., Boller, T., et al. 1999, A&A, 349, 389
—. 2000, VizieR Online Data Catalog, IX/29
Wake, D. A., Bundy, K., Diamond-Stanic, A. M., et al. 2017, AJ, 154, 86
Walt, S. v. d., Colbert, S. C., & Varoquaux, G. 2011, Computing in Science & Engineering, 13
Wilkinson, D. M., Maraston, C., Goddard, D., Thomas, D., & Parikh, T. 2017, MNRAS, 472, 4297
Wilkinson, D. M., Maraston, C., Thomas, D., et al. 2015, MNRAS, 449, 328
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
Yan, R., Bundy, K., Law, D. R., et al. 2016, AJ, 152, 197
York, D. G., Adelman, J., Anderson, Jr., J. E., et al. 2000, AJ, 120, 1579
Zasowski, G., Cohen, R. E., Chojnowski, S. D., et al. 2017, AJ, 154, 198