Preface

In March 2013, overlooking the oasis village of San Pedro de Atacama in Region II of the Republic of Chile, nestled in the altiplano above the Atacama Desert, the Atacama Large Millimeter/submillimeter Array (ALMA) was entering operation. ALMA is a partnership between North America, Europe, East Asia, and the host country of Chile. It is a truly global radio astronomy project and, arguably, the most complex ground-based astronomical instrument ever built.

By the end of that same year, the array would consist of 66 radio antennas, with 54 of them 12 m in diameter, and the remaining 12 measuring 7 m across. These antennas are electronically linked and able to operate as one instrument, a telescope with the sensitivity of a single antenna almost 90 m across. Arranged in various configurations, the antennas can also operate in a way that sees as much detail as a much larger telescope, up to 16 km across. By moving the antennas so that their largest separation approaches this distance, ALMA can image the radio sky with more than 10 times the detail of the legendary Hubble Space Telescope. ALMA is designed to operate at radio wavelengths ranging from about 0.35 to 7 mm. This is a huge operating range, and to provide full scientific coverage of the sky at these wavelengths, each of the ALMA antennas is equipped with 10 receivers, each cooled to 4 K (–269 C or –452 F) to minimize background noise.

ALMA was envisioned to provide information on the structure and chemical makeup of astronomical objects as close as the Sun and its planets, and as far away as the stars and galaxies of the early Universe. Its capabilities would reveal never-before-seen details in the formation process of nearby stars and their planetary systems, and the birth of galaxies and their coalescence into growing clusters. In the 10 years after its inauguration, ALMA would anchor a coordinated, worldwide collaboration of radio telescopes that would image the black holes at the center of the galaxy M87 and our own Milky Way. Most

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exciting of all are the discoveries that will be made by astronomers not yet born, discoveries that cannot as yet be fathomed, but which will certainly need the unparalleled capabilities of the array. ALMA was designed at the outset for decades of operation, built to be improved as technology progresses and the questions deepen.

This book is the story of the 40 years of ALMA, from the death in 1982 of the NRAO's proposal to the NSF for a 25 m radio telescope, to the inauguration of ALMA in 2013, and first decade of operation. It is a complex story. The participants in the ALMA project melded their initial technical visions of how to answer the biggest questions of modern astronomy in a drawn-out ballet of discussions, studies, and negotiations that ended up with a global partnership involving more than 20 nations. Management of the project was challenged by profound cultural differences and the fact that no partner had a majority share, slowing the process for making decisions, but ultimately enabling more than any single partner could have accomplished alone. A near-death crisis occurred when it was found that the initial costs were significantly underestimated. It is a story with more than one lucky break and also a story that ends in success. Today, ALMA is one of the top producers of scientific results in the world.

The authors observed this history first-hand. Paul Vanden Bout was NRAO Director from 1985 to 2003 and oversaw the creation of the proposal to build the Millimeter Array (MMA), the US antecedent of what became ALMA. Vanden Bout served as ALMA Director (interim) between 2002 and 2003 and as the head of the NAASC within NRAO from 2005 to 2007. Bob Dickman began as a program officer within the NSF Division of Astronomical Sciences (AST) in late 1991, with responsibility for the Arecibo Radio Telescope. He became Coordinator of the Radio Facilities Unit, newly formed within AST in 1993, and was given responsibility for advocating within NSF for the ALMA project on behalf of the US astronomy community, and for securing all the approvals required over many years to construct the instrument. He was also a member of the team that drafted and negotiated the first official ALMA agreement with NSF's international partners, and he served on the ALMA Board. Adele Plunkett was Fellow of the ESO stationed at the ALMA headquarters in Santiago, Chile, from 2015 to 2018. She currently works in the NAASC as an NRAO staff scientist.

The decades-long span covered by this book was a period of enormous progress for astronomy, and by the turn of the twenty-first century, millimeter wave astronomy had matured as an observational science. The basic skeleton of the discipline had been fully defined, and much of the low-hanging fruit of discovery had been picked. It was also becoming clear that, in order to be scientifically worth building, the next millimeter wave radio telescope would have to be vastly more capable than any of its predecessors. As a consequence, it would

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also be correspondingly much more complex and expensive. Probably more than anything else, this single fact drove NSF's insistence, when funding began to flow, that ALMA be an international partnership, and that its construction be subject to far more structured project management and cost accounting processes than had previously been the case at the NSF. Both of these new requirements were major challenges for the ALMA project, and both are now part of the funding culture for US science projects.

We wrote this book to convey to the generation of astronomers now using ALMA how long and difficult it is to start and bring to completion such a project, and the role chance and circumstance appear to play in the course of events. We hope that the audience for the book will prove to be larger than the research astronomers and physicists who work in our field and will include, perhaps, students of project management, science historians, managers in the federal government and at private foundations, and even members of the general public. In establishing the historical record, we have included a level of detail that may go beyond the interest of some of our readers. We beg their indulgence. We believe it would be a mistake to assume that such a diverse potential audience has a background in astronomical science. As a result, where necessary we provide the scientific background required to understand not only the decisions that led to the ALMA instrument but also the increasing excitement generated by the instrument's potential as its design took shape and matured. The subject of radio astronomy is introduced in an appendix written for the lay reader.

Ours is necessarily an American perspective on this history. We have written first of all about what we observed ourselves. The voluminous material available in the NRAO Historical Archives has been invaluable in authenticating our recollections, as has material from numerous other sources. We have placed citations to sources of the material we used in notes at the end of each chapter. Our book could not have been written without the help of professional archivists Ellen Bouton and Heather Cole, who guided us through the vast trove of records in the Archives to relevant material, added items to the Archives that we had located elsewhere, and now maintain an index of the links to the digital items we cite, ensuring that the links will remain functional. Lance Utley and Kristy Davis, NRAO librarians, were most helpful in providing copies of obscure articles in the scientific literature. We are beyond grateful to all of them for their support of our project.

We are also grateful for the invaluable help of Pat Donahoe, a longtime employee of Associated Universities, Inc. (AUI), the science management corporation that operates NRAO for NSF, in assembling and organizing historical material related to the formation of the ALMA partnership; accounts of the

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subsequent meetings of the partners in committees, telecons, and board meetings; negotiations with the Republic of Chile for the ALMA site; and the procurement of the ALMA antennas. The ALMA Project was more concerned with establishing a record of accomplishment than with organizing the documentation of that record. Donahoe has done us and the Project an invaluable service by sorting and organizing this material. He was uniquely qualified for the task, having served as secretary to the ALMA Board for many years.

We are also indebted to our colleagues and supporters at the NSF who have watched over NRAO for more than 70 years, and whose support, expertise, and insights helped make ALMA a reality: Neal Lane, former NSF Director, who approved the funds for MMA design and development and insisted that the project have international support, graciously granted us an interview to go over the events of that time; Bill Harris, Bob Eisenstein, and Mike Turner, all former NSF Assistant Directors for the NSF Directorate for Mathematics and Physical Sciences, who played key roles in supporting ALMA within NSF and on ALMA oversight bodies; Vernon Pankonin, former AST Program Officer who advanced the cause of the MMA at NSF during and following the Barrett Report, clarified in an interview his activities on behalf of the US millimeter astronomy community during that period; and Hugh van Horn, former AST Director, was helpful in confirming actions at NSF to promote the MMA.

Thanks are due to Anneila Sargent, California Institute of Technology, for providing historical data for the Owens Valley Radio Observatory and the Combined Array for Research in Millimeter-wave Astronomy, and for her excellent Foreword to this book. We are also grateful to Bob Wilson for his account of the discovery of interstellar carbon monoxide and the history of the Bell Telephone Laboratory 7 m Telescope.

We wish to acknowledge the help of colleagues at NRAO past and present, scientists, engineers, and business managers whose expertise helped lay the path for ALMA: Fred Lo, who as NRAO Director guided the North American partnership through the difficult times of antenna procurement, rebaselining the ALMA budget, and the long road that led to East Asia as a third ALMA partner; Frazer Owen, the NRAO scientist who suggested building a "millimeter Very Large Array," and who more than anyone else developed and promoted the MMA concept; Peter Napier, NRAO staff scientist, who served on the committees that developed the specifications for the ALMA 12 m diameter antennas and later on the antenna contract selection committee for NRAO; Bill Porter, NRAO business manager for ALMA, who with Pat Donahoe clarified for us the antenna procurement process; Al Wootten, North American ALMA Project Scientist, whose minutes of the ALMA Science Advisory Committee were most useful; Tony Beasley, current NRAO Director

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We acknowledge our colleagues in the international astronomical community, whose intellects helped foreshadow ALMA and give it concrete form: Peter Shaver, ESO scientist, who successfully marshalled the effort in Europe to realize Roy Booth's vision of a large millimeter array in the Southern Hemisphere. We deeply appreciate his help in establishing for us the European narrative of ALMA; Masato Ishiguro, scientist at the National Astronomical Observatory of Japan, who was one of the key individuals in the development of the Large Millimeter/Submillimeter Array and the path to Japan's entrance into ALMA. We are most grateful to him for his willingness to share the material he assembled for his own account of millimeter astronomy in Japan, from the Nobeyama Radio Observatory to ALMA; Pierre Cox and Thijs de Graauw, former ALMA Directors, who described the challenges that come with that position; Ewine van Dishoek for documents relevant to the Netherlands joining the MMA; Dennis Downes for material setting out his vision for the LSA; Pierre Encrenaz and Alain Omont for early history of the Institut de Radio Astronomie Millimétrique; Alain Baudry for early history of millimeter interferometry at the Bordeaux Observatory; Richard Kurz for accounts of events in Europe and Chile; Torben Anderson and Stephan Guilloteau for their memories of the meeting where it was agreed to pursue a merger of the MMA and LSA;

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In an attempt to broaden the perspective of our book, we have included vignettes written by colleagues in Europe, Japan, and Chile throughout the narrative. We are most grateful to Leo Bronfman, Paulo Cortes, Ewine van Dishoeck, Pat Donahoe, Viviana Guzmán, Masato Ishiguro, Pieter van de Kruit, Angel Otárola, Masao Saito, and Peter Shaver for their contributions.

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