Foreword

As this book goes to press, the Atacama Large Millimeter/submillimeter Array, ALMA, has been making cutting-edge observations of the Cosmos for over 10 years. It is managed jointly by a partnership between North America, Europe, and East Asia. Financial support for operations, as well as for the development construction in Chile, the host country, is also a shared enterprise and comes from the United States National Science Foundation (NSF), the European Southern Observatory (ESO), and the National Institutes of Natural Sciences of Japan (NINS). Canada, South Korea, and Taiwan also contribute funding through these partners. Indeed, over 20 nations are actively involved in ALMA. Worldwide teams of dedicated and persistent scientists and engineers worked together to design, develop, and construct this complex and unique array, beginning in the early 2000s. Sixty-six high-precision radio antennas, 54 of diameter 12 m and 12 of 7 m, each equipped with banks of detectors and supported by complex electronics, are now distributed over the high and dry Chajnantor Plateau that overlooks Chile's Atacama Desert. The technical capabilities and the emergent scientific results have outstripped expectations and are transforming our view of the Universe. Investigations span space and time, from billions of years ago when the first stars and galaxies were forming to the present when innovative and exquisitely detailed dynamical and chemical probes of star and planet formation in our own galaxy are illuminating the origins and evolution of other solar systems. ALMA has enormous promise for continuing such grand discoveries. This book describes how the international partnership came about and how, in spite of the enormous challenges that arose at every phase of this wildly ambitious project, the partners achieved dazzling success. It provides a wealth of detail about ALMA's design, development, and construction along with a sense of the roller coaster of highs and lows that accompanied the resolution of the many difficulties. It should appeal to a wide spectrum of readers.

Although this history views the ALMA project from a very American perspective, the authors bring to the table a hard-to-match acquaintance with many events that shaped the emergence of millimeter/submillimeter wavelength astronomy and the eventual construction of a millimeter/submillimeter observatory hundreds of times more powerful than any that could have been achieved without an international partnership. Their professional involvement extends from the 1970s to the completion of the array and current operations. By the 1980s, Paul A. Vanden Bout, then Director of the US National Radio Astronomy Observatory (NRAO), was a leading figure in efforts to build a large interferometer operating at millimeter wavelengths for the American astronomy community. The concept of the Millimeter Array (MMA) was an important precursor to the US ALMA effort. Robert L. Dickman, as leader of the Radio Facilities Unit of the NSF's Astronomy Division, became responsible for representing and promoting the burgeoning US millimeter wave interferometer program within the agency in the early 1990s. As the MMA plan merged into the international ALMA endeavor, he played a critical role in bringing the fledgling partnership to fruition, particularly in matters that required NSF acquiescence and financial support. Both he and Vanden Bout continued to be intimately involved in the critical decision-making processes for ALMA that followed. Adele L. Plunkett represents the modern face of ALMA. Her Yale Ph.D. dissertation relied partially on measurements from ALMA's first official cycle of observations. She went on to become an ESO Fellow in Chile before taking up her current position at the North American ALMA Science Center (NAASC) in Charlottesville, Virginia. I was amused to learn from this book that, as a beginning graduate student, she was part of an early team making experimental submillimeter observations on a peak near the Chajnantor Plateau.

The authors readily acknowledge that they present a largely American perspective but include relevant details on the evolution of the European and Japanese millimeter wave programs that proceeded independently. Together, these were the foundation for the ALMA partnership. For obvious reasons, the American saga is most in-depth and personal. I will not be surprised to see complementary accounts from Europe and East Asia in the future. That said, I was impressed by the clear intent to provide an accurate and objective recounting here. References to pertinent archives and available documents, some quite obscure, are frequent and verifiable. Moreover, the authors have unearthed numerous written records that might well have eluded others. In addition to the astrophysicists, students, instrument builders, and project managers targeted as readers, historians of science should enjoy the level of detail. Others, like me, may appreciate that very human reactions are on display amid the profusion of well-referenced scientific, technical, and management detail. Many

disappointments as well as the joys of accomplishment can be expected along the way to outrageously ambitious instruments such as ALMA. With a view to balancing the American perspective, individual essays – vignettes – with reminiscences by ALMA colleagues from Europe, East Asia, and Chile are included here. Although these are of necessity concise, they demonstrate that all partners experienced a similar range of reactions at one time or another.

I thought that the sometimes-whimsical quotations that precede each chapter also helped make the narrative relatable. For the most part, they set the tone for each chapter rather cleverly. In Chapter 1, Dutch astronomer, Ewine van Dishoek's vignette summarizes nicely how the detection of radiation from the carbon monoxide molecule "opens your eyes." Chapter 7's quotation, "Necessity never makes a good bargain," however, did give me pause. Indeed, the cost of this unique and transformational array made the international partnership necessary. But ALMA is now an undisputed success – surely a good bargain? Some degree of tension among the partners was probably inevitable. By the 1990s, the major research communities centered in the United States, Europe, and Japan had emerged and evolved, following the first tantalizing millimeter wavelength discoveries of interstellar molecules and dust two decades earlier. The years of scientific and technical planning for North America's MMA, not to mention its perennial financial struggles, dominate the beginnings of this ALMA history. However, the scientific potential of submillimeter as well as millimeter detections also inspired ambitious studies and the construction of ever-more-capable telescopes in Japan and Europe and culminated in the Large Millimeter Submillimeter Array (LMSA) and Large Southern Array (LSA) concepts, respectively. Not surprisingly, all three groups had similar and exciting science objectives for their technical visions of a powerful array of many large-diameter millimeter/submillimeter antennas. These are detailed in the initial ALMA proposal text presented here. Many readers may enjoy, as I did, the graphic account of the driving questions provided in ESO astronomer Peter Shaver's succinct vignette. The technical requirements for instruments that matched these objectives were staggering in their complexity and similar for each group. The precision of the surfaces of the many large antennas would have to be a factor of at least a hundred times greater than had yet been achieved for smaller telescopes. Each would be equipped with banks of detector/receivers exquisitely sensitive to the various selected detection bands in the millimeter/submillimeter window and would rely on state-of-the-art electronics. The inherent difficulties in constructing such a unique and complex instrument would be exacerbated by the need for a location on a high, dry site, eventually identified as Chajnantor. Although they came to their decisions independently, Europe, Japan, and North America all agreed on these requirements.

However, as this book emphasizes, the partners also brought different cultural expectations and different fiscal patterns to the ALMA project. The effects were already evident at the time of the first agreements between Europe and North America. Japan was not included, despite an established working relationship between the LMSA and MMA teams. In a poignant vignette Masato Ishiguro, then Director of the Japan's National Radio Observatory, vividly expresses his surprise and dismay. The immediate problem was smoothed over, and Japanese representatives continued to participate at all stages of the ALMA project, but later negative decisions by the Japanese government delayed the entrance of Japan into the ALMA partnership for several years. As a result, ALMA stands alone among large international ground-based observatories not only because of its unique science contributions but also because of its unusual organizational structure. Europe and North America are equal partners with significant but lesser participation by East Asia. Until Japan formally joined the collaboration, the equal partnership between Europe and North America required that they reach acceptable compromise, if not consensus, on every aspect of bringing together the LSA and MMA concepts. The negotiations could be difficult and sometimes tortuous, often continuing over meetings and between meetings, as I witnessed while a member of the ALMA Board representing the US astronomy community. The narrative here, along with the vignette from astronomer Pieter van der Kruit, then Chair of ESO Council, reflects frustrations on both sides of the Atlantic with regard to the long-drawn-out decision-making processes. Van der Kruit has suggested that ALMA's organizational structure contributed significantly to the situation. In fact, the merger of the EU and NA projects began collegially and proceeded well for some time under the bipartite structure. Together, the partners faced and overcame a number of significant challenges. These included budget reviews and the completion of the memoranda of understanding that defined every construction task required to construct ALMA, as well as the associated implementation plans. Negotiations with Chile, the host country, especially concerning the Chajnantor site, were concluded successfully, and preparations for Japan's joining the partnership continued cordially. Although there were some initial impediments when it came to the details of distributing the construction tasks among the partner countries, a small international team of ALMA leaders settled these in a timely manner.

The truly "contentious" matters of Chapter 7 were largely confined to decisions regarding the choice of telescopes and vendors for ALMA, the location in Santiago of the ALMA headquarters, the Joint ALMA Office, and whether North America or Europe would employ the necessary Chilean labor force. The authors have not shied away from presenting the scale and scope of the disagreements.

In these exchanges, cultural differences and funding arrangements often played significant roles. Readers can follow in some detail the considerations involved, and gain some insight into whether, overall, the compromises were less than ideal. What is undeniable is that ALMA, conjured from these negotiations, is a unique, complex, and incredibly powerful instrument that is delivering results far beyond the hopes of its most enthusiastic proponents. Moreover, it is an international endeavor in so many ways. In the end, each partner chose an internal vendor so that the fifty-four 12 m diameter antennas encompass 3 different telescope designs, 25 European, 25 North American, and 4 Japanese. Likewise, teams all over the world assembled the components for banks of sensitive detectors for each telescope and for the innovative associated electronics.

Chapter 10 compares expectations with results and presents an optimistic assessment for ALMA's future. To that assessment, I would add the potential for new discoveries based on the combination of array observations with results from large optical/infrared telescopes, both ground- and space-based. Combining ALMA molecular line and NASA's James Webb Space Telescope measurements, for example, could enable unprecedented studies of the earliest stages of galaxy formation and even add to our understanding of the evolution of dark matter in the Universe. ALMA's scientific bonanza is transforming astronomy as a whole.

At this time when international collaborations to construct ever more sophisticated large telescopes are becoming commonplace, it is well worth considering the question of how ALMA became such an astounding success, despite every challenge that arose. Certainly, the endeavor had its fair share of the "barely survived disasters" alluded to in the Preface. Every project of this scope should expect these. In this regard, the "Lessons Learned" section is insightful and should be heeded, especially where the effects of cultural differences and the role of politics in funding decisions are concerned. On the other hand, it is obvious from the very human reactions that permeate this account that everyone involved in ALMA was passionate about creating an instrument that would enhance our scientific view of the Universe. That spirit fueled the determined perseverance of the ALMA partners and enabled the project to survive the most acrimonious negotiating sessions and the numerous almost-disasters. The authors' words encapsulate the foundation of that spirit and of ALMA's spectacular success. Everyone believed – and believed deeply – "it's all about science." That shines through in this account.

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