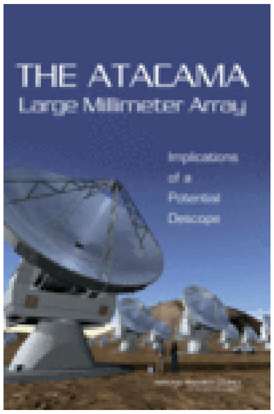

The Atacama Large Millimeter Array (ALMA): Implications of a Potential Descope

Committee to Review the Science Requirements for the Atacama Large Millimeter Array, National Research Council

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THE ATACAMA
Large Millimeter Array

Implications of a Potential Descope

Committee to Review the Science Requirements for the
Atacama Large Millimeter Array

Committee on Astronomy and Astrophysics
Board on Physics and Astronomy
Space Studies Board
Division on Engineering and Physical Sciences

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This study was supported by the National Science Foundation. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

Cover: An artist's conception of the completed Atacama Large Millimeter Array (ALMA). Each of ALMA's 64-antenna dishes will measure 39 feet (12 meters) wide. The ALMA antennas will be movable. At its largest, the array will measure 10 miles (14 kilometers) wide, and at its smallest, only 500 feet (150 meters). The ALMA correlator, or specialized computer that combines the information received by the antennas, will perform an astounding 16,000 million-million (1.6 × 1016) operations per second. When completed (in 2011), ALMA will be the largest and most capable imaging array of telescopes in the world. Image courtesy of National Radio Astronomy Observatory and Associated Universities, Inc.; computer graphics by European Southern Observatory.

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Preface

The prioritized list of instruments recommended in the 1991 astronomy and astrophysics decadal survey included the Millimeter Array (MMA):

> . . . an array of telescopes operating at millimeter wavelengths [that] would provide high-spatial- and high-spectral-resolution images of star-forming regions and distant star-burst galaxies. With spatial resolution of a tenth of an arcsecond at a wavelength of 1 mm, the MMA would bring new classes of objects into clear view for the first time.[1]

With the addition of an equal contributing European partner, plans for the MMA have since evolved into the Atacama Large Millimeter Array (ALMA), a proposed array of 64 transportable 12-meter antennas capable of enabling transformational science. This project has been accepted by the National Science Board for inclusion in the National Science Foundation's (NSF's) Major Research Equipment and Facilities Construction queue. Increases in cost driven primarily by an increase in commodity prices have forced the NSF to consider reducing the number of antennas.

[1]National Research Council, *The Decade of Discovery in Astronomy and Astrophysics*, National Academy Press, Washington, D.C., 1991, pp. 4-5.

The Committee to Review the Science Requirements for the Atacama Large Millimeter Array (the ALMA Committee) was established by the National Research Council under the Board on Physics and Astronomy and the Space Studies Board with oversight and guidance from the Committee on Astronomy and Astrophysics in March 2005 at the request of NSF's Astronomy Division. The committee was charged with assessing the following issues related to a possible descope of the ALMA array to 40 or 50 12-meter antennas:

1. What would be the impact on the attainability of the technical performance specifications?
2. What would be the loss of speed, image quality, mosaicing ability,[2] and point-source sensitivity?
3. What would be the impact on the scientific reach of the project? Would ALMA still be sufficiently transformational in terms of its scientific potential to warrant continued support by the United States?
4. Is there a particular threshold in the number of antennas below which ALMA would suffer a degradation in its performance sufficiently serious that it would not merit the scientific priority accorded it in the 1991 survey of astronomy and astrophysics?

The membership of the ALMA Committee was designed to bring together experts in millimeter- and centimeter-wave interferometry, as well as experts in the scientific areas ALMA will address, to consider the charge.

The committee expresses its appreciation to the following individuals for their contributions to its work and the completion of this report: Robert Dickman (NSF), Jean Turner (UCLA), Mark Holdaway (NRAO), Ewine van Dishoeck (Leiden Observatory), and Al Wooten (NRAO).

[2]Mosaicing refers to the mapping of areas larger than the field of view of a single antenna, by using multiple pointings, up to a thousand in extreme cases.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Michael Davis, SETI Institute,
Paul F. Goldsmith, Cornell University,
Eve C. Ostriker, University of Maryland,
Joseph H. Taylor, Jr., Princeton University,
William J. Welch, University of California at Berkeley, and
David J. Wilner, Harvard-Smithsonian Center for Astrophysics.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to en-

dorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Jacqueline N. Hewitt of MIT. Appointed by the National Research Council, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Summary

The Committee to Review the Science Requirements for the Atacama Large Millimeter Array conducted a study to evaluate the consequences of a descope of the Atacama Large Millimeter Array (ALMA), which is intended to be the major, ground-based observational facility for millimeter and submillimeter astronomy for the next three decades. The committee was asked to consider the scientific consequences of reducing the number of active antennas from 60[1] to either 50 or 40 antennas. The committee concluded that:

- A 60-element array would be greatly superior to any current or planned comparable instrument for several decades and would revolutionize millimeter and submillimeter astronomy.
- Two of the three level-1 requirements, involving sensitivity and high-contrast imaging of protostellar disks, will not be met with either a 40- or a 50-antenna array. It is not clear if the third requirement, on dynamic range, can be met with a 40-antenna array even if extremely long integrations are allowed for.

[1]Although the plan is to construct 64 antennas, only 60 will be operational at any one time. Likewise the committee assumes that 50- and 40-antenna arrays will require the construction of 54 and 44 antennas, respectively.

- Speed, image fidelity, mosaicing ability,[2] and point-source sensitivity will all be affected if the ALMA array is descoped. The severest degradation is in image fidelity, which will be reduced by factors of 2 and 3 with descopes to 50 and 40 antennas, respectively.
- Despite not achieving the level-1 requirements, a descoped array with 50 or 40 antennas would still be capable of producing transformational results, particularly in advancing understanding of the youngest galaxies in the universe, how the majority of galaxies evolved, and the structure of protoplanetary disks, and would warrant continued support by the United States.
- Furthermore, it is the committee's appraisal that a 40-antenna array would retain ALMA's strong support within the general astronomical community. However, the rapid decline in imaging capability that would result with a further reduction below 40 antennas would erode this support.

[2]Mosaicing refers to the mapping of areas larger than the field of view of a single antenna, by using multiple pointings, up to a thousand in extreme cases.

1

Introduction

The Atacama Large Millimeter Array (ALMA) is an international project to construct an interferometer, operating between wavelengths of 300 microns and 1 centimeter at an altitude of 5 kilometers at an exceptionally dry site in Northern Chile. The project is currently a partnership between North America through the National Radio Astronomy Observatory (NRAO), Europe through the European Southern Observatory (ESO), Japan through the National Astronomical Observatory of Japan (NAOJ), and Chile. ALMA was initially planned by North America and Europe as an array of 64 12-meter antennas; Japan's participation brought two additional receiver bands to the instrument along with a compact array comprising 4 separate 12-meter antennas and 12 7-meter antennas. The ALMA array is designed to have an angular resolution of 6 milliarcseconds at its shortest operating wavelength and a sensitivity that will enable fundamental investigations of the origin and evolution of planets, stars, and galaxies—investigations that are not possible with other instruments observing in other areas of the spectrum.

The behavior of the troposphere is a major factor in the quality of astronomical observations in the millimeter-wave region of the spectrum, because it can change both the amplitude and the phase of a celestial signal. The ALMA site, in the Atacama desert, is thought to be the best accessible site in the world for millimeter and submillimeter astronomy. It is likely to attract other facilities.

The NRAO-ESO agreement was for a $650 million budget, with construction shared between the two continents. Following recent increases in commodity costs, it has become necessary to contemplate a descope of the project. An investigation by the project and the ALMA Science Advisory Committee (ASAC) found that the only descope option that could lead to significant savings without catastrophic loss of scientific capability was a reduction in the number of antennas.

The committee has read the ASAC reports dated September 2004 and March 2005, the relevant chapters of the ALMA Project Book, the ESO document "Science with ALMA," and the 1999 Report of the Antenna Size Committee. It has also listened to presentations by Wayne van Citters on behalf of the National Science Foundation, Ewine van Dishoeck, representing ESO, and Jean Turner, ASAC chair. Mark Holdaway of NRAO kindly explained aspects of the ALMA imaging philosophy.

As the premier instrument in the world for the exploration of planets, stars, galaxies, and the unknown for several decades, ALMA will be a long-term investment for frontier research by the U.S. astronomy community. One salient feature of the ALMA project is the array's planned accessibility to the broader U.S. astronomy community. Previous radio and millimeter arrays have required users to be highly proficient in interferometric techniques. In contrast, ALMA is designed to be an observatory accessible to astronomers who normally observe at other wavelengths. ALMA's unprecedented number of antennas is the key driver for this accessibility, and the potential descope will significantly curtail the number of astronomers who will be able to use the observatory.

Observatory facilities have a long active life. The Very Large Array (VLA) is 24 years old and will likely operate for twice as long. ALMA is currently expected to have a 30- to 50-year productive lifetime. From this perspective, the incremental cost of completing the array is a small fraction of the observatory's lifetime cost. If the operating costs are estimated to be 10 percent per year, then reductions by 10 or 20 in the number of antennas are roughly equivalent to only 1 or 2 years of operation, i.e., roughly 2.5 percent or 5 percent of the total project cost. In addition, smaller arrays would take smaller quantities of data during ALMA's lifetime and would be far less user friendly when high-fidelity images are required.

The committee concludes that a 60-element array would be greatly superior to any current or planned comparable instrument for several decades and would revolutionize millimeter and submillimeter astronomy.

2

Technical Performance Specifications

ALMA is being designed according to three level-1 technical performance requirements that were specified in the original proposal.[1]

REQUIREMENT 1: The ability to detect spectral line emission from CO or [CII] in a normal galaxy like the Milky Way at z = 3 in less than 24 hours of observation.

Millimeter emission lines are formed by the cool gas from which stars are born. Studying them in distant galaxies is one of the most promising ways to understand the evolution of galaxies. So far, more than 30 galaxies have been detected in this manner beyond a redshift of $z = 2$. However, these detections have been limited to luminous objects that are unrepresentative of normal galaxy formation. ALMA will make it possible to detect star-forming gas in normal galaxies like the Milky Way.

[1]See Annex B of the ALMA Agreement, dated June 11, 2002, between the European Southern Observatory and the National Science Foundation. Annex B is reprinted in Appendix B of this report.

The rotational lines of carbon monoxide are well understood and can be observed through Earth's atmosphere. The committee finds that a 60-antenna ALMA just meets Requirement 1 and that 50- and 40-element arrays would take 36 and 56 hours, respectively, to detect a galaxy similar to the Milky Way at $z = 3$ and so would fail the benchmark. In practice the smaller number of antennas would limit the number of objects that could be studied using carbon monoxide.

A forbidden line of singly ionized carbon, [CII], is more intense than the carbon monoxide line, but since there is only one strong [CII] emission line it will not be observable from many redshifts since it will be shifted to a frequency for which Earth's atmosphere is too opaque, even above the superb ALMA site. For example, while it may be detectable from $z = 3$ or somewhat higher, [CII] would not be detectable in the range $2.2 < z < 2.6$ due to atmospheric absorption. If selection is limited to only those redshifts up to $z = 3$ at which the atmosphere would be transparent, then a high signal-to-noise detection of [CII] is still possible in 24 hours, even with a 40-element array. The committee notes, however, that even with this consideration, the implicit scientific goal of tracing star formation in galaxies up to $z = 3$ will not be met, because, unlike the case with carbon monoxide, the [CII] line does not directly trace the cold molecular component of the galaxies in a well-understood or systematic way.

REQUIREMENT 2: The ability to image the gas kinematics in protostars and protoplanetary disks around young stars at a distance of 150 pc (roughly the distance to star-forming clouds in Ophiuchus or Corona Australis), enabling one to study their physical, chemical, and magnetic field structures and to detect the gaps created by planets undergoing formation in the disks.

Elucidating the evolution of young gas and dust disks and planets has always been one of ALMA's strongest science drivers. However, progress requires high-quality images, excellent sensitivity, and the highest angular and spectral resolution possible. In order to assemble a large enough sample (20-30) of disks for study over a range of inclinations and developmental stages, ALMA is required to observe these objects out to a distance of 150 parsecs (pc). The disks themselves could be as large as several arcseconds, but the interesting science is on a smaller angular scale. Disks are expected to have central holes as large as 30 milliarcseconds. The regions associated with planet formation in our solar system are less than a few tenths of an arcsecond in angular size. In the planet-forming regions, disks should exhibit gaps, tidally swept out by bloated, Jupiter-mass planets. To resolve gaps will require the limiting resolution of 6 milliarcseconds at the highest observing frequency (900 GHz). Reducing the number of antennas will not affect the angular resolution, because their maximum spacing will remain unchanged. However, it will lead to a serious degradation in the quality of the images on account of the poorer coverage of the Fourier transform plane.

Figure 1 presents a simulation of a face-on disk-gap-planet-ring system seen in continuum (dust) emission with 60 antennas from 50 pc (with 600-hour observing[2]). The structure is clearly visible, and even the central star can be seen. Although there is one system at this distance, TW Hya, the chances that the TW Hya disk has a gap with a bloated Jupiter are small. To understand disk evolution and giant planet formation and migration, a statistical sample of a large number of young disks must be observed. Such a sample can be obtained only by observing regions of star formation that lie at about 150 pc. Repeating the simulation at this distance, with a three-times-smaller angular size and only 10 percent of the flux, leads to an extremely blurred image. It is the view of the committee that by working hard with real data, it would be possible to recover from a 60-antenna array the principal desired features, holes and gaps. However, this benchmark will be very difficult to achieve if the array size is reduced to 50, and achieving the benchmark may not be possible with a 40-antenna

[2]Although not unprecedented, 600 hours is an extremely long observation time.

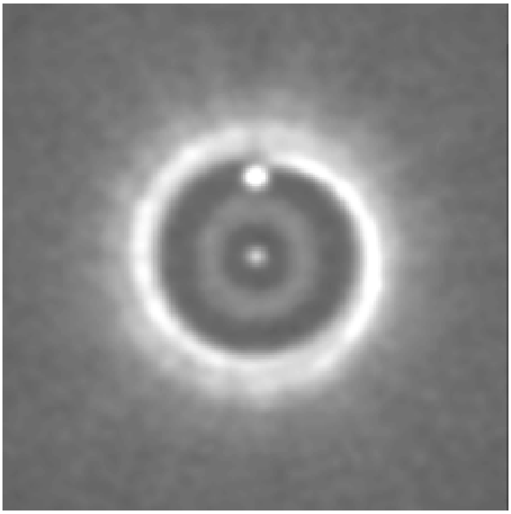

FIGURE 1 *Simulation performed by Sebastian Wolf and image processed by Mark Holdaway for a face-on gaseous disk orbiting a young star at a distance of 50 pc, with 600-h observing on a 64-antenna array. The dark ring is the gap in the gas and dust, and the white circle in the gap (top) is a bloated Jupiter at 5 AU.*

array on account of the strong scaling of the image fidelity and the sensitivity with antenna number.

Although imaging the gaps in continuum emission from dust is significant, observations in lines of the gas in the disks will be just as important in order to constrain the physical structure of the disk, the evolving chemistry, the location of the frost line, where water changes to ice, the origin of the outflowing winds, and the gas kinematics. It is the study of the gas that brings understanding of how planets form. With 60 antennas, measurement of the kinematics and chemistry at high spatial resolution takes 3 days of observing for just one disk found in the nearest region of star and planet formation. The required time increases by factors of 1.4 and 2.3 for a 50- and a 40-antenna array, respectively, just to recover the same sensitivity. In addition, the image quality will be degraded unless the antenna configuration is changed and yet more observing time is expended. Factoring in the number of sources that must be studied in order to understand the evolution of gas and dust into planets, it is clear that smaller arrays become increasingly impractical.

Whether imaging the gas or the dust, it is possible, in principle, to build up an image by changing the antenna configuration and integrating for much longer times. In the case of ALMA, the improvements will be limited by calibration and pointing errors and the fact that sources under study are dynamical and thus change. Combining images in this manner under varying atmospheric conditions is extremely challenging technically.

> ***REQUIREMENT 3: The ability to provide precise images at an angular resolution of 0.1″. Here the term "precise image" means accurately representing the sky brightness at all points where the brightness is greater than 0.1 percent of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.***

Much of ALMA's work will concern extended sources where the extremely high angular resolution needed to meet Requirement 2 is less crucial. The challenge will be to create images with high dynamic range so that faint components can be seen in the presence of bright components. Reducing the number of antennas would reduce the number of different baselines that could be utilized in a single pointing and would distribute the power over the raw map. Some of the lost information could be recovered through image processing, although calibration uncertainties and noise set a fundamental limit to how well the image can be reconstructed.

Based on its scrutiny of image simulations made for differing array configurations, the committee concluded that Requirement 3 can be met with a 50- and a 60-antenna array, if very long integration times and a change in the telescope configuration are allowed. The capability with a 40-antenna array is unclear and needs further study. However, the committee is not confident that multi-configuration data could be processed through automated pipelines and still achieve adequate quality. This would jeopardize meeting the requirement that ALMA be accessible to a large community.

The committee concludes that two of the three level-1 requirements, involving sensitivity and high-contrast imaging of protostellar disks, will not be met with either a 40- or a 50-antenna array. It is not clear if the third requirement, on dynamic range, can be met with a 40-antenna array even if extremely long integrations are allowed for.

3

Performance Degradation

In Table 1, the committee considers the four performance measures listed in the charge, in turn giving the relevant scaling with *N*, the number of antennas, and *D*, the dish diameter.

Comparison of the performance of 40-, 50-, and 60-antenna arrays as shown in Table 1 clearly indicates a significant degradation of performance with a descoped array. The image fidelity and single field sensitivity measures are limitations in the science that the array can produce. The imaging speed and mosaiced image sensitivity relate to the time taken to perform an observation. In practice, they, too, will translate into a reduction in performance because of the difficulty of maintaining instrument and tropospheric stability over longer intervals. The severest performance degradation is in the image fidelity.

The committee concludes that speed, image fidelity, mosaicing ability, and point source sensitivity will all be affected if the ALMA array is descoped. The severest degradation is in image fidelity, which will be reduced by factors of 2 and 3 with descopes to 50 and 40 antennas, respectively.

TABLE 1 ALMA Configurations Compared with Other Arrays

	CARMA	PdB	SMA	Nobeyama	ALMA			
Latitude (degrees)	39	44	19	36	-23			
Altitude (ft)	7200	8300	13500	4400	17000			
Frequency Range (in GHz)	35-250	85-250	186-696	85-250	30-900			
Maximum Baseline (km)	3	1	0.5	0.35	12			
Best Resolution (mas) at Frequency (GHz)	80 at 250	240 at 250	200 at 696	690 at 250	6 at 850			
Usable Time Fraction (250 GHz)	0.25	0.25	0.5	0.1	0.9			
Usable Time Fraction (350 GHz)	-	-	0.3	-	0.8			
External User Access Fraction	0.3	0.05	0.1	0	0.35			
Antenna Number	23	6	8	6	60	50	40	30
Antenna Diameter (in meters)	3.5 - 10	15	6	10	12	50	40	30
Image Fidelity ~ N^3	0.056	0.001	0.002	0.001	1.00	0.58	0.30	0.13
Imaging Speed ~ N^2D^4	0.006	0.024	0.001	0.005	1.00	0.69	0.44	0.25
Single Field Sensitivity ~ ND^2	0.12	0.16	0.03	0.07	1.00	0.83	0.67	0.50
Mosaiced Image Sensitivity ~ ND	0.20	0.13	0.07	0.08	1.00	0.83	0.67	0.50

NOTE: Comparison of ALMA performance as a 30-, 40-, 50-, and 60-antenna array and with the performance of other arrays that are operating or will be operating soon, specifically the Combined Array for Research in Millimeter-wave Astronomy (CARMA) in California, the Plateau de Beure Millimeter Interferometer in France (PdB), the Submillimeter Array (SMA), and the Nobeyama Millimeter Array (Nobeyama). Performance measures are normalized to a 60-antenna ALMA array.

The CARMA array will be a combination of previously constructed arrays, and will therefore have antennas of different diameters, ranging from 3.5 m to 10 m.

Image fidelity (quality) is defined as the mean ratio of the median flux to the error as measured by a simulation. It depends on the source strength and the deconvolution technique used. The N^3 dependence is based on a series of simulations.

Imaging speed is interpreted as the inverse of the time needed to reach a given noise level per pixel. It is most important at high frequencies where the opacity and stability of Earth's atmosphere severely limit the continuous time available for observation.

The single field sensitivity is defined as the minimum flux that can be detected at a fixed significance level and scales inversely as the total collecting area.

Mosaicing refers to the mapping of areas larger than the field of view of a single antenna, by using multiple pointings, up to 1000 in extreme cases. It will be important for observing extended molecular line and dust continuum sources, the emission from the disks of external galaxies, and the interaction of protostars with their host molecular clouds. Mosaicing will be particularly important at the highest frequencies, since the field of view of ALMA is inversely proportional to the square of the frequency. ALMA was designed to provide detailed, high-fidelity maps over a large range of linear scales. The value in the table is the speed to produce a map with a given sensitivity.

4

The Threshold for Transformational Science

ALMA can produce transformational science in many areas. Examples of three such areas follow:

1. The early universe is particularly accessible to ALMA because dust emission in the infrared from young galaxies gets redshifted into the submillimeter band. Galaxies have already been observed emitting at a time when the universe was less than a billion years old. Millimeter emission from gas and dust already has been detected in extreme objects to redshift 6.4, as far back as optical emission has been detected. Thus ALMA should be a key instrument for understanding the formation of the very first galaxies.

2. ALMA will be the first telescope capable of detailed imaging of the gas/dust disks out of which planets form around young stars, and capable of distinguishing the subtle dynamical and chemical processes at work. Rapid strides in these fields have been made in recent years using single submillimeter dishes and millimeter interferometers. However, these instruments lack the sensitivity and resolution to perform as well as ALMA, even if it is descoped to 40 antennas, as Table 1 makes clear. There is no doubt that a detailed understanding of planet formation will be one of ALMA's greatest scientific legacies.

3. Galaxy formation is a rich and complex sequence of steps in which objects build up by mergers and accretion; these processes also trigger the star formation that produces most of the observable light in the universe. Immediately prior to star formation, gas collects in massive clouds that can be observed at millimeter wavelengths. Some of the light produced by star formation in young galaxies emerges in the optical and ultraviolet bands, but much is radiated into submillimeter wavelengths. Star formation also powers the synchrotron emission seen at decimetric radio wavelengths. Thus, understanding the birth and evolution of galaxies requires integration of results from a suite of new facilities: the giant segmented mirror telescope in the optical, the James Webb Space Telescope in the near infrared, ALMA in the millimeter and submillimeter, and the extended Very Large Array in the radio. Collectively these facilities will revolutionize our understanding of galaxies. All of them are needed to produce a comprehensive description.

The committee notes that the most important discoveries from major observatories are usually unanticipated. It is reasonable to expect that the same will be true for ALMA. Even if the array is reduced to 40 antennas, ALMA's performance in terms of image fidelity, imaging speed, single field sensitivity, and mosaiced image speed surpasses the performance of the best competitor instruments by factors of 6, 18, 4, and 3, respectively, thus opening up much discovery space. Further, these factors ignore the transparency of the atmosphere at the telescope sites, which greatly increases ALMA's gains at wavelengths near 1 millimeter and allows ALMA to dominate at submillimeter wavelengths where the other interferometers (CARMA [Combined Array for Research in Millimeter-wave Astronomy] and Plateau de Beure) cannot even operate. Finally, ALMA's unmatched ability to achieve angular resolution of 0.1 arcsecond or better is crucial for comparison to the results of observations made at other wavelengths.

The committee concludes that despite not achieving the level-1 requirements, a descoped array with 50 or 40 antennas would still be capable of producing transformational results, particularly in advancing understanding of the youngest galaxies in the universe, how the majority of galaxies evolved, and the structure of protoplanetary disks, and would warrant continued support by the United States.

5

Minimum Number of Antennas

Millimeter and submillimeter observations are very important to contemporary astronomy. No better defense of this proposition is needed than the list of advances in the 15 years that have elapsed since the 1991 astronomy and astrophysics decadal survey was written. Nonetheless it is legitimate to ask at what point a descoped telescope would fail to sustain support in the highly competitive environment for new facilities today. This committee's answer, inevitably somewhat subjective, is based on the performance measures presented in Table 1. Table 1 shows, for example, that a 30-antenna array has only 3 to 4 times the sensitivity of Plateau de Beure at wavelengths longer than 1 millimeter and would not have ALMA's potential enormous mosaicing speed advantage at high frequency over that of the Submillimeter Array (SMA), which is the one other high-altitude facility capable of observing at 900 GHz.

The committee concludes that a 40-antenna array would retain ALMA's strong support within the general astronomical community. However, the rapid decline in imaging capability that would result with a further reduction below 40 antennas would erode this support.

Appendixes

Appendix A

Letter of Request

NATIONAL SCIENCE FOUNDATION

4201 WILSON BOULEVARD

ARLINGTON, VIRGINIA 22230

1 February 2005

Dr. C. Megan Urry and Dr. Roger D. Blandford
Co-Chairs, Committee on Astronomy and Astrophysics
Board on Physics and Astronomy
National Research Council
National Academy of Sciences
2101 Constitution Avenue, NW
Washington, DC 20418

Dear Dr. Urry:

With this letter I am requesting that the Committee on Astronomy and Astrophysics (CAA) provide an assessment of the scientific impact of a possible change in the design of the Atacama Large Millimeter Array (ALMA).

First recommended in the 1991 Decadal Survey as the Millimeter Array, and now conceived in an international partnership as the Atacama Large Millimeter Array, ALMA was reaffirmed as a high priority for completion in the 2000 Decadal Survey.

ALMA is a global project being carried out between North America (the US and Canada), the European Southern Observatory (ESO, and Spain), and Japan. The core instrument has been planned as an array of 64 12-meter-diameter antennas spread over a region up to ~14 km in diameter, located on a large, high desert plateau in northern Chile, and equipped with dual-polarization receivers covering 4 millimeter- and sub-millimeter-wave atmospheric windows. The antennas will have an rms surface error of <25 μm and the array will operate at up to a frequency of at least 720 GHz. ALMA construction costs are estimated to be $552M (FY 2000 dollars), with construction spread over a period of 10 years. Japan will supply significant enhancements to the core instrument, notably a "compact array" of four 12 m and twelve 7 m antennas to significantly improve the quality of large-field images produced by the core array, and receivers covering 4 additional receiver bands.

The ALMA project has three level-l science requirements:

1) The ability to detect spectral line emission from CO or C+ in a normal galaxy like the Milky Way at a redshift of z = 3, in less than 24 hours of observation.

2) The ability to image the gas kinematics in a solar-mass protostellar/protoplanetary disk at a distance of 150 pc (roughly, the distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation.

3) The ability to provide precise images at an angular resolution of 0.1". Here the term *precise image* means accurately representing the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.

The Committee is requested to evaluate the following issues related to a possible descope of the array to a number of antennas in the range 36-56. Were such a descope to be carried out,

- what would be the impact on the attainability of the level-l science requirements?
- what would be the loss of speed, image quality, mosaicing ability and point-source sensitivity? (A parametric representation of these performance changes would be welcome.)
- would ALMA still be sufficiently transformational to warrant continued support by the United States?
- is there a particular threshold in the number of antennas, below which ALMA would suffer a significant degradation in its performance

in the above or other relevant scientific areas sufficiently serious to warrant attention?

The Astronomy Division would require the results of your evaluation by May 2005, as input to its recommendations to the National Science Board.

If you have any questions regarding ALMA, please contact Dr. Robert Dickman at 703-292-4893 (rdickman@nsf.gov), the ALMA Staff Associate at NSF.

Sincerely,

G. Wayne Van Citters
Director
Division of Astronomical Sciences

Appendix B

ALMA Level-1 Science Requirements

ANNEX B: SCIENCE REQUIREMENTS

ALMA has three level-1 science requirements:

1) The ability to detect spectral line emission from CO or C+ in a normal galaxy like the Milky Way at a redshift of $z = 3$, in less than 24 hours of observation.

2) The ability to image the gas kinematics in a solar-mass protostellar/protoplanetary disk at a distance of 150 pc (roughly, the distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation.

3) The ability to provide precise images at an angular resolution of 0.1". Here the term *precise image* means accurately representing the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.

These requirements drive the technical specifications of ALMA. A highly simplified flow-down of science requirements into technical specifications can be given as follows:

NOTE: This appendix is reprinted from the ALMA Agreement, June 11, 2002, between the European Southern Observatory and the National Science Foundation.

1) High-redshift Galaxy Detection: The sensitivity of an array is primarily controlled by three major factors: total collecting area, the noise performance of the receivers, and atmospheric transparency and phase stability. The detection requirement for high-redshift galaxies therefore has a direct impact on ALMA's collecting area, polarization and frequency requirements, and site.

Contemporary millimeter arrays have collecting areas between 500 and 1000 m^2 and can detect CO emission from the brightest high-redshift galaxies (which are amplified by gravitational lensing) in one to two days of observations; signals from normal, unlensed objects will be typically 20-30 times fainter. Current millimeter-wave receiver technology has approached fundamental quantum limits, and the noise level of ALMA's detectors cannot be reduced beyond this point by much more than a factor of 2; an important additional factor of $\sqrt{2}$ in sensitivity is gained by requiring that ALMA support front-end instrumentation capable of measuring both states of polarization. The proposed ALMA site will minimize the noise contributions of the atmosphere, so that the remaining factor of 7-10 in sensitivity can only be gained by increasing the collecting area by a similar amount. Hence, ALMA must have at least 7000 m^2 in collecting area.

The molecular spectral lines which generally serve as diagnostics of the gas content and dynamics of galaxies early in the history of the Universe have frequencies that are fixed in the rest frame of the galaxy, but will be observed at frequencies that depend upon redshift. Since galaxies are found at every redshift (i.e., *age*) ALMA should ideally provide access to all atmospheric windows from 30-950 GHz, so that galaxies of all ages may be studied. Initially, however, the array will support observations in the four highest-priority frequency bands. Additional capabilities may be added in the operational phase of ALMA. Since the redshift of the galaxies will initially be essentially unknown, the instantaneous bandwidths of the receivers and the correlator should also be as large as possible; this will also maximize the continuum sensitivity of the array.

2) Protoplanetary/Protostellar Disks: These requirements have impacts on ALMA's operating frequency, baseline size, frequency resolution, and polarization. Theoretical calculations indicate that the gaps created by Jupiter-mass objects in protoplanetary disks will be ~1 AU in extent. Combined with the distance to the nearest star-forming regions (60-150 pc), the requirement that such gaps be resolvable in protoplanetary disks implies an angular resolution of 0.010" or better. This can be achieved by combining high-frequency ($f > 650$ GHz) observations with array baselines of at least 10 km. Proper study of the kinematics of the disk images further requires that spectroscopy be carried out at velocity reso-

lutions finer than 0.05 km/s. As a result, the spectral resolution provided by the ALMA correlator must be as small as a few tens of kHz. The study of the magnetic field and its properties in disks requires that the ALMA receiving systems are equipped with full polarization capability in order to measure all the Stokes parameters.

3) Precise Imaging. The requirement for high fidelity imaging constrains the number of antennas in the array, since a sufficient number of baselines to cover adequately the *uv* plane (i.e., the time/frequency domain plane in which the data are sampled) is required. Detailed studies of the imaging performance of aperture synthesis arrays have shown that the requisite imaging performance implies a minimum number of antennas, 40 or above, and accurate measurements of the shortest baselines, as well as of the large scale emission measured by total power from the antennas. Such accurate measurements can only be obtained with high quality antennas, with superior pointing precision. High fidelity imaging also requires the ability to perform calibrations to ''freeze'' the atmospheric turbulence which distorts the radiation coming from celestial sources.

The combination of these three major requirements calls for a reconfigurable zoom-lens array covering baselines from a few meters up to several kilometers, observing over the full millimeter and submillimeter atmospheric windows. The maximum size of the individual antennas is driven by the required pointing and surface precision: a choice of 12-m antennas offers an excellent technological compromise. To provide no less than 7000 m^2 of total collecting area, 64 antennas are needed, which is a large enough number to guarantee excellent imaging performance. Dual polarization is mandatory to provide enough sensitivity in spectral line mode. ALMA will offer a full-polarization mode to offer new capabilities to the astronomical community.

To minimize the impact of atmospheric noise, a dry site with minimal attenuation, but also with high phase stability, has been selected. The ALMA site has been monitored for more than 7 years in order to assure that it is optimal from both standpoints. However, because ALMA will have kilometer-long baselines, more active measures will be required to cancel the effects of the atmospheric disturbances. To do this, each ALMA antenna will be equipped with a Water Vapor Radiometers (WVR) to measure atmospheric path length variations and correct the image distortions which such phase variations create.

The final major scientific requirement affects the diverse community that will use and benefit from the scientific capabilities that ALMA brings to extend their research endeavors: ALMA should be "easy to use" by novices and experts alike. Astronomers certainly should not need to be experts in aperture synthesis to use ALMA. Automated image processing will be developed and applied to most ALMA data, with only the more intricate experiments requiring expert intervention.