Astro2020 APC White Paper

Multiwavelength Astrophysics in the Era of the ngVLA and the US ELT Program

Type of activity: Ground-based project(s); State of the Profession Consideration

Proposing Teams: The US Extremely Large Telescope Program (US-ELTP) and the Next Generation Very Large Array (ngVLA) Project

Primary Contacts:

Anthony J. Beasley (AUI/NRAO), tbeasley@nrao.edu
Sidney Wolff (AURA), scwhr465@gmail.com

Authors: Anthony J. Beasley (AUI/NRAO), Mark Dickinson (NOAO), Eric J. Murphy (NRAO), Sidney Wolff (AURA)

Contributing authors: Rachael Beaton (Princeton University), James Braatz (NRAO), Alessandra Corsi (Texas Tech University), Imke de Pater (University of California, Berkeley), Ryan Loomis (NRAO), Raffaella Margutti (Northwestern University), Alycia Weinberger (Carnegie DTM), and Michael H. Wong (University of California, Berkeley)

Abstract

Two major ground-based astronomy initiatives for the 2020s, the US Extremely Large Telescope Program (US-ELTP) and the Next-Generation Very Large Array (ngVLA), have been described in separate APC white papers. This submission explores the science synergy of these remarkable facilities, and identifies key areas of research enabled by US access to these capabilities.

We examine the issues raised by the costs of building and operating flagship facilities, and strategies that might be effective in maintaining the health of the US astronomical community and its international leadership. We propose a time-phased strategy to develop both facilities that would enable completing them in the coming decade.

Next Generation Research in Optical/Infrared and Radio Astronomy

An increasing number of the foremost problems in astrophysics that will be ripe for discovery in the next decade require new observatories capable of achieving unprecedentedly high angular resolution and sensitivity at optical/infrared (OIR) and radio wavelengths (Figure 1). These capabilities will open up new observational parameter space to enable major advances in many fields of research, including

- the formation and evolution of planetary systems around other stars;
- atmospheric physics of gas giant planets in our Solar System;
- the growth of galaxies in the early Universe;
- testing new cosmological physics through precision measurements of cosmic expansion;
- the origin, evolution, and strong-field gravity of massive black holes; and
- fundamental physics of merging compact objects, revealed by gravitational waves and electromagnetic signals (i.e., multi-messenger astrophysics).

Radio and OIR observations provide complementary information about physical processes and compositional constituents of planets, stars, gas and galaxies and provide independent means to cross-check essentially important measurements (e.g., in the areas of cosmology and fundamental physics).

The US ELT Program (US-ELTP)[1]: At OIR wavelengths, the required gain in resolution and sensitivity will be achieved by Extremely Large Telescopes (ELTs) with primary mirror diameters greater than 20m. Adaptive optics (AO) in the infrared will enable these telescopes to observe at their diffraction limits, λ/D = 7 mas * (30m/D) at 1 micron, and to achieve sensitivity gains proportional to D^4 or even greater in crowded fields. The US ELT Program seeks to provide an open-access share of 25% or more of the observing time on the two ELT projects with US leadership: the 24.5m Giant Magellan Telescope (GMT) in Chile, and the Thirty Meter Telescope (TMT) in Hawaii. This program will offer US astronomers unique access to ELTs in both hemispheres, with a broader range of instrumentation than would be available on a single observatory platform. The National Optical Astronomy Observatory (NOAO) will provide user support for the US astronomical community, including data science resources to facilitate research using all archived TMT/GMT data.

The Next-Generation Very Large Array (ngVLA)[2]: At radio frequencies from 1.2 to 116 GHz (wavelengths 25 to 0.26 cm), the required gain in sensitivity and angular resolution to achieve our scientific ambitions will be provided by the ngVLA, which will complement the exquisite performance of ALMA at submm wavelengths and the future SKA-1 at decimeter to meter wavelengths. Building on the superb cm observing conditions and existing infrastructure of the VLA site in the US southwest, the ngVLA will deliver an order of magnitude improvement in

[1] For a full description of the US-ELTP, see the APC white paper by S. Wolff et al. 2019.
[2] For a full description of the ngVLA, see the APC white paper by M. McKinnon et al. 2019.

both sensitivity and angular resolution compared to existing and planned radio facilities. By combining a compact array core with extended baselines reaching across North America, the ngVLA will achieve a synthesized beam with FWHM ≤ 1 mas at frequencies ≳10 GHz, thereby opening up extensive new discovery space through ultra-sensitive imaging of thermal line and continuum emission down to milliarcsecond scales. The US will be the coordinating partner of ngVLA construction and operations, and NRAO will oversee the day-to-day activities of the observatory, including user support and dissemination of science ready data products.

Here we briefly highlight several areas of forefront research in which the combination of observations with the ngVLA and GMT/TMT will offer major new advances in understanding. We then consider opportunities to enable both of these capabilities in the coming decade.

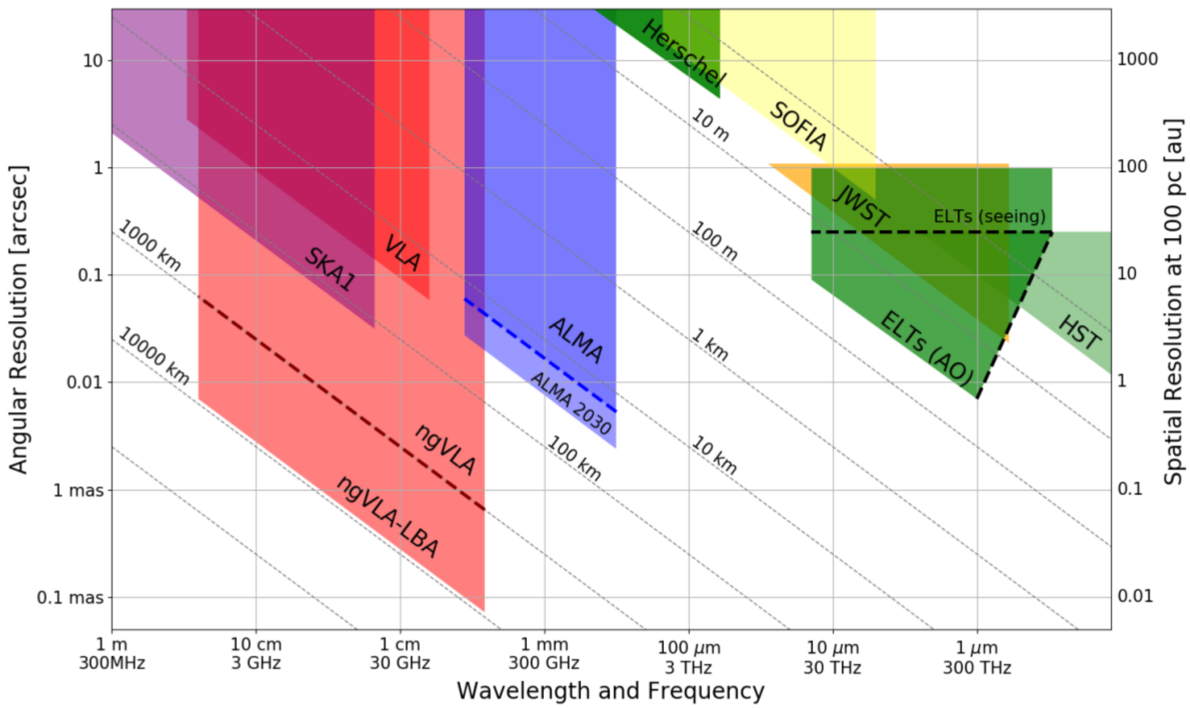

Figure 1: Angular resolution versus wavelength for current and future-generation facilities, including the Next Generation Very Large Array (ngVLA), 30m-class Extremely Large Telescopes (ELTs), and a possible future expansion of ALMA with maximum baselines up to 30 km (ALMA 2030). A dashed line separates the ngVLA main array from the continental-scale Long Baseline Array (LBA). For ELTs, the lower left envelope indicates diffraction-limited AO performance in the infrared, and dashed lines schematically indicate a transition to seeing-limited performance in the optical. The scale at right shows spatial resolution (in AU) for observations of forming planetary systems at a distance of 100 pc.

The formation and evolution of planetary systems and the chemistry of life

The investigation of extrasolar planetary systems is one of the defining pursuits of contemporary astronomy. By observing with unprecedentedly high angular resolution at wavelengths that provide essential, complementary information, the ngVLA, ELTs and ALMA will enable systematic investigations of planetary systems in all phases of their lifecycle. Such joint studies will uniquely open up pathways to investigate planet formation and evolution, comparative planetology, planetary system architectures, astrochemistry of forming solar systems, and the search for signatures of life in exo-planetary atmospheres (e.g., Isella et al. 2019; Jang-Condell et al. 2019, Weinberger et al. 2019).

Planet formation begins as the leftover gas and dust from star formation settles into a disk rotating about the central star. Extant facilities lack the combined angular resolution and sensitivity to precisely study the mass flow through disks, which is critical to understanding where and how planets form and migrate. Migration rates depend on the gas-to-dust ratio and radial pressure structure of the disk. ALMA images of disks with large (many AU) dust ring structures suggest that radial pressure bumps can confine dust of certain sizes (e.g., Pinilla et al. 2012; van der Marel et al. 2015). However, how these pressure maxima are created and whether they are sustained is an open question. To understand radial drift, we must measure the gas pressure and turbulence in a radially resolved manner, and the gas-to-dust ratio as close to the midplane as possible. Both of these will require a pan-chromatic approach with a spatial resolution of a few AU, covering warm gas at the near- to mid-infrared (ELTs), small dust grains in scattered light (high performance coronagraphs on ELTs), and larger dust grains and cooler gas (ngVLA).

The radial drift problem for planetary embryo growth becomes the migration problem for planetary cores, for which rapid inward movement should be driven by torques induced by density waves. Planets massive enough to open gaps in the disks should move inward with gas accretion. Physical constraints on the interaction can come in the form of imaging of disk gaps, warps, and spirals created by planets and by studying the non-Keplerian motion of gas. Hydrodynamic simulations predict that gaps and spiral arms can be caused by planets embedded in and interacting with the disk (e.g., Kley & Nelson 2012; Dong et al. 2015a). The appearance of gaps and spiral arms can also reveal planet properties (e.g., Debes et al. 2013; Dong et al. 2015b; Fung et al. 2014) or indicate gravitational instability (e.g., Pérez et al. 2016; Dong et al. 2018). OIR imaging highlights structure and also the scale height by resolving features produced by shadowing within the disk system. Thermal emission over the full range of inner to outer disk wavelengths, from 10 μm to 1 mm, reveals the surface density of material. If planets can be directly imaged within disks (Figure 2), their masses (as inferred from their luminosities) can be compared to the disk structure to diagnose the disk physics, including density and turbulence.

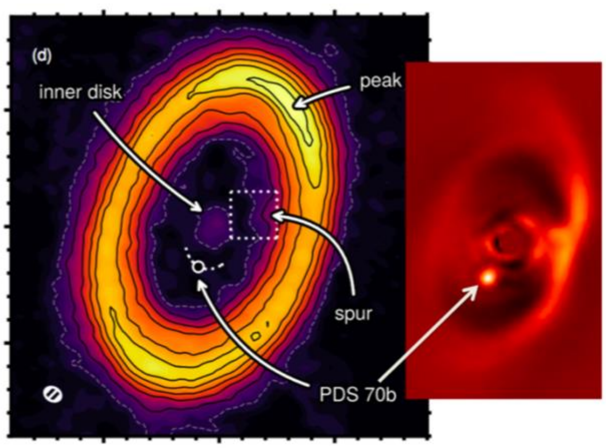

Figure 2: (Left) 870 mm ALMA continuum image of the PDS 70 disk with 0.07" (8 AU) resolution (Keppler et al. 2018). (Right) 1.6 mm image of the planet PDS 70b, located at the center of a dust-depleted gap as predicted by planet—disk interaction models (Müller et al. 2019). Fig. from Isella et al. 2019.

Understanding the conditions that ultimately lead to habitability is another growing area of research for which joint, high-resolution radio and OIR observations are critical. Extraterrestrial amino acids, the chemical building blocks of the biopolymers that comprise life as we know it on Earth, are present in meteoritic samples and in comets, but our understanding of the chemical and physical pathways to the formation of these prebiotic molecules is highly incomplete. The ELTs will revolutionize our understanding of habitability by being able to directly characterize exoplanet atmospheres for large statistical samples for the first time (Dragomir et al. 2019; Lopez-Morales et al. 2019). Understanding of how these atmospheres are formed, and being able to relate them back to the larger population of exoplanets, requires observations of their initial conditions through studies of the spatial and temporal evolution of the complex chemistry in the mid-planes of protoplanetary disks. The ngVLA will deliver such observations (Öberg et al. 2019), thereby solidifying our accounting of the chemical inventories for critical, low-abundance species to inform, expand, and constrain chemical models of these reactions (e.g., McGuire et al. 2019). Consequently, combining ngVLA and ELT observations will yield our first major view into the formation pathways of exoplanet atmospheres, their diversity, and ultimately their habitability.

The growth of galaxies in the early Universe

In standard cosmological models, baryonic material flows from the circum-galactic medium (CGM) into the gravitational potential wells of dark matter halos, cooling, condensing, and eventually fueling star formation in early galaxies. The physical processes suggested for triggering, modulating, and even suppressing star formation are numerous and still poorly understood. On very small scales, the instantaneously available local fuel supply must play a crucial role in star formation (e.g., Kennicutt 1998, Bigiel 2008; Leroy et al. 2008). On the largest scales, the galaxy clustering environment also clearly plays an important role (e.g. Dressler et al., 1997; Butcher & Oemler, 1978, 1984; Desai et al., 2007). Active Galactic Nuclei (AGN) harboring supermassive black holes are also fed by the inflowing gas, and their energetic emission is thought to regulate and even terminate galactic star formation. Winds driven by star formation, supernovae and AGN drive material out of the galaxy and back into the CGM and intergalactic medium (IGM), enriching it with metals. To piece together a fully consistent understanding of galaxy growth requires tracing each of these processes on the full range of linear scales over which they operate for a large, heterogeneous set of physical conditions, observed at the peak epoch of cosmic star formation, roughly $1 < z < 3$.

Together, the ELTs, ngVLA and ALMA will observe the critical baryonic phases in early galaxies with the sensitivity and high angular resolution necessary to resolve the physical processes at work (Figure 3). Optical multi-object spectrographs on TMT and GMT will measure the structure, kinematics and chemical composition of the CGM using UV absorption lines detected in the spectra of faint background galaxies – similar to QSO absorption line studies today, but with a far higher sky density of sightlines to sample individual galaxy halos with multiple probes (Rudie et al. 2019). Diffraction-limited near-infrared imaging and integral field spectroscopy will resolve galaxy structure, stellar populations, ionized gas excitation, metal abundance, and velocity fields on scales of 150 pc or smaller, the size of giant star clusters and molecular cloud complexes that are the base units of star formation in galaxies. Then ngVLA will resolve the spatial and velocity structure of molecular gas on similar scales by observing low-J CO (Carilli et al. 2019) and dense gas tracers (e.g., HCN; Decarli et al. 2018), mapping the fuel supply for star formation. ALMA provides complementary information on molecular excitation and far-infrared atomic fine structure lines that cool the ISM, as well as cold dust. Together the ELTs and ngVLA will characterize the multi-phase (ionized, atomic and molecular) outflows that drive gas and metals out of galaxies. The ngVLA will also yield robust maps of star formation unaffected by dust in high-redshift galaxies by accessing free-free emission (e.g., Murphy et al. 2019). Comparison of resolved star formation efficiencies with spatially resolved studies of the ionized ISM and stellar populations achievable by the ELTs (e.g., Newman et al. 2019) will allow us to precisely determine the role that chemical abundances, extinction, and kinematics play in affecting star formation across cosmic time. Ultimately, by combining sub-kpc molecular gas imaging with equally high-angular resolution imaging of the ionized gas and stellar populations from ELTs, we will usher-in the era of 'precision galaxy formation', providing information on the cosmic baryon cycle in early galaxies at a level of detail approaching what is now currently possible only for nearby galaxies and the Milky Way.

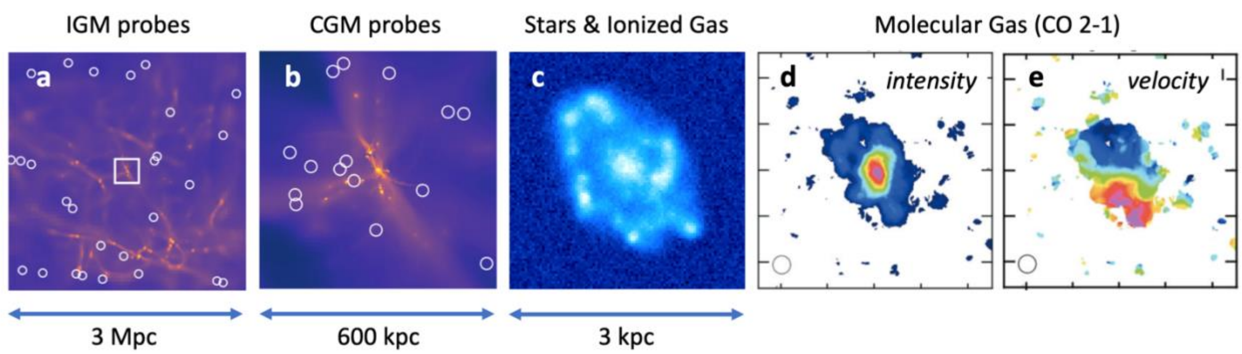

Figure 3: Together, observations with ELTs and the ngVLA will study critical components of the cosmic baryon cycle of galaxies at z ≈ 2 ("cosmic noon") from megaparsec environments to 100 pc scales characteristic of massive star-forming clusters. From left to right: (a, b) Multi-object spectrographs on GMT and TMT will measure intergalactic and circumgalactic gas (IGM, CGM) using UV absorption lines measured in the spectra of faint background galaxies. (c) AO imaging and integral field spectroscopy will observe stars and ionized gas with resolutions of order 150 pc. (d, e) The ngVLA will observe low-J transitions of CO at high angular resolution, tracing the detailed spatial and velocity structure of the fuel for star formation.

Compact object mergers and multi-messenger astrophysics

Thanks to the remarkable discovery of gravitational waves (GWs) and light at all wavelengths from the neutron star (NS)-NS merger dubbed GW170817, a new frontier has been opened in the realm of multi-messenger time-domain astronomy. The expected progress in sensitivity of ground-based gravitational wave detectors in the next decade will lead to higher detection rates (order of 10s per year) of merger events involving NSs out to distances of several hundred Mpc. Based on what we learned from GW170817, this increased sensitivity will produce GW detections at distances where the expected optical and radio counterparts of binary mergers containing at least one NS are likely to be exceedingly dim (Figure 4). Thus, without an upgrade in sensitivity on both current radio and optical facilities, we will effectively have no opportunity to constrain the larger population of NS-NS and NS-BH mergers, and we will be limited to studying the tip of the iceberg composed of only the very nearby or exceptionally bright events.

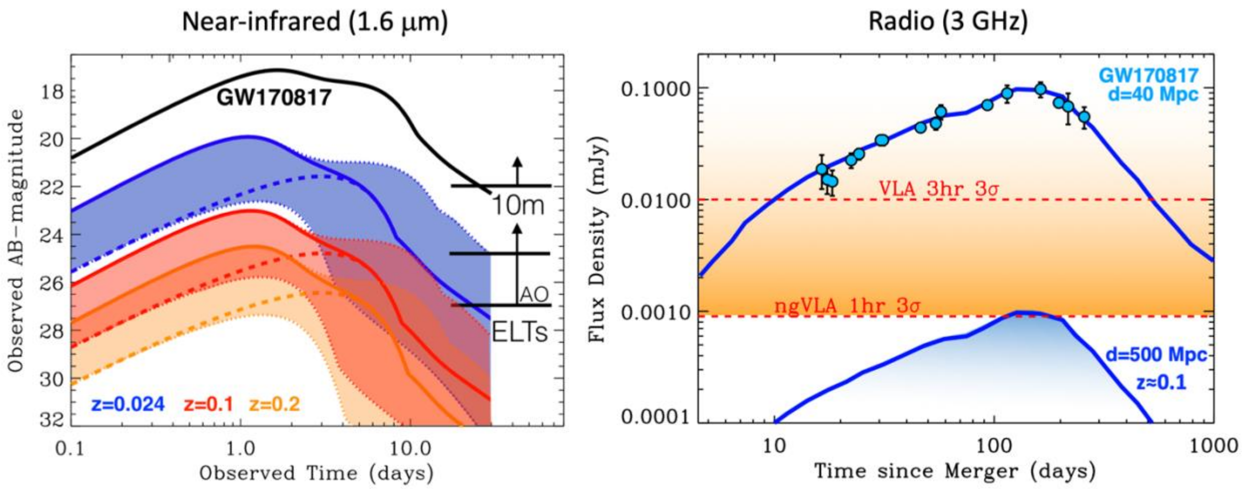

Figure 4: Near-infrared (left) and radio (right) light curves for the gravitational-wave inducing kilonova GW170817 (d = 40 kpc; top curves/points in both panels). Fiducial sensitivities for ~1 hour observations with 10m telescopes (spectroscopy) and the VLA are indicated, as well as corresponding sensitivities for AO-assisted ELTs and the ngVLA. The colored swaths at left show models with contributions from blue and red kilonova components (solid and dashed lines, respectively), at various redshifts to which future upgrades to gravitational wave detectors will be sensitive. The lower curve at right rescales GW170817 to a distance of 500 Mpc (z ≈ 0.1). Adapted from Chornock et al. 2019 and Margutti et al. 2018.

Ultimately, ELTs (Chornock et al., 2019) and future radio arrays such as the ngVLA (Corsi et al., 2019), working in tandem, would enable us to reach a key goal of joint GW and electromagnetic time-domain astronomy across the electromagnetic spectrum: building a statistically significant sample of merger events to constrain the equation of state of NSs, the nature of the merger remnants, the physics behind the launching mechanism and the structure of the fastest jets we know of in the Universe, and the total mass available for r-process nucleosynthesis.

Upgraded sensitivities in optical and radio would also enable crucial progress in the characterization of the rarest cosmic stellar explosions (supernovae; SNe) that seed the Universe with BHs and NSs, such as broad-lined type Ic (BL-1c) and engine-driven supernovae (see, e.g., Kulkarni et al., 1998; Berger et al., 2003; Soderberg et al., 2010; Margutti et al., 2013, 2014, 2019; Corsi et al., 2017). The radio can map the density of the medium, and hence the mass-loss history of the SN progenitor before death, while very late-time spectroscopy has the potential to reveal the presence of a central engine in the form of an accreting BH or a spinning-down NS. The current sample of engine-driven and BL-Ic SNe is limited to few local events with high-quality optical and radio monitoring – too small to enable statistically significant studies of the population that these rare explosions come from (e.g., Corsi et al., 2016 and references therein). A synergistic effort with TMT/GMT and the ngVLA has the potential to greatly improve the current state-of-the art of this field and to increase the maximum distance at which the rarest form of massive star explosions are detectable.

Other synergies

Giant Planets: Understanding the physical processes operating in gas giant atmospheres requires mapping structure, composition, and velocities over a large range of altitude, from the stratosphere down to the deep (many bars) atmosphere. Ideally, this 3D mapping requires simultaneous observations from the OIR (and space-based UV) for high-altitude features to centimeter radio data that probe deep into the atmospheres. The ELTs and ngVLA will resolve structure on scales that have only been accessible with fly-by missions, and will address questions ranging from planetary origin and evolution, to the detailed workings of convection in hydrogen-dominated atmospheres (de Pater et al. 2019a, Wong et al. 2019). The sensitivity of ngVLA will permit time-resolved measurements (the current VLA requires long integrations and planetary rotation smears longitudinal structure). Observations of planetary satellites will be similarly productive, with ELTs measuring reflected light and thermal emission at the satellite surface, while the ngVLA will measure the thermal profile in deeper, less processed subsurfaces (de Kleer et al. 2019, Wong et al. 2019).

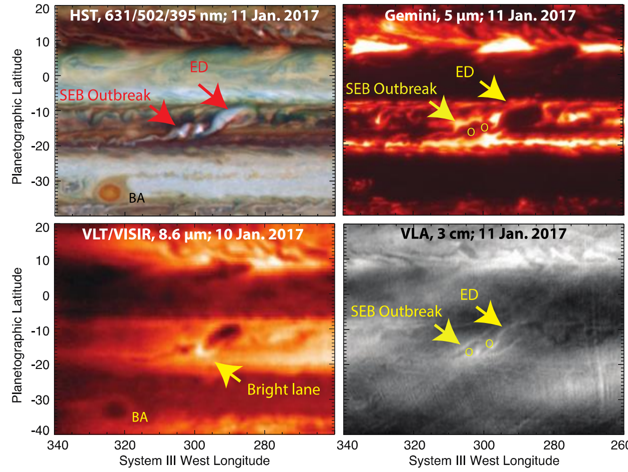

Figure 5: Jupiter South Equatorial Belt (SEB) outbreak of 2017, imaged at high resolution by HST, Gemini, VLT and the VLA. The various wavelengths are sensitive to different gasses and/or aerosols, and hence probe different depths and temperatures. From de Pater et al. 2019b, submitted.

Supermassive Black Holes (SMBHs): The high angular resolution of ELTs will allow spectroscopic determination of black hole masses through stellar dynamics out to high redshifts(Gultekin et al. 2019). Correspondingly high resolution observations with the ngVLA will resolve nuclear accretion from star formation at high redshift (Pope et al. 2019). Together, the ELTs and ngVLA will be powerful tools to study the co-evolution of black holes and galaxies throughout cosmic history. ELTs will also search for intermediate mass black holes (IMBHs, 10^3—10^5 $M_\odot$) in globular clusters using stellar proper motions and velocities, and in low-mass galaxies via stellar velocity dispersions within the black hole's sphere of influence (Greene et al. 2019). The ngVLA will enable complementary and extremely sensitive searches for IMBH accretion in extragalactic globular clusters (Wrobel et al. 2019) and in the cores of nearby dwarf galaxies (Plotkin et al. 2019). The ELTs will test general relativity in the strong gravity regime by observing stellar orbits near the black hole in our Galactic Center (Do et al. 2019), while ngVLA can make complementary tests using Galactic Center pulsars (Bower et al. 2019).

The Hubble Constant: Recent measurements of H_0 with 1—2% accuracy find values (~74 km s^{-1}) that appear to be significantly (4.4σ) different than that (~67 km s^{-1}) derived from Planck measurements of the cosmic microwave background (Riess et al. 2019). This discrepancy could imply new physics to explain cosmic expansion, but it must be tested and verified using precise and robust new measurements using several fully independent methods. ELTs will provide 1% distance calibration throughout the Local Group from observations of detached eclipsing binaries, and will extend precise distances well out into the Hubble Flow using infrared tip of the red giant branch (TRGB) measurements (Beaton et al. 2019), while ngVLA will make an independent geometric measurements using large samples of H_20 megamasers around SMBHs (Braatz et al. 2019). ELTs can also measure H_0 to 1% accuracy using time delays in multiple-image gravitationally lensed QSOs and supernovae (Beaton et al. 2019).

Programmatic Challenges to Large Facilities

Costs of Flagship Facilities

In many disciplines, the facilities required to expand our scientific frontiers and continue our discoveries require significantly more resources than needed just a few decades ago. Astronomy best illustrates this evolution through the construction of ground-based observatories. In the 1980s, a leading-edge OIR or radio telescope cost ~$100M. In the 1990s forefront observatories cost $400-500M. In the 2020s and 2030s the facilities needed to answer the key scientific questions of our times will cost in the range $1-2B. Other international consortia are already making investments on this scale, with the European ELT and the SKA being examples. To support the next-generation of astronomy facilities and maintain US leadership in the field, the NSF must address the need for increased resources for ground-based astronomy. The existing $200 million per year funding level of NSF's Major Research Equipment and Facilities Construction (MREFC) account cannot support the construction of the ELTs or the ngVLA, especially since that account is destined to be redirected by FY2025, according to NSF's own funding projections described in its FY2020 budget request.[3] Growth, upgrades and new facilities in other areas of NSF interest (e.g., physics, geophysics, biology, polar programs) will further strain the scarce MREFC resources.[4]

The current funding environment also limits investments in mid-scale projects to explore new technologies and make unique measurements, and train the next generation of scientists, engineers and students to lead the field. Mid-scale projects now often cost as much as the state-of-the-art telescopes of the 1980s-90s. While NSF has recently requested new funding for a mid-scale initiative within the MREFC account, the proposed level may not be sufficient to result in significant progress or impact in any discipline, including astronomy.

Since annual operating costs of astronomy facilities are typically a few percent of the capital costs, it is clear that closing old facilities, with their much lower capital costs and hence operating costs, cannot release sufficient funds to operate new flagship facilities. NSF has appropriately continued to evaluate and manage its portfolio with respect to older facilities (with some success and new opportunities/capabilities seen), but the pressure on the NSF AST operating budget has not been lowered appreciably.

Astronomy has traditionally flourished on the basis of a balanced research portfolio. Major facilities, mid-scale initiatives, and the grants programs to support researchers that exploit

---

[3] https://www.nsf.gov/about/budget/fy2020/pdf/34a_fy2020.pdf

[4] On average for FY2014-2018, enacted MREFC funding was 2.7% of the annual total NSF appropriation.

these instrumental capabilities are all essential. Maintaining international competitiveness, while at the same time sustaining a healthy astronomy ecosystem, requires not only an increase in funding for facility construction and operations, but also new strategies for deploying that funding. The challenge of addressing these issues falls primarily to the NSF, which remains the primary funder of ground-based astronomy in the US.

The conclusion is clear: ground-based astronomy cannot make major advances under the current funding environment at NSF, and US leadership in the field is being eroded. As the Decadal Committee considers the next decade of astronomy and astrophysics at all scales, recognizing the need for increased funding for NSF should be part of its fundamental considerations. Moving forward, the astronomy community should work with other NSF-funded science disciplines to advocate advancing NSF's funding. For their part, the large-scale ground-based astronomy teams are proposing a fiscally-responsible approach to deliver world-class, cutting edge science by offering a coordinated and collaborative funding profile for development the next decade's observatories.

Addressing the Challenge: Construction of Major New Facilities

The issue of how to accommodate the growing costs of major new facilities is not one that confronts astronomy alone. Other disciplines also require new facilities with costs of hundreds of millions of dollars or more. Current and future budget profiles of NSF are not consistent with the initiation of large-scale next-generation projects in any field.

A doubling by 2023 of MREFC funding from the typical recent value of ~$200M/yr would probably be sufficient to build both the ELTs and the ngVLA in the 2020s (Figure 6). To be accommodated within this higher budget level, the two projects would have to be phased. We suggest that the US ELT Program should be funded early in the decade because TMT and GMT are in a more advanced state of readiness. Astronomy projects on this scale will require 5-6 or more years to complete and need to commit a large percentage of the major capital expenditures in the first 2-3 years. After the US-ELTP completes its peak construction funding and then begins to ramp down spending, ngVLA could ramp up mid-decade. Historically, optical and radio astronomy construction projects have often alternated, with significant knowledge and skill transfer between the projects allowing sharing of best practices and adoption of common standards.

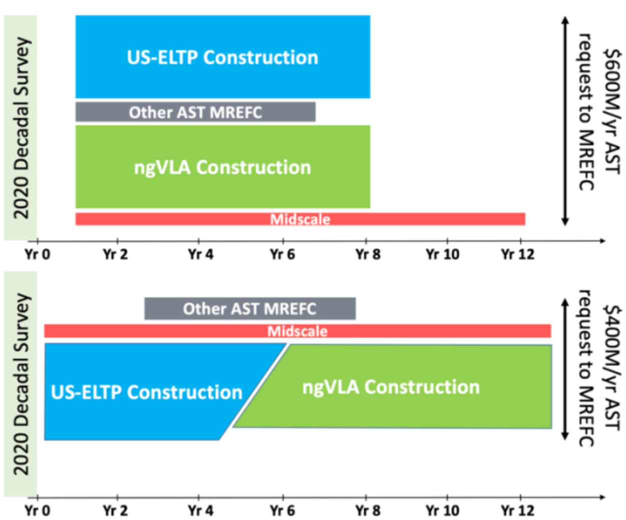

Figure 6: Two schematic scenarios for NSF-AST facility construction funding in the coming decade.

It is likely that simply doubling MREFC funding would not, however, address the fundamental problem. There are surely other research disciplines with growing aspirations. A strategic plan that assesses the needs for construction funding by all the NSF-funded disciplines would serve to quantify the implications for the evolution of MREFC support. It is also important for many research areas, including astronomy, to have more opportunities for mid-scale projects. Whatever the new level of the MREFC program in the coming decade, it may prove appropriate to set aside about 20 percent of the funds for mid-scale initiatives.

Addressing the Challenge: Life Cycle Funding

Completed flagship facilities present two additional challenges. First, the costs of operating billion-dollar facilities cannot be managed within the existing budgets of the directorates, even with sharp contractions in support for grants and portfolio management (closure of older instruments). MREFC guidelines now require that construction proposals include detailed plans for, and costs of, operations. Therefore, it is possible to know estimated full life-cycle costs well in advance, and realistic planning to cover those costs should be a prerequisite for authorizing construction. We suggest costs should probably be shared between some "central facilities fund" at NSF and the relevant directorate so that the directorate remains committed to the program. The support required from the central fund by the directorate should be consistent with maintaining a vigorous grants program.

The second challenge is that flagship facilities are often built to last for decades; GMT, TMT, and the ngVLA are being designed for ~50-year lifetimes. Indefinite long-term commitments to operations funding can deter the construction of new facilities. Consideration should be given to establishing, in analogy with NASA, a "prime mission" lifetime. For ground-based telescopes, this lifetime should probably be at least 20 years. A few years before the expiration date for each facility, a review conducted by members of the astronomical research community (not the Agency) would weigh the merits of continued operation against other priorities. Enough time should be allowed to find alternative sources of funding or new missions for the instrument.

In summary, the scientifically-compelling and world-leading optical and radio astronomy projects proposed for the 2020s can be achieved only by significant increases in the resources available for both construction and operations of ground-based facilities. Advocacy for growth of the MREFC (and successor) program at the NSF is a key enabling step to create these futures. Growth of the NSF budget would benefit not only astronomy but other disciplines that also depend on large, complex, broadly-accessed facilities.

Rather than eliminate MREFC's funding, Congress has opposed any requested downward trajectory in recent fiscal years in both the NSF R&RA and MREFC accounts, as was the case in the FY2019 Appropriations bill. Congress recognizes that these accounts must gradually grow in order to adequately support the next generation of science infrastructure in the US. With the Decadal Committee's recognition, the astronomy community – like other science disciplines that depend on the next generation of large-scale facilities – should continue to work with Congress, as it has in recent years, to lay the groundwork for having future projects by requesting NSF to consider a funding pipeline for supporting such future projects. Having the astronomy community showcase a fiscally-responsible collaboration and forethought will serve as a hugely important and effective message when advocating for the necessary federal funding to maintain the US's leadership in astronomy.

References

[References to Astro2020 science white papers are given as URL-linked titles.]

Beaton, R., et al. 2019, "Measuring the Hubble Constant Near and Far in the Era of ELTs"

Berger et al., 2003, ApJ, 599, 408

Bigiel, F., et al. 2008, AJ, 136, 2846

Bower, G., et al. 2019, "Fundamental Physics with Galactic Center Pulsars"

Braatz, J., et al. 2019, "H_2O Megamaser Cosmology with the ngVLA"

Butcher, H., and Oemler, A., 1978, ApJ, 219, 18

Butcher, H., and Oemler, A., 1984, ApJ, 285, 426

Carilli, C., et al. 2019, "Imaging molecular gas in high redshift galaxies at <=1 kpc resolution"

Chornock, R., et al. 2019, "Multi-Messenger Astronomy with Extremely Large Telescopes"

Corsi, A., et al. 2016, ApJ, 830, 42

Corsi, A., et al. 2017, ApJ, 847, 54

Corsi, A., et al. 2019, "Radio Counterparts of Compact Object Mergers in the Era of Gravitational-Wave Astronomy"

de Kleer, K., et al. 2019, "Solar System Satellites: Key Science Enabled by the ngVLA"

de Pater, I., et al. 2019a, "Potential for Solar System Science with the ngVLA: the Giant Planets"

Debes, J. H., Jang-Condell, H., Weinberger, A. J., Roberge, A., & Schneider, G. 2013, ApJ, 771, 45

Decarli, R., et al. 2018, in *Science with a Next Generation Very Large Array*, ASP Conference Series, 517, 575

Desai, V., et al. 2007, ApJ, 660, 1151

Do, T., et al. 2019, "Envisioning the next decade of Galactic Center science: a laboratory for the study of the physics and astrophysics of supermassive black holes"

Dong, R., Najita, J. R., & Brittain, S. 2018, ApJ, 862, 103

Dong, R., Zhu, Z., Rafikov, R. R., & Stone, J. M. 2015a, ApJ, 809, L5

Dong, R., Zhu, Z., & Whitney, B. 2015b, ApJ, 809, 93

Dragomir, D., et al. 2019, "Characterizing the Atmospheres of Irradiated Exoplanets at High Spectral Resolution"

Dressler, A., et al. 1997, ApJ, 490, 577

Fung, J., Shi, J.-M., & Chiang, E. 2014, ApJ, 782, 88

Greene, J., et al. 2019, "The Local Relics of Supermassive Black Hole Seeds"

Gultekin, K., et al. 2019, "Black Holes Across Cosmic Time"

Isella, A., et al. 2019, "Observing Planetary Systems in the Making"

Jang-Condell, H., et al. 2019, "Protoplanetary Disk Science Enabled by Extremely Large Telescopes"

Kennicutt, R., 1998, ARAA, 36, 189

Keppler, M., et al. 2018, A&A, 617, A44

Kulkarni et al. 1998, Nature, 395, 663

Leroy, A., et al. 2008, AJ, 136, 2782

Lopez-Morales, M., et al. 2019, "Detecting Earth-like Biosignatures on Rocky Exoplanets around Nearby Stars with Ground-based Extremely Large Telescopes"

Kley, W., & Nelson, R. P., 2012, ARA&A, 50, 211

Margutti, R., et al. 2013, ApJ, 778, 18

Margutti, R., et al. 2014, ApJ, 797, 107

Margutti, R., et al. 2018, ApJ, 856, L18

Margutti, R., et al. 2019, ApJ, 872, 18

McKinnon, M., et al. 2019, "ngVLA: The Next Generation Very Large Array"

McGuire, B., et al. 2019, "Revealing Chemical Evolution Throughout the Star-Formation Process"

Müller, A., et al. 2018, A&A, 617, L2

Murphy, E., et al. 2019, "Robustly Mapping the Distribution of Star Formation in High-z Galaxies"

Newman, A., et al. 2019, "Resolving Galaxy Formation at Cosmic Noon"

Öberg, K., et al. 2019, "Astrochemical Origins of Planetary Systems"

Pérez, L. M., Carpenter, J. M., Andrews, S. M., et al. 2016, Science, 353, 1519

Pinilla, P., Benisty, M., and Birnsteil, T., 2012, A&A, 545, A81

Plotkin, R., et al. 2019, "Local Constraints on Supermassive Black Hole Seeds"

Pope, A., et al. 2019, "Simultaneous Measurements of Star Formation and Supermassive Black Hole Growth in Galaxies"

Riess, A., et al. 2019, ApJ, 876, 85

Rudie, G., et al. 2019, "Observing Galaxies and Dissecting their Baryon Cycle at Cosmic Noon"

Soderberg, A., et al., 2010, Nature, 463, 513

van der Marel, N., et al. 2015, ApJ, 810, L7

Weinberger, A., et al. 2019, "A Strategy for Understanding Planet Formation"

Wolff, S., et al. 2019, "The US Extremely Large Telescope Program"

Wong, M. H., et al. 2019, "Solar system Deep Time-Surveys of atmospheres, surfaces, and rings"

Wrobel, J., et al. 2019, "Intermediate-Mass Black Holes in Extragalactic Globular Clusters"

Acknowledgements

The authors would like to thank Chris Carilli, Andrea Isella, Brian Kent, Brenda Matthews, Patrick McCarthy, Adam Riess, Fabian Walter, and Jeremy Weirach for their helpful comments and suggestions.