

Astro2020 APC White Paper

Panel on Radio, Millimeter, and Submillimeter Observations from the Ground

The Case for a Fully Funded Green Bank Telescope

Brief Description [350 character limit]: The NSF has reduced its funding for peer-reviewed use on the GBT to ~3900 hours/year, 60% of available science time. This greatly increases the telescope pressure & fragments the schedule, making it very difficult to allocate time for even the highest rated projects planned for the next decade. Here we seek funding for 1500 more hours annually.

Principal Author: K. O'Neil (Green Bank Observatory; karenoneil@gbobservatory.org)

Co-authors: Felix J Lockman (Green Bank Observatory), Filippo D'Ammando (INAF-IRA Bologna), Will Armentrout (Green Bank Observatory), Shami Chatterjee (Cornell University), Jim Cordes (Cornell University), Martin Cordner (NASA GSFC), David Frayer (Green Bank Observatory), Luke Zoltan Kelley (Northwestern University), Natalia Lewandowska (West Virginia University), Duncan Lorimer (WVU), Brian Mason (NRAO), Maura McLaughlin (West Virginia University), Tony Mroczkowski (European Southern Observatory), Hooshang Nayyeri (UC Irvine), Eric Perlman (Florida Institute of Technology), Bindu Rani (NASA Goddard Space Flight Center), Dominik Riechers (Cornell University), Martin Sahlan (Uppsala University), Ian Stephens (CfA/SAO), Patrick Taylor (Lunar and Planetary Institute), Francisco Villaescusa-Navarro (Center for Computational Astrophysics, Flatiron Institute)

Endosers: Esteban D. Araya (Western Illinois University), Hector Arce (Yale University), Dana Balsler (NRAO), Robert Benjamin (U of Wisconsin-Whitewater), Tracy Becker (Southwest Research Institute), Anamaria Berea (Ronin Institute), Sriram Bhiravarasu (Lunar and Planetary Institute), Amber Bonsall (Green Bank Observatory), Michael Busch (SETI Institute), Natalie Butterfield (Green Bank Observatory), Tzu-Ching Chang (JPL), Suchetana Chatterjee (Presidency University), Claudia Cicone (University of Oslo), Mark J Claussen (NRAO), Jeremy Darling (University of Colorado), Simon Dicker (University of Pennsylvania), James Di Francesco (National Research Council of Canada), Timothy Dolch (Hillsdale College), Chuanfei Dong (Princeton University), Olivier Doré (JPL/Caltech), Eric Feigelson (Penn State), Andrew Fox (STScI), Rachel Friesen (NRAO), Tapasi Ghosh (Green Bank Observatory), Andrew Harris (University of Maryland), Carl Heiles (University of California at Berkeley), J. Colin Hill (Institute for Advanced Study), J. Christopher Howk (University of Notre Dame), Tanveer Karim (Harvard), Amanda Kepley (NRAO), Alvaro Labiano (Center for Astrobiology, CSIC-INTA), Michael Lam (West Virginia University), Lynn Matthews (MIT Haystack Observatory), Brett McGuire (NRAO), Chiara Mingarelli (Center for Computational Astrophysics, Flatiron Institute), Anthony Minter (Green Bank Observatory), Larry Morgan (Green Bank Observatory), Hamsa Padmanabhan (Canadian Institute for Theoretical Astrophysics), Ue-Li Pen (CITA), Dominic Pesce (Center for Astrophysics/Harvard & Smithsonian), Francesco Piacentini (Dipartimento di Fisica, Sapienza University of Rome), Philipp Richter (University of Potsdam), Edgard G. Rivera-Valentín (Lunar and Planetary Institute - USRA), Graca Rocha (JPL/Caltech), Erik Rosolowsky (U.

Alberta), Sarah Sadavoy (SAO), Hannah Sizemore (Planetary Science Institute/Green Bank Observatory), Martin Slade (JPL/Caltech), David Thilker (Johns Hopkins University), John Tobin (National Radio Astronomy Observatory), Trey Wenger (Dominion Radio Astrophysical Observatory), Jun-Hui Zhao (Center for Astrophysics/Harvard & Smithsonian)

I. The Green Bank Telescope – Status

The Robert C. Byrd Green Bank Telescope (GBT), with its 100-m diameter collecting area, unblocked aperture, and excellent surface, offers the scientific community unrivaled research capabilities. The GBT is the world's largest fully steerable telescope, with 85% sky coverage. The GBT began regular science operations in 2001, is one of the newer astronomical facilities of the NSF. More importantly, the GBT was designed to take advantage of future improvements instrumentation beyond what was available at the time of construction. As a result, in 2012 (after approximately a decade of surface accuracy and telescope pointing refinements), the GBT began significant operations in the 3mm band, opening up enhanced capabilities for spectroscopy and continuum studies over 67–116 GHz. The GBT has achieved excellent 3mm capabilities, with 35% and 18% aperture efficiency at 90 and 115 GHz, respectively, and r.m.s pointing uncertainties of ~2". It currently operates over nearly three decades in frequency from 0.29–116 GHz (1m – 2.6mm wavelengths), and plans are underway to further enhance the surface control and pointing accuracy that will usher in a new area of cost-effective, world-class science. The GBT is becoming a pivotal complement to ALMA and the VLA for the U.S. scientific community.

The GBT operates 362 days annually using a dynamic scheduling system that optimizes each observing project's scientific goals given the predicted weather conditions. In a typical year, the GBT offers 6,500 hours of observing time, equivalent to an operational availability of 74%.

Currently (FY19), National Science Foundation (NSF) funds approximately 60% of the GBT's operational costs for peer-reviewed ("open-skies") science, about 4,100 hours annually¹. The NSF is currently considering a new five-year management proposal for the Green Bank Observatory, covering FY20 through FY24. At the same time, the National Science Board (NSB) has voted to accept a new Record of Decision for the Observatory. While the final record of decision has not yet been published, **it is expected that the Record of Decision (RoD) for the Green Bank Observatory will encourage the NSF continuing to look for partnerships to fund the facility. As a result, at best the GBT will remain only available 60% of the time for peer-reviewed, open skies science, and it is quite possible the number of hours available for peer-reviewed science on the GBT will in fact decline over the next few years as new NSF partners are found. Here we look at the current status of the GBT and argue for increasing the overall funding for open skies GBT science, expanding the telescope availability beyond the currently expected RoD.**

2. Science in the Next Decade with the Green Bank Telescope

2.1 Overview

Driven by the priorities of the scientific community, the research program of the GBT covers a broad and dynamic spectrum that cuts across traditional disciplinary boundaries. Over decade, the unique capabilities of the GBT will allow for major advances in the study of the Solar System, interstellar chemistry, fundamental physics, the environment of black holes, star formation, the

¹ While it is true that some funds used to purchase GBT time for "private" use currently come from peer-reviewed NSF grants to individuals or consortia, these uses of the GBT have not been peer-reviewed relative to other possible uses of the telescope, and are not seen by the GBT TAC. There is also no requirement that private funds be peer-reviewed.

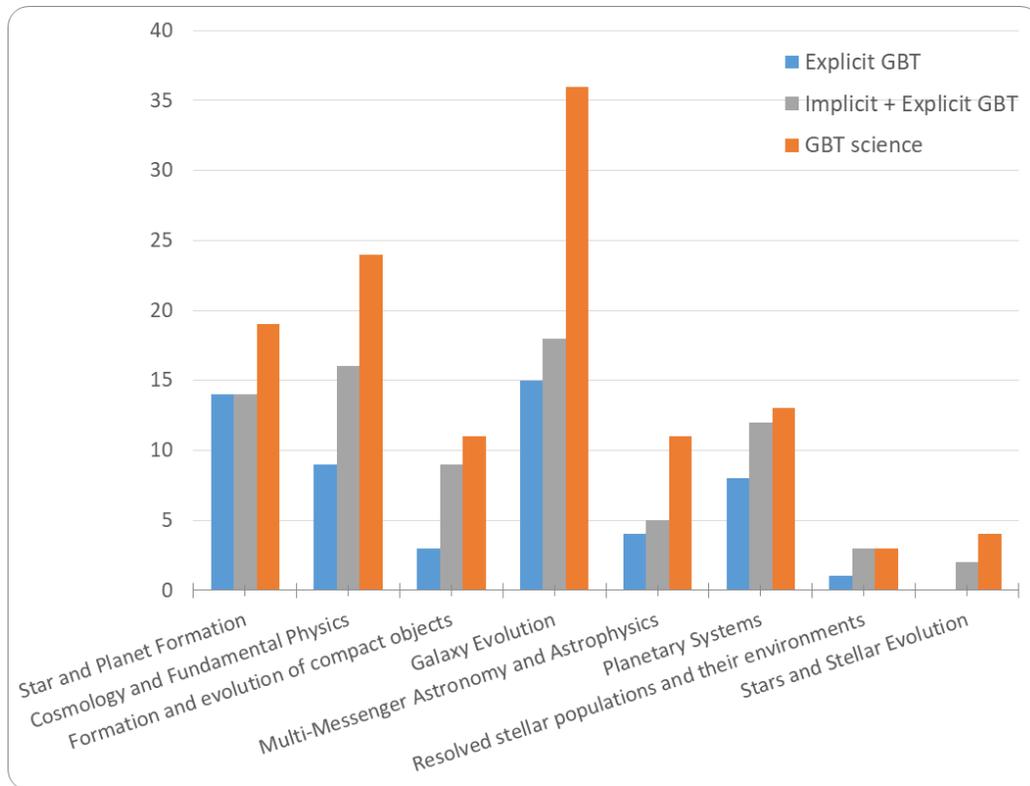


Figure 1. Breakdown of the papers submitted to the Astro2020 *Call for Science White Papers* which either explicitly request the GBT (blue), explicitly + implicitly request the GBT (grey), and all papers with science which would benefit greatly from use of the GBT (orange). Implicit use of the GBT includes requests for, e.g. the HSA and/or large single dish radio telescopes which work at 3-mm.

structure and evolution of galaxies and galaxy groups, and cosmology. Of the next approximately 570 unique submission to the Astro2020 *Call for Science White Papers*, 38 (7%) explicitly requested the GBT to accomplish their desired scientific goals, while an additional 25- 50 papers would benefit greatly from using of the GBT to achieve their scientific goals. A breakdown of the scientific categories of these whitepapers is given in Figure 1.

More information on GBT science can be found at <http://greenbankobservatory.org/astro2020>. Here we look at a subset of the submitted Astro2020 White Papers to probe the breadth of science to be done with a fully funded GBT in the 2020-2030 time range. While not a complete list from all white papers, the list below nonetheless shows the breadth of science possible if the instrument has sufficient time available for peer reviewed observations.

2.2 Star and Planet Formation

- The GBT will be key in determining the chemical inventory of the Galaxy and the relation between chemistry and phases of star and planet formation through spectral line surveys and mapping of molecular clouds. More than 200 distinct molecular species have been detected in various astronomical environments, but we still lack a chemical theory for their formation. This is a critical gap as chemistry is an integral part of star-formation and the processes that eventually results in the organic molecules that have been detected in

meteors and, likely, life on Earth (Remijan, et al. 2019; McGuire, et al. 2019a). In the last several years it has been shown that there may be a significant amount of previously undetected carbon, which is influencing the star and planet formation process. GBT observations will be crucial in understanding the role of these PAHs in stellar (and planetary) life cycles (McGuire, et al. 2019a; McGuire, et al. 2019c).

- While molecular emission traces a cloud's total mass, HII regions mark the location where that material has been converted into massive stars that are the endpoint of the star formation process. Understanding the relationship between HII regions and molecular clouds, and the interaction between massive stars and the ISM, provides critical insight into the lifecycle of the ISM gas (Anderson, et al. 2019). The GBT will provide otherwise unattainable sensitivity to planned large surveys of the Warm Ionized Medium and related HII regions.
- The integrated gas content of galaxies has been surveyed extensively. However, the link between environment and cold gas density, turbulence, excitation, dynamical state, and chemical makeup remains poorly understood (Leroy, et al. 2019). Over the next decade, a major survey of cold gas across the entire local galaxy population will determine the connection between the state of the gas, its ability to form stars, and the impact of stellar feedback. The GBT, which is particularly well-suited to map the cold gas given its capability to target low-J spectral transitions, will map molecular line emission from large areas of the sky with great surface brightness sensitivity, resolving nearby galaxies and accessing the detailed physical conditions in their cold gas and the cold gas of the Milky Way.
- A key question in star formation theory is the timescale and efficiency of the conversion of gas into stars (e.g. Kruijssen et al. 2018). Within our own galaxy, the GBT will map entire molecular clouds, including their star forming filaments and cores, with high sensitivity and an angular resolution as high as 7" (0.017 pc at 0.5 kpc). Maps will cover spectral lines from NH₃ through HCN, CN, and N₂H⁺ over a range of Galactic environments, to characterize cloud physical conditions, structure, and evolution, and to understand the efficiency of star formation in an observational parameter space largely inaccessible to ALMA (Friesen, et al. 2019; Kauffman, et al. 2019).
- Working at 3-mm as part of the High Sensitivity Array, the GBT will be able to resolve bright maser emission from massive protoclusters to measure accretion and outflow motions in Galactic star formation regions, such as around massive proto-stars (e.g. Hunter, et al. 2019). Addition of the GBT to the existing VLBA increases the sensitivity on each baseline by a factor of four to five.

2.3 Cosmology and Fundamental Physics

- Comparisons between the redshifts of multiple spectral transitions from distant galaxies provide a sensitive probe of secular evolution in fundamental constants such as the fine structure constant and the proton-electron mass ratio over cosmological epochs. The GBT will provide a substantial increase in the number of redshifted radio absorbers in

mm-wavelength lines of CO and HCO⁺ toward distant sources, including new and improved samples of SDSS Type-2 quasars (Ghosh, et al. 2019).

- The Sunyaev-Zeldovich (S-Z) effect is now a mature tool for performing high-resolution studies of the warm and hot ionized gas in and between galaxies, groups, and clusters. Galaxy groups and clusters are powerful probes of cosmology, and serve as hosts for roughly half of the galaxies in the Universe. The GBT, with its high resolution and sensitivity at 3-mm, particularly when outfitted with broadband, wide field bolometric arrays such as MUSTANG-2 and potential upgrades will probe scales from 10's of kpc to those nearly as large as the cluster virial radius (> 1 Mpc) across the epoch of cluster formation ($z < 2$) (Mroczkowski, et al. 2019). S-Z studies would also be fundamental for the study of filamentary structures between galaxy clusters and shed light on the open problem of the missing baryons in our Universe as well as on the hierarchical structure formation scenario (Battistelli, et al. 2019). Finally, S-Z studies will be used to understand the co-evolution of massive galaxies at high- z with their circumgalactic medium (CGM) (Emont, et al. 2019).

2.4 Formation and Evolution of Compact Objects

- The last decade has seen the rapid, concurrent development of new classes of energetic astrophysical transients - Fast Radio Bursts; extremely luminous of transients, such as the super luminous supernova; and "ultra long" GRBs with durations exceeding thousands of seconds. It is possible these transients are all manifestations of magnetar birth (Law, et al. 2019). The GBT, with its wide frequency range, 85% sky coverage, and high instantaneous sensitivity, is one of the critical instruments in this field, used as a single dish to detect and characterize the transients (e.g., Michilli, et al. 2018) and for high angular resolution high sensitivity interferometry (e.g., Mooley, et al. 2018).
- Our understanding of the neutron star population is informed to a great degree by large surveys that have been carried out by radio facilities during the past fifty years. The GBT has been, and will continue to be, a key instrument for these surveys. By the end of the next decade, a significantly more complete census of the Galactic pulsar population will be done. Among the anticipated discoveries are pulsar-black hole binary systems that will provide further of our understanding of gravity in strong-fields, as well as large numbers of millisecond pulsars that are crucial to enhancing the sensitivity of timing arrays for low-frequency gravitational waves (Lorimer, et al. 2019).
- The GBT will continue to contribute its enormous sensitivity to VLBI studies of AGN and black holes. It will produce high-resolution maps of H₂O masers in accretion disks and mass constraints for supermassive black holes with uncertainties of only a few percent (e.g. Zhao, et al. 2018). The appearance of a prominent, jet-like structure observed through GBT VLBI in a merging galaxy is interpreted as tidal disruption of a star by a black hole (Mattila, et al. 2018). In just the last few years the GBT has developed the ability to participate in VLBI observations at 3mm, but these are already producing spectacular results on the jet in M87 (Hada, et al. 2016; Kim, et al. 2018) and the Milky Way's central black hole, Sgr A* (Issaoun, et al. 2019).

- Active galactic nuclei with relativistic jets are the most powerful and long-lived particle accelerators in the Universe. In the 2020s, VLBI techniques, including the extremely sensitive GBT as part of the array, will supply unique information to answer three critical questions regarding the nature of AGN jets: What are the dissipation and particle acceleration processes? Where are the high-energy dissipation sites located? Is the gamma-ray emission related to the jet structure? (Rani, et al. 2019).

2.5 Galaxy Evolution

- The GBT will make several spectral surveys of the inner Milky Way in the next decade. The Fermi Bubbles, two giant plasma lobes emanating from the Galactic center, are a local example of energetic nuclear feedback that can shape a galaxy's evolution. Sensitive 21 cm HI and CO observations with the GBT, combined with optical and UV spectroscopy, will track gas entrained within the outflow, revealing its morphology, extent, kinematics, and mass loss (Fox, et al. 2019b). The GBT will map molecules in the dust lane within the Galactic Bar to determine its physical properties, connection to the Central Molecular Zone, and potential for star formation (Butterfield, et al. 2019).
- The Magellanic Stream is the most spectacular example of a gaseous stream in the local Universe. Its interwoven filaments trailing the Magellanic Clouds as they orbit the Milky Way are thought to be created by tidal forces, ram pressure, and halo interactions, making it an excellent benchmark for dynamical models of galaxy evolution. A combination of 21-cm HI observations from the GBT and UV spectroscopy will resolve a number of key issues, including the mass inflow rate of gas and the Stream's total spatial extent. (Fox, et al. 2019a).
- There is a growing focus on measuring the total molecular/atomic gas that surrounds gas-rich galaxies in proto-clusters. The GBT will complement interferometric studies of these redshifted systems by supplying information on low surface-brightness molecular emission over angular scales missing from the interferometer data. The GBT will map the redshifted [C I](1-0), CO(1-0; 2-1; 3-2) line emission surrounding the most over-dense regions at $3.3 < z < 5.6$ searching for previously undetected, low-excitation, gas-rich systems. This will reveal how the gas depletion time changes with distance to the proto-cluster core, and how the brightness temperature of dense gas tracers depends on the CGM (Harrington, et al. 2019; Emonts, et al. 2019; Casey, et al. 2019).
- Lyman- α and metal line absorption observations have established the ubiquity of a gas-rich circumgalactic medium around star-forming galaxies at $z < 0.2$, potentially containing half of the missing baryonic mass within galaxy halos. However, such studies leave open the question as to how this gas flows from the CGM onto the disks of galaxies to fuel ongoing star formation. Planned observations with the GBT will complete the census of HI in the local CGM at $N_{\text{HI}} < 10^{17} \text{ cm}^{-2}$, a sensitivity level unattainable by interferometers (Pisano, et al. 2019). Through deep HI mapping the GBT will also shed light on the origin of high-velocity clouds, which may mediate between the CGM and the disk of galaxies, thus constraining gas accretion processes in the local universe (Lockman, et al. 2019).

- The current knowledge of star formation in low-density, HI-dominated gas is significantly sparser than our understanding of star formation in the metal-rich disks of spiral galaxies. Understanding these low density environments is vital to understanding dwarf galaxies, the most common galaxies in the Universe. A multi-wavelength approach is required over the next decade, including deep, sensitive maps of molecular gas in a wide variety of low-density environments made with multi-pixel cameras on GBT (Thilker, et al. 2019).

2.6 Multi-Messenger Astronomy and Astrophysics

- Precision pulsar timing at the level of tens to hundreds of nanoseconds allows detection of nanohertz gravitational waves (GWs) from supermassive binary black holes and, potentially, from exotic sources such as cosmic strings. With modest projected increases in current sensitivity in the near term as additional milli-second pulsars are monitored, the stochastic background is expected to be detected within the next several years and GWs from individual SMBH binaries before the end of the next decade. The GBT will provide sensitivity and sky coverage that is key to the success of this program (Cordes, et al. 2019; McWilliams, et al. 2019).
- Precision timing data from the GBT will yield precision masses of neutron stars orbiting other compact objects, constraints on the equation of state of nuclear matter, and precision tests of General Relativity, the Strong Equivalence Principle, and alternative theories of gravity. Timing can also lead to stringent constraints on the photon mass and on changes in fundamental constants and could reveal low mass objects (rogue planets, dark matter clumps) that traverse pulsar lines of sight. Data sets also allow modeling of the density, magnetic field, and turbulence in the interstellar plasma (Cordes, et al. 2019; Lorimer, et al. 2019; Siemens, et al. 2019; Kelley, et al. 2019; Lynch, et al. 2019; Fonseca, et al. 2019; Taylor, et al. 2019; Stinebring, et al. 2019).
- The direct detection of gravitational waves (GW) from merging objects has opened a new window on the Universe and ushered in the era of multi-messenger astrophysics. Electromagnetic (EM) follow-up of GW events is essential to localizing the event and studying different facets of the merger; e.g., resolved imaging using VLBI techniques represents the only direct way to map the kinematic distribution of merger ejecta (Corsi, et al. 2019). The potential for discoveries in GW-EM science is vast, as it is expected that a year of GW network operations would yield a few tens of events just from the merger of neutron stars (Cowperthwaite, et al. 2019). The GBT used as an element of a long-baseline array will continue to provide unique data for radio studies of GW events, e.g., the weak radio emission associated with the binary neutron star merger GW170817 (Mooley 2018; Ghirlanda 2019). There is no instrument either current or proposed that can replace the GBT's role in these long-baseline measurements. Additionally, while EM studies of GW events have been confined thus far to cm-wavelengths, there is the possibility of EM counterparts at mm-wavelengths. Here the GBT is exceptional. At 3mm wavelength the GBT-ALMA combination is more sensitive by a factor >20 than any other instrumental combination for the highest resolution imaging (see Fig. 1 of Issaoun, et al. 2019) and will remain so for the foreseeable future.

- Rapid response is an essential part of multi-messenger science and this need will only grow as GW detectors become more sensitive and the LSST opens a new era of discovery space in time-domain astronomy. Uses of the GBT will include searches for pulsars in newly-discovered compact objects, bi-static radio studies of near-Earth objects, and VLBI observations to characterize the evolution of energetic events at an angular resolution of tens of micro-arcsec (Roy, et al. 2013; Naidu et al. 2016; Michilli et al. 2018; Casadio et al. 2019).

2.7 Planetary Systems

The GBT will continue to be used to measure properties of objects in solar systems, both our own and others, as a stand-alone facility, for long-baseline interferometry, and as the passive element of bistatic radar studies.

- Due to line-of-sight effects, the solar chromosphere and transition regions are currently largely unresolved. In the next decade, millimeter wave observations of the Sun, taken with the GBT, will provide considerable understanding into the dynamics of the solar chromosphere and related transition region (Kobelski, et al. 2019).
- Understanding the nature of planetary cores is vital to understanding the formation and evolution of the planets. For the Solar System's terrestrial planets and ocean worlds this can be done through a bistatic radar speckle technique which will show not only the liquidity of the bodies' core but also the nature of the coupling between the worlds' exterior shell and interior core (Margot, et al. 2019a).
- GBT bistatic radar observations of the Solar System's terrestrial planets and ocean worlds reveal details that otherwise cannot be seen without dedicated missions to visit the planetary bodies. Observations of Venus in the coming decade will test numerous hypotheses regarding the dynamics and super-rotation of the planet's atmosphere, and its connection to surface features on the planet. Bistatic observations will also allow for detailed maps of the surface of the Jovian satellites, Mercury, and Mars in the coming decade (Margot, et al. 2019b, Campbell, et al. 2019).
- Small bodies (comets and asteroids) are a window into the formation, evolution, and dynamic environment of our Solar System. GBT observations of asteroids and comets provide high spectral resolution, instantaneously sensitive images of faint, extended, and time-variable sources such as cometary comae and ion tails. For asteroids, the flexibility and sensitivity of the GBT is ideal for surveys to characterize different population (NEOs, main-belt, centaurs/TNOs) (Lovell, et al. 2019; Salter, et al. 2019a).
- Characterizing and tracking the asteroid population of the Solar System relates the properties and origins of these objects to the formation and evolution of the Solar System, and is a vital part of the National Science and Technology Council's strong recommendation to address the hazards of near-Earth object (NEO) impacts over the next 10 years. In the next decade the number of known asteroids will skyrocket with

LSST and NEOCam coming online. Characterization of these asteroids, though, requires mono- and bi-static radar observations that would include the GBT (Rivera-Valentín, et al. 2019).

- Measurement of the magnetic field of a planet is one of the few remote sensing means of constraining the properties of planetary interiors. Because Earth's magnetic field may be partially responsible for its habitability, knowledge of an extra-solar planet's magnetic field may be critical to understanding its possible habitability. Accurate measurements of the magnetic field of Solar System bodies will refine our understanding of when and how to apply this technique outside the Solar System. Young planets may sustain large magnetic fields, detectable by the GBT at cm-wavelengths (Lazio et al. 2019).
- The search for technosignatures from outside our Solar System will continue to advance in the 2020s. Studies of the Earth's radio usage and transmissions will provide a baseline understanding of the types of signal expected through radio leakage from Earth-like civilizations (DeMarines, et al. 2019; Haqq-Misra, et al. 2019). Significant improvements in the data science field, such as improved detection and deep learning techniques, will also greatly enhance the use of data from the GBT and other telescopes (Berea, et al. 2019). New surveys will greatly increase the fraction of the available volume and frequency space sampled (Margot, et al. 2019b).

2.8 Stars, Resolved Populations, and Stellar Evolution

- Large, single dish telescopes working alone and as part of high sensitivity VLBI observations, are the major contributor to the discovery and study of slow, secular transient events. These phenomena include tidal disruption events caused by stars passing within the tidal radius of SMBH, core collapse of supernovae, and transient maser emission typically associated with OH/IR stars (Salter 2019b).
- More than half of the dust and heavy elements in galaxies originates from the winds and out-flows of low-to-intermediate mass asymptotic giant branch stars, and many questions regarding this process remain. In the coming decade, more sensitive VLBI observations which include the GBT will provide high time- and spatial-resolution images of masers in a sample of nearby ($d < 1$ kpc) AGB stars spanning a wide range of properties. This will enable a deeper understanding of the atmospheric physics and mass-loss processes in these objects (Matthews, et al. 2019).

3.0 The Case for a Fully Funded GBT

While the Record of Decision from the National Science Board (NSB) for Green Bank Observatory has not yet been formally announced, it is expected that the NSB will recommend the NSF continue to partially fund the Green Bank Observatory while also continuing to look for new partnerships to offset the operational cost of the facility. Under the current Cooperative agreement, the NSF funds approximately 60% of available GBT science hours for peer-reviewed astronomy, while the remaining 40% is allocated to paid use of the telescope by private parties and institutions. The result is already a significant cut in the ability of the GBT to meet the

scientific demands of the U.S. community. With additional partners, it can be assumed that the hours available for open skies science will decrease further. For many research areas, this means that only a few of the desired scientific goals for the decade will be accomplished. But the result of the current and potential cuts in available hours on the GBT are much more severe in some especially interesting areas of science. Projects that require a specific observing cadence, coordination with other instruments, significant time at 3-mm wavelengths, or observations at specific times are especially hard hit as they must compete for time in a schedule that has significantly fewer openings than before. Examples include:

- Multi-messenger astrophysics: The GBT used as an element of a high sensitivity long-baseline array is key to radio studies of gravitational wave events. The GBT is often the most sensitive telescope in these arrays, and is critical to their ability to study the weak radio emission associated with, for example, binary neutron star mergers (Mooley 2018; Ghirlanda 2019). At 3-mm wavelength, the GBT-ALMA combination is more sensitive by a factor >20 than any other instrumental combination for the highest resolution imaging (see Fig. 1 of Issaoun 2019) and will remain so for the foreseeable future. Because VLBI requires use of the GBT at fixed times set by coordination with other diverse instruments, the 60% reduction in peer-reviewed observing slots has reduced the use of the GBT for VLBI by a factor of three.
- Pulsar timing: The use of pulsars for astrophysical studies often requires that their period be measured at pre-determined intervals. For example, measurement of the relativistic Shapiro delay, which has been used to establish new mass limits on pulsars, requires observations when the pulsar is nearly behind its companion (e.g. Demorest et al. 2010). Regular measurement of precise pulse arrival times is also key to the detection of gravitational radiation by pulsar timing arrays (Cordes et al. 2019). Finally, when a new pulsar is discovered, its period is established by observing for ~ 30 min every day for a week, then weekly, and finally monthly (e.g. Lynch et al. 2019). With the reduction in available peer-reviewed GBT time, observations such as these become nearly impossible to fit into the fragmented telescope schedule.
- Planets, the Moon, and near-Earth Asteroids: Using the GBT as the receiving instrument with transmitters at Arecibo and NASA's Goldstone facility, bi-static radar observations have established the spin state of Mercury, mapped pyroclastic flows on the Moon, and determined the structure and orbit of near-Earth asteroids (Brozovic et al. 2017; Margot et al. 2007; Campbell et al. 2017). Because these require observations at specific times fixed by the object under study and the availability of the transmitters, they have become extremely difficult to fit into the limited blocks of GBT peer-reviewed science time.
- Time Domain Astronomy: When the GBT 100% funded for peer-reviewed science, it could be scheduled flexibly, particularly when notified of a triggering event. The loss of a significant amount of peer-reviewed telescope time makes it much more difficult to create room in the schedule for unforeseen projects. This very much limits the use of the GBT for this exciting new field and ultimately restricts the community's access to the radio counterparts of these events.

- Molecular Spectroscopy at 3-mm: When the GBT was operated full time for peer-reviewed research, it was possible to match individual projects to the most suitable weather conditions. This is especially important for spectroscopy in the 3-mm band where there are only ~1,000 hours of prime weather conditions throughout the year (Lockman & Maddalena, 2010). With peer-reviewed use of the GBT now in the minority, critical flexibility of scheduling is lost. The reduction in peer-reviewed use of the GBT by 60% has produced an effective reduction of a factor of 0.45 in the amount of time available at the highest frequencies.

While it would be ideal if the GBT were fully funded for peer-reviewed research, here we propose NSF funding for only an increase of 1,500 hours/year, which would take the research time from 3,900 hours (60% time for peer-reviewed science) to 5,400 hours (83% time for peer-reviewed science), up a factor of 1.38. This would translate into an increase in scientific output of a factor between 1.38 and at least 3, depending on the program, supplying critical capabilities to the U.S. community. The cost for this increase would be of order \$3M annually (FY19 \$).

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