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The year covered by this report was one of transition at Arecibo. After decades of stewardship under Cornell University, the responsibility for the management and operations of Arecibo Observatory was awarded by the National Science Foundation to SRI International, operating in partnership with the Universities Space Research Association (USRA) and Universidad Metropolitana. While on site this has resulted in many changes, the main work of Arecibo continues unabated, and our large community of users continues to have the same access to this marvelous facility as they ever did: observing proposals are submitted, and after evaluation the accepted programs are scheduled on the telescope, with our staff working hard all the while to ensure that the observations are successfully accomplished.

The significance of the astronomy being done at Arecibo, in this 50th year of its existence, is hinted at by the handful of science articles that make up much of this report. Take a peek at the remarkably productive, recently completed, ALFALFA survey, probing the local universe with unparalleled sensitivity. Then marvel at how the GALFA-HI survey is mapping atomic hydrogen across the entire Arecibo sky while using almost no dedicated telescope time. The contribution from the GALFACTS collaboration hints at the results to come from this investigation of the magnetic universe. The NANOGrav collaboration then provides a progress report on the quest to directly measure perturbations to the metric of spacetime caused by propagating gravitational waves. They use millisecond pulsars to do this — high-precision stellar clocks, an extraordinary example of which, in a hierarchical triple system, is then described. All of these projects rely on the enormous collecting area of the 305-meter Arecibo reflector. The presence of a megawatt transmitter, supported by NASA, makes Arecibo the world’s most powerful planetary radar facility. The sort of dramatic and impactful work enabled by this combination is summarized in the article on near-Earth asteroid Bennu, now the target of a sample return mission.

Since the telescope upgrade of the mid-1990s, we have had a wide complement of receivers available for astronomy use, spanning 0.3—10 GHz. Naturally, some of these are used more frequently than others, and this demand also varies with time. Much of the observing time spent on radio astronomy at Arecibo since 2004 has been dedicated to large-scale surveys using ALFA, the seven-pixel receiver operating at frequencies near 1.4 GHz. While seeking to obtain a complete listing of all the refereed papers containing previously unpublished Arecibo data for the past 15 years, we have also gathered statistics on receiver usage over time, and we present both in this report.

We also summarize some operational matters, such as a revision of the proposal disposition and telescope scheduling procedures, and continuing work to develop new capabilities. Arecibo remains uniquely suited to address questions that require exquisite sensitivity at centimeter wavelengths. We request the collaboration of our user community, and welcome feedback on any matter, to help make Arecibo the best that it can be.

Fernando Camilo
Director of Astronomy
Arecibo Operations

Fernando Camilo
(National Astronomy and Ionosphere Center)

The principal instrument of Arecibo Observatory/NAIC is the 305-meter-diameter spherical radio reflector and associated systems. Radio sources with declinations between approximately -1 and +38 degrees can be tracked for up to 2.6 hours. Receiving systems currently available span the entire range between 1 and 10 GHz, and also include 327 MHz and 430 MHz. Transmitting systems include a 2380 MHz radar used for observations of planets, moons, asteroids, and comets, and a 430 MHz radar used primarily for ionospheric incoherent scatter experiments, but which can also be used for planetary observations. For atmospheric science studies, the observatory also has an optical facility for passive airglow and lidar observations. The Angel Ramos Foundation Visitor Center conducts extensive education and public outreach programs. Activities in these areas are enabled by approximately 100 scientific, engineering, technical, maintenance, operations, educational, and support staff, under observatory director Robert Kerr.

Telescope observing proposals. Arecibo Observatory welcomes the submission of observing proposals from any qualified scientists. Proposals are typically evaluated on a semester basis, with nominal submission deadlines of March 1 and September 1. As of 2012, numerous proposals on the 305-m telescope had been active for many years, and several long-term projects had had little review of late. One consequence was a very large backlog of time to schedule. It was also difficult to judge the relative merits of long-standing projects and newly proposed activities. In consultation with staff, the user community, and external reviewers, we developed modified proposal handling and telescope scheduling procedures. Essentially, time is now awarded only on a semester-by-semester basis, and every proposal is reviewed at least annually. The revised procedures applied as of the September 2012 deadline, corresponding to the Spring 2013 observing semester (January 1-June 30, 2013). Fifty proposals were submitted at that deadline, compared to about 30 for recent deadlines. The Spring 2013 semester was transitional, and we expect that in future the new proce-

Figure 1. — Arecibo telescope time requested for radio astronomy at the September 2012 proposal deadline (corresponding to observations during the first six months of 2013), plotted as a function of Local Sidereal Time in 15-minute intervals for pulsar projects (bottom) and other passive radio astronomy (top). The bump at ~ 19 hr LST for pulsars corresponds to observations of the inner Galaxy. For other radio astronomy, nighttime observations are often required, and the corresponding bumps largely correlate with LSTs in nighttime during the Spring semester. (Credit: Hector Hernandez, NAIC.)
dures will allow us to develop a clearer picture of time demand and to schedule the telescope more efficiently. For example, Figure 1 shows separately the new time requested at the September 2012 deadline for pulsar and all other passive radio astronomy projects. This does not correspond to the full radio astronomy time pressure for Spring 2013 because of holdover projects concluding during that semester.

**Telescope usage statistics.** In 2012, 5450 hours of 305-m telescope time were used for scientific observations. The remainder of the hours of the year were more or less evenly divided between commissioning/technical tasks, and maintenance. Of the time dedicated to scientific observations, 950 hours were nearly evenly split between atmospheric and planetary radar projects. Of the 4500 hours used for radio astronomy, 6% were spent on VLBI experiments together with other telescopes (including the orbiting RadioAstron dish). Of the remainder, 1/3 was spent on pulsar projects, and 2/3 on other radio astronomy. A more detailed breakdown of the percentages corresponding to these categories is shown in Figure 2.

**Arecibo/Fermi joint-proposal opportunity.** The Fermi Gamma-ray Space Telescope, with its Large Area Telescope, has revolutionized the study of the very-high-energy sky (1-100 GeV) since its launch in 2008. Much “Fermi work” is multi-wavelength in nature, and radio telescopes have provided fundamental contributions, e.g., in the areas of pulsars and AGNs. In order to enhance this successful collaborative enterprise, Fermi has entered into joint proposal agreements with observatories such as NRAO and NOAO. Starting in 2013, Arecibo and Fermi now provide joint proposal opportunities, whereby potential radio observers submit proposals for Fermi funding and future Arecibo observations through the Fermi guest investigator portal. More details can be found at [http://fermi.gsfc.nasa.gov/ssc/proposals/arecibo.html](http://fermi.gsfc.nasa.gov/ssc/proposals/arecibo.html). The next deadline for taking advantage of this opportunity is on January 16, 2014, corresponding to Fermi Guest Investigator Cycle 7.

**New capabilities.** During 2012, the technical and scientific staff at Arecibo, often together with external collaborators, continued work on a number of projects that aim to improve the scientific capabilities of the observatory. We provide here a brief listing of the main ones that will (or now do) provide new astronomical potential.

- **New receiver for planetary radar science:** an S-band radar receiver with lower system temperature now enables observations of increased sensitivity.
- **New VLBI backend:** a Roach digital backend together with Mark 5C recorder now allows improved sensitivity observations by increasing the maximum recorded data rate from 1 to 2 Gbps.
- **New pulsar backend:** PUPPI (the Puertorican Ultimate Pulsar Processing Instrument) now allows the coherent sampling of up to 800 MHz of bandwidth for much improved sensitivity in timing and search experiments (see Figure 3 on page 20).
- **Octave-bandwidth C-band receiver:** work continues on making available a new C-band receiver that will cover the entire 4-8 GHz band. Apart from the scientific potential, the availability of this receiver is expected to free a slot in the Gregorian dome turret and to reduce weight on its rotary floor.
- **Wide-bandwidth IF/LO:** the current intermediate-frequency/local-oscillator chain has a bandwidth of 1 GHz. Work continues on a project to increase this bandwidth to 4 GHz. As currently structured, it is expected that over the coming year this project will lead to a “spigot” in the control room for up to 4 GHz of instantaneous bandwidth. We welcome input from the user community to help develop the backends required to fully exploit this capability.
- **12-m telescope:** work continues on commissioning the 12-m telescope, situated on a hill overlooking the 305-m dish, and integrating it with the main telescope. When operational, this dish will greatly improve the efficiency of Arecibo VLBI observations, and will also be available for stand-alone experiments.
Educational activities. Numerous graduate students are trained in the course of pursuing research at Arecibo in the areas of astronomy, space and atmospheric sciences, physics, and engineering. The Visitor Center conducts educational activities geared towards primary and secondary school students, as well as the general public. Here we highlight two Arecibo astronomy activities that focused on undergraduate students.

UAT Workshop: the NSF-sponsored Undergraduate ALFALFA Team held its fifth annual workshop at Arecibo on January 16-18, 2012. The group numbered 31 participants, including 18 undergraduates (40% women) from 13 UAT institutions (see Figure 3).

At these workshops, undergraduates experience the functioning of a scientific collaboration first hand, interacting with their faculty mentors, peers at other institutions, Arecibo staff, and the leaders of the ALFALFA project. Workshop observations are planned in the same way as any large collaborative project. Students read preparatory online material and work together on the observing proposal, which is reviewed and officially granted observing time. Observations in 2012 were the first in the UAT-proposed follow-up of the most intriguing quasi-dark ALFALFA sources (see page 11). The three 7-hour-long observing sessions were attended by students and faculty observing in small groups for hour-long blocks. Each session was led by an experienced graduate student or faculty member, but the students instructed those in succeeding groups, communicating what they learned about observing procedures and monitoring.

Workshop activities also included guided tours of the telescope platform and dish, and invited talks given by Arecibo astronomers and engineers. Additional follow-up observing runs of ALFALFA candidates were conducted on-site by other UAT students and faculty in March (seven nights) and November (five nights). Finally, UAT participants at four institutions did on-campus remote Arecibo observing in Fall 2012, helping to complete the very last ALFALFA observing season.

Summer students: in summer 2012, three undergraduates from UPR Humacao undertook Puerto Rico NASA Space Grant-sponsored research projects under the mentorship of Arecibo staff. Clarissa Vazquez and Roberto Rodriguez worked with Rhys Taylor and Robert Minchin on data from the Arecibo Galaxy Environment Survey (AGES), while Yamil Nieves worked with Chris Salter, Tapasi Ghosh and Robert Minchin on a molecular line survey of two star-forming galaxies. All three students went on to present posters describing their work at the 221st American Astronomical Society meeting in January 2013.
In Figure 1 we show the number of refereed publications containing previously unpublished astronomical data obtained with the Arecibo telescope, as a function of year between 1998 and 2012. We also show, as of the end of 2012, the average and median number of citations to papers published in each of those 15 years.

These data are clearly related to the scientific productivity of Arecibo, but require some interpretation. For instance, as of end 2012 the ALFALFA collaboration (see page 9) listed 49 refereed publications, of which only 26 are contained in Figure 1. If Arecibo discoveries presented in one paper lead to follow-up optical studies presented elsewhere, and the second paper does not contain previously unpublished Arecibo data, both may quite naturally be ALFALFA collaboration publications, and both are very much a part of the Arecibo scientific legacy, but only the former paper makes it to Figure 1, by design of our methodology. We do this because it enables us to answer a well-posed question consistently across the years. The resulting data are useful particularly for comparing Arecibo with Arecibo and as a baseline for future investigation, and care should be exercised if comparing to seemingly related statistics available for other facilities, due to possible differences in methodology.

We obtained these data by doing full-text searches for “Arecibo” on NASA’s Astrophysics Data System, and then inspecting all of the
thousands of returned publications to identify which actually contained previously unpublished Arecibo data\textsuperscript{1}. We selected 1998 as the starting year since it corresponds, more or less, to the return of Arecibo to full operations following its extensive upgrade in the mid-1990s. A total of 476 publications with 13,282 citations are represented in Figure 1. The “top 40 [10]” radio [radar] papers (10% of the total in each category) account for 40% of the total number of citations in each category. A full listing of all the publications, including complete bibliographic information, and further statistics, is available at http://www.naic.edu/~astro/publications/grandsum_1998-2012.pdf and http://www.naic.edu/~astro/publications/topten_1998-2012.pdf.

Because we inspected each of the 476 publications that made the final cut for Figure 1, we were able to record the receivers or transmitters used to obtain the data presented in each publication. We summarize that information in Figure 2.

Figure 2 shows that over the period in question there is a preponderance of use of the L-band (1.4 GHz) receivers. Figure 3 breaks this down by year, showing the evolution of use of receivers over time, as reflected in publications. Some trends can be discerned: the preponderance of L-band is clear, and since about 2005 there is a ramp-up in ALFA publications, as well as a reduction in 430 MHz publications, while S-, C-, and X-band receivers have been used fairly steadily over the past decade.

\textsuperscript{1}VLBI publications can present a challenge, since sometimes the telescopes contributing to the results are not identified individually; we supplemented the ADS-derived results with additional publications where known.
Making use of the mapping speed of the Arecibo L-band Feed Array (ALFA) and the instantaneous sensitivity enabled by the telescope’s huge collecting area, the Arecibo Legacy Fast ALFA (ALFALFA) extragalactic survey has been designed to survey and detect gas-bearing galaxies in a large enough volume that its resultant catalog would offer a “fair” sampling of the local universe. Because the galaxy distribution is far from locally homogeneous, small samples or ones covering small volumes are likely to be strongly impacted by cosmic variance, possibly missing entirely the rarest objects or stumbling upon them only by luck. ALFALFA was specifically designed to cover a sufficiently large solid angle (6500 square degrees) with enough sensitivity and spectral resolution to sample in a robust way the full population of neutral atomic hydrogen (HI)-bearing galaxies in the present-day universe. With the survey observations completed only in October 2012, the full ALFALFA extragalactic HI catalog is not yet available, but already its harvest has revealed some surprising and important results which bear directly on the cosmological implications of its final census.

Evidence of the link between gas-richness and the spin of the dark matter halo. Semi-analytical models predict that the overall low star formation efficiencies found in gas-rich galaxies can be explained if their disks are characterized by very large scale lengths and low stellar mass surface densities because their host dark matter halos have more widely distributed angular momenta, measured by a larger than average halo “spin”. As shown in Figure 1, a detailed analysis of the partially complete ALFALFA catalog (α.40) has produced concrete evidence that the gas-rich population preferentially favor these high-spin dark matter halos, thereby suggesting that the angular momentum distribution of the dark matter halo plays a significant role in determining the processes by which present day galaxies convert gas into stars.

High HI mass galaxies: more than predicted. A pleasant surprise for ALFALFA is its higher than expected detection rate: ALFALFA detects 29 times more sources per square degree on the sky than did the earlier HIPASS survey done with the Parkes telescope in Australia. Because of its powerful combination of sensitivity and frequency coverage, an especially important consequence of this greater detection rate is that ALFALFA has detected many more extremely massive HI disks than were predicted by the previous HIPASS results. ALFALFA’s combination of sensitivity, spectral and angular resolution, bandwidth and solid angle enables the first robust census of the HI-bearing population in the present-day universe. The higher detection rate at the high HI mass end also has important and positive implications for the HI detection rate of blind surveys to be undertaken in the era of the Square Kilometre Array (SKA) and intensity mapping experiments at higher redshift.

**Figure 1.** — Left: Distribution of the dark matter halo “spin parameter” \( \lambda \) for the ALFALFA galaxies (solid black line) in comparison with the distribution derived for an optically selected sample of galaxies (dot-dash red line). An attempt to fit the ALFALFA distribution to the functional form predicted by theory produces a bad match (dashed blue line). The distribution of halo spins for the ALFALFA galaxies just doesn’t match the distributions either of the optical galaxies or that predicted by simulations for the dark matter halo population. Right: The relationship between the gas fraction (y-axis; on a logarithmic scale) and the stellar mass (x-axis; on a logarithmic scale) for galaxies of different spin parameter; the color coding traces the value of the halo spin parameter as given in the color bar to the right. The results for ALFALFA show that gas-rich galaxies reside preferentially in dark matter halos of higher than average spin, suggesting that the angular momentum distribution of the dark matter halo plays a role in how gas is converted into stars. (From Huang et al. 2012.)
In the “downsizing” scenario, massive galaxies are most efficient in consuming their gas reservoirs early on, suggesting that very massive galaxies with substantial cold gas should be extremely rare in the local universe. At the same time, the coupling of high spin and gas richness is a natural consequence of galaxy formation models in which high spin disks are formed from recently accreted gas. In order to explore how the very massive and gas-rich disks detected by ALFALFA have managed to retain their gas without converting it into stars, we are conducting a detailed multiwavelength study of the gas content and distributions, stellar populations and star formation histories, and dark matter properties of a set of 30 very high mass (greater than $10^{10}$ solar masses of HI), high gas fraction galaxies dubbed the ALFALFA HighMass sample, spanning a range of stellar masses, morphologies, colors, star formation rates and efficiencies. Some of the HighMass galaxies are shown in Figure 2. The left panels show both ultraviolet and ionized hydrogen (Hα) optical images of a few objects; they are clearly forming stars at a healthy rate. The right panels show maps, obtained with the Very Large Array, of the atomic hydrogen of two objects; these maps can be used to understand the physical mechanisms by which star formation is occurring in them and to deduce the structure of their dark matter halos. Though the understanding of these sources is not yet clear, they are not simply exceptional curiosities. The HighMass galaxies are all forming stars (as evident in Figure 2) but, for their stellar masses, their star formation efficiencies are very low; in other words, they contain too much gas, not too few stars. In fact, they are the $z \sim 0$ analogs of the HI massive disks detected at $z \sim 0.2$ and the objects most likely to dominate the deep surveys being planned for even higher redshift with the SKA.

**ALFALFA and the “missing satellites”.** While remarkably successful at reproducing the large scale structure visible in the universe today, the currently-favored $\Lambda$CDM cosmological model faces several important observational challenges on the scale of galaxies.
As evident above, at the low mass end of the baryonic mass fraction shown here. (From Papastergis et al. 2012.)

Figure 3. — The variation in the baryonic mass fraction $\eta_b$ (y-axis) as the dark matter halo mass (x-axis) grows. The dotted line at the top shows the cosmic baryon fraction predicted by numerical simulations while the bottom curves trace the distribution derived from surveying the starlight only (gold) and combining both the stars and gas (gray). Especially among the lower mass galaxies, it is imperative to include the gas contribution to the baryon census. In fact, in those objects, the mass contained in atomic hydrogen often exceeds the amount of mass contained in all the stars. The detection by ALFALFA of thousands of low mass galaxies has enabled the accurate determination of the baryonic mass fraction shown here. (From Papastergis et al. 2012.)

CDM (cold dark matter) structure formation predicts a multitude of low-mass halos, seemingly in contradiction with the relatively small number of low-mass galaxies observed in surveys. The resolution of these observational challenges has been hampered by the fact that the formation and evolution of dwarf galaxies involves a complex interplay between the dark matter halo properties and poorly understood baryonic feedback processes. Settling the interpretation involves testing the viability of alternative dark matter models which might suppress the formation of low-mass halos as well as seeking evidence of stellar and AGN feedback processes leading to baryon depletion and a diminution of the galaxy-halo connection at low masses. Just as at the high HI mass end, ALFALFA’s combination of sensitivity, wide areal coverage and high spectral resolution makes it particularly well suited to detect very low mass galaxies. Because their masses are low, they are only found locally. Already, ALFALFA has detected almost 600 galaxies with HI mass less than 10 million solar masses, and more than 50 with less than 1 million, allowing an exploration of the HI velocity function to widths as low as 20 km/s and suggesting, under the assumption of a direct correspondence between optical luminosity and dark matter halo mass, that the rotational velocities derived for dwarf galaxies underestimate the true maximum rotational velocities of the host dark matter halos. Most importantly, analysis of the ALFALFA population has shown that, even when their atomic gas content is included, very low mass halos have very low baryon fractions, reaching values as low as 2% of the cosmic value ($\eta_b = 0.02$), well below the value predicted by numerical simulations which include only the effects of cosmic reionization. Although inclusion of the atomic gas detected by ALFALFA increases the baryon content (stars plus gas) relative to that measured in stars only, the much smaller baryon fraction seen in real galaxies relative to the prediction of the simulations (see Figure 3) suggests that additional feedback mechanisms such as supernovae blowout must be efficient in depleting low mass halos of their baryons.

**ALFALFA discovery of Leo P.** As evident above, at the lowest halo masses, the baryon fraction drops precipitously and may even render such halos entirely “dark”. One of the main aims of ALFALFA has been to hunt for optically “dark” but HI bearing low mass dark matter halos, but the challenge is to distinguish them from the plethora of Galactic HI clouds of similar characteristics. Without identifiable optical counterparts, it is impossible to estimate the distance and thereby prove their extragalactic nature. Hence, the search for “dark” galaxies is best carried out as a search for “almost dark” galaxies, low mass, gas-dominated dwarfs with at least some visible stars. A prototype of this class of object is the Local Group ultrafaint dwarf galaxy Leo T, located at a distance of 420 kpc from the Milky Way and discovered via its resolved stellar population in the imaging data of the Sloan Digital Sky Survey. Looking for Leo T analogs among the most compact high velocity HI cloud population has been one of the main aims of ALFALFA. During the normal course of ALFALFA grid processing, a previously unknown HI source with a heliocentric recessional velocity of 264 km/s and a velocity width of 24 km/s was detected in the constellation of Leo. A quick check of the SDSS data at the centroid of the ALFALFA HI source showed no obvious optical counterpart but some faint blue-ish emission. (In fact, what we now know is Leo P was erroneously identified as a distant group of galaxies.) Members of the ALFALFA team have used the VLA, the GMRT, the WIYN 3.5m telescope and the LBT to confirm the association of the low HI mass source with a faint, low surface brightness dwarf galaxy. Preliminary analysis of on-going HI synthesis mapping suggests an ordered rotational velocity field, while nebular spectroscopy of its lone HI region indicates an extremely low metal abundance, suggesting its name: Leo P, with “P” for pristine (see Figure 4). In fact, Leo P is an extreme example of a star forming low mass, gas dominated dwarf, located just beyond the outer bounds of the Local Group at a distance of about 1.75 Mpc. The discovery of Leo P validates the idea that some of the ultra-compact high velocity clouds identified by ALFALFA may be associated with low mass dark
matter halos. The hard work to determine their rotational properties, uncover their associated stellar populations and determine their distances is underway.

**ALFALFA: much more to come.** ALFALFA survey observations were completed in October 2012 after an allocation of 4300 hours of telescope time, spread over 6.5 years. The results presented here were extracted from less than half of the expected final survey, and as the full catalog is completed, we expect further bounty from the ALFALFA harvest.

**Publications, doctoral theses, and undergraduate involvement.**

To date, 58 papers based on ALFALFA work have appeared in or been submitted to the refereed literature – see http://egg.astro.cornell.edu/alfalfa/pubs.php. Also, more than 20 PhD theses based on ALFALFA work have been completed or are underway – see http://egg.astro.cornell.edu/alfalfa/projects/teamprojects.php.

In addition to the heavy involvement of graduate students, ALFALFA serves as the backbone of scientific and educational activities of the Undergraduate ALFALFA Team (UAT), a collaboration of 19 mainly undergraduate teaching institutions around the United States and Puerto Rico. The cornerstone activity for the UAT is an annual workshop bringing 35 faculty and students to Arecibo each January (see page 6). For further details, see http://egg.astro.cornell.edu/alfalfa/ugradteam/ugradteam.php.

**References**

The Galactic Arecibo L-Band Feed Array HI (GALFA-HI) Survey

Mary Putman and Josh Peek (Columbia University) for the GALFA-HI team

Figure 1. — Galactic HI structure revealed by the GALFA-HI survey (4' resolution). The image shows the Galactic Plane region in the direction of the Galactic anti-center (RA = 06°13′−04°19′; Decl. = +22° − +38°). The colors represent intensities in different GALFA-HI velocity channels.

Hydrogen is the basic baryonic building block of galaxies. Hydrogen gas flows into the dark matter potential well of a galaxy, condenses in the disk in atomic form, and subsequently forms molecular material and then stars. The GALFA-HI survey is mapping the atomic hydrogen (HI) distribution in the Galaxy and Local Group across the entire Arecibo sky (13,000 deg²) and is providing significant insight into how these processes occur. Figure 1 highlights the Galactic HI structure revealed by GALFA-HI. This type of detail was not possible with previous large-scale surveys. For example, Figure 2 shows how the data compare to the commonly used LAB survey (Kalberla et al. 2005). GALFA-HI will be our best window into Galactic HI for some time, as none of the planned future Galactic HI surveys are designed to exceed its combination of sensitivity and angular resolution (see Table 1).

The vast majority of the GALFA-HI survey utilizes Arecibo’s commensal capabilities, i.e., the data are taken at the same time as a formally scheduled extragalactic or Galactic program. This is depicted in Figure 3, where it can be seen that 90% of the data were taken in conjunction with another survey being the primary project (all labeled TOGS). GALFA-HI’s commensal observing has maximized the efficiency of the telescope and increased its scientific output. Below we note some of the recent science highlights from the GALFA-HI survey.

- In the GALFA-HI data covering ~ 1/2 of the Arecibo sky, we have discovered ~ 2000 of the smallest HI clouds in existence. These are presented in “The GALFA-HI Compact Cloud Catalog” (Saul et al. 2012). In this paper we find distinct populations of cold and warm clouds in the halo and at the disk-halo interface that provide important clues to Galactic accretion and feedback processes. The distinct populations have subsequently been confirmed and linked to the ionized gas through an investigation of their dust content (Saul et al. 2013).
- In “A High Resolution Study of the HI-H₂ Transition across the Perseus Molecular Cloud” (Lee et al. 2012) the GALFA-HI data for the Perseus molecular cloud are used in combination with

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<th>Survey</th>
<th>Telescope</th>
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<th>Sensitivity</th>
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<td>IGPS</td>
<td>various</td>
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<td>5%</td>
<td>1′ - 2′</td>
<td>1.5K – 2.7K</td>
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<td>LAB</td>
<td>IAR &amp; Dwingeloo</td>
<td>1980 – 2005</td>
<td>100%</td>
<td>36″</td>
<td>~100 mK</td>
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<td>GALFA-HI</td>
<td>Arecibo</td>
<td>2005 – 2013</td>
<td>32%</td>
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<td>planned</td>
<td>8%</td>
<td>3′ – 20″</td>
<td>50 mK – 3 K</td>
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Table 1. — A comparison of Galactic HI surveys. For interferometers the data can be reduced in different ways, leading to different resolutions and sensitivities. The sensitivity listed is for a 1 km/s channel, to put the surveys on equal footing, though at 0.184 km/s GALFA-HI has a much higher spectral resolution than other extant surveys.
extinction data to estimate the cloud’s H$_2$ distribution. At spatial scales of 0.4 pc, the HI surface density across Perseus shows a uniform level of 6-8M$\odot$/pc$^2$, suggesting a minimum HI surface density required to shield H$_2$ against photo-dissociation. A remarkably tight and consistent relation is found between the H$_2$ fraction and the total gas surface density. The findings are consistent with theoretical predictions for H$_2$ formation in equilibrium, suggesting that turbulence may not be of primary importance for H$_2$ formation in molecular clouds.

- The prospect of new dwarf galaxies within the velocity range $|V_{\text{LSR}}| \sim 30$−650 km/s is investigated in the paper “Potential New Dwarf Galaxies in the GALFA-HI Survey” (Grcevich et al. 2013). This work uses the GALFA-HI compact cloud catalog to identify candidate dwarf galaxies by their similar HI properties to existing Local Group dwarf galaxies. Optical follow up of these ~ 50 targets is ongoing and will confirm or refute their potential dwarf status.

- In “The Inner Galaxy ALFA (I-GALFA) Low-Latitude HI Survey” (Gibson et al., in preparation) images of over 1650 deg$^2$ of the inner Galactic disk are presented ($32^\circ \leq l \leq 77^\circ$, $|b|$ up to ~ 20$^\circ$). The future public release of these data, and the combination with other GALFA-HI data sets, will serve as a landmark resource for Galactic science.

- The most local work presented thus far with GALFA-HI data is in the paper “The Local Leo Cold Cloud and New Limits on a Local Hot Bubble” (Peek et al. 2011a). In this paper an ultra-cold HI cloud is mapped with GALFA-HI, and shown to be within 23 pc of the Sun through stellar absorption lines. X-ray shadowing rules out the standard local hot bubble picture and shows that most of the soft X-rays emanate from solar wind charge exchange.

- For further highlights from the GALFA-HI survey, see https://sites.google.com/site/galfahi. Or follow the Data link on this page to download full data cubes and do your own science with GALFA-HI.
Magnetic fields are ubiquitous in the universe and known to be an important factor in astrophysical phenomena over the full range of scales from pulsars to clusters of galaxies. However, understanding the origins of cosmic magnetic fields, and their role in galaxy evolution and processes within the interstellar medium, are hampered by the difficulty of detecting their presence and mapping their relationship to the matter content of the universe. The polarization of radio waves is a powerful tracer of magnetic fields. The commissioning of powerful spectrometers capable of multi-channel imaging over large bandwidths has opened up the possibility of using the propagation effect of Faraday rotation to measure the effects of fields within both our Milky Way Galaxy and extragalactic radio sources.

The Galactic ALFA Continuum Transit Survey (GALFACTS) project, a collaboration of over 40 researchers from the US, Canada, Europe, Australia and India, is using the seven-beam ALFA receiver system to perform a broad-band spectro-polarimetric continuum survey of the whole Arecibo Sky (Taylor & Salter 2010). The project is creating full-Stokes image cubes at an angular resolution of 3.5′ and spectral resolution of 0.4 MHz between 1225–1525 MHz, with a band-averaged theoretical sensitivity of 90 μJy/beam. The data provide the most sensitive imaging yet of polarized radiation over almost one third of the sky. Further, the high spectral resolution, full-Stokes cubes, enable Faraday rotation synthesis to be applied to both the diffuse emission of the Galactic magneto-ionic medium and a high-density grid of polarized extragalactic sources.

GALFACTS images the sky using the “meridian-nodding” technique. Full-Stokes data are acquired via the Mock spectrometers, while the telescope is scanned up and down along the meridian at 1.53° per minute. Such scanning creates a zig-zag track pattern in celestial coordinates, with the tracks from individual beams separated by 1.83′, close to Nyquist sampling for the 3.5′ FWHM beams. On consecutive days the tracks are shifted by 51 sec in right ascension. With 18.2°-long declination scans, 29 observing days provide complete coverage.

As part of the processing, a model of the declination dependence of the system temperature is removed. However, the data have both an arbitrary zero level for the sky brightness and uncertainty in the lowest spatial frequencies of the emission (i.e., on angular scales of order 10° and larger). To accurately represent the polarization vector field it is critical that the total power be known and that the emission on large spatial scales be present in the data. Absolutely-calibrated, low-spatial frequency information will be incorporated into GALFACTS using the lower-resolution Global Magneto-Ionic Medium Survey, GMIMS (Wolleben et al. 2010).

**Figure 1.** The eight main GALFACTS observing regions plotted in Galactic coordinates over an image of the Bonn 1420-MHz survey. Observations are complete for all 8 main subfields (S1 – S4, N1 – N4), and for 3 of the 4 narrow “zenith strips”.

Russ Taylor (University of Calgary) and Chris Salter (NAIC)
The GALFACTS survey consists of eight major subfields (Figure 1), each requiring 29 observing days, and covering 6.3 hours in RA. Four subfields cover the area south of the zenith (S1 – S4), with four others covering the north (N1 – N4). Four small strips cover the gap (~3°) at the zenith between the North and South fields caused by the telescope’s zenith-angle restrictions. In total, GALFACTS requires over 2000 hours to cover the entire Arecibo sky. As of mid-2013, its observations are over 90% completed.

The data are being processed at the University of Calgary using the High Performance Computing and storage infrastructure of Compute Canada. The NAIC Mock spectrometers produce data streams for each of four polarization states for all seven ALFA beams and for 4096 spectral channels in two overlapping 172-MHz bands covering 1225-1525 MHz. The complex receiver gains are continuously calibrated by the injection at position angle 45° of a 25-Hz switched noise diode signal. The 56 data streams (7 beams × 4 polarizations × 2 bands) are each sampled at 1 msec intervals giving an aggregate data rate of 460 MB/s. These raw data streams are processed to yield full-Stokes spectral image cubes which are the primary science data product of the survey.

The image cubes give spectro-polarimetric representations of the sky at unprecedented sensitivity, angular and spectral resolution, with high fidelity to diffuse emission both at low and high Galactic latitudes. Figure 2 (a) shows the Stokes-I (total intensity) image for the S1 subfield averaged over the GALFACTS upper frequency band. The image covers 6 hours of right ascension by 18° of declination. The bright emission band in total intensity running semi-diagonally across the image to the right of center is the Galactic plane. On either side the image extends out of the plane to latitudes of |b|~40° (see Figure 1). Both the detailed structure and the wide distribution of the diffuse Galactic emission are seen, as discrete sources down to mJy flux densities. The very bright, circular, extended object at the center is the Rosette Nebula, which is saturated white in this image. The larger, faint, circular object to the right is the ionized hydrogen of the λ Orionis nebula at the “head” of Orion, while below is the top of Barnard’s Loop that surrounds Orion’s belt.

Figure 2 (b) presents the Stokes-U component of linear polarization from the S1 subfield, showing pervasive and complex polarized emission structures. These arise from Galactic synchrotron emission but are not visible in total intensity, which is intrinsically smooth, particularly away from the Galactic plane. The polarized structures are produced during propagation by differential Faraday rotation in the intervening magneto-ionic medium (the so-called Faraday Screen), which imposes complex structure due to the resulting spatial variations in the emergent polarization position angle. In general, these propagation effects dominate over intrinsic polarized emission structure. The spatial scale of structure is seen to be finest near the Galactic plane, becoming larger farther away.

Figure 2. — Images of the GALFACTS S1 region. (a) GALFACTS total-intensity emission at 1445 MHz, and (b) Stokes-U polarized intensity. Panel (c) shows the same region in 60-μm emission from IRIS (Miville-Deschenes & Lagache 2006). The images span 6 hr in RA by 18° in declination centered on RA ~ 6°30′′, Decl. ~ +8.1°, approximately 12% of the GALFACTS region. The bright source near the center is the Rosette Nebula, while the large diffuse cloud to the right of center is the λ Orionis nebula (see Figure 3).
The distribution of the magneto-ionic material with Faraday depth will be derived from the full-Stokes spectro-polarimetric data using Faraday tomography. In many cases, the Faraday polarization structures can be related to the presence of gas and dust in the ISM and to energetic phenomena, as can be seen by comparing the Stokes-I image of Figure 2 (a) with Figure 2 (c), which presents the IRIS 60-μm dust emission (Miville-Deschenes & Lagache 2006). Figure 3 shows a close up of the λ Orionis nebula, an HII region and bubble formed by the energetic radiation and winds from a central star cluster. The thermal emission from the HII is clearly visible in the GALFACTS total-intensity image (upper left). To the upper right, the shell of dust surrounding the HII region is seen. The Stokes Q and U images show a region of lower polarization within the nebula likely due to Faraday depolarization by small-scale turbulence within the HII region. The outer regions of the bubble are delineated by a sharp polarized edge and fingers of polarized structure that extend beyond, reflecting an impact on the magneto-ionic medium well beyond the boundary of the HII nebula.

These initial GALFACTS images are beginning to reveal how rich a data set will be available for studies of the magnetic fields and the magneto-ionic medium of our Galaxy, and their relationship to the range of astrophysical phenomena and processes that drive the evolution of the ISM of galaxies. The data from diffuse emission, as pictured here, and from the vast number of compact extragalactic objects, will be used by the GALFACTS consortium to study a broad range of phenomena from Galactic astrophysics, to extragalactic and inter-galactic magnetic fields, to foreground studies for investigations of the Cosmic Microwave Background and the Epoch of Reionization. Given its brightness sensitivity, and with spatial and spectral resolution exceeding those of other polarization surveys, the GALFACTS data will serve as an enduring legacy. The SPASS survey with Parkes, which is imaging the sky below declination zero at 2.3 GHz, will complement the GALFACTS data, albeit at lower angular resolution (9′). The GALFACTS data will be released to the public domain via the International Virtual Observatory following the completion of the observations by early 2014, and the processing to incorporate low spatial frequencies.

For more details, see www.cyberska.org/pg/groups/301/galfacts-consortium.

References

Figure 3. — GALFACTS Stokes-I (top left), Stokes-Q (bottom left) and Stokes-U (bottom right) images of the λ Orionis region. The IRIS 60-μm dust emission is also shown (upper right). The effect of the stellar wind on the magneto-ionic medium of the Galaxy is clearly seen in the polarization images.
Searching for Gravitational Waves via Pulsar Timing

David Nice (Lafayette College) and Paul Demorest (NRAO) for the NANOGrav collaboration

The NANOGrav collaboration is using millisecond pulsar timing observations at Arecibo and the Green Bank Telescope in a program designed to directly detect gravitational waves.

The first millisecond pulsar was discovered at the Arecibo Observatory in 1982 (Backer et al. 1982). In the years following that discovery, measurements made at Arecibo of the arrival times of pulses from this and other millisecond pulsars showed these objects to be superb astrophysical clocks. In the best cases, pulse arrival times can be measured and predicted with accuracy of order 100 ns on time scales of years.

Arrival times of pulses measured at a telescope are perturbed by anything that changes the distance between the pulsar and the telescope. Gravitational waves, a key prediction of Einstein’s theory of general relativity, are a tantalizing source of such perturbations. As a gravitational wave passes, it changes the space-time metric along the line of sight from pulsar to observatory, causing pulses to arrive at the observatory slightly earlier or later than they otherwise would. Our millisecond pulsar timing observations are designed to detect these perturbations over time scales of several years. Periods of several years correspond to frequencies of nanohertz, hence our collaboration name, NANOGrav, which stands for North American Nanohertz Observatory for Gravitational Waves.

Gravitational waves are quantified by their strain, $h$, the fractional change in proper distance as a gravitational wave passes. Thus a $h = 10^{-15}$ gravitational wave would perturb the proper length of a 1 m long rod by $10^{-15} m$, roughly the size of an atomic nucleus. A gravitational wave with period of ten years and a strain amplitude of $10^{-15}$ would perturb measured pulse arrival times by $\sim (10^{-15})(10 \text{ yr})/2\pi = 50$ ns. This would be observed as gradual increases and decreases in pulse arrival times of this magnitude.

The most likely sources of gravitational waves detectable by pulsar timing are merging massive black hole binary systems. Black holes with masses $10^6$ to $10^9$ solar masses can be found at the centers of galaxies. Galaxies are known to undergo mergers. Following a merger of two host galaxies, dynamical friction causes the central black holes to sink toward each other, forming a binary system. This binary decays over time, eventually coalescing into a single, larger black hole. The strongest expected gravitational wave signal in the nanohertz band is the stochastic background created by the sum of all such binary systems with orbital periods greater than 1 year. If we are lucky, and there is such a black hole binary sufficiently close to us, it may be possible to resolve individual black hole binary systems in addition to detecting the background signal (Sesana et al. 2009).

Strong indirect evidence for gravitational waves comes from the discovery of the first binary pulsar at Arecibo (Hulse & Taylor 1975). Observations over more than three decades have shown the pulsar orbit to be decaying at the rate predicted due to loss of energy and angular momentum from gravitational radiation emission, with measurement precision of $0.2\%$ (Weisberg et al. 2010). Similar results from more recently discovered pulsars, including the double

![Figure 1](image-url) — Top panel: Expected correlation and anti-correlation of perturbations in arrival times between the pulsars on the sky expected from a background of gravitational waves. This is the characteristic signature of gravitational waves we hope to detect. Bottom panel: Timing correlations between pulsar pairs measured in 5 years of NANOGrav Arecibo and Green Bank Telescope data (Demorest et al. 2013). The blue points are the 15 smallest-uncertainty correlation points, while those with larger uncertainties are shown in gray. The red lines show a $\pm 2\sigma$ fit to the expected correlation function, the results of which are consistent with no detectable gravitational wave signal, and imply $h < 7 \times 10^{-15}$ on a time scale of 1 year.
pulsar system, have confirmed and extended this result. These experiments, compelling as they are, do not directly measure the metric perturbations, as we expect to do with the NANOGrav millisecond pulsar timing observations.

A challenge in the detection of gravitational waves by pulsar timing is that some other physical phenomenon might influence the measured pulse arrival times in a way that mimics the expected signature of gravitational waves. Indeed, young (non-millisecond) pulsars are known to exhibit “timing noise,” irregularities in rotation which, although small, swamp any gravitational signal. The level of timing noise in millisecond pulsars is small, but it may be present at some level in some or all such sources. Thus, a secure measurement of gravitational waves will likely require detection of the same gravitational wave signal in many pulsars observed quasi-simultaneously. Such a set of observations is called a pulsar timing array.

Hellings and Downs (1983) showed that an isotropic gravitational wave background generated by the combination of many sources, such as massive black hole binary systems, produces a distinct pattern of correlation and anticorrelation between signals from pairs of pulsars depending on the angle between the pulsars on the sky (Figure 1). In Demorest et al. (2013), we used NANOGrav pulsar timing data collected at Arecibo and Green Bank over 5 years to seek out the correlation predicted by Hellings and Downs. We also analyzed individual pulsar time series to seek out long-period perturbations characteristic of gravitational waves. We have not yet detected gravitational waves, but we put an upper limit on the massive black hole strain amplitude spectrum of $h_c < 7 \times 10^{-15}$ on a time scale of 1 year.

Pulsar timing arrays are complementary to other techniques attempting to directly detect gravitational waves. The gravitational wave frequencies to which pulsar timing arrays are sensitive (around $10^{-9}$ Hz) are orders of magnitude away from the frequencies probed by proposed space-based detectors such as eLISA (around $10^{-2}$ Hz) and by ground-based detectors such as LIGO (around $10^{-2}$ Hz) — see Figure 2. Using these three separate techniques to explore the gravitational wave spectrum is analogous to

Figure 2. — Comparison of current and planned gravitational wave detectors, showing characteristic strain ($h_c$) versus gravitational wave frequency. Pulsar timing observations probe a region of the gravitational spectrum space complementary to other existing and proposed detectors.
using three separate bands, radio, optical, and X-ray, to explore the electromagnetic spectrum. Indeed, the ratio of the gravitational wave instrument frequencies, $10^{-3} : 10^{-2} : 10^2$, is the same as the ratios of the frequencies of radio, optical, and hard X-ray electromagnetic radiation, $10^8 : 10^{15} : 10^{19}$. Each band of the gravitational spectrum offers its own unique, exciting science.

We are presently observing an array of 19 millisecond pulsars at Arecibo and a similar number of sources, primarily those outside the Arecibo declination range, with the Green Bank Telescope. Further, we have joined with astronomers worldwide to form the International Pulsar Timing Array (IPTA) consortium, which facilitates collaboration and exchanges of pulsar timing data. Pooling millisecond pulsar timing data from radio telescopes worldwide gives access to sources throughout the northern and southern skies, increases observing time and radio frequency coverage, and allows verification of data integrity by comparison of data collected using completely independent observing systems.

Sensitivity to the gravitational wave background is directly proportional to the number of high-precision sources under observation. Pulsar search programs such as the PALFA survey underway at Arecibo (Lazarus et al. 2013) are finding millisecond pulsars at an unprecedented rate. As new, high-precision millisecond pulsars are discovered in surveys, they are added to the NANOGrav long-term timing program.

In 2012, we began using a new data acquisition system, PUPPI (Puertorican Ultimate Pulsar Processing Instrument), for pulsar observations at Arecibo. Developed at NRAO and based on the open-source CASPER FPGA hardware/software suite, PUPPI digitizes the telescope voltages with 8-bit precision and uses a cluster of GPU-
enabled computers for real-time coherent dedispersion of pulsar signals, a necessary step in high precision timing. PUPPI can process bandwidths up to 800 MHz, an order of magnitude more than previous-generation instruments. This gives a large increase in signal-to-noise ratio and hence improvement in timing measurement precision. Further, as shown in Figure 3, pulsar signals observed at Earth show scintillation, random patterns of constructive and destructive interference resulting in regions of stronger and weaker pulsar signals across the observing band; PUPPI’s wide bandwidth makes it much more likely that strong signals will be present in the observing band, increasing the reliability of pulsar detection in any given observation. As measurement precision is improved, the prospect of detecting gravitational waves is good, possibly within the next couple of years (Siemens et al. 2013).

For more about NANOGrav and the IPTA, see http://www.nanograv.org/ and www.ipta4gw.org. A repository for public distribution of our NANOGrav data products is under development at http://data.nanograv.org.

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A Millisecond Pulsar in a Stellar Triple System

One of the main goals of any pulsar survey is to find new and interesting pulsar systems. In 2012, we found a relatively bright new millisecond pulsar (MSP) smack in the middle of Arecibo’s declination range as part of the GBT Driftscan pulsar survey from 2007. And it is most certainly an exotic and interesting system. Our initial observations showed that the pulsar was orbited every 1.6 days by a white dwarf star of about 0.2 solar masses. That in itself is not surprising as we believe that millisecond pulsars are effectively created—or recycled as we say—when mass is transferred by the red giant precursor to the white dwarf onto the neutron star, thereby spinning it up.

What was surprising was that the pulsar’s motion, as measured by exquisitely precise pulsar timing, could not be completely explained by that 1.6-day orbit. We began a massive observing campaign with Arecibo, the GBT, and Westerbork (which observed the pulsar every day or two for over a year) to figure out where this other motion was coming from. It turns out that there is an older, cooler, 0.4 solar mass white dwarf orbiting that inner binary every 327 days, making a hierarchical triple system.

Figure caption: A schematic of the millisecond pulsar triple-system J0337+1715. The pulsar spinning every 2.7 milliseconds is orbited every 1.6 days by a ~ 0.2 solar mass white dwarf, and that inner system is orbited every 327 days by a ~ 0.4 solar mass white dwarf. To help with a sense of scale, the distance from the Earth to the Sun is about 500 light-seconds (lt-sec), while the radius of the Sun itself is only 2.3 lt-sec.

Three-body systems are notorious in physics and astronomy because, unlike with their two-body counterparts, it is impossible to write down simple analytic formulae for their orbits. Their gravitational interactions can be incredibly complex. Yet here we have a system comprised of three compact objects (meaning that only gravitational interactions between them are important), orbiting on relatively short timescales, and where one of them is an incredibly precise clock! In fact, with Arecibo and the new PUPPI backend, we can measure the arrival times of pulses to better than 1 microsecond in only about 10 seconds of observing time, which translates roughly to a measurement of the pulsar’s position to better than a kilometer while it is moving on orbits which are tens of millions of kilometers across!

Just recently, we fully “solved” the complex orbits of the system using high-precision three-body integrations of the gravitational equations of motion matched to our timing observations. The masses of all three objects are measured to better than a part in 10,000, the inclinations of both orbits are measured to about a hundredth of a degree (and, surprisingly, are almost perfectly co-planar), and the complex gravitational interactions are seen with high-significance over time scales as short as a single day.

In addition, the inner white dwarf is hot and optically bright, and members of our team have made beautiful photometric and spectroscopic observations of it, measuring its radial velocity (which matches predictions from pulsar timing), surface gravity and temperature. We have also detected the pulsar with the VLBA and a campaign is underway to measure a high-precision parallax distance to the pulsar within the next year. With a known distance and masses, J0337+1715 will likely become an important calibration point for white dwarf models.

The system is already one of the highest precision examples of a gravitational three-body system known (except perhaps for the Earth-Moon-Sun system, which is dramatically complicated by the non-compactness of the bodies), and continued timing observations may allow high-precision tests of parts of General Relativity and inclusion into NANOGrav for gravitational wave detection. Finally, the complicated evolution of the system, involving the “deaths” of three main-sequence stars, will provide fodder for astrophysical studies for years to come.

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Planetary Radar Observations of Asteroid (101955) Bennu

Mike Nolan (NAIC)

One of the most dramatic uses of Arecibo Observatory involves the imaging of asteroids using the planetary radar. In 1999 and 2005, we imaged the asteroid (101955) Bennu, then called 1999 RQ₃₆, and used the images to make a 3-D model of its shape. In part because we have this 3-D model available for mission planning, Bennu is the primary target of the OSIRIS-REx Asteroid Sample Return Mission, selected by NASA as the third New Frontiers mission in May 2011. OSIRIS-REx will thoroughly characterize near-Earth asteroid Bennu. This asteroid is both the most accessible carbonaceous asteroid and one of the most potentially hazardous asteroids known (Milani et al. 2009). The information obtained from radar characterization of this asteroid was critical in mission target selection and supports OSIRIS-REx science definition and mission planning. A more complete version of this article appears in Nolan et al. (2013).

Observations of Bennu. Bennu is in a pseudo-resonance with the Earth, and makes close passes about every six years, though at varying distances. It has been observed at every apparition since its discovery. The radar observations with Arecibo and the Goldstone planetary radar systems were carried out shortly after discovery, from 21 to 25 September, 1999, and again from 16 September to 2 October in 2005. Further radar observations obtained in September 2011 had too low a signal-to-noise ratio (SNR) to be useful for characterizing the shape of the asteroid. Chesley et al. (2013) used them, along with the other observations noted here, for computing its orbit: Bennu now has the best-determined orbit of any near-Earth asteroid. The observations at Goldstone have lower SNR (by a factor of about 20) than the Arecibo images, but many were obtained at times when the object was not visible from Arecibo. No further ground-based radar observations will be possible until 2037 with existing facilities. Some additional optical observations may be possible in 2017, though it will be quite faint, $M_v = 20$, making detailed studies difficult.

A delay-Doppler image is a measure of the object’s extent along the line-of-sight and its instantaneous velocity dispersion from its own rotation (in the reference frame of the observer). The absolute range and orbital velocity are measured and used to refine the orbit, but are removed in the shape modeling process. The two axes are independent and unrelated in spatial resolution. Each image pixel is a combination of contributions from any area of the surface that has the same distance and line-of-sight velocity from...
the observer, which is generally two locations on a convex object (the “north-south ambiguity”) and can be more than two on an irregular object (Ostro et al. 2002). In the shape modeling, synthetic radar images (or light-curve points) are computed from the shape and compared to the observations. The shape is then adjusted to improve the fit between the synthetic images and the observations. Examples of delay-Doppler images of Bennu are shown in the first column of the panels in Figure 1. The asteroid’s motion in the sky changes the viewing geometry both within a day and between days, so that it is possible to solve for the pole orientation and object shape. If the coverage is extensive enough, the ambiguities within each image can be resolved, and a unique shape can be derived for the asteroid. It is common that ambiguities can only be partially resolved, so that, for example, a feature can be identified and located in latitude and longitude, but not whether the latitude is positive or negative.

Shape model. Figure 1 shows a sample of the radar images and model fits. In each row the observed radar image is in the column on the left, the synthetic radar image generated from the model shape is in the center column, and the plane-of-sky view of the model shape as it would appear from the Earth is in the right column. The difference between the model radar image and the observed image is calculated and summed for each image in the data set to obtain the \( \chi^2 \) value. Weights are used to guide the modeling process, based on differences in the data quality and the type of data used. The actual “objective function” that is minimized is a sum of the reduced \( \chi^2 \) and a set of “penalty functions” that push the model to have “reasonable” behavior, such as enforcing principal-axis rotation and suppressing extreme shapes.

By visually examining the raw radar images, it is clear that Bennu is roughly spheroidal with some large-scale but fairly subtle surface features.

The best-fit shape is shown in Figure 2, projected along the three principal axes. The diameter is (492 ± 20) m. There does seem to be some north-south symmetry in surface features. Because of the nearly-equatorial viewing geometry, this is an artifact of the radar data, and the varying degree of symmetry in different parts of the object may result from variable rotational coverage.

The asteroid has a fairly smooth “spinning top” shape similar to that of binary asteroids such as 1999 KW4 (Ostro et al. 2006) and other “spheroidal” asteroids such as 2008 EV5 (Busch et al. 2011), but with a less well-defined equatorial ridge. The shape appears fairly smooth at small scales, with some large-scale features. There is one 10-20 m boulder on the surface that appears in both 1999 and 2005 radar images, but no other small-scale surface features are evident down to the radar resolution of 7.5 m.

Implications for spacecraft mission selection and design. The extensive knowledge database that exists as a result of the radar characterization of Bennu was critical in the selection of this object as the OSIRIS-REx mission target. These data provided critical refinement of the asteroid’s orbit and a substantial improvement of its ephemerides compared to optical astrometry. These data feed directly into the design of the overall OSIRIS-REx mission profile and constrain the launch period (now expected for 2016), the outbound and return cruise phases, and the timing and duration of asteroid proximity operations.

The radar-derived constraints on asteroid size and spin state also inform us about the nature of the asteroid environment. Radar astrometry has also revealed the action of the Yarkovsky effect (Chesley et al. 2013). This observation, when combined with the asteroid volume derived from the radar shape model and observational constraints on the thermal inertia of the body, allowed us to estimate the bulk density. Combining the derived density with the shape model provides the global asteroid gravity-field model, which allows the mission team to evaluate the stability of various orbits about the asteroid. The gravity-field model and the rotation state allowed us to develop a global surface-slope-distribution model and a global surface-acceleration model. These models are critical to evaluating our ability to safely deliver the spacecraft to the asteroid surface and maintain a nominal attitude during the five-second touch-and-go sampling event. Finally, combining the asteroid shape, rotation state, ephemeris, and albedo yields a global temperature model, which is a direct input into the mission Environmental Requirements Document. All of this information feeds directly into the design of the OSIRIS-REx flight and ground systems, reducing risk and greatly increasing the chances for mission success.

Radar observations also provide constraints on the physical and chemical properties of the asteroid regolith. The observed smooth surface, radar albedo, polarization ratio, and shape all provide evidence of the presence of loose particulate regolith on the surface of this target. We interpret variations in radar albedo as variations in near-surface regolith density structure and metal content, but additional work is required to constrain the radar characteristics of likely regolith material. The circular polarization ratio likely reflects variations in regolith block content. The global shape model of the asteroid indicates a body symmetrically disposed about the rotational axis in response to centrifugal forces. This result suggests that there is loose material capable of migrating into geopotential lows. Our global surface-slope-distribution model has a subdued slope distribution at the spatial resolution of the shape model (7.5 m/pixel). The average slope is 15°—24°, depending on the bulk density of the asteroid. The geopotential low of the asteroid is at the equator (Guibout & Scheeres 2003), suggesting that loose regolith should migrate down to this region, such as has occurred...
on Itokawa (Miyamoto et al. 2007). If sufficient migration has occurred, the gravels would build up a structure at the equator, a likely origin for the observed equatorial ridge on Bennu.

**Conclusions.** The best-fit shape and pole position of Bennu have been derived from radar images combined with optical light-curve data. The independent rotation rate determined from the light curve greatly increases the information that we can gain from radar images. Modeling of pole orientation of Bennu was complicated by the ridged shape characteristic of this object, which dominates its equatorial width. Using a too-simple ellipsoidal shape gave misleading results because the radar data emphasize the (apparent projected) equatorial diameter. Similar issues may affect pole determination by other methods, as the dependence of the visible area on viewing geometry does not follow a simple pattern. Bennu has a retrograde rotation direction with a rotation pole at ecliptic coordinates (-88°, 45°) ± 4°. This is consistent with it having been driven to a stable state by YORP (Vokrouhlický et al. 2003). The shape model derived is similar to that of the primary component of 1999 KW4. However, searches for a satellite for Bennu show nothing larger than 15 m. Radar observations are quite sensitive to satellites in near-Earth asteroids (NEAs), and are largely independent of viewing geometry or distance. The small size and spheroidal shape of this object suggest that it is a rubble-pile structure with little or no internal cohesion. This is not unusual among NEAs observed with radar, but it is not universal. Objects of similar size are also seen which must have internal strength to maintain surface material at their spin. The OSIRIS-REx spacecraft mission to this object will reveal new insights into the formation and evolution of NEAs, and possibly give clues to their origins in the main belt as

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**Figure 2.** The shape of Bennu showing the views along the principal axes. Some of the apparent north-south symmetry is a model artifact from the near-equatorial viewing geometry. The “boulder” feature is actually in the southern hemisphere.
well. Radar observations of NEAs in general also give invaluable information as to their sizes, shapes and diversity, and as a byproduct, give greatly improved orbits for any object observed.

This work was supported by NASA grants NNX10AP64G, NNX-12AF24G and funding from the OSIRIS-REx project. This material is based in part upon work supported by NASA under the Science Mission Directorate Research and Analysis Programs.

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The Arecibo Observatory is operated by SRI International in alliance with Ana G. Méndez-Universidad Metropolitana and the Universities Space Research Association, under a cooperative agreement with the National Science Foundation (AST-1100968).