A Radio Survey of the Galactic Bulge Region at 1-2GHz

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The Galactic Bulge Survey (GBS) Project

The GBS is a multi-wavelength effort to better understand the prevalence and distribution of many populations of objects in the Galactic Bulge region. The focus of the GBS was to find populations of compact stellar objects and binary systems in the inner part of the Galaxy, which are types of objects that emit X-rays. The project performed a survey in X-rays with the *Chandra* space telescope to find X-ray emitting sources, and also a deep survey in optical to find counterparts to try to classify the X-ray sources [1, 2]. After those data were published, the authors decided that a sensitive, high resolution survey in radio could further help to classify the X-ray objects, as well as find additional sources. Thus, a 'pilot' radio proposal was written for the Very Large Array radio telescope. It was a pilot in that only a portion of the GBS region was proposed to be observed to see if it would be worth completing the remaining parts in the future, since a radio survey of that quality had not been done in the region before. The GBS radio proposal was accepted and the observations were done in 2015, but the data had not been fully reduced before this.

This radio survey aims to identify radio counterparts to the sources already known from the optical and X-ray surveys, and to see whatever else there is in the Galactic Bulge region (GB), particularly pulsars. Pulsars are theoretically common in the GB. They form from massive stars, which are born and live a relatively short life in the Galactic Plane, where they then go supernova. Supernovae are generally asymmetric in their explosions, and this asymmetry can cause the newborn neutron star to receive a 'natal kick' from the collapse of the massive star. This natal kick can be up to several hundred kilometers per second and can cause the neutron star to travel away from the Galactic Plane and into the GB, so that hundreds of pulsars should populate the region. Currently, though, there are very few pulsars actually known there. It is unclear if there really are very few pulsars there, in which case the theory is incorrect, or if there are indeed plenty but there have not been proper observations in order to detect their population. Pulsars can be tricky to observe either though imaging as in this survey, or through pulsar timing searches – each method has its own difficulties, but deep imaging has the potential to find many candidate pulsars relatively quickly. One possibility of this survey is to find the candidate pulsar population and attempt to simulate the distribution of pulsars in the GB to compare to the theories about where exactly pulsars should be located in the galaxy. In addition, pulsars and neutron stars in general can be part of binaries, and the evolution path of binaries can take many forms, and is not well understood. The first step to properly understanding the evolution and distribution of any class of objects in astronomy is, of course, to actually find them, which this survey and project aims to accomplish.

Why the Galactic Bulge?

The Galactic Bulge is a very dense region of the Milky Way. It is not quite as dense as the Galactic Center, but it has the advantage that it does indeed bulge out and away from the plane of the galaxy. The plane is polluted with gas and dust that affects any light that travels though it, making it hard to make good quality observations of something as far away as the center of the galaxy. But the Galactic Bulge is slightly above and below the plane, and that is enough to avoid the worst of these effects, called extinction. This makes observations of the GB easier to do than the center, while still being able to look at a dense region of the galaxy that hosts all sorts of objects within it. Additionally, most observational efforts in the center of the galaxy have focused on the center itself, rather than the bulge, so this project will greatly expand what is known for this region regardless.

What types of sources produce radio emission?

AGN: Active Galactic Nuclei are hosted by galaxies. AGN are the supermassive black holes at the centers of massive galaxies that are actively accreting matter, and are very, *very* luminous. They can also efficiently produce a powerful jet powered by the energy of the accreting matter that launches at relativistic speeds and at potentially huge distances away from the black hole into the intergalactic medium that surrounds the host galaxy. The jet interacts with the low density material between galaxies, and this interaction emits strongly in the radio from synchrotron radiation. Radio emission can also come from the area immediately surrounding the supermassive black hole. AGN isotropically populate the sky, and can emit across the EM spectrum.

Pulsars: Pulsars are a type of neutron star that emits radio radiation from their magnetic poles. Pulsars also spin, and because the magnetic axis is generally not aligned to the rotation axis, it is possible that only once per rotation the magnetic pole points toward the Earth and the Earth receives a dose of radio emission, much like the rotating light on a lighthouse only looks bright if it points in your direction. Their name does indeed come from their appearance to pulse in the radio.

X-ray binaries: X-ray binaries are a type of compact binary, where one of the two objects is a neutron star or a black hole, and it accretes matter from a 'regular' stellar companion. The orbit of the binary is very close, so that the companion star feeds mass from itself to the accretor. As hinted by the name, X-ray binaries, or XRBs, are a source of X-rays, and can also produce radio emission from accretion-powered jets similar to the case of AGNs, just on a much, *much* smaller scale.

Planetary Nebulae: Despite the name, planetary nebulae, or PNe, have nothing to do with planets. PNe are produced when a Sun-like star, when it was near the end of its life, shed many layers of material from its bloated self in the 'giant' phase of its existence. The remaining star then collapsed into a white dwarf. White dwarfs are small but very hot, tens or hundreds of thousands of Kelvin in temperature, and the radiation from such a hot object is enough to heat up and ionize the surrounding expanded layers of material that the star shed off before collapsing. The heated nebular material is often visible in the radio.

Stars: Many types of stars can produce radio: protostars, dwarf stars, massive stars, and coronally active stars potentially can, but stars in general are generally not meaningful radio emitters. See the inset optical star field for comparison of just how many stars don't produce meaningful radio emission. (It's almost all.)

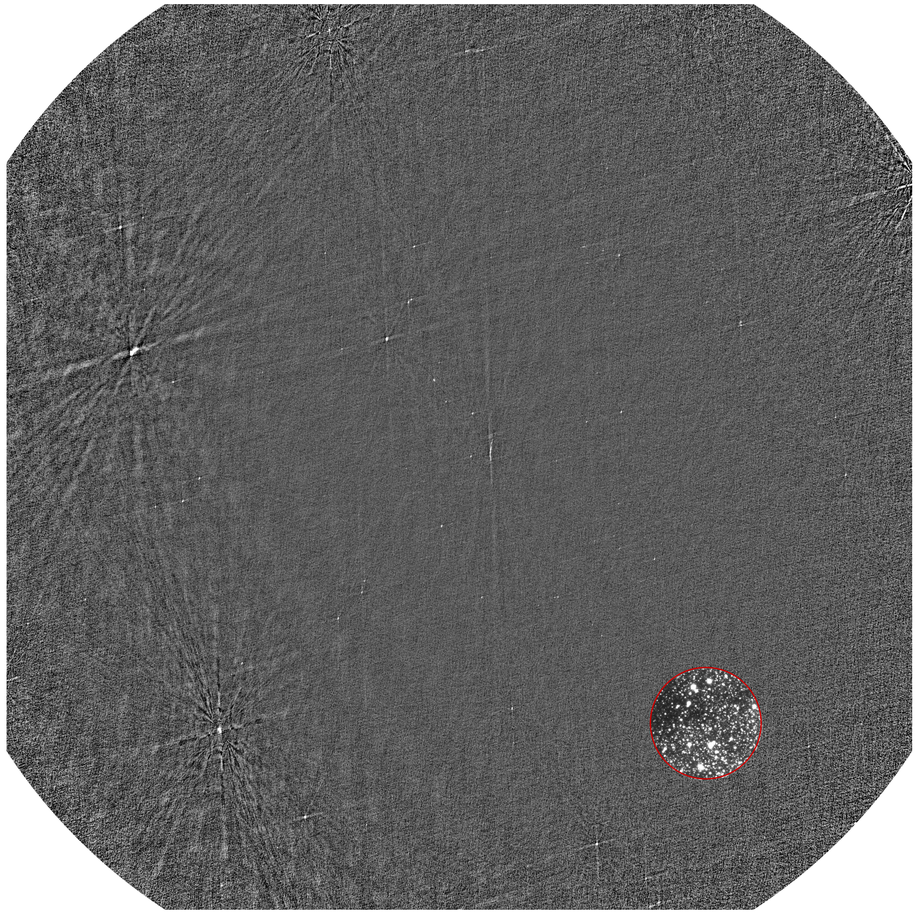
References

[1] Jonker et. al., 2011, ApJS, 194, 18. doi:10.1088/0067-0049/194/2/18

[2] Wevers at. al., 2016, MNRAS, 458, 4530. doi:10.1093/mnras/stw643

Results

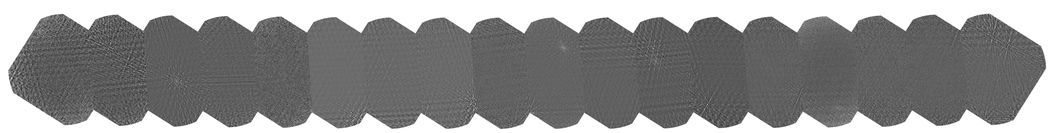
The survey covers about 2 square degrees of the sky, using 18 different fields. Analysis is currently ongoing. In total there are about 1200 unique radio sources in this survey region. Most of these sources are point sources, meaning that the angular size of the source is smaller than the resolution of the telescope. There are many that are not point sources, though, and this generally makes initial classification easier. There are about 120 sources that are either clearly or probably AGN based on their morphology – double lobe radio jets, or radio jet hotspots. There are a handful of AGN that are of a noteworthy subclass as well. An additional 33 sources are previously known planetary nebulae, most of which are extended sources. Most extended sources fall into these two classes of objects, but there are some that are still unknown. For the many point sources, the classification becomes harder, and relies more on the spectral index and possible counterparts in other wavelengths to determine what they are. Very steep, or negative, spectral indices are good candidates for being pulsars, as the steep spectral index is a characteristic of pulsar emission. Based on this, there seem to be about 100 pulsars, which would be a huge improvement over the number of currently known pulsars in this region, even if not all of them really are pulsars. Some of these candidate pulsars are bright enough to be followed up with pulsar timing to look for pulsing radio emission to confirm their classification. Moderately steep spectral indices can be point source AGNs or jet emission from X-ray binaries. There are a couple dozen radio sources found that are counterparts to X-ray sources. Half are AGN, and the other half are consistent with a galactic origin, though only two have been classified from the previous optical data. These dozen galactic sources will be looked into further and possibly followed up with new observations. We expect that the majority of radio sources will not be able to be classified, but if even a handful of interesting objects are confirmed or found by using the radio data, this will have been a success to the GBS, and prove this pilot radio survey to be a worthwhile effort and bolster a proposal to observe the remaining 10 square degrees of the GBS region in the radio.



Large: This is one of the 18 fields that the radio survey covered. Each field is about 30 arcminutes in diameter. For reference, the moon is 31 arcminutes in diameter, so each field is the size of the moon on the sky. The white dots are the radio sources, and the brighter ones are surrounded by 'artifacts,' which are a byproduct of using an array and synthesizing an image from it.

Inset: Displaying the optical image instead of radio for that specific region, showing how dense the galactic bulge region is with stars.

Below: All 18 fields, stitched together using their overlap. Together, they are 6° wide and 0.5° high, parallel to the Galactic Plane.



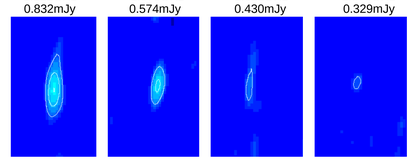
The Very Large Array (VLA), and Radio Astronomy

The VLA is a radio telescope array in New Mexico, near Socorro, and is run by the National Radio Astronomy Observatory. The current VLA is the upgraded version, sometimes called the expanded VLA (eVLA), or the Jansky Very Large Array, named after the original radio astronomer Karl Janksy. The VLA has a unique design in that each of the 27 telescope dishes can be moved along 3 straight 'arms' via railroad tracks to expand or contract the overall size of the array. There are also several radio frequency bands that can be observed in, similar to different optical filters. Depending on the target source and reason for the observation, astronomers use a particular combination of radio frequency and array size to obtain data. Radio interferometry is quite different from how optical telescopes and data work, since with radio arrays the telescopes are not actually taking images of the sky – rather, the images are assembled from complex data gathered from the individual dishes. Most radio telescopes have their own software to combine the raw data together, calibrate, and use the data to produce images. Radio wavelengths are between about a millimeter and extend all the way to many kilometers. While the data is more difficult, radio astronomy does have advantages over other wavelengths: observations can be done both during the day and night, the telescope dishes don't have to be perfectly smooth (or even solid!), and radio waves travel right through many materials that optical and X-ray do not. Most galactic sources do not produce meaningful radio emission, but for some types of objects radio emission is essential to understanding them. This means that the radio sky is very 'quiet,' and would look unrecognizable compared to the familiar optical night sky.

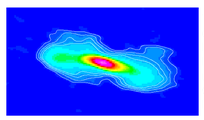
Spectral Index, and why it's important

Spectral indices in radio astronomy can be very useful for identifying what exactly is producing the radio emission. The spectral index is a measure of how rapidly the amount of flux per unit frequency changes with frequency – that is, if you look at a higher frequency, is there more or less flux per unit frequency for this same source? And by how much did the flux density change? Spectral index follow the equation $S_\nu \propto \nu^\alpha$, where S_ν is the flux density per unit frequency and α is the spectral index. Different radio emission processes have different characteristic spectral indices. Thermal emission from blackbodies generally have a positive spectral index: more flux density at higher frequencies, as you're travelling 'up' the Rayleigh-Jeans part of the blackbody toward higher energy. Non-thermal emission can have negative spectral indices: synchrotron emission, from charged particles accelerating circularly in a magnetic field, is around -0.7, and pulsars can be even more negative at -1.7 or so. The way that the spectral index was calculated for this data was by taking the 1-2GHz frequency range and splitting it into four consecutive subbands, each about 0.25GHz in bandwidth. An image was produced for each subband, and the flux density of each source in each of the four different frequency subbands was recorded, and then the data points were fit by a linear equation in logspace. The slope of the linear fit is the spectral index. Just the presence of radio emission can be helpful but is usually not defining, but when combined with the spectral index, the process producing the radio emission can be narrowed down, which can then point to a classification.

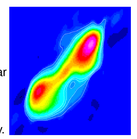
An example of a candidate pulsar from spectral index. This is the same source shown in each of the four subbands. Notice that the brightness of the source, called the flux density, decreases with increasing frequency. This source has a very negative spectral index of -1.8, characteristic of a pulsar. Also note that the angular size of the source decreases with increasing frequency; each subband has its own angular resolution due to being centered at different frequencies. Higher frequency means higher resolution, or smaller angular size.

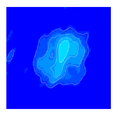


Some objects found in the survey

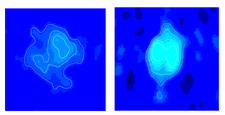


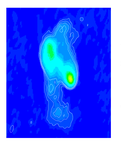
These are classic examples of a bright AGN. The host galaxy is comparatively small and invisible in the radio, but the supermassive black hole at the center is powering huge radio jets that can launch far beyond the extent of the galaxy itself. The left is an FR-I type, where the center is brighter than the lobes, and the right is a FR-II type, where the lobes are brighter than the center. AGN are some of the brightest radio sources in the sky, despite being huge distances away.



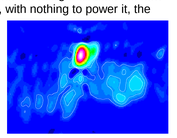


These are previously known planetary nebulae. At the center of these dusty nebulae are hot white dwarf stars, which ionize the material and cause them to radiate. It is believed that our Sun will eventually follow this same evolutionary path. Asymmetry is a common phenomena in PNe, though the exact cause is still debated.

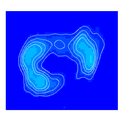




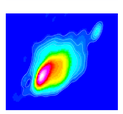
Left: This is what is called an X-shaped galaxy, which is a special occurrence of an AGN. There appears to be two separate radio emission groups, one that is solid and bright, and another that is patchier and faint. The theory of these sorts of AGN is that the patchy emission is from a previous orientation of the supermassive black hole. Sometime in the past, the host SMBH of this AGN underwent a dynamical interaction and eventually merged with another SMBH from another galaxy, and the merger caused the new BH to have an orientation that differed from the previous direction. Over time, with nothing to power it, the old emission will fade away.



Right: This may be another X-shaped galaxy, but a bit strange looking. Again there seems to be bright, new emission and fainter, old emission. The old emission appears to be V-shaped, which is characteristic of a narrow-angle tail galaxy. NATs are galaxies (and their SMBHs) travelling at high speeds through intergalactic medium, leaving being a trail of radio emission like the wake from a boat. For now, the exact classification is uncertain.



Similar to a NAT, a WAT is a wide-angle tail galaxy. WATs are also moving through intergalactic medium. While NATs are V-shaped, WATs are C-shaped. Both types of galaxies are most commonly found in galaxy clusters, which are groups of hundreds to thousands of galaxies that are gravitationally bound together. There is also an abundance of gas between the galaxies in the cluster. This gravitation and material provides the kinematics and intergalactic medium needed to host a NAT or WAT – high speed motion because of the high gravity, and plenty of medium for the jets of the SMBH to interact with and produce radio emission.



This is probably an AGN with a jet that is angled toward us. This is called beaming, and it causes the beamed jet to appear brighter than it actually is, and in extreme cases, cause apparent superluminal motion, or motion that is faster than the speed of light. Blazars are AGN with a jet pointed directly at us. While this is not a blazar, it is unusual to see such asymmetry in an AGN. The fainter source to the NE (east and west are projected backwards onto the sky) could either be the nucleus where the SMBH is, or the hotspot of the counterjet, the jet that points away from us.