Brightening of the Bridge: Reflections of a Past Sgr A* Outburst in Galactic Center Molecular Clouds

Nathalie Kanoelani Takiko Jones
Bard College, nj2518@bard.edu

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Brightening of the Bridge: Reflections of a Past Sgr A* Outburst in Galactic Center Molecular Clouds

A Senior Project submitted to
The Division of Science, Mathematics, and Computing
of
Bard College

by
Nathalie Kanoelani Takiko Jones

Annandale-on-Hudson, New York
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Abstract

Scientific Abstract

Giant molecular clouds in the Galactic Center region act as X-ray reflection nebula that may reveal the past activity of the central supermassive black hole Sgr A*. One of the giant molecular clouds in the Sgr A complex, the so-called “Bridge” cloud, is located about 18 parsecs in projected distance from Sgr A*. The most recent observation of the “Bridge” molecular cloud from 2020 by NuSTAR, combined with archival data from 2012 and 2016, has revealed that this molecular cloud has continued to brighten up in the past eight years. My analysis of these observations shows that the X-ray flux of this cloud has doubled in 2020 as compared to 2012. I performed spectral analysis on this data using both ad hoc and physical models. The most likely source of the increased flux of the “Bridge” cloud is a past X-ray outburst from Sgr A* that took place about 60 years ago. Such brightening of the Bridge may reveal more about Sgr A* activity in the past tens of years and constrain the X-ray reflection nebula models with NuSTAR’s broadband X-ray capacity.

Everybody Abstract

The center of our Milky Way galaxy is located more than 200,000 trillion km from Earth in the constellation Sagittarius. At the very center of our galaxy is a super-massive black hole called Sagittarius A*. The black hole is surrounded by many interesting objects, including molecular clouds. Molecular clouds are large, cold clouds of gas in which stars are formed. Telescopes like NuSTAR have observed X-rays (radiation 10,000 times higher in energy than visible light) coming from these molecular clouds. Since cold gas cannot create such high energy emission by itself, there must be some external source of radiation interacting with these clouds. In my senior project, I studied the “Bridge” molecular cloud, which is nearby Sagittarius A*. Using data from 2012, 2016, and 2020, I determined that the brightness of this cloud doubled over the last 8 years. The most likely cause for this change in brightness is that the “Bridge” cloud is reflecting a powerful outburst from the central black hole.
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Dedication

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O ke kumu o ka lipo, i lipo ai
O ke kumu o ka Po, i po ai
O ka lipolipo, o ka lipolipo
O ka lipo o ka la, o ka lipo o ka po
Po wale ho'i
Hanau ka po

The source of the darkness that made darkness
The source of the night that made night
The intense darkness, the deep darkness
Darkness of the sun, darkness of the night
Nothing but night
The night gave birth

– From ‘Ka Wa Akahi’ or ‘Chant One’ of the Kumulipo. Edited and translated by Martha Warren Beckwith (Chicago UP 1951)
Introduction

1.1 The Galactic Center

The center of the Milky Way Galaxy is about 8 kpc away from Earth and is located within the constellation Sagittarius\(^1\). This region cannot be observed in optical to soft X-ray wavelengths, due to the large column density of gas and dust obscuring the region. The development of radio, sub-millimeter, infrared, and most recently, X-ray and \(\gamma\)-ray instruments have allowed exploration of this fascinating region. The Galactic Center (GC) of our own Milky Way is the closest galactic nucleus to us on Earth, allowing high-resolution observations that are impossible for distant galactic nuclei.

The Galactic Center was first observed at radio frequencies, with early observations providing an initial glimpse at Sgr A\(^*\), the supermassive black hole at the very center of our galaxy. This region was even observed by the first X-ray satellite instrument, Uhuru, which was launched in 1970\(^2\). However, X-ray imaging of the Galactic Center was not performed until 1979, with the Einstein Observatory. Other early observations by ROSAT and ART-P confirmed that the GC is

\(^1\)In writing this section I referenced Chapters 12 and 16 of *The Universe in X-rays* [9], NASA’s website[18][19][20], Mori et al. 2015, Zhang et al. 2015, Zhang et al. 2017, and Zhang et al. 2020; The parsec (pc) is a unit of distance used in astronomy that is equivalent to about 3.3 light years.

\(^2\)Uhuru was the first small space-craft surveying the sky for X-ray, \(\gamma\)-ray, and U-V sources. The primary focus of this instrument was to scan the celestial sphere in the energy range 2-20 keV. It was launched off the coast of Africa on December 12, 1970.
an inactive example of galactic nuclei. Later observations by high resolution and high sensitivity X-ray telescopes Chandra and XMM-Newton established that Sgr A* is an X-ray source.

Chandra and XMM-Newton also discovered the flaring activity of Sgr A*, which is typically a quiescent X-ray source and is one of the most under-luminous super massive black holes (SMBH) known. Sgr A* has a bolometric luminosity approximately $10^{-9}$ times the Eddington luminosity for a black hole of its $4 \times 10^6 \, M_\odot$ mass$^3$. This means that for its mass, its maximum allowed luminosity is much higher than its actual observed luminosity. The discovery of Sgr A*'s flaring activity between 2000 and 2002 was extremely exciting for X-ray studies of the Galactic Center.

Besides SMBH Sgr A*, the Galactic Center is also populated by several other exotic objects such as filaments, Pulsar Wind Nebulae (PWNs), and X-ray binaries. Filaments are long, thin structures that have been observed in radio and X-ray wavelengths within a few hundred parsecs of the GC. More than 100 radio filaments have been discovered by MeerKAT. Dozens of non-thermal X-ray filaments are still being discovered by Chandra and NuSTAR telescopes, including a few hard X-ray filaments emitting photons above 10 keV. X-ray filaments are smaller in spatial scale than their radio counterparts and their emission mechanism is not well known. Filaments are thought to be magnetic structures that trap high-energy charged particles in the GC.

Other high energy sources in the Galactic Center include supernova remnants, X-ray binaries, and a few unique hard X-ray and Gamma ray sources. Cataclysmic variables (CVs) are small binary star systems that emit X-rays due accretion of matter onto the compact object$^4$. The scale of these binary systems are on the same scale as the Earth-moon system and consist of a white dwarf primary and any normal secondary star. Other types of X-ray binaries include systems where a neutron star or a black hole is the accretor. Supernova remnants are the remains of a supernova explosion and can accelerate high energy particles like protons and electrons. There are also several PWN candidates in the Galactic Center, as well as ultra-high $\gamma$-ray source

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$^3$The symbol $\odot$ refers to the sun. In this case, $M_\odot$ refers to the mass of the sun or solar mass, which is used as a unit of mass in astronomy.

$^4$Accretion is the process of growth in mass of any celestial object due to gravitational attraction. The object whose mass is increasing is known as the accretor. [10]
1.2 GALACTIC CENTER MOLECULAR CLOUDS

HESS J1745-290 and hard X-ray source IGR J17456-2901. These latter objects were discovered by CANGAROO-II, HESS, VERITAS, MAGIC, and INTEGRAL observatories.

Lastly, the Galactic Center is home to many expansive molecular clouds, which have been observed emitting X-rays despite being clouds of neutral gas. Galactic Center molecular clouds (GCMC) are the focus of my study and are discussed in detail in the next section.

1.2 Galactic Center Molecular Clouds

1.2.1 Molecular Clouds

Molecular clouds are, as the name suggests, large clouds of molecules in the interstellar medium, composed primarily of molecular Hydrogen. They were discovered by William Herschel in 1785, who noticed large patches along the Milky Way where very few stars were seen. This is due to the fact that dust clouds obscure radiation from stars. All stars are formed in molecular clouds, which are also known as “stellar nurseries” for that reason.

Molecular clouds are categorized based on their size, mass, Hydrogen column density $N_H$, and visual extinction $A_V$. Diffuse molecular clouds are the most opaque, with $A_V < 1$. Dark clouds are, indeed, the darkest category, with $A_V$ ranging from 20 to $\sim 100$. Molecular clouds are most often found grouped together in complexes, although they are also sometimes observed in isolation. A giant molecular cloud (GMC) complex is a gravitationally bound group of GMCs and other smaller clouds. GMC’s have large total masses, about $10^5$ to $10^6 \times M_\odot$. These complexes are between 25 to 200 pc in size with column densities ($N_H$) between 50 to 300 cm$^{-2}$.

In a GMC, most of the gas and dust is relatively cold. However, atomic Hydrogen in some regions will become ionized, especially in regions of recent star formation. Molecular clouds are theorized to have turbulent fluid motions, which could create “shocks” that would then cool the gas. However, molecular cloud turbulence and shock speeds are not well understood. There is also strong evidence that magnetic fields have additional dynamic importance, especially in molecular cloud clumps with $N_H > 3000$ cm$^{-2}$.

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5When writing this section, I referenced the Glossary of 21st Century Astronomy[13], Chapter 32 of Physics of the Interstellar and Intergalactic Medium[2], and a webpage written by Craig Kulesa [4].
1.2.2 The Central Molecular Zone

The Central Molecular Zone (CMZ) is a region in the center of the Milky Way Galaxy with a high concentration of molecular clouds. This molecular gas is strongly concentrated in the central hundreds of light years (or 200 to 300 pcs) of the galaxy and has a large mass, approximately $10^7 \, M_\odot$. While the CMZ is less than 1% of the volume of the Milky Way, it contains about 10% of the galaxy’s molecular gas. Pinning down the distance to and the line-of-sight velocity of Galactic Center molecular clouds is difficult because the CMZ is most likely not in orbit around Sgr A*\(^\star\). The region is instead dominated by the gravitational potential due to stars within the clouds. These stars are distributed in a bar shape, which may be the cause of the region’s non-circular motion.

Molecular clouds in the Galactic Center have been observed to emit X-rays, despite being composed of cold neutral matter. The source of this radiation is a compelling mystery for X-ray observations of this region. The most likely theory is that GCMCs are reflecting X-ray outbursts from Sgr A*\(^\star\). These light fronts can not only expose past emission of Sgr A*\(^\star\), they can also aid in the mapping of the spatial distribution of these clouds. Ponti et al. (2010) discuss that the black hole should have had an active period of about 400 years, which implies that a large number of clouds in the CMZ (about 30%) should still be reflecting radiation from Sgr A*\(^\star\) flares.

There are several large molecular cloud structures in the CMZ, including Sgr B2, Sgr C, and the Arches cluster. Sgr B2 is the densest and most massive cloud in the region. It has a complicated structure with several dense star-forming cores. Sgr B2 is the first Galactic Center molecular cloud from which the Fe (Iron) K\(\alpha\) line was measured in 1996. This strong feature at 6.4 keV was first discovered by ASCA. Galactic Center molecular clouds have been studied below 10 keV for many years. However, observations by NuSTAR in the hard X-ray band (10 - 79 keV) are crucial to our understanding of the region.

\(^6\)References for this section include Ponti et al. 2010, Mori et al. 2015, Zhang et al. 2015, Molinari et al. 2011, and Sunyaev et al. 1998.
1.2. GALACTIC CENTER MOLECULAR CLOUDS

Figure 1.2.1: Figure 3 from Mori et al. 2015. This 10 - 20 keV NuSTAR image shows the Sgr A complex region, including the “Bridge” molecular cloud and SMBH Sgr A*. This image represents an area which is approximately 30 pc by 50 pc. Images from telescopes like NuSTAR show us the face-on orientation of the GC. However, the distribution of these objects along the line of sight (front to back) can be hard to constrain.

1.2.3 Sgr A Complex Molecular Clouds

The Sgr A complex is the region between SMBH Sgr A* and Sgr B2 along the galactic plane. This region is home to many molecular clouds including the “Bridge” molecular cloud, MC1, MC2, and G0.11-0.11 (see Figure 1.2.1). All of these clouds were observed during the NuSTAR mini-survey in 2012, as well as by XMM-Newton in the same year. These clouds are optically thin, with Thomson optical depth $\tau_T \sim 0.1^8$. The “Bridge” cloud, MC1, and the Arches cluster all feature a Fe Kα 6.4 keV emission line.

1.2.4 The Bridge

The “Bridge” is the nickname of a Galactic Center molecular cloud located about 18 parsecs from Sgr A*. This region is likely called the “Bridge” because it spans the distance between

---

7While writing this section I referred to Mori et al. 2015 and private communication with Shuo Zhang.
8Optical depth $\tau$ is the measure of opaqueness along the path of the photon from the source to a detector. It is the absorption of light passing through a medium and is related to absorbance and attenuation. Optical depth can be represented as the natural logarithm of the ratio of flux received by a medium to flux transmitted by a medium: $\tau = \ln(\frac{\text{received}}{\text{transmitted}})$.
9For this section I referenced Ponti et al. 2010 and Zhang et al. 2020.
objects in the immediate GC region, i.e. Sgr A*, MC1, and MC2, and the giant molecular cloud G0.11-0.11 and X-ray filament G0.13-0.11. The projected angular size of the “Bridge” region is 1.92 arc-minutes or at least 15 light-years. In my analysis, I used a circular source region of 50″ for the “Bridge” as required by our data. Ponti et al. (2010) determined that the “Bridge” cloud is likely located behind Sgr A*. They also report that this cloud has typical physical parameters for a molecular cloud located in the CMZ, with a high line of sight velocity, high internal temperature, and consistent column density. Sgr A* is located south-west of the “Bridge” molecular cloud.

Additionally, Ponti et al. (2010) discovered a super-luminal echo within the “Bridge” molecular cloud. They divided the cloud into seven smaller source regions and performed analysis on each, in order to tease out the motion of the observed light front through the cloud. Ponti et al. (2010) observed progressive illumination of the “Bridge” region over 2 to 5 years. Variation on this time-scale implies a superluminal velocity at least 4 times the speed of light. Superluminal motion is motion that seems to be faster than the speed of light observed in celestial objects such as radio galaxies and Active Galactic Nuclei (AGN). It arises from the difference between the apparent speed of the distant moving object and the actual speed, if one were to measure it at the source. Superluminal motion is generally observed near black holes, powerful objects which seemingly bend many laws of physics. Ponti et al. (2010) determined that the source of the super-luminal echo must be outside of the “Bridge” cloud, at a significant distance away. Furthermore, they conclude that the most likely source of the light front observed in the “Bridge” molecular cloud is Sgr A* because the alternate explanation, emission from Black Hole X-ray Binaries, have too short of an outburst cycle. Moreover, there are no other X-ray sources near the cloud bright enough to produce the observed phenomenon. The propagation of light observed in this region directly correlates with the direction towards Sgr A*, as the illuminations starts in the west and propagates east. This observed super-luminal echo in the “Bridge” cloud correlates with an active period of Sgr A* lasting about 400 years.

10 A Dictionary of Physics defines line of sight velocity as the component of a celestial body’s velocity along the line of sight of the observer, usually given in reference to the Sun and not the Earth, due to Earth’s complicated orbital motion.
Figure 1.2.2: Figure 11 from Ponti et al. 2010. This figure shows the Galactic Center as seen from the galactic north pole (top-down view). Earth is in the $-y$ direction. From Earth, we see all of these objects fairly close together along the $x$ axis. This diagram shows their spatial distribution with respect to the $y$ direction. The “Bridge” cloud is the red rectangle on the top of the image, located 18 pc behind Sgr A*\(^\star\). The parabolas represent light-fronts emitted by Sgr A*\(^\star\), which are indicated by the asterisk at the origin.

1.3 X-ray Emission from Galactic Center Molecular Clouds

There are two distinct processes that produce X-rays in molecular clouds: fluorescence and continuum emission\(^{11}\). Fluorescence is the process by which an incoming X-ray (or other kinds of high energy radiation) knocks out an electron from the innermost shell of an atom. Once the electron is knocked out, it leaves a vacancy in that first shell. Then an electron from one of the outer shells jumps down to fill the vacancy. The innermost shell is called the “K” shell, the next is called “L”, after that “M”, and so on. The Greek letters $\alpha$ and $\beta$ represent whether electrons are jumping from the next highest shell or from two shells above K. For example, “K$\alpha$” represents an electron jumping from the L to the K shell, whereas “K$\beta$” represents an electron jumping from the M to the K shell. Electrons in higher shells have more energy than electrons in the lowest shell (K). Therefore, when electrons jump down to fill the K shell, they must emit

\(^{11}\)For this section, I referenced Ponti et al. 2010, Zhang et al. 2015, The SAO Encyclopedia of Astronomy website[26] and a worksheet from U Georgia[3].
energy, which takes the form of a photon. The emitted photons have a characteristic wavelength representing the difference between the electron’s initial and final energy. These characteristic energies are called emission line energies. They are visually distinct in a spectrum and correspond to specific elements. Additionally, $\alpha$ lines are more common than $\beta$ lines because it is more likely for an electron to jump down from a neighboring shell than from a higher one. However, $\beta$ lines are still significant because they have very similar energies to $\alpha$ lines of adjacent elements and may be counted in another element’s peak. This phenomenon is called spectral overlay. The key fluorescence line for Galactic Center molecular clouds is the Fe K\(\alpha\) emission line at 6.4 keV. Fe K\(\alpha\) and Fe K\(\beta\) lines are included in spectral models of GCMCs as important indicators of a high-energy illumination process.

There are several explanations for the presence of the 6.4 keV neutral iron line in Galactic Center molecular clouds, the least likely being hot plasma, which produces collisionally-ionized iron atoms with line energies in the 6.5-6.9 keV range\(^{12}\). However, hot plasma cannot be confined in the region and its regeneration would require too much energy. Another explanation is propagation of cosmic-ray particles within molecular clouds. Collisions with Low-Energy Cosmic Ray electrons (LECRe) and protons (LECRp) can produce Fe K\(\alpha\) emission. However, the source of the distinct 6.4 keV emission line is likely photo-ionization by high energy photons. This last explanation is the “X-ray reflection nebula model,” wherein cold molecular clouds reflect incoming X-ray photons.

Continuum emission is a term that groups together the different sources of emission from Galactic Center molecular clouds. This includes Inverse Compton Scattering, Thomson scattering, Bremsstrahlung, and Synchrotron emission. Compton scattering is the scattering of a photon off of a particle, usually an electron. This process results in the photon losing energy, having transferred a portion of its energy to the electron during the interaction. A decrease of energy means an increase in wavelength for the photon. The scattering angle of the photon also depends on how much energy is lost to the electron in the process. Inverse Compton scattering is

\(^{12}\)References include, Ponti et al. 2010 and Zhang et al. 2015.
the opposite phenomenon, where a photon gains energy by interacting with an electron. In this case, the electron loses energy and the photon is promoted to a significantly high energy, usually at X-ray or γ-ray wavelengths. Bremsstrahlung, or “breaking radiation,” is radiation produced by particles undergoing a change in velocity because of interactions with other particles. Due to conservation of energy, a change in velocity requires a change in energy. Extra energy is then emitted as a photon. Synchrotron emission is generated by electrons spiraling around electric field lines at velocities close to the speed of light. Similarly to Bremsstrahlung, due to the electron’s helical path around the field, energy must be released as the particle changes direction. Depending on the electron energy and the strength of the field, photons will be released with X-ray or γ-ray wavelengths.

1.3.1 X-Ray Reflection Nebula Model

The most likely explanation for the 6.4 keV emission line observed in Galactic Center molecular clouds is reprocessed radiation from an external source. Continuum emission above ~ 8 keV from a nearby compact source would produce Thomson scattering in the dense molecular gas of the GC. Thomson scattering is an elastic scattering process between a photon and a free electron and can be thought of as the low-energy-transfer limit of Compton scattering, where the photon’s energy is much smaller than the mass energy of the electron:

\[ E_{\text{photon}} \ll m_e c^2. \]  

The source of the continuum emission is photon excitation in the X-Ray Reflection Nebula (XRN) Model. Reprocessed radiation requires a powerful source of primary X-ray emission and the most probable suspect for the source of this emission in the Galactic Center is Sgr A*.

The GC is very large, spanning hundreds of parsecs. This means that even light takes a long time to travel across the region. Since the “light-crossing time” of the Galactic Center is hundreds of years, observed reprocessed emission in molecular clouds can be traced back to a

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13 While writing this section I referenced Sunyaev et al. 1998, Zhang et al. 2015, and private communication with Matthew Deady.
source that which may look dim now but was very bright in X-rays hundreds of years ago. The source luminosity required to produce a 6.4 keV emission line is:

\[
F_{6.4\text{keV}} = \phi \frac{\Omega}{4\pi D^2} Z_{Fe} \tau_T I(8) \tag{1.3.2}
\]

where \(\Omega\) is the solid angle of the cloud from the illuminated source, \(D\) is the distance to the observer, \(Z_{Fe}\) is the iron abundance relative to solar abundance, \(\tau_T\) is the optical depth due to Thomson scattering, and \(I(8)\) is the illuminating source flux at 8 keV. \(\phi\) is a factor of unity which depends on the spectrum and is analogous to photon index \(\Gamma\) (for \(\Gamma \sim 2, \phi = 1.18\)). Flux is given in units photons cm\(^{-2}\) s\(^{-1}\). Sunyaev et al. (1998) discuss and reject the following scenarios: the source is located at the center of the cloud, the case where several sources are distributed throughout the cloud, the source being hot plasma surrounding the cloud, and the case where Sgr A* is obscured from our point-of-view on Earth. They additionally conclude that the emission of the source should be on a shorter time scale than the light crossing time of the cloud for this reflection model. Since Sgr A* outbursts are on the order of years, reprocessed emission in molecular clouds should not be static and the flux will undergo a time evolution. In the case of Sgr B2, it was determined that emission from the cloud should decrease over \(\sim 10\) years.

Sunyaev et al. (1998) models the cloud illumination using the surface of a parabola to describe the wavefront of the a short outburst from a source (see Figure 1.3.1). The surface of the parabola is given by:

\[
\frac{z}{c} = \frac{(t^2 - (x/c)^2)}{2t} \tag{1.3.3}
\]

where \(t\) is the propagation time from the source and \(c\) is the speed of light. The \(x\) direction of this function is along the galactic plane and the \(z\) direction is along the line of sight. This function describes how the wavefront travels. In Figure 1.3.1, the molecular cloud interacting with the wavefront is shown as a yellow circle. The arrow shows the path of the scattered light from the source to the viewer. They show two parabolas to represent the beginning and end of the flare.
1.3. X-RAY EMISSION FROM GALACTIC CENTER MOLECULAR CLOUDS

Since the source flare is short, the observed surface brightness is due to the density of the cloud at the parabola’s surface. Ponti et al. (2010) uses a similar parabolic model to represent objects in the Galactic Center and how they interact with wavefronts of light in Figure 1.2.2. In general, this is a useful way to visualize how Sgr A* outbursts are thought to interact with molecular clouds over time.

If the source of the flux is located at a large distance from the cloud, the morphology of the surface brightness should be fairly uniform. The cloud should reflect based on its optical depth or density. Due to energetic processes like photo-absorption and Thomson scattering, the molecular cloud will reflect asymmetrically, meaning that the region of the cloud closest to the radiation will be brighter than farther sections.

It is also important to note that in reality, photons scatter multiple times within a molecular cloud. This is significant because one or more scatterings can change the energy of a photon. A small number of photons (~14%) will undergo elastic scattering and, therefore, will not have a change in energy. Some photons will excite Hydrogen atoms vibrationally and/or rotationally. However, the majority of photons will undergo Compton scattering with Hydrogen atoms, causing electron ionization and a decrease in photon energy. These various processes leads to the measurement of a wide range of photon energies. Multiple scatterings can also shift the absorption edge (or the 6.4 keV emission limit) to lower energies. An equivalent width\(^{14}\) of 1 keV for the 6.4 keV emission line indicates the presence of a scattering component.

1.3.2 Low-Energy Cosmic Ray Interaction Model

Another explanation for the 6.4 keV emission line energy and continuum emission observed in Galactic Center molecular clouds are interactions with Low Energy Cosmic Rays (LECRs) in the neutral gas clouds\(^{15}\). Cosmic rays are high energy particles from space that travel at velocities close to the speed of light. Cosmic rays are most commonly protons (aka Hydrogen nuclei) but

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\(^{14}\)It is useful to convert the area under a spectral line profile (\(A\)) into a rectangle of the same area whose width is equivalent width \(b\). Therefore, \(A = I \times b\), where \(I\) is the continuum intensity level. [25] Equivalent width can be calculated in Xspec using the command “eqwidth.”

\(^{15}\)When writing this section, I referenced NASA’s Imagine the Universe website [16], the Hyperphysics webpage [21], Tatischeff et al. 2012, a text file by V. Tatischeff, and private communication with Matthew Deady.
other elementary particles like electrons, neutrons, and neutrinos have also been detected. The energy range of these particles is on the order of GeV ($10^9$ eV) to TeV ($10^{12}$ eV). The presence of non-thermal radio filaments in the Galactic Center can be interpreted as evidence that there is a large population of cosmic rays in the the region.

The cosmic ray interaction model assumes LECRs are produced in some acceleration region outside a molecular cloud and then penetrate the neutral cloud at a constant rate. The cosmic ray particles need some minimum energy ($E_{\text{min}}$) to escape the acceleration region and enter the cloud. Once LECRs enter a molecular cloud, they can produce non-thermal X-rays through atomic collisions (the source of the 6.4 keV line emission) and Bremsstrahlung (the main contributor of the power-law continuum). Particles traveling in the gas cloud may slow down, due to ionization and radiative energy losses in the cloud. Eventually, the particles will either stop or eventually even escape the cloud. The model also assumes that after some time, the LECR particles escape the cloud after an energy-independent path length ($\Lambda$). Although the path length can be estimated from the cloud size, Tatischeff et al. (2012) assume a slab model and energy-
independent path length $\Lambda$ in order to decrease the number of free parameters in their model. Additionally, since the process of cosmic ray penetration is not well known, they assume that any LECR with a kinetic energy greater than threshold energy $E_{\text{min}}$ is able to freely penetrate the cloud.

The rate of primary\textsuperscript{16} cosmic rays entering the clouds is assumed to be a power-law in kinetic energy above $E_{\text{min}}$. This is represented by the equation:

$$\frac{dQ_i}{dt}(E) = C_i \times E^{-s} \quad (1.3.4)$$

for $E > E_{\text{min}}$. Additionally, $dQ_i$ is the differential rate of LECRs entering the cloud, $s$ is the photon index, and $C_i$ is the spectrum normalization constant. This normalization constant can be used to estimate the power injected into the molecular cloud by primary cosmic rays (see Equation 2.2.3).

Cosmic ray protons in particular have been theorized to contribute to the background Galactic Center X-ray emission. This is a much more likely scenario than LECR\textsubscript{p} being responsible for the huge flux variations of molecular clouds. X-ray emission by LECRs requires a very long time scale and also requires very high energies.

1.4 NuSTAR Telescope

The Nuclear Spectroscopic Telescope Array, known as NuSTAR, was launched on June 13, 2012\textsuperscript{17}. NuSTAR is the first focusing high-energy telescope, operating in the soft to hard X-ray band of 3 to 79 keV (a schematic of the telescope is presented in Figure 1.4.1). The observatory was launched with a mass of 350 kg and power of 600 W. NuSTAR is in Low Earth Orbit, at around 600 km above Earth’s surface, with an expected orbit lifetime of 10 years. The telescope’s spectral resolution is 400 eV at 10 keV and 900 eV at 68 keV.

\textsuperscript{16} Primary cosmic rays are the particles emitted from the source. Secondary cosmic rays are high energy particles produced by reflection or another emission process within the cloud.

\textsuperscript{17} When writing this section, I referenced Harrison et al. 2013 and Pavón-Carrasco et al. 2016.
The telescope’s low orbit inclination of 6° was chosen to minimize NuSTAR’s passage through the Southern Atlantic Anomaly (SAA). The SAA is an anomaly in Earth’s magnetic field which experiences high radiation. Due to the weakness in the magnetic field, a large number of high energy particles enter Earth’s atmosphere in this area. This high density of cosmic rays is dangerous to satellites and can also disrupt communications on Earth’s surface.

The NuSTAR observatory consists of two co-aligned identical hard X-ray telescopes which are pointed at targets by a three-axis-stabilized spacecraft. These two instruments are referred to as Focal Plane Module A (FPMA) and Focal Plane Module B (FPMB) or simply, Modules A and B. The spacecraft uses sensor readings to determine how to maintain the desired altitude and orientation in space, then uses thrusters to reach the desired position. The observatory is powered by a solar array which is kept optimally pointed at the sun. The optics and detectors are separated by a unique deployable mast. NuSTAR is designed for long observations (from one day to about a week).

NuSTAR’s optics are two Wolter I conical approximation X-ray optics, which focus onto two independent solid state plane detectors. The telescope’s long focal length of 10.14 m is enabled by the deployable mast. The two sets of optics and detectors are designed to be as identical as possible, so that focal plane images can be added to increase telescope sensitivity (in other words, increase the amount of photons that can be gathered). The combination of the low graze optics and the multilayer coatings on the optical shells enable collection of photons up to ~79 keV. NuSTAR’s optics have smaller graze angles as compared to soft X-ray telescopes. The two detectors or focal plane modules consist of a $2 \times 2$ array of detectors, each with $32 \times 32$ 0.6 mm pixels, which together provide a $12'$ field of view.

The observatory communicates with ground stations in Malindi, Kenya and Na‘ālehu, Hawai‘i, USA. Data is then sent to NASA’s Johnson Space Center and the mission control center at UC Berkeley. Data files are input into a database and processed at CalTech. After the data is made accessible to the public, all NuSTAR data files can be accessed and downloaded on the NASA HEASARC archival website, HEASARC Browse.
1.4. NUSTAR TELESCOPE

Figure 1.4.1: Image of the NuSTAR observatory from https://heasarc.gsfc.nasa.gov/. This image shows a schematic of the full observatory at the top and a closer look at the detector set-up at the bottom. NuSTAR was launched in 2012 and orbits about 600 km above Earth’s surface.

1.4.1 NuSTARDAS

The NuSTAR Data Analysis Software or NuSTARDAS is a set of programs developed to process and analyze data from the NuSTAR telescope\(^{18}\). NuSTARDAS includes FITS (‘Flexible Image Transport System’) file utility programs and data analysis tools specific to NuSTAR. The software is written in NASA’s FTOOLS. NuSTARDAS is designed to process FITS data to create calibrated event files, sky images, energy spectra, light-curves, and exposure maps. More details on how I use this software can be found in Section 2.2.

1.4.2 Telescope Contamination

NuSTAR imaging of the Galactic Center is very difficult, due to the high amount of background emission in the region\(^{19}\). After all, we are observing the very center of an entire galaxy. Some of the background emission is produced by cosmic rays in this region. However, most of the

\(^{18}\)References include Harrison et al. 2013 and the NASA HEASARC website.

\(^{19}\)When writing this section, I referenced the Appendix of Mori et al. 2015.
background is caused by non-ideal photon interactions with NuSTAR’s optics. Focused diffuse background is caused by photons in the field of view that are reflected twice by the telescope optics before being focused on the detector. Ghost-rays are photons from outside the field of view that are then reflected only once by the optics and captured by the detector. Lastly, stray light contamination is due to photons that do not go through the optics and directly hit the detector plane. Stray light contamination has a distinct curved pattern and an example of this contamination can be seen in the top image of Figure 3.0.1.
Observation and Data Analysis of the “Bridge” Molecular Cloud

2.1 NuSTAR Observations of the Bridge

The “Bridge” molecular cloud has been observed by the NuSTAR observatory five times since the telescope began operating in 2012. First, I analyzed the newest observation from 2020. Then I analyzed the three 2012 observations and lastly, the 2016 observation. Since the analysis was out of order, I will not discuss the observations sequentially by year. Rather, throughout this work I will talk about the observations in the order I worked on them: 2020, 2012, and lastly, 2016.

2.1.1 2020 Observation

This project began with the most recent observation of the “Bridge” molecular cloud by the NuSTAR telescope in 2020 (ObsID: 40501005002). The original purpose of this observation was to analyze the non-thermal X-ray filament G0.11-0.13. However, my research group noticed that the “Bridge” molecular cloud, which neighbors the filament, seemed to be brightening up and thus, the observation of the cloud was worth further explanation. Therefore, I decided to focus my analysis on the “Bridge” cloud. This newest observation took place between February 14-17, 2020 with a total exposure time of ~ 99 ks (see Table 2.1.1 for more details). The 50" source
region I selected for the “Bridge” molecular cloud is centered at RA = 266.54848°, Decl. = -28.88666° (fk5) for Module A and for Module B, RA = 266.55353°, Decl. -28.88988° (fk5).

2.1.2 2012 Observations

To test the hypothesis that the “Bridge” molecular cloud is brightening up, I then analyzed three archival observations from 2012. These three observations (Obs ID: 40010004001, 40010005001, and 40010006001) were part of a mini-survey of the Galactic Center and took place between October 15th and 16th in 2012. All three observations have exposure times of ∼ 25 ks (see Table 2.1.1). For several reasons, I was not able to use data from both Module A and B for all of the observations. One data set (Obs ID: 40010004001) had significant stray light contamination (see Section 1.4.2) on the FPMB image in the area containing the source region. For the second observation’s FPMB image (Obs ID: 40010005001), the source region was on the edge of the detector’s panel. Initially, I fit the Module B data jointly with Module A and noticed that the absorbed flux values for Module B were much lower than the results from the other two observations and Module A. Therefore, I concluded that the source region did not fully fit on the detector panel and decided to exclude the second observation’s Module B data from my analysis (Obs ID: 40010005001). In total, I used three FPMA observations and one FPMB observation to analyze the spectrum of the “Bridge” cloud in 2012.

2.1.3 2016 Observation

The “Bridge” molecular cloud was additionally observed by NuSTAR in 2016. The observation took place between October 28 and 31, with an exposure time of ∼150 ks. This observation is the longest of the “Bridge” NuSTAR observations and provided excellent statistics for data analysis. Initially, when I loaded in the event file for Module B of this observation, the source region I defined for the Bridge was shifted off the bright areas of the cloud. The observation coordinates were most likely shifted somehow while processing the uncleaned event files with ‘nupipeline’ (defined in Section 2.2.1). In order to correct for this shift, I used the nearby filament G0.11-0.13 as a reference point. First, I loaded the source region centered on the filament coordinates
Table 2.1.1. NuSTAR Observations of Galactic Center Molecular Cloud “The Bridge”

<table>
<thead>
<tr>
<th>Observation ID</th>
<th>Observation Date</th>
<th>Exposure Time (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40010004001</td>
<td>10/15/2012</td>
<td>24.032</td>
</tr>
<tr>
<td>40010005001</td>
<td>10/15-16/2012</td>
<td>25.992</td>
</tr>
<tr>
<td>40010006001</td>
<td>10/16/2012</td>
<td>23.563</td>
</tr>
<tr>
<td>40202001002</td>
<td>10/28-31/2016</td>
<td>150.856</td>
</tr>
<tr>
<td>40501005002</td>
<td>2/14-17/2020</td>
<td>99.046</td>
</tr>
</tbody>
</table>

Note. — Information regarding all 5 observations of the “Bridge” molecular cloud by the NuSTAR telescope, including Observation ID, date(s) of observation, and exposure time. The first three observations in 2012 were part of a survey of the GC. The next observation of this gas cloud took place in 2016 and is the longest of the observations. Most recently, the “Bridge” cloud was observed by NuSTAR in 2020. The aim of the observation was to study a nearby filament, however, unexpected brightness of the cloud prompted further study.

2.2 Data Analysis Procedure

In X-ray astronomy, the primary data is a table of “events” of individual photons hitting the detector panels. X-ray instruments measure three things: spatial point the photon hit on the detector, time of arrival, and photon energy. Scientific data products such as spectra and images are produced from this very simple array (Arnaud et al. 2011). There are three levels of data
2. OBSERVATION AND DATA ANALYSIS OF THE “BRIDGE” MOLECULAR CLOUD

Figure 2.2.1: Flow chart explaining the data analysis process. First, “level one” or unfiltered event files are cleaned with ‘nupipeline’. Then the cleaned event files (“level two”) are viewed in DS9. Source and background extraction regions are selected, which are then used to run ‘nuproducts’ to create data files used in spectral analysis.

files in X-ray spectral analysis: “level one,” which refers to the unfiltered event files, “level two,” cleaned event files, and “level three,” data products such as spectra and light curves.

2.2.1 ‘nupipeline’ and DS9

First, unfiltered raw data from NuSTAR in the form of ASC II event files are reduced by the standard NuSTAR data reduction tool NuSTARDAS, which is part of the HEASOFT v.6.19 software package. The ‘nupipeline’ script produces cleaned event files for the data from both modules, i.e. going from “level one” data to “level two.” Cleaned event files are then loaded into DS9, an imaging program that presents event files as images. DS9 is also used to add false-coloring, contour lines, compasses, grids, and other helpful modifications to make the images look professional (for example, I added a compass and 100” ruler to each image).

Once an event file is loaded into DS9, the first task is to make the adjust the image and make it more recognizable by selecting a false color scale and adjusting scale parameters. The color scale
I use is option b, which represents dark areas as black and blue, areas of moderate brightness as red and orange, and the brightest regions as yellow and white. The color scale along the bottom of these images also assigns values to certain colors. Once the scale parameters are adjusted, the four detector panels of NuSTAR are more clearly presented. When first studying the image, note the area(s) of interest and any significant “stray light” contamination. Then the image is smoothed using a Gaussian smoothing kernel. The smoothing radius and sigma, along with the scale parameters, are adjusted as needed to produce a clear image.

With the area of interest now clearly visible, the next task is to select source and background regions. The 50" source region I used throughout the analysis of the “Bridge” molecular cloud was selected from the 2020 data (seen clearly in Figure 3.0.2). I centered the circular source region such that it contained the brightest areas of the molecular cloud. This process was repeated for both FPMA and FPMB. Source region files are saved for each module. After source regions are selected and saved, background extraction regions are selected. Background regions are large rectangular regions that are at least $\sim 70"$ away from the source region, while remaining on the same detector panel. The regions are selected to be as large as possible while avoiding significantly bright areas (see Figure 3.0.1 for examples of background regions). The background areas are also saved as region files to be used in nuproducts for spectral analysis. Unique background areas are selected for each observation because the “pointing” or orientation of the telescope is different each time.

2.2.2 ‘nuproducts’ and Spectral Analysis

With cleaned event files and the source and background region files, I then proceed to the third stage of X-ray analysis: producing spectra and light curves. In order to run the ‘nuproducts’ tool and produce spectral files, a python script is used to define the arguments and commands required for ‘nuproducts’. In this script, paths to the data are indicated, as well as corresponding source and background region files. The python script is also used to indicate that the “Bridge” cloud is an extended source, as opposed to a point source, and other ‘nuproducts’ settings such as “psfflag” and “grflag” are adjusted accordingly. After double-checking the energy range
‘nuproducts’ draws data from (channel 35 to 1935, corresponding to 3 to 79 keV), I run the script which prints out the full command for ‘nuproducts’, which then produces spectral files used in the program Xspec to perform spectral analysis.

However, before the spectra are loaded into Xspec it must be binned using GRPPHA, a task within the HEASARC FTOOLS package. GRPPHA defines channel grouping associated with the channels in a spectral file. The task can also sets data to a ‘good’ or ‘bad’ quality, which is useful when performing spectral analysis. According to NASA’s HEASARC webpage, GRPPHA does not change the data set, it simply groups the data into a series of energy channels for software used down the line, like Xspec. Spectra extracted for the “Bridge” region are grouped with bins of a minimum of 30 counts/bins. GRPPHA excludes any ‘bad’ channels when grouping.

Next, a binned spectrum can be loaded into Xspec. When using data from both Module A and B they are loaded in together for a joint spectral fit. The next step is to designate the corresponding background, rmf, and arf files for the observations, if the files are not automatically recognized and loaded in by Xspec. Then a plotting window is opened using XQuartz/X11, in order to view a plot of the spectrum. The spectrum is plotted logarithmically, with X-ray flux (counts/s/keV) on the Y-axis and photon energy (keV) on the X-axis. Next, ‘bad’ data points, as well as points outside of the NuSTAR 3 to 79 keV energy range are ignored. This step usually cleans up the spectrum significantly.

Once the basics are set up, I perform model fitting. The photoionization cross-sections, or how well Hydrogen can absorb photons in the photoelectric process, are set to the parameters determined by Vernieret et al. (1996). The solar abundance table is set to the values from Wilms, Allen & McCray (2000). Solar abundance is used in plasma emission and photoelectric absorption models, according to HEASARC’s online guide. “Vern” and “wilm” are the standard settings for X-ray spectral analysis. Then, I invoke a model, first the ad hoc model and then physical models MYTorus, LECRe, and LECRp, which are discussed in the following sections.
2.2. DATA ANALYSIS PROCEDURE

Ad hoc models are purely phenomenological\(^1\) and do not “notice” the physics of the molecular cloud. The purpose of an ad hoc model is instead to use components from Xspec, like the power law and gaussians, to best fit to the data. Physical models, on the other hand, are self constrained, meaning that the model itself can explain the overall measured spectrum (Zhang, Private communication). Moreover, physical models speak to the actual physics that produces X-rays we observe with instruments like NuSTAR.

After fitting the model, flux is calculated. There are two different kinds of flux, absorbed (or observed) and unabsorbed. The first method uses the “flux” command, which calculates the absorbed flux of the current model in a specific energy band. Flux is given in units of ergs/cm\(^2\)/s and is calculated for the energy ranges 2 to 10 keV (the “traditional” X-ray band), 3 to 79 keV (NuSTAR’s full energy range), and 10 to 79 keV (NuSTAR specific range). The second technique is to use “cflux,” a convolution model that is multiplied by model components to calculate the unabsorbed flux specific to each component. This allows measurement of the true value of the flux at the cloud, whereas the “flux” command gives the flux at the telescope detector after absorption from the interstellar medium\(^2\).

2.2.3 Ad Hoc Model

- Ad hoc model: \texttt{const*tbabs*(powerlaw + gaussian + gaussian)}
- Absorption \(N_H\) left free or frozen to \(17.5927 \times 10^{22}\) cm\(^{-2}\)
- Photon index \(\Gamma\) helps to constrain photon energy distribution
- Freeze second gaussian to 7.1 keV (with line width \(\sigma = 0.01\) keV)
- After fitting, calculate error and flux

The ad hoc model I used is \texttt{tbabs*(powerlaw + gaussian + gaussian)}. The first component of this model is the absorption component, “tbabs” or the Tuebingen-Boulder ISM

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\(^1\)Dictionary.com defines phenomenological as “of relating to, or based on observed or observable facts.”

\(^2\)The interstellar medium (or ISM) is defined as “everything that is in between the stars,” including interstellar gas and dust. [2]
absorption model. This component calculates the cross section of X-rays as they travel through the ISM or, in other words, how many photons are lost from the source while traveling through space to the telescope. There are several absorbing mechanisms that this model takes into account: absorption due to the gas-phases of the ISM, interstellar grains\(^3\), and Hydrogen molecules present in the ISM. According to HSEARC’s online manual, “the effect of shielding by the grains is accounted for, but it is extremely small.” Additionally, the gas-phase cross section considers the photoionization cross section of different elements (weighted by abundance) and takes into account “depletion onto grains.” The output parameter for “tbabs” is \(N_H\), the equivalent hydrogen column density\(^4\) in units \(10^{22}\) atoms/cm\(^2\). In this ad hoc model, the \(N_H\) measured is the combined foreground and intrinsic cloud flux.

The second component of this model is a power law component, a basic power law model:

\[
A(E) = KE^{-\Gamma},
\]

where \(\Gamma\) is the photon index of the power law, a dimensionless quality, and \(K\) is the normalization or strength constant with units photons/keV/cm\(^2\). Since the spectra produced are log-plots (i.e. both the y and x axes represent the logarithm of the flux and energy), one would expect this component to produce a straight line function. However, multiplying by the absorption component creates the curved shape of the spectral fit. Photon index \(\Gamma\) is one of the main parameters of this model and represents how evenly spread the emission is over the entire 3 to 79 keV energy range.

The Gaussian components of this model represent the Fe K\(\alpha\) and K\(\beta\) emission lines at 6.4 keV and 7.1 keV respectively. As discussed in the Introduction (see Section 1.3), these emission lines are important signals of the X-ray reflection in GCMCs. The line width of these peaks is represented by parameter \(\sigma\). Since the resolution of NuSTAR is \(\sim 0.5\) keV, \(\sigma < 0.01\) keV are not realistic. If model fitting results in values below 0.01 keV, \(\sigma\) is frozen to 0.01 keV.

\(^{3}\)Interstellar grains are submicron solid particles (aka dust) dispersed throughout interstellar gas that may absorb and scatter light traveling through the ISM. [1]

\(^{4}\)Column density is a measure of the amount of intervening matter between the observer and the object, typically measured as the number of Hydrogen atoms per cm\(^2\) projected along the line of sight. [24]
When joint fitting data from Module A and B, a constant term is added to the model:
\[ \text{const}\cdot\text{Tbabs}\cdot(\text{powerlaw} + \text{gaussian} + \text{gaussian}) \]. This constant helps to constrain how similar the spectra are from each module. The constant is set to 1 for the Module A data and left free for B. When fitting the 2020 data, the neutral Hydrogen absorption \( N_H \) is left free. However, for the 2012 and 2016 spectra, \( N_H \) is frozen to the value of the 2020 result: \( N_H = 17.5927 \times 10^{22} \) cm\(^{-2}\). For all data sets, the second Gaussian emission line or the Fe K\( \beta \) emission line at 7.1 keV is also frozen, as well as its corresponding line width (frozen to 0.01 keV). However, for the 2012 and 2016 data sets the normalization of the 7.1 keV line is linked to the normalization for the first emission line, such that it is always 15\% of the normalization of the 6.4 keV gaussian line.

After model fitting, error and flux are calculated (both absorbed and unabsorbed flux). Multiplying “cflux” times “powerlaw” gives the power law continuum flux, which is calculated for the ranges 2 to 10 keV and 3 to 79 keV. The 6.4 keV line emission flux is calculated by multiplying “cflux” by the first Gaussian component for the energy range 6.0 to 6.8 keV.

### 2.2.4 X-Ray Reflection Model MYTorus

- Introduce physical model MYTorus: \[ \text{const}\cdot\text{wabs}\cdot(\text{apec}+\text{MYTorus}) \]
- Intrinsic absorption frozen to \( N_H(i) = 4 \times 10^{22} \) cm\(^{-2}\)
- “apec” model parameters: \( kT \) (free), \( z \), and metal abundance (\( z \) and abun. frozen)
- MYTorus model parameters: freeze inclination angle \( \theta \) and redshift \( z \); photon index \( \Gamma \) and absorption \( N_H \) are left free.
- Calculate error

MYTorus is a table model used in Xspec that was originally developed to study the X-ray spectra of Compton-thick (or high \( N_H \)) Active Galactic Nuclei (AGNs).

\(^5\) In writing this section I referenced Yaquoob & Murphy 2009, Zhang et al. 2015, and Mori et al. 2015.
distribution of matter centrally illuminated by X-rays. Galactic Center molecular clouds are not toroidal and are approximated as a spherical section of the torus. The cloud flux needs to be scaled with respect to the solid angle of the torus and so that only the flux of the cloud is calculated and not the flux of the entire torus. The model is insensitive to the toroidal geometry when $\theta < 60^\circ$ and $N_H < 10^{24} \text{ cm}^{-1}$.

The best-fit power-law index $\Gamma$ measured by MYTorus has a very low error and can be adopted as the value for the primary X-ray source, instead of results from an ad hoc model. Mori et al. found using simulations that the ad hoc model yields a significantly lower flux and column density $N_H$ 2 to 3 times lower than from the MYTorus model. Again, $\Gamma$ is an important parameter and constraining the value accurately is very useful, especially for comparisons with Sgr A$^*$. The MYTorus model assumes solar abundance. This is significant because non-solar abundance affects the Fe fluorescence lines at 6.4 keV and 7.1 keV. However, continuum emission above $\sim$10 keV due to Compton scattering is a much greater contribution than fluorescence or photo-absorption and decreases the effect of the Fe fluorescence. Despite this, new physical models with varying metallicity are anticipated to improve analysis of Galactic Center molecular clouds. MYTorus also assumes the central X-ray continuum source is emitting isotropically and interacting with cold neutral matter, not ionized gas.

The full model is: \texttt{const*wabs*(apec+MYTorus)}. The Xspec component “apec” represents diffuse X-ray emission of the Galactic Center, one component of the background signal (Zhang, private communication). The emission spectrum of “apec” is that of collisionally ionized diffuse gas calculated from an atomic database, according to HEASARC’s online manual. In this model, I used the absorption component “wabs” instead of “tbabs” in order to be consistent with previous results from GCMCs. Xspec model component “wabs” is an older photo-electric absorption model which uses cross-sections from Morrison & McCammon 1983 and is represented by the equation

$$M(E) = e^{-N_H \sigma(E)}, \quad (2.2.2)$$
2.2. DATA ANALYSIS PROCEDURE

where \( \sigma(E) \) is the photo-electric cross section and \( N_H \) is the measured equivalent Hydrogen column, given in units \( 10^{22} \) atoms/cm\(^2\). The best-fit parameters of “apec” are the plasma temperature \( kT \), metal abundance, redshift \( z \), and a normalization constant. The last component of this model is, of course, MYTorus. The MYTorus model actually has three components, transmitted continuum (MYTZ), scattered continuum (MYTS), and iron fluorescence lines (MYTL). The components I used are MYTS and MYTL, as for the case of a molecular cloud, the cloud itself is not creating and transmitting the X-rays. Instead, the cloud is reflecting light from a far away source. Therefore, the model used in Xspec looks more like:

\[
\text{const \* wabs \* (apec + MYTS + MYTL)}
\]

Each MYTorus component has five parameters: column density \( N_H \), inclination angle \( \theta \), photon index \( \Gamma \), redshift \( z \), and normalization \( N_{MYT} \). All parameters are linked between MYTS and MYTL, creating a “coupled” mode. The termination energy of the incident power law is selected to be 500 keV and the centroid of the Fe K\( \alpha \) line is at \( \sim 6.44 \) keV, with an energy offset of 40 eV. In Xspec, the model is input as a table model using the command “atable.”

The MYTorus manual by Yaquoob & Murphy notes that this model should not be fit blindly, meaning that initial parameters should not be chosen randomly before model fitting. Several components are frozen: \( N_H \) from “wabs” is frozen to \( 4 \times 10^{22} \) atoms/cm\(^2\) (the intrinsic column density of the “Bridge” as measured by Ponti et al. (2010)), “apec” abundance set to 1 (aka solar abundance), “apec” and MYTorus redshift, \( z \), both set to 0, and inclination angle \( \theta \) to 60°. While the MYTorus \( N_H \) component (which measures the intrinsic column density) is left free, I initially input \( 0.17 \times 10^{24} \text{ cm}^{-2} \), which is approximately the value measured by the ad hoc model. Lastly, “apec” temperature \( kT \) is initially set to 1 and photon index \( \Gamma \) to 2. After fitting the model, which takes a several minutes due to the complexity of physical models, error bars are calculated using the Xspec “error” command.

2.2.5 Cosmic Ray Interaction Models LECRe and LECRp

- Introduce physical model LECR: \( \text{const \* wabs \* (apec + wabs \* LECR)} \)
• Intrinsic absorption frozen to $N_H(i) = 4 \times 10^{22} \text{ cm}^{-2}$

• LECR model parameters: power law index $s$, minimum energy $E_{\text{min}}$, metallicity $Z/Z_\odot$, and path length $\Lambda$ (frozen, rest are left free)

• Normalization constant relates to power injected by cosmic rays

The LECRe (Low Energy Cosmic Ray electron) and LECRp (Low Energy Cosmic Ray proton) models are cosmic ray interaction models\(^6\). They are utilized as table models in Xspec using the “atable” command. As previously discussed, cosmic ray particles can produce non-thermal X-rays through atomic collisions within a neutral gas cloud. The LECR models have 4 free parameters: Power law index, $s$, the logarithm of minimum energy with units keV, the metallicity of the ambient medium $Z/Z_\odot$, and the logarithm of path length of cosmic rays $\Lambda$. The range of $s$ is between 1.5 to 5 for the LECRe model and 1 to 5 for LECRp. Log($E_{\text{min}}$) can range from 0.5 to 4, representing 3.2 keV to 10 MeV, for LECRe and 1.5 to 5 or 32 keV to 100 MeV for LECRp. Metallicity is represented in terms of solar abundance, ranging from 0.5 to 4 times solar abundance ($Z_\odot$) for both models. Lastly, $\Lambda$ can range from 0 to 5, representing a path length on the order of $10^{21}$ to $10^{26}$. The normalization for this component, $N_{\text{LECR}}$, has units ergs/cm$^2$/s. This normalization component represents the power injected into the gas cloud by cosmic ray electrons or protons between $E_{\text{min}}$ and $E_{\text{max}} = 1\text{GeV}$:

$$\frac{dW}{dt} = N_{\text{LECR}} \times 4\pi D^2,$$

where $D$ is the distance to the source in units cm.

In addition to the cosmic ray interactions, photoelectric absorption must also be taken into account when modeling in Xspec. A multiplicative absorption model like “wabs” or “tbabs” is the natural choice. Additionally, the component “apec” is added to account for scattering as discussed in the previous section. Therefore, the full model input into Xspec is $\text{const}\times\text{wabs}\times(\text{apec}+\text{wabs}\times\text{LECR})$.

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\(^6\)When writing this section, I referenced Zhang et al. 2015, Tatischeff et al. 2012, and a text file written by V. Tatischeff.
When fitting the LECRe model, the foreground absorption is set to the value measured for the Bridge by Ponti et al. (2012): $N_H(i) = 4 \times 10^{22}$. For the ‘apec’ components, redshift, $z$, is frozen to 0 and the metal abundance is set to 1. The parameter $kT$ and the normalization are left free. All LECRe components are left free except path length $\Lambda$, which is frozen to 4, corresponding to $\Lambda \sim 10^{24}$ atoms cm$^{-2}$. In some cases, a better fit was obtained by freezing $E_{\text{min}}$ to either the minimum value of 3.2 keV or some other value (see Table 4.3.1 for results). The fitting process for LECRp was very similar, the only difference being that $E_{\text{min}}$ is frozen to 32 keV for all observations. After model fitting both LECRe and LECRp, error bars are calculated using the “error” command.
30.2. OBSERVATION AND DATA ANALYSIS OF THE “BRIDGE” MOLECULAR CLOUD
In this chapter, I present NuSTAR 3 to 79 keV mosaic images of the “Bridge” molecular cloud for all observations of the cloud with NuSTAR. These observations took place in 2012, 2016, and 2020. The images are presented using the program DS9, as discussed in Chapter 2.2.1. I also discuss the morphology or shape of the “Bridge” cloud as seen in these images. Lastly, I will compare the morphology of the “Bridge” in two significant energy bands, 6 to 7 keV and 10 to 20 keV, for the 2020 and 2016 observations, as well as for one of the 2012 observations. Images in different energy bands help us understand how the flux of the “Bridge” cloud changes over time.

3.1 X-Ray Morphology of the Bridge

3.1.1 X-Ray Images of 2020 Observation

Figures 3.0.1 and 3.0.2 show the 3 to 79 keV images of the molecular cloud nicknamed the “Bridge.” In both figures, the Galactic Center is towards the south-west, along the galactic plane. Using the line tool in DS9, I measured that the center of the molecular cloud is ~ 125” away from non-thermal X-ray filament G0.13-0.11.

The term “morphology” refers to the structural properties of a celestial object[24]
3. IMAGES AND MORPHOLOGY OF THE “BRIDGE” MOLECULAR CLOUD

Figure 3.0.1, the zoomed out images of NuSTAR’s entire field of view, show that the data from FPMA suffers from more stray-light contamination than FPMB. The bright curved area at the top left of the FPMA image is the distinct signature of stray-light contamination (for further discussion see Section 1.4.2). In the less contaminated image from FPMB, we can also see that the “Bridge” molecular cloud stretches out a little bit into the top right panel. Despite the contamination I describe, both data sets are usable since the contamination is in another detector panel and does not interfere with the area of interest.

Figure 3.0.2 is a zoomed in view that only focuses on the bottom right panel, where we see the “Bridge” cloud and molecular cloud G0.11-0.11, which contains the filament G0.13-0.11. The top image of Figure 3.0.2 shows the image produced by FPMA. In this image, the brightest white and yellow region of the molecular cloud fits within a 50\textquoteleft radius. Outside of the circle, the intensity quickly drops to dark orange and red. The brightest white areas are not concentrated in the center, instead arching from the center to the south-east segment of the source region. The shape of the bright region is slightly oblong, instead of being perfectly round. In the FPMA image, several bright spots are visible in between the two molecular clouds.

The image produced by FPMB (the bottom image of Figure 3.0.2) is slightly different. The first thing to notice is that this image is less bright, and slightly more blurry in this zoomed in perspective, although I used the same Gaussian smoothing radius of 2 for both of these images. I also used identical scale parameters, 0 to 13. The bright region of the cloud fits neatly into the 50\textquoteleft source region and is more round, as opposed to the oblong shape shown in FPMA. In fact, there are less white spots (the highest intensity of the color scale) in this image, both within the source region but also in the neighboring molecular cloud G0.11-0.11 and in the area in between them. However, this image also reveals bright spots that the FPMA images does not in the region above the source region. On the other side of the panel gap, there is a bright clump with dots of bright yellow and white. Not only does FPMB reveal the bright intensity areas, the density is higher and the overall size of this region is larger than in the FPMA image. Perhaps this is due to lower levels of stray light contamination in the FPMB image. Another feature to
notice in this image is that there is more red areas scattered below the molecular clouds. This means that there was more emission in the background region extracted for the FPMB data set than for FPMA (see Figure 3.0.1 to reference the selected background regions).

I also used the “dmcopy” command in CIAO, the Chandra X-ray telescope’s analysis tools, to extract FPMA images from four different energy bands: 3 to 10 keV, 10 to 20 keV, 20 to 40 keV, and 40 to 79 keV. From these images, (displayed in Figure 3.0.3), it is obvious that the majority of the photons captured during this observation were soft X-rays in the lowest energy band of 3 to 10 keV. This image is not significantly different from Figure 3.0.2. In the next band of 10 to 20 keV (also called the “continuum emission”), there are still a good amount of photons detected. The brightest regions of the cloud in this image are more towards the southeast area of the source region than grouped in the northwest. For the 20 to 40 keV images, the cloud is much dimmer with only one bright point near the center of the cloud. This could represent the “core” of the cloud. Lastly, the 40 to 79 keV image shows barely any photons. Splitting up the 2020 observation into images of distinct energy bands demonstrates that most of the photons emitted by the “Bridge” molecular cloud have lower energies, tapering off into the hard X-ray band. This corresponds to the negative slope of the power law model component used in spectral analysis.

3.1.2 X-Ray Images of 2012 Observations

The three observations from 2012 (see Figure 3.0.4) are visually distinct from the 2020 observation (compare with Figure 3.0.2) of the “Bridge” molecular cloud. While the 2020 images show a large, bright area reaching beyond the 50” radius source region, the images from 2012 generally show a few bright spots neatly contained into that same circular region. The dimness is due to the short exposure time of ~ 25 ks for these observations, as the images are not corrected for exposure time.

In the first image from 2012 (Obs Id: 40010004001), the bright spots are on the south and south west edges of the source extraction circle, with a few bright clumps right outside the edge
of the region. The bright areas within the source region are from the southern to eastern edges. The image from the second observation (Obs Id: 40010005001) looks very similar.

Finally, the last set of 2012 images are slightly more interesting (Obs Id: 40010006001), perhaps due to scale parameter or smoothing adjustments made in DS9. In the FPMA image, there are several bright areas clustered near the south eastern edge of the source region. The points on the very edge of the circle are particularly bright. The bright areas are slightly more central in the FPMB image, filling more of the circular source region.

3.1.3 X-Ray Images of 2016 Observation

The 2016 NuSTAR observation of the “Bridge” molecular cloud took place in October of 2016 and has a long exposure time of $\sim 150$ ks (Obs Id: 40202001002). These images (as seen in Figures 3.0.5 and 3.0.6) are not exposure-corrected and thus, seem brighter than the images from 2020. However, this visual difference is due to exposure time (see Table 2.1.1). As detailed in Section 2.1.3, I shifted the source region for the FPMB data. However, the source region is still not centered exactly on the brightest regions of the cloud (see bottom panel of Figure 3.0.6). The FPMA image shows the brightest regions of the “Bridge” molecular cloud contained within the source region, with the most photons coming from the very center of the cloud (represented by the bright white spots). Similarly to the FPMA image from 2020, the brightness of the cloud branches off from the center towards the northwest. However, there is an additional branch mostly outside of the source extraction region pointing towards the southwest. This “v” shape is also seen in the FPMB image. Despite this, the brightest (white) regions are also located centrally in the FPMB image. The nearby CV CXOUUGC J174622.7-285218 is visible in the FPMA image. It is the bright spot located on the northeastern edge of the detector panel across from the “Bridge” cloud. Galactic Center super massive black hole Sgr A* can be seen in the bottom right corner of the detection panel, south-west from the “Bridge” molecular cloud.
3.2 Comparing X-Ray Images for Significant Energy Bands

In order to take a closer look at significant energy ranges, I split the event files using the command “dmcopy” in CIAO, isolating count events from only within the specified energies. The ranges are 6 to 7 keV, which features the 6.4 keV Fe Kα emission line, and 10 to 20 keV, the X-ray continuum. These “split” images are featured in Figure 3.2.1. It is important to remember that these images are not exposure-corrected and the apparent brightness relies heavily on the exposure time length. While the lower end of the color scale was set to minimize the visibility of the background emission, the upper limit of color intensity was set using the values that showed the 2020 observation clearly. Note that I used data from FPMA for all of these images.

At first glance, the 6 to 7 keV images and the 10 to 20 keV images look very similar. The 2012 6 to 7 keV image is very dark and shows a few random blue spots within the source region. This corresponds to the lower line emission flux observed in 2012, as compared to 2020. Comparing the 2016 and 2020 6 to 7 keV images shows that there is emission coming from the central, south, and northwest segments of the source region circle. However, the 10 to 20 keV images seem to indicate that more X-ray continuum emission is present in the northern side of the cloud source region than in 2020. Once again, the 10 to 20 keV image for 2012 shows very few photon counts, represented by a couple blue splotches contained in the source region.
Figure 3.0.1: 2020 NuSTAR 3-79 keV mosaic image of the “Bridge” Galactic Center molecular cloud. (FPMA, top and FPMB, bottom). This zoomed out image shows the source and background regions I selected for spectral analysis from both modules in the program DS9, as well as the stray light contamination also captured by the telescope (see in the top left of FPMA image). Images from NuSTAR are count maps, with units of photons/pixels.
3.2. COMPARING X-RAY IMAGES FOR SIGNIFICANT ENERGY BANDS

Figure 3.0.2: 2020 NuSTAR 3-79 keV mosaic image of the “Bridge” GCMC. The image from FPMA is above and FPMB, below. The circled region is the extracted source region of the molecular cloud. The molecular cloud G0.11-0.11 and bright CV CXOUUGC J174622.7-285218 are seen to the left of the “Bridge” cloud.
Figure 3.0.3: This collection of images shows the 2020 NuSTAR observation of the “Bridge” molecular cloud extracted for different energy bands. 3 to 10 keV is shown in the top left, 10 to 20 keV in the top right, 20 to 40 keV is shown in the bottom left, and 40 to 79 keV in the bottom right. From these images, we learn that the X-ray photons coming from the “Bridge” cloud are mostly in the soft X-ray band (below 5-10 keV), with photon intensity tapering off moving into the hard X-ray band (greater than 10 keV).
3.2. COMPARING X-RAY IMAGES FOR SIGNIFICANT ENERGY BANDS

Figure 3.0.4: NuSTAR 3 to 79 keV images of the “Bridge” molecular cloud from 2012. The image in the top left is from FPMA of the first observation (Obs ID: 40010004001). The top right image is the FPMA image from the second observation (Obs ID: 40010005001). The bottom images are from the final 2012 observation (Obs ID: 40010006001), with the image from FPMA on the left and FPMB on the right. The circular regions are the source region used for the “Bridge” cloud and the rectangular regions are the background extraction regions.
Figure 3.0.5: NuSTAR 3 to 79 keV mosaic image of the “Bridge” molecular cloud from 2016 (Obs Id: 40202001002). The image from FPMA is shown on the top and FPMB, on the bottom. Significant stray light background is seen in the FPMB image. The green circles are the source extraction regions and the green rectangles are the selected background extraction regions.
Figure 3.0.6: Close up NuSTAR 3 to 79 keV mosaic image of the “Bridge” molecular cloud from 2016 (Obs Id: 40202001002). This images clearly show that the bright regions of the Bridge branch out from the center to the north and south west, in a “v” shape. The nearby CV CXOUUGC J174622.7-285218 can be see at the northeastern edge of the FPMA image. It is the bright spot directly across from the “Bridge”.

Figure 3.0.6: Close up NuSTAR 3 to 79 keV mosaic image of the “Bridge” molecular cloud from 2016 (Obs Id: 40202001002). This images clearly show that the bright regions of the Bridge branch out from the center to the north and south west, in a “v” shape. The nearby CV CXOUUGC J174622.7-285218 can be see at the northeastern edge of the FPMA image. It is the bright spot directly across from the “Bridge”.

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Figure 3.0.6: Close up NuSTAR 3 to 79 keV mosaic image of the “Bridge” molecular cloud from 2016 (Obs Id: 40202001002). This images clearly show that the bright regions of the Bridge branch out from the center to the north and south west, in a “v” shape. The nearby CV CXOUUGC J174622.7-285218 can be see at the northeastern edge of the FPMA image. It is the bright spot directly across from the “Bridge”.
3. IMAGES AND MORPHOLOGY OF THE “BRIDGE” MOLECULAR CLOUD

Figure 3.2.1: The left column features 6 to 7 keV FPMA images of the “Bridge” molecular cloud, while the right displays 10 to 20 keV FPMA images. The top row features the longest observation from 2012 (Obs Id: 40010005001), the middle is the 2016 observation (Obs Id: 40202001002), and the bottom row displays images from 2020 (Obs Id: 40501005002). These images are not corrected for exposure time so it is hard to make any conclusions about the time variation of the flux. However, it is clear that the “Bridge” cloud is emitting at a similar intensity in both energy bands.
4
Spectra and Analysis Results

4.1 Ad hoc Model

The ad hoc model detailed in Chapter 2.2.3, was applied to all five observations of the “Bridge” molecular cloud by NuSTAR between 2012 and 2020. Important results are summarized in Tables 4.1.1 and 4.1.2. Spectra of the “Bridge” cloud fit with the ad hoc model are presented in Figures 4.1.1, 4.1.2, 4.1.3, and 4.1.5.

4.1.1 Spectral Analysis Results of 2020 Observation

Applying the ad hoc model confirmed the hypothesis that the “Bridge” molecular cloud was unexpectedly bright as observed in February 2020 (Obs ID: 40501005002). The model fits to the data well, with a reduced \( \chi^2 \) of 1.1 for 459 degrees of freedom. The spectra from FPMA and FPMB were fit jointly for this observation. The constant parameter for FPMB, which was left free, is found to be 0.96. The combined foreground and intrinsic column density is \( N_H = 17.6 (-3.2, +3.5) \times 10^{22} \text{ cm}^{-2} \) and the best-fit photon index is \( \Gamma = 1.8 (\pm 0.1) \). This spectrum features a neutral iron emission line at 6.31 (±0.02) keV (Fe K\( \alpha \)) with a line width of \( \sigma = 0.09 (-0.05, +0.04) \) keV. The second neutral iron emission line is frozen at 7.10 keV (Fe K\( \beta \)) with line width \( \sigma = 0.01 \). Error bars are at 90% confidence for all of these values.
The absorbed flux of this molecular cloud is $F_{2-10} = 1.8 \times 10^{-12}\text{ ergs/cm}^2/\text{s}$ for Module A and $F_{2-10} = 1.7 \times 10^{-12}\text{ ergs/cm}^2/\text{s}$ for Module B in 2 to 10 keV. In the energy range of 10 to 79 keV, the absorbed flux is $F_{10-79} = 5.2 \times 10^{-12}\text{ ergs/cm}^2/\text{s}$ for Module A and $F_{10-79} = 5.0 \times 10^{-12}\text{ ergs/cm}^2/\text{s}$ for Module B. Lastly, the absorbed flux in the entire NuSTAR range of 3 to 79 keV is $F_{3-79} = 6.9 \times 10^{-12}\text{ ergs/cm}^2/\text{s}$ for Module A and $F_{3-79} = 6.7 \times 10^{-12}\text{ ergs/cm}^2/\text{s}$ for Module B. The unabsorbed power law continuum flux is $F_{2-10} = 2.8 (\pm 0.1) \times 10^{-12}\text{ ergs/cm}^2/\text{s}$ in the 2 to 10 keV range and $F_{3-79} = 7.5 (\pm 0.2) \times 10^{-12}\text{ ergs/cm}^2/\text{s}$ in 3 to 79 keV. Additionally, the 6.4 keV line emission flux is $F_{6.4\text{keV}} = 3.4 (\pm 0.2) \times 10^{-13}\text{ ergs/cm}^2/\text{s}$. With these flux values in hand, I was able to compare this newest 2020 observation with past observations to understand the flux trend of the Bridge molecular cloud.

The unabsorbed line emission flux value of $F_{6.4\text{keV}} = 3.4 (\pm 0.2) \times 10^{-13}\text{ ergs/cm}^2/\text{s}$ gives a luminosity of $L_{6.4\text{keV}} = 6.7 \times 10^{38}\text{ ergs s}^{-1}$, assuming the “Bridge” cloud is 18 pc from Sgr A$^*$. This value on the same order of magnitude as the Eddington luminosity of a solar mass black hole and is on the same order of magnitude as the value found by Ponti et al. in 2010.

4.1.2 Spectral Analysis of 2012 Observations

In order to compare the three 2012 observations to the results from 2020, I used the same data analysis procedure described in Chapter 2.2.3. The ad hoc model fit the three observations (Obs ID: 40010004001, 40010005001, and 40010006001) well, with a reduced $\chi^2$ of 1.2 (47 d.o.f.), 1.0 (43 d.o.f.), and 1.1 (100 d.o.f.) respectively. The combined foreground and intrinsic absorption column density was frozen to $N_H = 17.5927 \times 10^{22}\text{cm}^{-2}$, the result from 2020. The best fit photon index for the observations are $\Gamma = 1.7 (\pm 0.2), 1.8 (\pm 0.3), \text{and } 2.0 (\pm 0.2)$.

For the first spectrum (Obs ID: 40010004001), the first gaussian line emission is at 6.48 (-0.09, +0.11) keV, with line width $\sigma = 0.23 (-0.11, +0.15)\text{ keV}$. Note the large sigma, which corresponds to the wideness of the Gaussian peak (see the top image in Figure 4.1.2). The second spectrum (Obs ID: 40010005001) has a slightly narrower peak frozen at 6.4 keV with $\sigma = 0.18 (-0.18, \text{keV})$.

---

1 Luminosity $L$ is calculated by $L = F_{6.4\text{keV}} \times \pi r^2$, where $r$ is the total distance from Earth to the source. Assuming the Galactic Center is 8 kpc from Earth, the total distance to the “Bridge” molecular cloud is 8,018 pc. 1 pc is equal to $3.1 \times 10^{16}\text{ km}$. 
4.1. AD HOC MODEL

Figure 4.1.1: 2020 3-79 keV spectrum of the “Bridge” molecular using ad hoc model. This model fits very well, with a reduced $\chi^2$ of 1.1 for 459 d.o.f. The 6.4 keV gaussian emission line, a distinct feature of Galactic Center molecular clouds, is significantly detected in this plot. Notice that the peak of this plot is around 0.02 counts/s/keV, as opposed to the 2012 observations, whose peaks are around 0.01 counts/s/keV.

+0.22) keV. The last spectrum (Obs ID: 40010006001) is the only 2012 observation fit jointly with data from both Module A and B. This spectrum features the first Gaussian peak frozen at 6.4 keV, with the line width also frozen at $\sigma = 0.01$ keV. The Module B constant is $1.1 \pm 0.1$, representing a very close fit between the data from the two modules. This observation has the best statistics, with 100 degrees of freedom and the spectrum is featured in Figure 4.1.3.

The flux values for 2012 observations were about half the levels measured in 2020. For example, the unabsorbed power law continuum flux is $F_{3-79 \text{ keV}} = 7.5 \pm 0.2 \times 10^{-12}$ ergs/cm$^2$/s in 2020. In the 2012 the unabsorbed fluxes $F_{3-79 \text{ keV}}$ are $3.7 \pm 0.4$, $3.9 \pm 0.5$, and $3.5 \pm 0.2$, all with units $10^{-12}$ ergs/cm$^2$/s. An increase of luminosity by a factor of two within 8 years in the Bridge cloud is significant and exciting. This trend is reflected in all fluxes calculated, which are presented in Table 4.1.1, along with the model fitting parameters calculated for all three 2012 observations.
Figure 4.1.2: 3 to 79 keV FPMA spectra for two 2012 observations (Obs ID: 40010004001 (top) and 40010005001 (bottom)) of the “Bridge” molecular cloud. Both spectra only use data from Module A of NuSTAR, due to contamination on Module B. The same ad hoc model is applied to both observations, with $N_H$ frozen at $17.5927 \times 10^{22} \text{cm}^{-2}$ and with $\Gamma = 1.7 \ (\pm 0.2)$ (top) and 1.8 ($\pm 0.3$) (bottom).
Table 4.1.1. Ad Hoc Model Fitting Result of 2012 NuSTAR Observations of the “Bridge”

<table>
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<th>2012 (6001)</th>
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<td>1.0 (43)</td>
<td>1.1 (100)</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>keV</td>
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<td>1.8 (±0.3)</td>
<td>2.0 (±0.2)</td>
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<tr>
<td>Line Energy</td>
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<td>6.40 (frozen)</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>keV</td>
<td>0.23 (-0.11, +0.15)</td>
<td>0.18 (-0.18, +0.22)</td>
<td>0.01 (frozen)</td>
</tr>
<tr>
<td>$F_{2-10keV}$</td>
<td>ergs/cm$^2$/s</td>
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<td>1.6 (±0.2)</td>
<td>1.7 (±0.1)</td>
</tr>
<tr>
<td>$F_{3-79keV}$</td>
<td>ergs/cm$^2$/s</td>
<td>3.7 (±0.4)</td>
<td>3.9 (±0.5)</td>
<td>3.5 (±0.2)</td>
</tr>
<tr>
<td>$F_{6.4keV}$</td>
<td>ergs/cm$^2$/s</td>
<td>2.1 (±0.5)</td>
<td>1.8 (±0.7)</td>
<td>1.5 (±0.4)</td>
</tr>
</tbody>
</table>

Note. — This table presents the parameters and flux values for the ad hoc spectral analysis of three observations of the “Bridge” molecular cloud from 2012. The free parameters are photon index $\Gamma$, and Gaussian line energy with characteristic width $\sigma$. The calculated flux are the unabsorbed flux calculated for the energy ranges 2 to 10 keV and 3 to 79 keV and Gaussian Line Emission flux at the 6.4 keV Fe K$\alpha$ line.

Figure 4.1.3: 2012 3 to 79 keV FPMA and FPMB joint-fit spectrum of the “Bridge” molecular cloud (Obs ID: 40010006001). The black line and data points represent the data from Module A and the red, for Module B. This spectrum features the ad hoc model, which the data fits nicely to, with a reduced $\chi^2$ of 1.1 for 100 degrees of freedom. Additionally, the Gaussian line emission peak is frozen at 6.4 keV, with $\sigma$ frozen to 0.01 keV. This spectrum has the best statistics of the 2012 observations of the “Bridge” cloud.
In order to achieve better statistics and a better fit, I jointly fit the three 2012 observations, with the three data sets from Module A (Obs ID: 40010004001, 40010005001, and 40010006001) and one from Module B (Obs ID: 40010006001). Additionally, I was curious to find the total flux for the “Bridge” molecular cloud in 2012 in order to compare to 2020 and 2016. This data was satisfactorily fit to the ad hoc model, with a reduced $\chi^2$ of 1.1 (195 dof). Once again, the combined intrinsic and foreground column density was frozen to $N_H = 17.5927 \times 10^{22}$ cm$^{-2}$. The fit resulted in power law index $\Gamma = 1.9 (\pm 0.1)$, with the first Fe Kα line emission at 6.39 (-0.04, +0.05) keV with line width $\sigma = 0.11 (\pm 0.1)$ keV. The line energy for this combined spectra is close to the true Fe Kα line energy at 6.40 keV. As this was a joint fit, I used a constant parameter in my model to measure how closely each spectrum matched each other. The data from the first observation (Obs ID: 40010004001) was the first data set in the joint fit with the constant frozen to 1. The constant value found for the second observation (Obs ID: 40010005001) is 1.1 (-0.1, +0.2). For the last observation (Obs ID: 40010006001), the constant for the Module A data is 1.1 (±0.1) and for Module B, 1.2 (±0.1). All four data sets are thus found to match pretty consistently, which is reflected by the separate spectral fits reported earlier.

The flux calculated from the joint fit of the 2012 data confirms that the flux levels doubled from 2012 to 2020. The unabsorbed power law continuum flux is $F_{2-10 \text{ keV}} = 1.4 (\pm 0.2) \times 10^{-12}$ ergs/cm$^2$/s for the 2 to 10 keV band and $F_{3-79 \text{ keV}} = 3.4 (\pm 0.4) \times 10^{-12}$ ergs/cm$^2$/s, for the entire NuSTAR energy band. The 6.4 keV Gaussian line emission flux is $1.6 (0.3, +0.4) \times 10^{-13}$ ergs/cm$^2$/s. All flux and parameter comparisons can be found in Table 4.1.2. Additionally, the joint fit spectrum can be found in Figure 4.1.4.

### 4.1.3 Spectral Analysis of 2016 Observations

Next, I analyzed the observation of the “Bridge” from 2016. The ad hoc model detailed in Chapter 2.2.3 fit the 2016 data (Obs ID: 40202001002) well, with a reduced $\chi^2 = 1.1$ (538 dof) (see spectrum in Figure 4.1.5). This is partially due to the length of the observation and the number of events recorded, as this observation had the longest exposure time of all five data sets used in this analysis. Other parameters showed a close correlation to previous (and past)
Figure 4.1.4: 2012 3 to 79 keV joint-fit spectrum of the “Bridge” molecular cloud (Obs ID: 40010004001, 40010005001, and 40010006001). This plot is rather busy, as it features all three observations from 2012 fit together, with 3 observations from FPMA of NuSTAR and 1 from FPMB. These observations fit the ad hoc model well, with a reduced $\chi^2$ of 1.1 (195 dof). Additionally, the fit resulted in $\Gamma = 1.9 \pm 0.1$ and Line Emission at 6.39 (-0.04, +0.05) keV with $\sigma = 0.11(\pm 0.1)$ keV.
observations with power law index $\Gamma = 1.90 \pm 0.04$. The first Fe Kα emission line is at 6.35 (±0.02) keV with line width $\sigma = 0.12 (-0.04, +0.03)$ keV. The flux measured in 2016 is fairly close to the results from 2020, slightly lower but still significantly larger than the Bridge’s flux in 2012. For example, the unabsorbed power law continuum flux in 2016 is $F_{2-10} = 2.6 \pm 0.1 \times 10^{-12} \text{ergs/cm}^2/\text{s}$, whereas in 2020 it is $F_{2-10} = 2.8 \pm 0.1 \times 10^{-12} \text{ergs/cm}^2/\text{s}$. However, across the entire NuSTAR energy band, the flux difference is more significant. In 2016 it is $F_{3-79} = 6.0 (\pm 0.2) \times 10^{-12} \text{ergs/cm}^2/\text{s}$ and in 2020, $F_{3-79} = 7.5 (\pm 0.2) \times 10^{-12} \text{ergs/cm}^2/\text{s}$. The Gaussian line emission flux is measured to be $2.8 (\pm 0.2) \times 10^{-13} \text{ergs/cm}^2/\text{s}$ in 2016. Comparisons of flux across all of the observations can be found in Table 4.1.2 and further discussion of luminosity trends can be found in the Discussion, Chapter 5.

Figure 4.1.5: 2016 3 to 79 keV joint-fit spectrum of the “Bridge” molecular cloud (Obs ID: 40202001002) with the ad hoc model. The data from FPMA of NuSTAR is shown in black while the data from FPMB is shown in red. This was a satisfactory fit, with a reduced $\chi^2 = 1.1$ for 538 degrees of freedom. The fit resulted in $\Gamma = 1.90 (\pm 0.04)$ and Gaussian Line Emission at 6.35 (±0.02) keV with $\sigma = 0.12 (-0.04, +0.03)$ keV.
4.2. **MYTORUS**

Table 4.1.2. Ad Hoc Model Joint Fitting Result of the “Bridge” Molecular Cloud

<table>
<thead>
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<th>2016</th>
<th>2012</th>
</tr>
</thead>
<tbody>
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<td>$\chi^2$ (dof)</td>
<td></td>
<td>1.1 (459)</td>
<td>1.1 (538)</td>
<td>1.1 (195)</td>
</tr>
<tr>
<td>$N_H$</td>
<td>$10^{22}$ cm$^{-2}$</td>
<td>17.6 (-3.2, +3.5)</td>
<td>17.5927 (frozen)</td>
<td>17.5927 (frozen)</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td></td>
<td>1.8 (-0.1)</td>
<td>1.90 (±0.04)</td>
<td>1.9 (±0.1)</td>
</tr>
<tr>
<td>Line Energy</td>
<td>keV</td>
<td>6.31 (±0.02)</td>
<td>6.35 (±0.02)</td>
<td>6.39 (-0.04, +0.05)</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>keV</td>
<td>0.09 (-0.05, +0.04)</td>
<td>0.12 (-0.04, +0.03)</td>
<td>0.11 (±0.1)</td>
</tr>
<tr>
<td>$F_{2-10}$ keV</td>
<td>$10^{-12}$ ergs/cm$^2$/s</td>
<td>2.8 (±0.1)</td>
<td>2.6 (±0.1)</td>
<td>1.4 (±0.2)</td>
</tr>
<tr>
<td>$F_{3-79}$ keV</td>
<td>$10^{-12}$ ergs/cm$^2$/s</td>
<td>7.5 (±0.2)</td>
<td>6.0 (±0.2)</td>
<td>3.4 (±0.4)</td>
</tr>
<tr>
<td>$F_{6.4}$ keV</td>
<td>$10^{-13}$ ergs/cm$^2$/s</td>
<td>3.4 (±0.2)</td>
<td>2.8 (±0.2)</td>
<td>1.6 (−0.3, +0.4)</td>
</tr>
</tbody>
</table>

Note. — This table presents the results of fitting with an ad hoc model for 3 different years of NuSTAR observations of the “Bridge” molecular cloud. The values from 2012 represent a joint fit of three separate observations taken that year. The ad hoc model is characterized by combined foreground and intrinsic column density $N_H$, photon index $\Gamma$, Gaussian Line Emission energy and the width of its peak $\sigma$, the Observed Continuum Emission Flux and the 6.4 keV Line Emission Flux.

Table 4.1.3. Observed Flux FPMA of the “Bridge” Molecular Cloud

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>2020</th>
<th>2016</th>
<th>2012 (4001)</th>
<th>2012 (5001)</th>
<th>2012 (6001)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{2-10}$ keV</td>
<td>$10^{-12}$ ergs/cm$^2$/s</td>
<td>1.7509</td>
<td>1.5893</td>
<td>0.8589</td>
<td>1.0007</td>
<td>0.9913</td>
</tr>
<tr>
<td>$F_{10-79}$ keV</td>
<td>$10^{-12}$ ergs/cm$^2$/s</td>
<td>5.2099</td>
<td>3.9516</td>
<td>2.7369</td>
<td>2.4723</td>
<td>2.1883</td>
</tr>
<tr>
<td>$F_{3-79}$ keV</td>
<td>$10^{-12}$ ergs/cm$^2$/s</td>
<td>6.9221</td>
<td>5.5014</td>
<td>3.5803</td>
<td>3.4486</td>
<td>3.1526</td>
</tr>
</tbody>
</table>

Note. — Absorbed flux values for FPMA observations of the “Bridge” cloud in 2020, 2016, and 2012. These values were calculated using the “flux” command in Xspec. This data shows us that the flux doubled from 2012 to 2020.
Table 4.1.4. Observed Flux FPMB of the “Bridge” Molecular Cloud

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>2020</th>
<th>2016</th>
<th>2012 (6001)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{2-10\text{keV}}$</td>
<td>$10^{-12}$ ergs/cm$^2$/s</td>
<td>1.6824</td>
<td>1.6351</td>
<td>1.0821</td>
</tr>
<tr>
<td>$F_{10-79\text{keV}}$</td>
<td>$10^{-12}$ ergs/cm$^2$/s</td>
<td>5.0062</td>
<td>4.0655</td>
<td>2.3888</td>
</tr>
<tr>
<td>$F_{3-79\text{keV}}$</td>
<td>$10^{-12}$ ergs/cm$^2$/s</td>
<td>6.6514</td>
<td>5.6600</td>
<td>3.4414</td>
</tr>
</tbody>
</table>

Note. — Absorbed flux values for FPMB observations of the “Bridge” molecular cloud. As with other flux calculations, these values demonstrate that flux of the “Bridge” cloud doubled over the last 8 years.

Table 4.2.1. MYTorus Model Fitting Result for the “Bridge” Molecular Cloud

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>2020</th>
<th>2016</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$ (dof)</td>
<td></td>
<td>1.5 (461)</td>
<td>1.3 (538)</td>
<td>1.1 (195)</td>
</tr>
<tr>
<td>$N_H(i)$</td>
<td>$10^{22}$ cm$^{-2}$</td>
<td>22.1 (-8.1, +7.9)</td>
<td>14.9 (-11.2, +8.3)</td>
<td>3.1 (-0.2, +0.3)</td>
</tr>
<tr>
<td>kT</td>
<td>keV</td>
<td>0.9 (-0.1, +0.3)</td>
<td>0.9 (-0.5, +0.3)</td>
<td>0.9 (-0.4, +0.7)</td>
</tr>
<tr>
<td>$\Gamma_{MYT}$</td>
<td></td>
<td>2.0 (±0.1)</td>
<td>2.0 (±0.1)</td>
<td>~ 2.2</td>
</tr>
<tr>
<td>$N_{MYT}$</td>
<td>$10^{-2}$ ph cm$^{-2}$ s$^{-1}$</td>
<td>2.6 (-0.4, +0.5)</td>
<td>3.2 (-0.5, +0.4)</td>
<td>1.4 (-0.6, +1.6)</td>
</tr>
</tbody>
</table>

Note. — Results of spectral fit of data from the “Bridge” molecular cloud from NuSTAR using model: \texttt{wabs*(apec+MYTorus)}. MYTorus is a physical model input as a table model in Xspec. The foreground absorption $N_H$ (f) was frozen to $4 \times 10^{22}$ cm$^{-2}$ for all observations. Additionally, the inclination angle $\theta$ was frozen to 60°. Note that I was unable to constrain $\Gamma_{MYT}$ for the 2012 observation.
4.2 MYTorus

4.2.1 Spectral Fitting 2020 Data with MYTorus Model

The MYTorus model as described in Chapter 2.2.4 did not fit the 2020 data set (Obs ID: 40501005002) well, with a reduced $\chi^2$ of 1.5 for 461 degrees of freedom. This is due to the large residual around the 6.4 keV Fe Kα emission line (see bottom panel of Figure 4.2.1). When fitting the 2020 observation with the ad hoc model, I found that the measured line emission is slightly lower than 6.4 keV at 6.31 ($\pm 0.02$) keV. The MYTorus fit resulted in an intrinsic column density for the cloud of $N_H = 22.1 (-8.1, +7.9) \times 10^{22} \text{ cm}^{-2}$, photon index $\Gamma_{MYT} = 2.0 (-0.1, +0.3)$, and normalization $N_{MYT} = 2.6 (-0.4, +0.5) \times 10^{-2} \text{ ph cm}^{-2} \text{s}^{-1}$. Additionally, the best-fit temperature of the “apec” component of the model is 0.9 (-0.1, +0.3) keV. These values can be compared with the results of the 2016 and 2012 spectral fits in Table 4.2.1.

I tried several modifications to the model to attempt to improve the fit, for example adding another “apec” component to the model: $\text{constant*wabs*(apec+apec+MYTorus)}$. The only modification that improved the model fitting statistics was to add a Gaussian component instead of “apec”: $\text{constant*wabs*(gaussian+MYTorus)}$. This result gave a reduced $\chi^2$ of 1.3 for 460 degrees of freedom, which is still not a very satisfactory fit. Interestingly, the extra Gaussian component gave a line energy of $\sim 6.16$ keV, once again pointing to the fact that the Fe Kα emission line shifted to a lower energy. There is also still a residual around 6.4 keV, as seen in the bottom panel of Figure 4.2.2.

In order to probe the source of this residual, I separately fit the data from Module A and B. Separately fitting the data form each module could reveal an instrumental error because the two modules of NuSTAR are designed to be as identical as possible. However, the residual around 6.4 keV is clearly seen in the data from both modules (see Figure 4.2.3). Both fits also had an unsatisfactory reduced $\chi^2$ of 1.5, for 237 degrees of freedom for Module A and 220 degrees of freedom for Module B.
4.2.2 Spectral Fitting Results for 2016 and 2012 Data

After fitting the MYTorus model to the 2020 data and experimenting with additional model parameters, I jointly fit the 2016 observation and all 2012 observations with the “standard” MYTorus model described in Chapter 2.2.4. I was interested to see if the residual trend would continue for all of the observations. The MYTorus model did not fit to the 2016 data from the “Bridge” cloud (Obs ID: 4020020001002) well, with a reduced $\chi^2$ of 1.3 for 538 degrees of freedom. And while this fit is slightly better than the 2020 fit ($\chi^2 = 1.5$ for 461 dof), there is still a significant residual around 6.4 keV (see bottom image of Figure 4.2.4). For the 2016 observation, the intrinsic column density is $N_H = 14.9 (-11.2, +8.3) \times 10^{22}$ cm$^{-2}$. The power law index is $\Gamma_{MYT} = 2.0 (\pm 0.1)$ and the normalization $N_{MYT}$ is equal to $2.6 (-0.4, +0.5) \times 10^{-2}$ ph cm$^{-2}$ s$^{-1}$. The best-fit temperature of the “apec” component is 0.9 (-0.5, +0.3) keV.

The 2012 data (Obs ID: 40010004001, 40010005001, and 40010006001) does not show a significant residual around the 6.4 keV line (see upper panel of Figure 4.2.4) and is a fairly satisfactory fit to the MYTorus model, with a reduced $\chi^2$ of 1.1 for 195 degrees of freedom. This is the best reduced $\chi^2$ for all of the observations of the “Bridge” cloud fit with MYTorus. The intrinsic column density is measured to be $3.1 (-0.2, +0.3) \times 10^{22}$ cm$^{-2}$, the normalization $N_{MYT}$ is equal to $1.4 (-0.6, +1.6) \times 10^{-2}$ ph cm$^{-2}$ s$^{-1}$, and the best-fit temperature is 0.9 (-0.4, +0.7) keV. I was unable to constrain the power law index $\Gamma_{MYT}$, which is about $\sim 2.2$. Again, all MYTorus fitting results can be compared in Table 4.2.1.

4.3 Low Energy Cosmic Ray Electron and Proton Models

4.3.1 LECRe Model Fitting Results

As with the MYTorus model, the fit of the “Bridge” molecular cloud data with the LECRe model was unsatisfactory for the 2020 and 2016 data but fair for 2012, with a reduced $\chi^2$ of 1.4 (460 dof), 1.2 (537 dof), and 1.1 (194 dof), respectively. Similarly to the MYTorus model, there is a visible residual around the 6.4 keV (the location of the Fe Kα emission line) in the 2020 spectrum. However, there is no drastic residual around the emission line present for the 2016
4.3. LOW ENERGY COSMIC RAY ELECTRON AND PROTON MODELS

Figure 4.2.1: 2020 3 to 79 keV joint-fit spectrum of the “Bridge” MC using physical model MYTorus: wabs*(apec+MYTorus). This fit is unsatisfactory, with a reduced $\chi^2$ of 1.5 (461 dof) and a large residual seen around 6.4 keV in the bottom panel of the graph. This fit resulted in parameters $N_H = 22.1(-8.1, +7.9) \times 10^{22}$ cm$^{-2}$, $\Gamma_{MYT} = 2.0 \ (\pm 0.1)$, and $N_{MYT} = 2.6 \ (-0.4, +0.5) \times 10^{-2}$ ph cm$^{-2}$ s$^{-1}$.

and 2012 fits (See Figure 4.3.1). However, I am hesitant to conclude that the 2012 data resulted in a better fit because the resulting model parameters have some of the largest error bars across all results.

There is some consistency present in all three spectral fits, generally between the results from 2020 and 2016. For example, the measured intrinsic column density is similar for 2020 and 2016, with $N_H(i)$ equal to $18.3 \ (-5.3, +5.9) \times 10^{22}$ cm$^{-2}$ and $18.8 \ (-4.6, +5.5) \times 10^{22}$ cm$^{-2}$, respectively. While the value of the column density measured in 2012 is greater than $\sim 18 \times 10^{22}$ cm$^{-2}$, this result has very large error bars, with $N_H(i)$ equal to $26.0 \ (-20.0, +24.5) \times 10^{22}$ cm$^{-2}$. Therefore, since all $N_H(i)$ values are technically within the same range, they could be considered consistent. However, the ad hoc model showed that the luminosity of the “Bridge” MC increased after 2012, so one would expect a lower intrinsic column density to be observed in 2012. As mentioned in Chapter 2.2.5, the foreground column density was frozen to $N_H(f) = 4 \times 10^{22}$ cm$^{-2}$ for all
4. SPECTRA AND ANALYSIS RESULTS

Figure 4.2.2: 2020 3 to 79 keV joint-fit spectrum of the “Bridge” MC (Obs ID: 40501005002) using a modified MYTorus model: \textit{wabs*(gaussian+MYTorus)}. This fit slightly improved upon the standard MYTorus model used for all “Bridge” cloud observations. However, the fit is still unsatisfactory with a reduced $\chi^2$ of 1.3 (460 dof). Interestingly, the Gaussian line emission measured in this modified fit shifted to a lower energy, at $\sim 6.16$ keV. Yet, the residual around 6.4 keV remains, despite the addition of an extra Gaussian component.

observations, as measured by Ponti et al. 2010. The trend of the result from 2012 being different from 2016 and 2020 can also be seen in the results for abundance $Z/Z_\odot$, with $Z/Z_\odot = 3.0$ ($\pm 0.3$) in 2020 and 3.1 ($\pm 0.3$) in 2016. In 2012, the abundance is measured to be $Z/Z_\odot = 4.0$ (-0.8, +0), the highest value allowed by the model. However, $Z/Z_\odot \approx 4$ is unreasonably high for the “Bridge” MC (Mori et al. 2015). The metallicity of the Galactic Center been measured to be around one to two times solar abundance instead (Zhang et al. 2015). The best-fit results for the “apec” temperature $kT$ of $\sim 0.9$ and power law index $\Gamma_{MYT}$ of $\sim 3$ are more consistent for all years and can be found in Table 4.3.1.

For the LECRe model, parameters minimum energy $E_{\text{min}}$ and normalization $N_{\text{LECR}}$ point to the physics of the process being investigated. As I explain in more detail in Chapter 2.2.5, these parameters calculate the required power of cosmic ray electrons to illuminate the molecular cloud. For the 2020 observation, freezing $E_{\text{min}}$ at 3.2 keV, the lowest limit allowed by the model,
Table 4.3.1. Model Fitting Results for the “Bridge” Cloud Using the LECRe Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>2020</th>
<th>2016</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$ (dof)</td>
<td></td>
<td>1.4 (460)</td>
<td>1.2 (537)</td>
<td>1.1 (194)</td>
</tr>
<tr>
<td>$n_H$ ($i$)</td>
<td>$10^{22}$ cm$^{-2}$</td>
<td>18.3 (-5.3, +5.9)</td>
<td>18.8 (-4.6, +5.5)</td>
<td>26.0 (-20.0, +24.5)</td>
</tr>
<tr>
<td>$kT$</td>
<td>keV</td>
<td>0.9 (-0.5, +0.4)</td>
<td>0.9 (±0.5)</td>
<td>1.1 (-0.8, +0.7)</td>
</tr>
<tr>
<td>$\Gamma_{MTY}$</td>
<td></td>
<td>2.9 (±0.1)</td>
<td>3.1 (±0.1)</td>
<td>3.0 (-0.3, +0.4)</td>
</tr>
<tr>
<td>$E_{\text{min}}$</td>
<td>keV</td>
<td>3.2 (frozen)</td>
<td>5.0 (-1.8, +1.2)</td>
<td>5.6 (frozen)</td>
</tr>
<tr>
<td>$Z/Z_{\odot}$</td>
<td></td>
<td>3.0 (±0.3)</td>
<td>3.1 (±0.3)</td>
<td>4.0 (-0.8, +0)</td>
</tr>
<tr>
<td>$N_{\text{LECR}}$</td>
<td>$10^{-7}$ ergs/cm$^2$/s</td>
<td>6.1 (-1.4, +2.2)</td>
<td>$\sim$ 4.7</td>
<td>1.8 (-0.9, +2.2)</td>
</tr>
</tbody>
</table>

Note. — Spectral fitting results for the Bridge molecular cloud using the physical model LECRe, input in Xspec as: wabs*(apec + wabs*LECRe). Note that the upper limit of abundance $Z/Z_{\odot}$ is 4.

gave the best fit. With the 2016 data, $E_{\text{min}}$ was left free and is equal to 5.0 (-1.8, +1.2) keV. Lastly, for the 2012 fit $E_{\text{min}}$ was frozen to 5.6 keV, as this value gave the best and most stable fit. By definition,

$$dW/dt = 4\pi D^2 \times N_{\text{LECR}},$$  \hspace{1cm} (4.3.1)

giving the power injected by LECR electrons into the cloud region (Tatischeff et al. 2012). The resulting normalization constants are $N_{\text{LECR}} = 6.1 (-1.4, +2.2) \times 10^{-7}$ ergs/cm$^2$/s in 2020 and $1.8 (-0.9, +2.2) \times 10^{-7}$ ergs/cm$^2$/s in 2012. I was unable to constrain this parameter for 2016 and the result was about $\sim 4.7 \times 10^{-7}$ ergs/cm$^2$/s. These values point to the luminosity trend measured by the ad hoc model, with the photon flux of the cloud increasing from 2012 to 2020.

4.3.2 LECRp Model Fitting Results

The spectral fitting results for the LECRp model followed the same pattern as analysis with the other physical models: the spectra show an unsatisfactory fit for the 2020 and 2016 observations but a fair fit for data from 2012. The fits resulted in a reduced $\chi^2$ of 1.4 for 460 degrees of freedom in 2020, 1.2 for 537 degrees of freedom in 2016, and 1.1 for 194 degrees of freedom in 2012. Indeed, the spectra show a large residual around 6.4 keV for the 2020 and 2016 observations.
Additionally, the fitting results gave large error bars for several parameters across all observations and I was not able to constrain some parameters.

As described in Chapter 2.2.5, the foreground column density was frozen to the value measured by Ponti et al. (2012), \( N_H(f) = 4 \times 10^{22} \text{ cm}^{-2} \). The intrinsic column density measured in 2020 is \( 10.7 (-1.8, +4.1) \times 10^{22} \text{ cm}^{-2} \), in 2016 it is \( 13.9 (-4.7, +5.7) \times 10^{22} \text{ cm}^{-2} \), and in 2012, \( 22.3 (-17.2, +14.6) \times 10^{22} \text{ cm}^{-2} \). Similarly to the result from the LECRe model, the error is larger for the 2012 and 2016 observations. Furthermore, Mori et al. (2015) note that their result for intrinsic column density of the Bridge is \( \sim 9 \times 10^{22} \text{ cm}^{-2} \), which is closest to my LECRe fitting result from 2020. Some parameters were consistent across all observations, like \( \Gamma_{MT} \) and \( E_{\text{min}} \), the latter of which was frozen to 32 keV (see Table 4.3.2 for more details). Abundance \( Z/Z_\odot \) is also consistent for all observations, at \( 1.7 (-0.3, +1.1) \) in 2020, \( 1.0 (\pm 0.1) \) in 2016 and \( 1.4 (-0.5, +0.4) \) in 2012. All three results agree with measurements of the Galactic Center, which has a metallicity of one to two times solar abundance (Zhang et al. 2015). Other parameters gave variable results, like best-fit “apec” temperature \( kT \), which is \( 1.1 (-1.0, +1.9) \) keV for the 2016 fit and \( 1.2 (-0.6, +0.9) \) keV for 2012. However, I was unable to constrain the temperature for the 2020 fit, which gave a result of about \( \sim 64 \text{ keV} \), the highest value allowed by the model and a very high temperature for a cold gas cloud.

The best-fit result of the normalization is very in 2016 at \( N_{\text{LECR}} = 14.4 (-9.2, +18.8) \times 10^{-6} \text{ ergs/cm}^2/\text{s} \), almost five times higher than the normalization result in 2020. I was unable to constrain the result for 2012, which was about \( \sim 2.1 \). The huge variation in the result of this parameter reflects the instability experienced when fitting this model to the “Bridge” data.
Table 4.3.2. Model Fitting Results for the “Bridge” Cloud Using the LECRp Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>2020</th>
<th>2016</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$ (dof)</td>
<td></td>
<td>1.4 (460)</td>
<td>1.2 (537)</td>
<td>1.1 (194)</td>
</tr>
<tr>
<td>$N_H(i)$</td>
<td>$10^{22}$ cm$^{-2}$</td>
<td>10.7 (-1.8, +4.1)</td>
<td>13.9 (-4.7, +5.7)</td>
<td>22.3 (-17.2, +14.6)</td>
</tr>
<tr>
<td>$kT$</td>
<td>keV</td>
<td>$\sim 64$</td>
<td>1.1 (-1.0, +1.9)</td>
<td>1.2 (-0.6, +0.9)</td>
</tr>
<tr>
<td>$\Gamma_{MTY}$</td>
<td></td>
<td>2.5 (±0.3)</td>
<td>2.7 (-0.2, +0.1)</td>
<td>2.5 (-1.5, +0.5)</td>
</tr>
<tr>
<td>$E_{\text{min}}$</td>
<td>keV</td>
<td>32 (frozen)</td>
<td>32 (frozen)</td>
<td>32 (frozen)</td>
</tr>
<tr>
<td>$Z/Z_\odot$</td>
<td></td>
<td>1.7 (-0.3, +1.1)</td>
<td>1.0 (±0.1)</td>
<td>1.4 (-0.5, +0.4)</td>
</tr>
<tr>
<td>$N_{\text{LECR}}$</td>
<td>$10^{-6}$ ergs/cm$^2$/s</td>
<td>3.0 (-2.4, +5.4)</td>
<td>14.4 (-9.2, +18.8)</td>
<td>$\sim 2.1$</td>
</tr>
</tbody>
</table>

Note. — Best-fit parameters for observations of the “Bridge” molecular cloud using physical model LECRp. In Xspec, this model was input as: $\text{wabs}*(\text{apec + wabs*LECRp})$. Some parameters, like $kT$ in 2020 and normalization $N_{\text{LECR}}$ in 2012, were unable to be constrained.
4. SPECTRA AND ANALYSIS RESULTS

Figure 4.2.3: Separate spectral fit of 2020 data of the “Bridge” molecular cloud (Obs ID: 40501005002) using the MYTorus model: \texttt{wabs*(apec+MYTorus)}. The Module A data is the top image and the Module B fit on the bottom. The purpose of fitting the Module A and B data separately was to investigate if the unsatisfactory fit and residual around the 6.4 keV Fe Kα emission line is an instrument error. However, both fits were unsatisfactory with a reduced \(\chi^2\) of 1.5 (237 dof for Module A and 220 dof for Module B) and the residual is clearly seen in the bottom panel of both plots.
Figure 4.2.4: 3 to 79 keV spectrum of the “Bridge” MC from 2012 (top image) and 2016 (bottom image) fit with the physical model MYTorus. The 2012 fit is satisfactory, with a reduced $\chi^2$ of 1.1 (195 dof). On the other hand, the 2016 data does not give a satisfactory fit, with reduced $\chi^2$ of 1.3 (538 dof), due to the residual around the 6.4 keV Fe Kα line. Both are better fits than the 2020 MYTorus fit, due to the large residual around that same line. This seems to indicate that the Fe Kα line shifts to a lower energy between 2012 and 2020.
Figure 4.2.5: 5 to 9 keV spectra of the “Bridge” MC fit with the MYTorus model for 2012 (top left), 2016 (top right), and 2020 (bottom). These “zoomed in” images show a clear residual around the 6.4 keV Fe Kα emission line (the first peak in the graph) in 2020 and 2016. However, in 2012 there is no clear residual in this area. This may indicate that the emission line shifted to a lower energy from 2012 to 2020 or that the 2012 observations were not long enough to constrain this line emission feature.
Figure 4.3.1: Spectra of the “Bridge” molecular cloud using the LECRe physical model from 2012 (top left), 2016 (top right), and 2020 (bottom image). Of the three observations, only the fit using data from 2012 is satisfactory. The large residual around 6.4 keV seen in the bottom panel of the 2020 plot indicates that the bad fit may be due to a shift in the Fe Kα emission line.
Figure 4.3.2: 3 to 79 keV spectra of the “Bridge” molecular cloud fit with data from 2012 (top left), 2016 (top right), and 2020 (bottom image) using physical model \texttt{wabs*(apec+LECRp)}. The fits with 2020 and 2016 data are unsatisfactory, with reduced $\chi^2$'s between 1.4 and 1.2. On the other hand, the 2012 fit has a reduced $\chi^2$ of 1.1. The bottom panel of each spectrum is the residual, which points to the large residual around 6.4 keV.
5
Discussion & Conclusions

5.1 X-Ray Reflection of Sgr A* in the “Bridge”

Observations of the “Bridge” molecular cloud by NuSTAR between 2012 and 2020 show the 6.4 keV line emission flux and hard X-ray continuum emission increasing over time. Indeed, both the observed and unabsorbed fluxes show this brightening trend. The trend seen in the data is that the flux value in 2020 is roughly twice the flux measured in 2012, while the 2016 fluxes are an intermediate value that is closer to the values in 2020 than in 2012. While Ponti et al. (2012) studied the flux variation of the “Bridge” molecular cloud between 2004 and 2009, the activity I have studied between 2012 and 2020 is a new flux stage and has never been analyzed before.

The best and most natural explanation for the increase in brightness is that the “Bridge” cloud is reflecting a past X-ray outburst from Galactic Center super-massive black hole Sgr A*. The NuSTAR observations show active illumination of the molecular cloud by a X-ray wave front outburst. Indeed, the flux variation between 2012, 2016, and 2020 indicate that the outburst reached the cloud and increased in brightness between 2016 and 2020. Ponti et al. (2012) concluded that the “Bridge” molecular cloud is most likely located 18 pc (or ~ 59 ly)\(^1\) behind Sgr A*. This points to the outburst originating from the black hole about 60 years ago.

\(^1\)1 parsec is equal to 3.26 light years [17]
The luminosity of the “Bridge” cloud in 2020 is \( L_{6.4\text{keV}} = 6.7 \times 10^{38} \) ergs s\(^{-1}\), as calculated with the 6.4 keV line flux. For optically thin molecular clouds, the primary source luminosity can be calculated using the fluorescence line or by considering the Compton scattering process and the measured hard X-ray continuum. While the 6.4 keV line is historically better constrained than the X-ray continuum emission, NuSTAR’s hard X-ray capacity makes it possible for luminosity to be calculated using the continuum flux. (Zhang et al. 2015).

Another hint that the “Bridge” cloud is reflecting a Sgr A* outburst is the measured photon index. Current Sgr A* flares, that is, flares measured from observations of the black hole itself, have a photon index \( \Gamma \sim 2 - 3 \) (Zhang et al 2015). The photon index of the “Bridge” cloud in 2020 is constrained by the ad hoc model to be 1.8 (±0.1) and 2.9 (±0.1), with the MYTorus model. While this first value, the result from the ad hoc model, agrees, the MYTorus photon index is a bit high. However, the 2020 data fit very poorly with the MYTorus model, due to a large residual around the 6.4 keV line. This may explain the high value of \( \Gamma \). Further study using physical models such as MYTorus is necessary, as the ad hoc model is not self-constrained and does not explain the physics of the observed process.

While the poor fitting results from the MYTorus model are puzzling, this motivates further study with MYTorus and other physical X-Ray Reflection Nebula models. I briefly investigated two other models: BORUS and CREFL16. The BORUS model, as discussed by Balokovic et al. 2019, models AGN emission as a sphere with conical cut-outs. We decided to not try this model due to this geometry, as it is more extreme than the already slightly contrived toroidal geometry of MYTorus. The CREFL16 or “uniform Cloud REFLection” model is specific to molecular cloud reflection. CREFL16 models a “uniform spherical cloud illuminated by a steady source” and also measures the radial Thompson optical depth \( \tau_T \) (Churazov et al. 2017). The ill fitting MYTorus results certainly motivates studying the “Bridge” observations using a molecular cloud specific model, such as this one.
5.1. X-RAY REFLECTION OF SGR A* IN THE “BRIDGE”

5.1.1 Flux Variation of the “Bridge”

The unabsorbed power law continuum flux is plotted in Figure 5.1.1 for energy ranges 2 to 10 keV (the traditional X-ray band) and 3 to 79 keV (NuSTAR’s full energy capacity). These plots show the flux trend clearly. For the 2 to 10 keV band, the slope of the plot between 2012 and 2016 (m = 0.3) is six times the slope between 2016 and 2020 (m = 0.05)\(^2\). The fluxes in 2016 and 2020 are very close, with \(F_{2-10} = 2.6 \times 10^{-12} \text{ ergs/cm}^2/\text{s}\) and \(F_{2-10} = 2.8 \times 10^{-12} \text{ ergs/cm}^2/\text{s}\) respectively. However, as the second plot indicates, the fluxes in the 3 to 79 keV band show a more gradual trend, with the slopes only differing by a factor of 2 (m = 0.65 between 2012 and 2016 and m = 0.375 between 2016 and 2020). The plot of the 6.4 keV line emission flux shown in Figure 5.1.2 shows a similar trend, with the slopes again deviating by a factor of 2, with m = 0.3 and 0.15. This indicates that by 2020, the wavefront energy increased over time, with more photons with energy above 10 keV reaching the Bridge in 2020 than in 2016. However, the 6.4 keV emission seems to increase gradually over time. Plots of observed flux give a similar result (see Fig 5.1.3), with the 2 to 10 keV flux being closer between 2016 and 2020 and a more gradual shape for the hard X-ray band.

Does this time delay relate to the superluminal echo discovered in the “Bridge” molecular cloud by Ponti et al. in 2010? In order to determine if this is the case, the NuSTAR observations of the “Bridge” cloud need to be divided into smaller regions (such as the seven used by Ponti et al.) and analyzed separately for the spatial variations of flux over time. Creating new, detailed images would be an interesting project, as the images I share in this project are very zoomed out. NuSTAR hard X-ray observations could potentially reveal density variations in this expansive molecular cloud. Further observation of the “Bridge” molecular cloud is required to confirm the source of flux variation.

\(^2\)Here, I simply calculated rise over run between the flux values to get a numerical sense on how the slope of the plots varied.
5. DISCUSSION & CONCLUSIONS

Figure 5.1.1: Plot of unabsorbed power law continuum emission flux of the “Bridge” molecular cloud for observations in 2012, 2016, and 2020. The top image shows the flux values for the energy band 2 to 10 keV, while the bottom plot shows the flux of the energy band 3 to 79 keV.

5.2 6.4 keV Emission Line Shift

Another interesting phenomenon is the apparent shifting of the 6.4 keV Fe Kα emission line over time. As noted in Table 4.1.2, the ad hoc model resulted in line energies 6.31 (±0.02) keV in
5.2. 6.4 KEV EMISSION LINE SHIFT

Figure 5.1.2: Plot of unabsorbed 6.4 keV Line Emission flux of the “Bridge” molecular cloud. The cloud was observed in 2012, 2016, and 2020 and the data from these observations reveal that the “Bridge” is brightening up. The 6.4 keV line is an important clue into the source of the flux increase.

2020, 6.35 (±0.02) keV in 2016, and 6.39 (-0.04, +0.05) keV in 2012. Initially, I had no concern over this variation, as the values are all fairly close to each other. However, the difference in line energy became apparent when fitting with physical models.

Fitting the data with the MYTorus model resulted in a poor fit and large residuals around 6.4 keV for the data from 2020 and 2016. I plotted the spectra from 5 to 8 keV for all observations to take a closer look at the problem area. As seen in Figure 4.2.5, the residuals are shifted to a lower energy for the 2020 data as opposed to 2016. While this may indicate the energy shifting over the years, I wonder if the 2012 observations are simply not long enough to constrain a line energy around ∼ 6.3 keV. As discussed in Section 4.2.1, this is probably not due to instrument error, especially since the values gradually change over time. However, there is no clear answer to why the emission line is shifting towards 6.3 keV instead of 6.4 keV.
5. DISCUSSION & CONCLUSIONS

Figure 5.1.3: Plot of Observed Flux of the “Bridge” cloud from FPMB data between 2012 and 2020. Flux plots for three different energy ranges are shown: the traditional 2 to 10 keV band (upper left image), the NuSTAR specific range 10 to 79 keV (upper right), and for the entire NuSTAR band of 3 to 79 keV (bottom image).

5.3 Cosmic Ray Bombardment

Since the LECR models had an equally good (or bad, in some cases) fit with the data as the MYTorus model, cosmic ray bombardment cannot be ruled out as a potential source of X-rays by spectral analysis alone. Indeed, cosmic rays are theorized to contribute to the background X-ray emission from galactic center molecular clouds, rather than a source of active illumination. The time variation of the “Bridge” flux points more obviously to X-ray reflection by the clouds. Additionally, the metallicity derived using the LECRe model is unphysical for all observations of the “Bridge” cloud, 3 to 4 times solar, whereas the metallicity of the Galactic Center has been measured as to 1 to 2 times solar abundance (Zhang et al. 2015). Further research needs to be conducted on the source of background X-ray emission in the Galactic Center to confirm if LECRs play a role.
5.4 Conclusions and Suggestions for Further Study

I studied the X-ray flux of Galactic Center molecular cloud, nicknamed the “Bridge,” with observations from the NuSTAR space telescope. In this thesis, I present the broadband spectra and images of the “Bridge” for three years of observation, 2012, 2016, and 2020. I also discuss the potential sources of X-ray illumination of this cloud, the most likely being reflection of a flare from Galactic Center super-massive black hole Sgr A*. The flux of this cloud increased from 2012 to 2020, with the values measured in 2016 at intermediate values. This flux variation within the cloud could be the detection of a new flare from Sgr A*. Mosaic images of the “Bridge” cloud reveal a bright clump centered within a 50″ source region. The cloud emits both 6.4 keV line emission and X-ray continuum emission within this same circular region. The molecular clouds of the Central Molecular Zone present a unique laboratory for the measurement of X-ray luminosity processes, including Sgr A* outbursts that took place about 60 years ago.

Firstly, I would suggest closer study into the morphology of the “Bridge” cloud between 2012 and 2020. Creating exposure-corrected images would provide a fairer comparison of the molecular cloud’s brightness. Additionally, zooming in and getting a close look within the source region of the cloud could expose interesting density differences across the expansive cloud. Using similar source regions to Ponti et al. (2010) would provide an interesting comparison to their study and might even point to another super-luminal echo. The calculations of equivalent-width and luminosity would aid in the direct comparison of the work laid out in that paper.

Additionally, the cause of the 6.4 keV line emission shift should be investigated further. Is this feature due to the lengthy observations of the “Bridge” molecular cloud or is this indicative of a new process that has never been studied before? Applications of other physical models is motivated by the poor fit of the 2020 observation with the MYTorus model. Molecular cloud specific models might fit the data better, despite the lower line emission I observed.
5. DISCUSSION & CONCLUSIONS
Appendix A
Alternate Image Captions for Everybody

While this senior project recounts a very technical and data analysis heavy endeavor, it was important to me to at least attempt aspects of inclusivity within this project. I believe that science is for everyone and that there is no such thing as being “smart enough” to understand physics. We interact with the laws of physics everyday and while X-ray astronomy may not be everyone’s cup of tea, I wanted to present my research here in a way hopefully anybody (including my family and friends) could understand if they are curious.

In this appendix, I present alternate captions to some of the most important images produced in my study. Visual images are a vital tool when learning new topics so I envisioned a format where a non-science person could flip through my senior project with these alternate captions by their side. The abstract and image captions tell a story in the order I’ve presented them in. Note that once you reach a relevant figure, my proofreaders found it helpful to briefly study the images before reading the caption so that you have some idea of what I am talking about. This appendix is an experiment that may or may not be successful. Please reach out to me if you are confused or need further explanation. Learning physics is hard for everyone. You’ve got this.
Everybody Abstract: The center of our Milky Way galaxy is located more than 200,000 trillion km from Earth in the constellation Sagittarius. At the very center of our galaxy is a super-massive black hole called Sagittarius A*. The black hole is surrounded by many interesting objects, including molecular clouds. Molecular clouds are large, cold clouds of gas in which stars are formed. Telescopes like NuSTAR have observed X-rays (radiation 10,000 times higher in energy than visible light) coming from these molecular clouds. Since cold gas cannot create such high energy emission by itself, there must be some external source of radiation interacting with these clouds. In my senior project, I studied the “Bridge” molecular cloud, which is nearby Sagittarius A*. Using data from 2012, 2016, and 2020, I determined that the brightness of this cloud doubled over the last 8 years. The most likely cause for this change in brightness is that the “Bridge” cloud is reflecting a powerful outburst from the central black hole.

Figure 2.2.1: This flow chart is an overview of my data analysis process. First, “level one” or raw, unfiltered data from the NuSTAR telescope is filtered using a program called “nupipeline.” Then the clean “level two” data can be presented as an image using a program called DS9. The program “nuproducts” converts the data into something usable for spectral analysis. Spectral analysis is one of the central tools of astronomy in which light particles detected by a telescope are sorted into a graph of intensity versus energy called a “spectrum”. The spectrum of a star or molecular cloud tells us many things about the physics and chemistry of that object.

Figure 3.0.1: What you are seeing here is the detector I of the NuSTAR telescope (which is in orbit around Earth as we speak!). Images from X-ray\(^1\) telescopes like NuSTAR are actually count maps. This means that the image we see is actually a map of how many light particles hit the detector in certain areas. For example, the blue areas here could represent 2 light particles collected in that area versus 13 light particles in the areas that are white. These colors are not true to the image, as the region is not actually blue or red or yellow. The color scale at

\(^1\)X-rays are radiation 10,000 times higher in energy than visible light. Human eyes cannot see high energy light particles like X-rays or low energy light particles like radio waves.
the bottom also tells us that bluer regions are the darkest and the yellow and white regions are the brightest. Note that there are two images in this figure because NuSTAR actually has two detectors. This is so we can compare the data between the two to check for accuracy or contamination. The top image is from detector “A” and the bottom image, from detector “B.” The images in Figure 3.0.1 are from an observation in February 2020. The circled area is the important one: this represents a region called the “Bridge” molecular cloud. This particular cloud was the focus of my project. The rectangular areas are called “background regions” and are used to correct the circular “source region” by subtracting background light.

**Figure 3.0.2:** These images are the same images from Figure 3.0.1 but zoomed in to focus on the “Bridge” cloud. Again, the “Bridge” region is circled in green. This circular “source region” is important because I used this region to extract the data relevant to my study. Using a program called “nuproducts,” I am able to isolate only the data from this region to graph in spectral analysis. In these images, we can clearly see that the center of the “Bridge” cloud is brighter than the outer regions (yellow/white = brightest regions).

**Figure 3.0.4:** These four images are of the “Bridge” molecular cloud in October 2012. One reason the “Bridge” looks less bright and exciting in this observation is because data was collected for a much shorter time period than in 2020 (about 7 hours versus 25 hours). However, I confirmed by studying “spectra” that the “Bridge” cloud was much dimmer in 2012 than in 2020. Again, the circular region is the “source region” (the same one was used for all of the data to be consistent) and the rectangles are the unique “background regions” I chose for each observation.

**Figure 3.0.5:** This figure shows what the “Bridge” cloud looked like in October 2016. Again, there are two images because the NuSTAR telescope has two detectors. One reason this is useful is because of contamination. As seen in this figure, the bottom image has significant contamination (the bright yellow region in the top left) that is not present in the top image.
This means a few light particles did not pass through the telescope correctly, adding a bright blob to the picture. These images tell us that the “Bridge” region increased in brightness from 2012 to 2016. Once again, source and background regions are indicated as the circles and rectangles, respectively. These images are also exciting because the black hole at the center of our galaxy (nicknamed Sagittarius A* (pronounced ‘A-star’)) is visible as the bright blob in the bottom right.

**Figure 3.0.6:** These pictures are a zoomed in look at the “Bridge” cloud in 2016. With these images, we can take a closer look at the shape of the cloud. The term for shape in astronomy is “morphology.” Astronomers can learn a lot about the structure and position of molecular clouds by simply studying pictures. One thing I noticed from this observation is that the bright areas of the “Bridge” are in a “v” shape centered in the circle and stretching out to the right. This could be an indication that light is not moving through the cloud in a uniform way due to the density of gas in that area or the cloud’s orientation to the source of the light.

**Figure 4.1.1:** This is an example of a spectrum of the “Bridge” molecular cloud. Notice that the top panel of the graph is sorted in counts/s/keV (keV is an energy unit) or “how many light particles are detected in a certain amount of time” versus the energy of the light particle. The vertical lines are data points while the curvy solid lines are the model. Matching the data points to a model tells us about the physics and chemistry of the cloud. The bottom part of the graph is called the “residual.” This tells me how much the data points agree with the model I’m trying to match the data with. The shape of this graph can also tell us a little bit about the physics of the “Bridge” cloud. For example, there is a peak around 6.4 keV meaning that there are a large number of light particles coming from the cloud with that specific energy. This 6.4 keV peak indicates that iron atoms in the cloud are being bombarded with very high energies and producing “fluorescence.” In general, the downward slope of this spectrum tells us that more light particles are detected at a lower energy (0 to 10) than at a higher energy (20 to 70).
**Figure 5.1.1:** What you are seeing in this figure are two graphs of flux. Flux is a measurement of how much energy passes through a certain area per an amount of time. A (silly) example of flux is the number of geckos that come through your window in an entire day (number/area/time). These graphs show that the amount of light particles coming from the “Bridge” molecular cloud increased from 2012 to 2016 and kept increasing until 2020. The most likely explanation for the increase in flux is that the “Bridge” cloud is reflecting a powerful flare from the black hole at the center of the galaxy Sagittarius A* (pronounced ‘a-star’).
A major part of my senior year has been applying for a Fulbright Grant to go to New Zealand and pursue a diploma in Indigenous studies after I graduate from Bard. I feel that my application essays need to be included here because writing them was difficult: I had to come to terms with what it meant to be a Native Hawaiian woman pursuing a career in astronomy. My identity is many ways is a contradiction.

One particular class at Bard changed everything for me: “Native American History” with the brilliant Christian Crouch. On the very first day of class (second semester of my freshman year), she showed us pictures that represented active colonization of Indigenous land in America. The very last of these was an image of the telescopes up on Mauna Kea. I was confused. For most of my life, those telescopes were a symbol of pride for my small island home. We, on the most isolated island chain in the whole world, were important to the field of astronomy and to the greater pursuit of human knowledge. Yet, in that moment, I was being told that this symbol of pride was not only bad, but morally wrong. That moment in Olin began an internal wrestling match that in some ways culminated in my application to the Fulbright program.
B.1 Personal Statement

About three years ago, I decided to go to college five thousand miles away from home. I am lucky and proud to call Honolulu, Hawai‘i my home since birth and grew up immersed in the unique cultural collision of the Aloha state. My identity as Native Hawaiian, Japanese, and white was never out of place, as the majority of Hawai‘i’s population is mixed race, and the food, culture, and traditions of many ethnicities are embraced as part of our larger local character. Similarly, my new home at Bard College in New York embraced my multiple interests as a musician, actor and theater tech, physics student, and nature lover. Unexpectedly, attending Bard has also helped me understand what it means to be Native Hawaiian.

Throughout my life, I have been fortunate enough to travel regularly with my family both throughout the United States and internationally, to places such as Japan, Cambodia, England, France, and Italy. Surprisingly, this exposure to different people and places did not prepare me for both the culture shock of the East Coast and how little mainland Americans know about my home state. As a first-year, introducing myself in class or to new friends immediately brought a slew of questions, whether on my foreign pronunciation of “Hawai‘i” or concerning the accuracy of Disney’s Lilo and Stitch. I suddenly became an expert on local politics, food, and culture, along with deeper questions about the history of Hawai‘i and annexation. Most questions were easy enough to answer off the top of my head based in my life experiences. However, some topics I simply did not know enough about. Researching the history of the Kingdom of Hawai‘i became a past-time I was extremely passionate about. While the expectation of Hawai‘i expertise was overwhelming, it was also empowering, as when I was younger, I often felt that I was not “Hawaiian enough”: In school I studied Japanese instead of ‘Ōlelo Hawai‘i (Native Hawaiian language), hula lessons were abandoned early on to focus on musical pursuits, and I only really learned how to surf this year during quarantine. But the people at Bard did not seem to care about my qualifications. I am a Hawaiian from Hawai‘i. Simple as that.

My home state of Hawai‘i has long been a significant site for astronomy, as the observing conditions on Mauna Kea are unparalleled. Astronomy is also important to Native Hawaiian
and to broader Polynesian culture as our ancestors were some of the best celestial navigators in the world. Groups of Native Hawaiians have recently demonstrated resistance to the construction of a new telescope on Mauna Kea, the Thirty-Meter Telescope (TMT), physically blocking the road up to the mountain and halting construction of the massive facility. The ki’ai (protectors) called for astronomers to take better care of the sacred mountain and to recognize its cultural and environmental importance to the Hawaiian people. The re-occupation of Mauna Kea during the summer of 2019 was a pivotal moment for me. I felt required to reconcile the deep conflict between two parts of my identity: aspiring astrophysicist and Native Hawaiian wanting to protect her home. More than anything, this event revealed the disconnect between astronomers working on Mauna Kea and the people who are deeply tied to the land these telescopes are located on. Consensus on whether construction of the TMT should continue has not even been reached among Native Hawaiian astronomers over a year after the protests.

The conflict on Mauna Kea helped me realize that I want to connect my two worlds and that my Native Hawaiian background would only enrich my work as an astrophysicist, especially considering Hawai’i’s rich history with astronomy. By increasing the number of Indigenous scientists in America, perhaps instances of conflict can transform into collaboration. When I return to the United States, I hope to become a scientist who has the courage to embrace difference and diversity in thought and background as opportunities for inclusion and innovation.

B.2 A Theory of Uniqueness: Embracing Indigeneity as an Aspiring Astrophysicist (Purpose of Grant Statement)

One of the most important lessons I have learned as an undergraduate physics student is the importance of community and collaboration, and that diversity of thought is essential to innovation. However, from what I can gather by listening to and interacting with seminar speakers, Bard physics alumni, and inspiring astrophysicists on social media, as well as by reading STEM diversity studies, the physics world is not yet one happy family. Issues such as gender and racial discrimination are still prominent, one example being the huge underrepresentation of Black,
Latinx, and Indigenous women in the field. According to a survey conducted by the Pew Institute in 2017, only 15% of astronomers and physicists in America are women. Out of that 15%, a tiny fraction are women of color (Funk & Parker). As a woman with both Native Hawaiian and Japanese ancestry, these numbers are daunting, yet also encouraging, as I have the opportunity to change that representation by pursuing a career as an astrophysicist.

As I continue to work in the field of astrophysics, my unique perspective as Native Hawaiian is important to bring to the table, especially in light of the recent conflict over construction of the Thirty-Meter-Telescope (TMT) on Mauna Kea. Some scientists from Hawai‘i already integrate Hawaiian values such as aloha ʻāina (deep love of the land) and kuleana (responsibility and privilege) into their work (Hosoda). Amplifying this approach throughout the United States and the world will contribute to a more inclusive and intellectually rich scientific culture. I also believe that astrophysical experiments would be enhanced through collaboration with Kānaka Maoli (Native Hawaiians). In January, the 235th meeting of the American Astronomical Society was held in Honolulu, Hawai‘i. I was fortunate to attend the meeting’s public lecture, “Physics of Pō,” which compared modern cosmology with the Kumulipo, the Hawaiian creation chant. Amazingly, the lecturers revealed several parallels between two seemingly unrelated stories of the evolution of our universe. This talk, along with the conflict over the TMT, inspired me to imagine a scientific culture that embraces indigeneity.

Therefore, I propose to pursue a Postgraduate Diploma in Indigenous Studies at the Victoria University of Wellington in Wellington, New Zealand during the 2022 school year. Through this program, I will gain the knowledge and skills necessary to understand both the friction and intersections between Western science and Indigenous wisdom. Classes such as “Indigenous Theories” and “Research as Praxis: Indigenous Perspectives,” will help me critically understand these differences. Not only is it important to embrace the Indigenous perspective when considering conflicts over land use, as on Mauna Kea, but it is also crucial to understand ethical implications. In my first trimester, I will take the courses “Indigenous Theories” and “Theory and Methods in Pacific Studies.” During the second trimester, I will enroll in “Research as
Praxis” and “Project in Indigenous Studies,” in which I will look closer at the specific instances of science versus Pacific peoples and present potential solutions for conflicts, such as the TMT on Mauna Kea. Additionally, I hope to collaborate with Dr. Pauline Harris and Dr. Ocean Mercier, faculty at the University of Wellington whose research focuses on connecting their Indigenous heritage with Western science. I also hope to connect with Dr. Emalani Case, a Native Hawaiian professor and activist, with regards to her involvement in the TMT protests.

My liberal arts education at Bard College has prepared me with both physics courses and classes related to Indigenous studies. Each semester at Bard, I have enrolled in courses which require writing research or analytical papers. Some of my favorite classes have been related to Indigenous studies and human rights, including “Native American History,” “Women’s Rights, Human Rights,” and “Photography and Empire,” which were especially eye opening to the historical role of Indigenous peoples in Western society. Further study at the University of Wellington will help me to understand what it means to be Indigenous in academia today. Additionally, in 2018 I participated in drug prevention research in my hometown of Honolulu as a National Institute for Drug Abuse summer intern. The Ho‘ouma Pono Drug Prevention Project is a curriculum designed for rural Native Hawaiian middle school students. Our group’s task was to evaluate the efficacy of the curriculum, which is based in traditional Hawaiian knowledge, language, and values. This experience was pivotal not only because I participated in scientific research for the first time, but also because the project allowed me to give back to my community and gain experience in qualitative research. As an intern on the Ho‘ouma Pono Project, I learned to transcribe interviews and analyze them through the consensus coding process. These skills will be useful during the “Project in Indigenous Studies” course I intend to take as I hope to conduct surveys regarding public opinion on conflicts between Indigenous peoples and scientific pursuits.

While studying in Aotearoa (New Zealand), I will gain perspective on the intersection of my identities. The Indigenous Māori people of Aotearoa are close cousins of the Native Hawaiians. In fact, the modern cultures of both New Zealand and Hawai‘i similarly blend native and Western
values and customs. One example is that both ‘Ōlelo Hawai‘i (Hawaiian language) and te reo Māori (Māori language) are used widely alongside English in both places. From the outside, it seems that the relationship between non-native and Māori people in New Zealand is navigated more smoothly than in Hawai‘i or in other places in the United States. One significant historical difference is that the Māori people actually have a treaty with the British government, unlike Kānaka Maoli. This treaty, the 1840 Treaty of Waitangi, informs Māori-Pākehā (New Zealanders of European descent) relations to this day (Sorrenson). By living in Aotearoa and by interacting with both Māori and Pākehā, I will investigate this balance and perhaps understand cultural improvements that can be implemented in Hawai‘i and throughout America.

In the future, I hope to be a bridge between Native Hawaiian communities and the astronomers who work on Mauna Kea. These skills could also be applied more generally, with other Indigenous or minority groups. I was immediately drawn to the University of Wellington because the university promotes te reo Māori by incorporating both English and Māori names for course names, professorial positions, and more. Additionally, the university adopts statutes to uphold principles such as Māori governance and self-determination codified within the Treaty of Waitangi. They also established the first marae (family/tribe meeting ground) on a university campus as the center of Māori student life. When I become a professor, I could advocate for similar measures at my institution and elsewhere. Indigenous studies at the Victoria University of Wellington will help me bring an empathetic and receptive approach to my work as an astrophysicist by reminding me that scientific knowledge belongs to everyone, especially Indigenous peoples like the Māori and Native Hawaiians.

Bibliography:


Bibliography


