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1. Introduction and Background

Ever since their discovery, cosmic rays have been studied extensively. They consist of mostly protons and helium ions (but also heavy nuclei) and reach energies up to 10^{21} eV. At energies below $\sim 10^{15}$ eV, cosmic rays are thought to be of Galactic origin.

The most promising sources of Galactic cosmic rays are supernova remnants (SNRs). They are not only energetically favorable but also provide a mechanism to accelerate particles to very high energies. In SNRs, charged particles may gain energy by repeatedly crossing the shock (Bell 1978b; Blandford & Ostriker 1978; Drury 1983). The process is thought to be facilitated by scattering off magnetic turbulences downstream and magnetic irregularities upstream (Blandford & Eichler 1987). Such diffusive shock acceleration (DSA) naturally leads to a power-law distribution of particles, which is seen for cosmic rays.

Evidence for the existence of high-energy electrons in SNRs first came with the detection of non-thermal emission in the radio and later in X-rays (e.g., Koyama et al. 1995; Bamba et al. 2000; Slane et al. 2001). There is clear evidence for the existence of high-energy electrons within these objects, which usually produce thin X-ray “filaments” associated with shocks (e.g., Gotthelf et al. 2001; Hwang et al. 2002; Long et al. 2003; Rho et al. 2002). The X-ray spectra of the filaments are consistent with synchrotron emission from particles as they move in an amplified magnetic field (e.g., Berezhko et al. 2002; Vink & Laming 2003; Berezhko & Völk 2004; Araya et al. 2010).

2. Objectives

Despite all the findings that link SNRs with high-energy electrons, direct evidence for the acceleration of ions by these objects is still lacking. In order to find a signature for hadronic acceleration, studying the photon spectrum of the sources at gamma-ray energies becomes fundamental. It is expected that at least a fraction of the emission at high energies would be caused by the decay of neutral pions, which should be produced through collisions of accelerated hadrons with cold ambient protons and ions. Other mechanisms can also contribute to the gamma-ray spectrum besides hadronic interactions. The high-energy electrons that are responsible for the synchrotron emission at radio and X-ray wavelengths can upscatter ambient photons to TeV energies; and interactions between these electrons and other charged particles result in bremsstrahlung emission, which can also contribute to the emission in the GeV-TeV range. It then becomes important not only to obtain observations in the gamma-ray regime but also to model the broadband leptonic emission in detail, in order to separate and quantify the hadronic contribution, if present. The main goals of this proposal are:

a) Contribute to answering the century-long question on the origin of Galactic cosmic rays.
b) Look for gamma-ray emission from unidentified sources to establish associations with SNRs.
c) Model the spectral energy distribution (SED) of the high-energy observations to constrain cosmic ray properties.
d) Carry out population studies of gamma-ray SNRs to better understand their properties.

3. Methodology

An important window of observations, with improved energy and angular resolution, mainly in the range from ~100 MeV to 300 GeV, has been opened with the launch of the *Fermi* observatory (Atwood et al. 2009). *Fermi* LAT (Large Area Telescope) data between the beginning of the mission, 04 August 2008, to the present is analyzed (refer to http://fermi.gsfc.nasa.gov/ssc). See Section 7 for a description of the Fermi LAT instrument.

Standard selection criteria are applied to the data selecting *Source* class events and a reconstructed zenith angle less than 100° to avoid contamination from gamma rays from Earth's limb. Recommended time intervals for data analysis are selected with the standard criteria (DATA QUAL==1) && (LAT CONFIG==1) && ABS(ROCK ANGLE)<52. The spectral analysis is restricted above 200 MeV due to uncertainties in the effective area and broad point spread function (PSF) at low energies, and below 100 GeV due to limited statistics. However, some of these selection criteria may vary depending on the specific region or source analyzed, this will be discussed later.

Events within a square region of $14^{\circ}\times14^{\circ}$ of the SNR's catalogued position are used in the analysis to account for the large PSF. The emission model from this region includes the positions and spectral shapes of the point sources reported in the LAT 4-year Source Catalog. The recently released Galactic diffuse emission model (*gll_iem_v05 rev1.fit*) is used to account for the local extended background. This model corrects for anomalously low molecular hydrogen emisivities used in previous models, which improves the quality of the analysis mostly for Galactic sources in the longitude range l = 70° to l = 300°. With the new Galactic background model, a considerable level of background emission that was previously unaccounted for is found to be particularly important near and at the SNR position. The isotropic extragalactic file *iso_source_v05.txt* is also used in the background model.

Spectral parameters of sources located beyond 10° of the SNR position are kept fixed to the values reported in the catalog. The fit is performed with the optimizer NEWMINUIT until convergence is achieved.

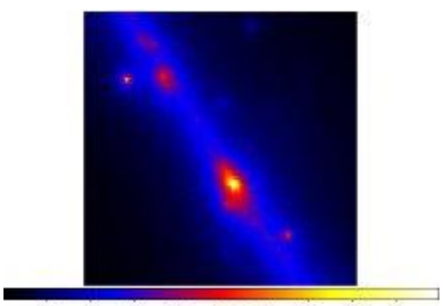
The spatial and spectral properties of LAT sources are obtained by means of a maximum likelihood analysis using the tool *gtlike*, which estimates the probability of obtaining the data given a source model and fits the parameters to maximize this probability (see http://fermi.gfsc.nasa.gov/ssc/data/analysis/scitools/binned_likelihood_tutorial.html). A previously detected *Fermi* source which might be seen towards the interior of the SNR may not be included in the analysis. The resulting model is referred to as the null hypothesis. On the other hand another nearby gamma-ray source, for example that lies at 1.4° from the SNR center but outside of the edge of the radio image and which has been associated with a background galaxy, may be treated as a background source.

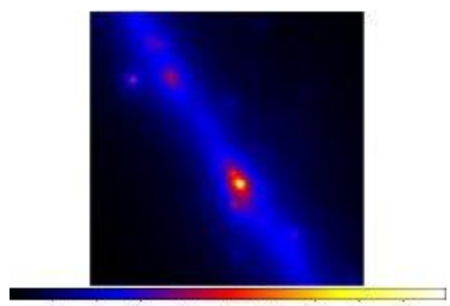
The significance of a source is estimated by the test statistic (TS) defined as

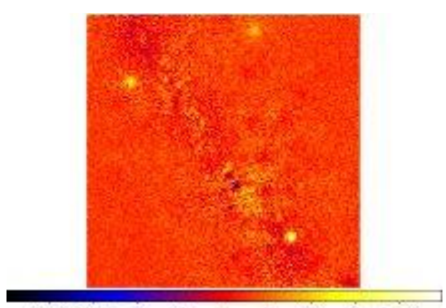
$-2 \log(L_0/L)$, where L_0 and L are the maximum likelihood values for the null hypothesis and for a model including the additional source, respectively (Mattox et al. 1996). For large number of counts the detection significance of the source is given by $\sqrt{TS}$ (however see Protassov et al. 2002, for some caveats).

The same methodology as described above for analyzing the gamma-ray emission from known sources will be used in detecting previously undiscovered gamma-ray sources. In order to probe for new gamma-ray sources in the data, a 'residuals map' is obtained above 1 GeV to take advantage of the narrower PSF at higher energies. The map is obtained by subtracting the observed counts map from the model map, which is constructed with the resulting likelihood fit to the data. Extended excess emission may be apparent.

Among the candidate new sources is G1.9 + 0.3, the youngest galactic SNR with an age of ~150 - 220 years. Following are displayed, respectively, the counts map, model map, and resulting residuals map. Excess gamma-ray emission is apparent:



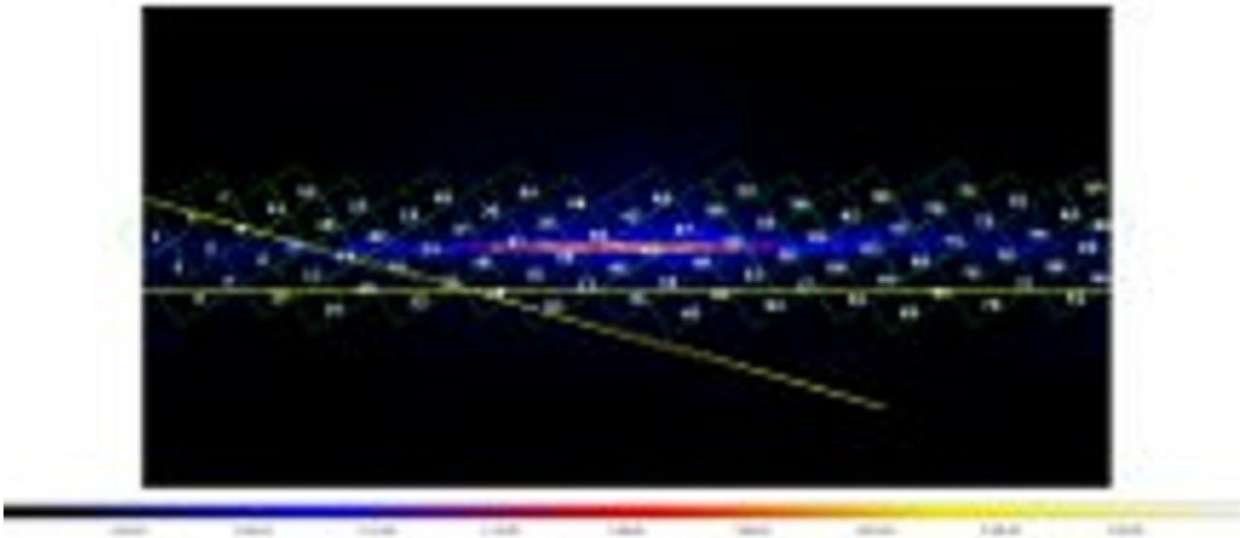


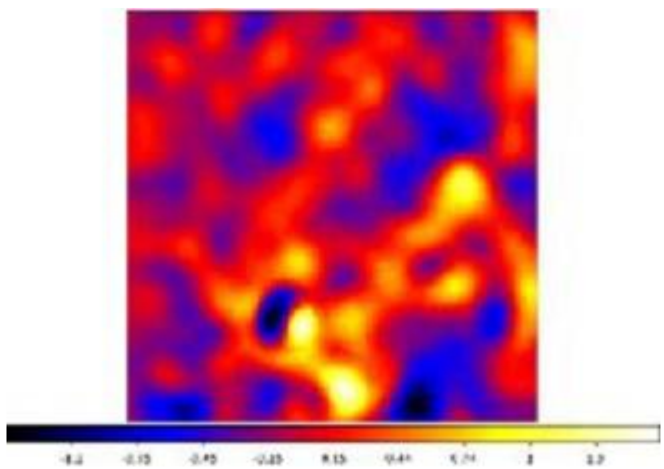


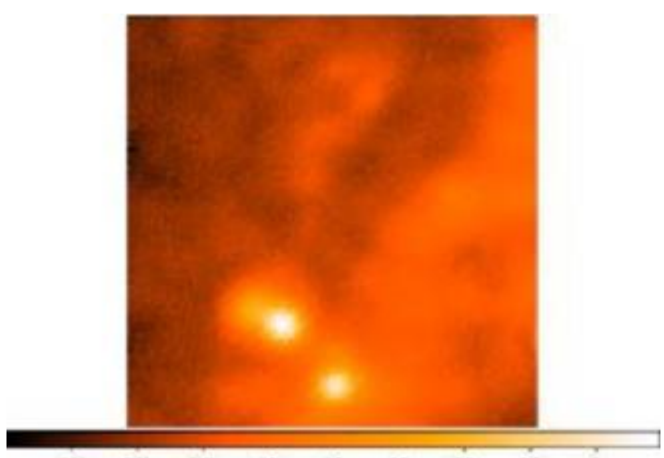
The parameter values resulting from the fit to the data are given below for the gamma-ray source, 2FGLJ1747.3-2825c, which is located the closest to the cataloged position of G1.9 + 0.3:

```
>>> like2.Ts('_2FGLJ1747.3-2825c')

1766.4122241809964


>>> like2.model['_2FGLJ1747.3-2825c']
   2FGLJ1747.3-2825c

_


    Spectrum: LogParabola
  155                    norm: 9.366e+00 2.818e-01 1.000e-04    1.000e+04( 1.000e-12)
  156                   alpha: 2.506e+00 2.882e-02 0.000e+00    5.000e+00( 1.000e+00)
  157                    beta: 3.870e-01 2.070e-02 0.000e+00    1.000e+01(1.000e+00)
  158                      Eb: 1.821e+03 2.276e+01 3.000e+01    5.000e+05( 1.000e+00)


>>> like2.flux('_2FGLJ1747.3-2825c',emin=200,emax=100000)

1.2440468812903987e-07


>>> like2.fluxError('_2FGLJ1747.3-2825c',e min=200,e max=100000)

5.9481207747162876e-09
```

A systematic study of all the galactic emission will be undertaken by subdividing the Galaxy disk into 86 regions, and doing a gamma-ray analysis of each region. A residuals map of the galactic plane will be made upon which will be plotted the positions of all the SNRs known. Following are displayed, respectively, the Galactic disk subdivision, the Region 1 residuals map, and the WMAP radio map. Correlation between the latter two is apparent:







4. Scope

The data points obtained from the observations are used to construct the SED. Combining archival data taken at radio and infrared wavelengths with state-of-the-art measurements at X-ray energies, a broadband SED is assembled over a broad spectral range from radio to gamma-ray, for modeling to obtain evidence for cosmic ray acceleration.

There are different models for different SNRs to explain their gamma-ray emission. The gamma-ray spectrum may be explained with inverse-Compton scattering (IC) alone, with both bremsstrahlung and IC, or with either a leptonic model (IC) or a hadronic model (pion-zero production). There is uncertainty about the nature of the gamma rays, because usually two or three different models can be used to fit the data. One of the problems that causes this is that much information about the parameters of the SNRs (such as age, density, magnetic field, ambient environment, etc.) are unknown, and even in some cases where these parameters are well-known, such as SN 1006 or Cas A, the model can still be leptonic or hadronic or a combination of both. The ideal case is to find a SNR whose emission can only be accounted for by a hadronic scenario.

To illustrate this, following are SED plots and the model fits to the data of current results from analyses of the SNR HB9 (Araya 2014), and the methodology of using new X-ray data to constrain the uncertainty about the nature of the gamma rays in the form of a currently submitted proposal to observe HB9 in the X-ray regime for comparison with gamma-ray data.

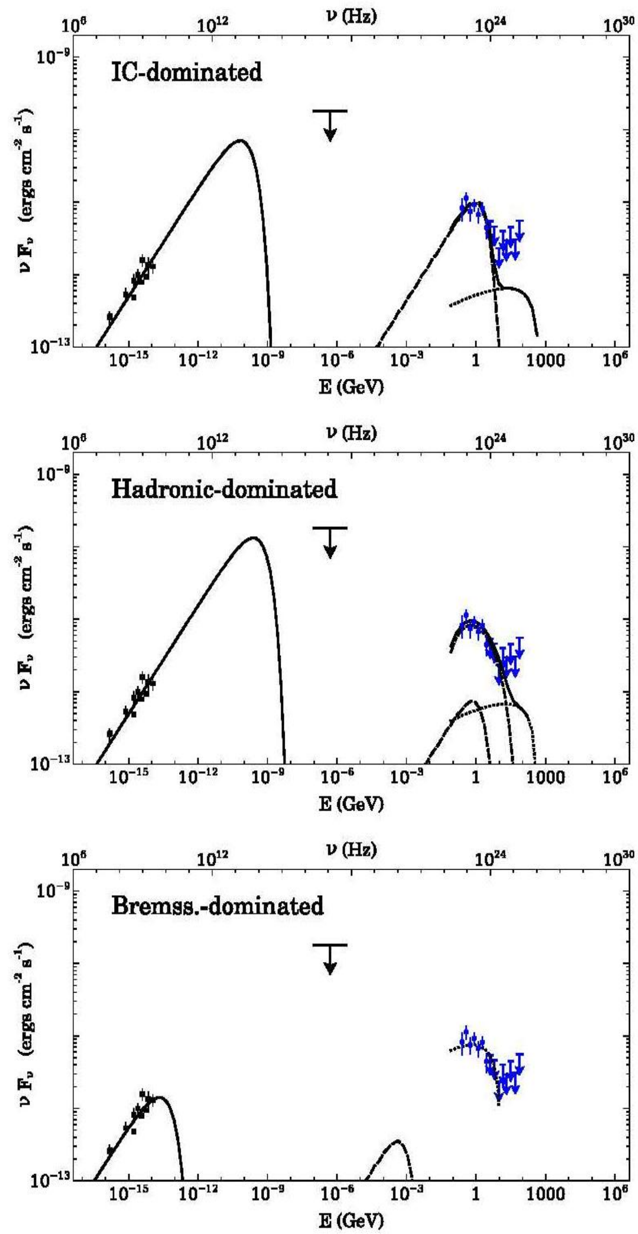


Fig. 2.— Emission scenarios for the broadband SED of HB9. The components are: synchrotron (solid line), IC-CMB (dashed line), non-thermal bremsstrahlung (dotted line), neutral pion decay (dash-dotted line) and total gamma-ray emission (solid line in the IC and hadronic scenarios). Blue circles are obtained from the LAT observation in this paper. Upper limits at the 95% confidence level are shown for intervals with no source detection.

New data acquired from current-generation satellite observations such as Swift XRT and XMM-Newton will be used for comparison with Fermi Lat data, and to further constrain SNR environment and plasma properties previously determined from Fermi Lat observation, as exemplified by the following recently submitted proposal for observing on the Chandra X-ray Observatory. See Section 7 for descriptions of the XRT, XMM, and Chandra ACIS-S instruments.

EXPLORING THE PROPERTIES OF THE GAMMA-RAY SOURCE HB9

PI: L. Larry

1. Abstract

Gamma-ray emission from the supernova remnant (SNR) HB9 has been discovered recently by the *Fermi* satellite. Little is known about the properties of its environment and X-ray-emitting plasma. The SNR's non-thermal radio emission shows a shell-type morphology, and a centrally brightened morphology in X-rays revealed by the ROSAT Observatory. No currently operating X-ray observatories have observed the shell of this SNR, whose plasma properties are important for understanding the origin of the gamma-ray emission. We propose this observation to constrain the plasma properties and the SNR's environment.

2. Description of the Proposed Program

A) Scientific Rationale:

X-ray observations of shell type supernova remnants (SNRs) have always been one of the best available tools to understand the properties of their environment and ejecta. Both young SNRs (such as the well-studied historical remnants, Cas A, Tycho's SNR, Kepler's SNR) as well as more evolved SNRs (such as the Cygnus Loop or IC 443) are known X-ray sources. Historical SNRs are sources of synchrotron and thermal X-rays, while older SNRs emit mostly thermal photons in the X-ray band.

The fast shocks of SNRs heat the circumstellar and ejecta material to very high temperatures, resulting in the emission of thermal X-rays. The X-ray spectrum from an SNR carries significant information about the temperature and ionization state of the plasma, the density distribution of the postshock material, and the composition of the ejecta. The study of these properties, in turn, gives information about the environment into which the SNR is expanding, the type of progenitor star and the effects of particle acceleration on the shock's dynamical evolution. The thermal X-ray emission comes from a bremsstrahlung continuum and line emission from recombination in the ionized gas, and can originate behind the forward shock, where circumstellar or interstellar material is swept-up and heated, or in the interior of the remnant, where the ejecta is heated by the reverse shock (see, e.g., Vink 2012).

SNRs are considered to be the main sources of Galactic cosmic rays, high-energy particles (mostly protons) that populate the Galaxy and arrive from every direction in the sky. These particles are thought to gain their energy by the mechanism of first order Fermi acceleration in the shocks of SNRs (Bell 1978; Blandford & Eichler 1987). High-energy electrons in SNRs are studied indirectly by observing their non-thermal photon spectrum from radio to gamma rays (e.g., Gaisser et al. 1998), while direct evidence for the acceleration of protons and ions could be obtained from a hadronic gamma-ray signal. Despite the new wealth of data obtained by the gamma-ray satellite *Fermi,* it has been difficult to completely discard or confirm a leptonic origin of the high-energy photons, although the spectrum of some sources, such as the famous SNR Cas A, as well as those of IC 443 and W44, might be better accounted for by hadronic processes (Araya & Cui 2010; Ackermann et al. 2013, respectively).

Statistical studies of the population of gamma-ray SNRs have also been inconclusive. These sources seem to be of three kinds: (a) young with strong non-thermal X-ray emission, (b) old SNRs interacting with molecular clouds, and (c) remnants of intermediate age such as the Cygnus Loop (Katagiri et al. 2011) or perhaps HB9 and PKS 1209-51/52 (Araya 2014, Araya 2013, respectively).

A great deal of the uncertainty regarding the nature of the gamma-ray emission from SNRs comes from a lack of knowledge of the properties of a SNR's environment and ejecta, such as their densities and magnetic field, as well as the dynamical structure and evolution of the exploded material. This is where X-ray observations of SNRs become so important and it is the reason why we propose to carry out a Chandra ACIS-S observation of the shell of HB9, including the ejecta and shock position, and which has never been seen before with the current generation of X-ray satellites. This region is a potential cosmic-ray source. Gamma rays possibly produced in the shell of this object have recently been discovered (Araya 2014), and it is known that this site is also the source of non-thermal radio emission and thermal X-rays (Leahy 1987; Leahy & Roger 1991; Leahy & Aschenbach 1995). The gamma-ray SED of HB9 is not flat as is that of PKS 1209-51/52 and the hadronic scenario for the emission requires the local proton density near the shock to be ~ 1.2 cm^{-3}. A non-thermal bremsstrahlung scenario for the gamma rays requires similar densities of

~ 1 cm^{-3}, which might be in conflict with previous X-ray observations (~ 0.05 cm^{-3}; Leahy & Aschenbach 1995).

The instrument ACIS-S, onboard Chandra, has ideal resolution to study extended X-ray sources, such as the shell of a SNR, and its spectral resolution would allow us to constrain the plasma properties in the shell, close to the forward shock, in the appropriate energy range. The X-ray emitting plasma near the shocks in SNRs is typically in a state of nonequilibrium ionization (Itoh 1977), which depends on the temperature and ionization timescale. Older plasma in SNRs might be better described by a Raymond-Smith model (Raymond & Smith 1977). The X-ray spectrum of shocked circumstellar medium yields the abundance of elements which can be used to infer the swept-up mass and remnant's age (Chevalier 2005). X-ray observations also give information on the plasma temperature, which can be compared to that derived from the shock velocity and thus if a lower temperature is observed, the amount of shock energy that is transferred to cosmic rays (Hughes 2000), as expected in models of particle acceleration, can be inferred. These constraints can be compared to the required energy in the particles to explain the gamma-ray fluxes discovered recently from HB9. The morphology of the X-ray emission is also important for studies of cosmic-ray content in SNRs, as seen in the remnant Tycho, where the distance between the forward shock and the contact discontinuity, observed in X-rays, is much smaller than predicted by models of dynamical evolution, unless some energy has been lost to some non-thermal process (Warren et al. 2005).

B) Immediate Objectives:

Even though our objective is related to understanding the origin of the gamma-ray emission from this source, we are proposing an ACIS-S observation of part of the shell and forward shock of the SNR HB9, in a region where *ROSAT* has shown that the X-ray emission peaks, as well as the non-thermal radio emission, where at least part of the extended gamma-ray emission observed by *Fermi* might be originated.

The goal of the proposed study is to obtain good quality spectra of the ejecta and shocked material, which will be modeled to gain information on unknown plasma properties, such as density, temperature and amount of plasma energy, which define crucial aspects of a SNR relevant to understanding the process of cosmic-ray acceleration. Obtaining images of the selected regions will also be useful for morphological studies of the emission.

A spatial study of the radio emission in the band 408-1420 MHz has shown that synchrotron emission from the center of the shell is softer than that from the outer shell (Leahy & Tian 2007). The proposed study will determine spatially-dependent particle acceleration and so draw definitive conclusions regarding any possible variation of the flux level or of the spectral parameters across the source.

HB9 is believed to be located near the molecular clouds Sh217 and Sh219 (Leahy & Roger 1991), but no definitive interaction with a molecular cloud has been claimed. The proposed study will determine possible interactions with these HII regions which could provide target material for cosmic-ray collisions for both the hadronic and bremsstrahlung scenarios, and as a result be responsible for an enhancement of gamma-ray emission.

3. Justification of Requested Observing Time, Feasibility, and Visibility

We are proposing an ACIS-S observation of the SNR: an elliptical shaped (~ 90' east-west by 30' north-south) region of the shell of the SNR centered on coordinates RA (J2000) = 4h 56.4m, Dec (J2000) 46deg 19', where Einstein IPC X-ray observations of HB9 (Leahy 1987) show it to be brightest. The desired ACIS-S mode is the Timed Exposure (TE) mode (20 ks observation). Figure 1 shows a simulated spectrum, fitted with a Raymond-Smith model, and obtained with a 20 ks ACIS-S observation. The expected (absorbed) ACIS-S count rate and flux is (with 90% confidence level errors) ~ (1.9±0.3) counts s^{-1} and (1.3±0.4) × 10^{-10} ergs cm-2 s^{-1}, respectively. In Fig. 1, interstellar absorption is taken into account with a fixed column density of 3 × 10^{21} cm^{-2}, the model assumes standard abundances and the plasma temperature can be constrained to be ~ 0.8 keV (90% c.l.).

Due to the relatively high expected count rate, the overall significance of the detection will be high (> 10σ), and the background levels negligible. After fitting the thermal X-rays with several plasma models (such as the Raymond model shown in Fig. 1), an idea of the elemental abundances and temperature would be used to infer the amount of mass involved (such as the swept-up mass) and the cosmic-ray energy, which are important to compare with the values inferred from the gamma-ray observations and thus understand the origin of the high-energy emission from this object.

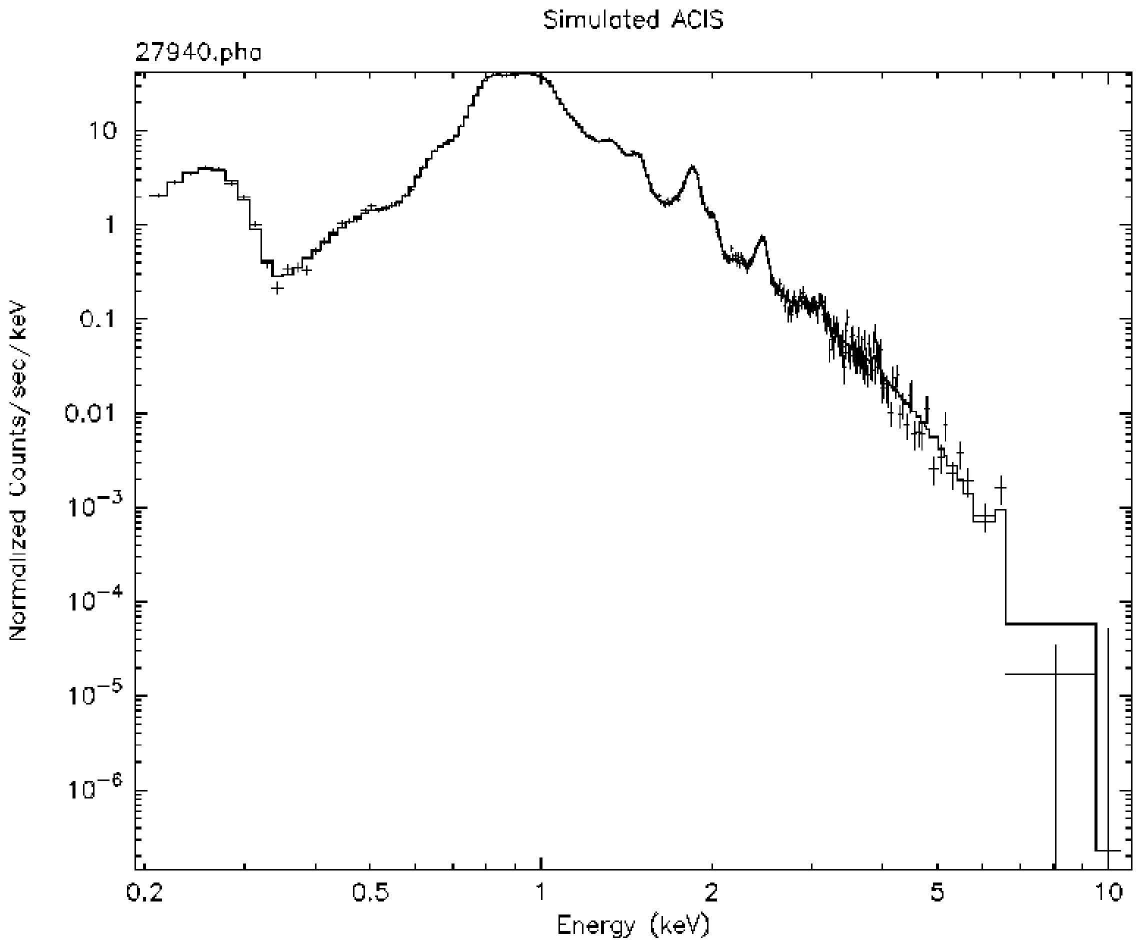


Figure 1: Expected ACIS-S spectrum of the southwestern shell of HB9 with a fit to a Raymond-Smith model (Raymond & Smith 1977) for X-ray emitting plasma with standard abundances and interstellar absorption.

5. Project Schedule

Data collection	August 2015 to February 2016
Data analysis	March 2016 to September 2016
X-ray data analysis	October 2016to June 2017
Radio data collection	July 2017 to September 2017
SED modeling	October 2017 to December 2017
Obtaining results	January 2018 to May 2018
Conclusions	June 2018 to August 2018

6. Work Abroad

HAWC (High-Altitude Water Cherenkov Observatory) is an international gamma-ray collaboration including INAOE (National Institute of Astrophysics, Optics and Electronics) and CINESPA (Center for Space Research). The facility is designed to observe TeV gamma rays and cosmic rays with an instantaneous aperture that covers more than 15% of the sky. With this large field of view, the detector will be exposed to two-thirds of the sky during a 24-hour period. HAWC will be used to perform a high-sensitivity synoptic survey of the sky at wavelengths between 100 GeV and 100 TeV. My advisor works as a member of the collaboration and I will have the opportunity to work at INAOE or HAWC for a semester abroad.

7. Resources

The Fermi Large Area Telescope (LAT), the primary instrument on the Fermi Gamma-ray Space Telescope (Fermi) mission, is an imaging, wide field-of-view, high-energy γ-ray telescope, covering the energy range from 20 MeV to more than 300 GeV. The LAT is a pair-conversion telescope; individual γ-rays convert to e +e − pairs, which are recorded by the instrument. By reconstructing the e +e − pair the energy and direction of the incident γ-ray are deduced. Accordingly, LAT data analysis is entirely event-based: each incident particle are recorded and analyzed separately.

The *Chandra* X-Ray Observatory (*CXO*), combines an efficient high-resolution (≤ 1/2 arcsec) X-ray telescope with a suite of advanced imaging and spectroscopic instruments. *Chandra* was designed to provide order-of-magnitude advances over previous X-ray astronomy missions with regards to spatial and spectral resolution. The Advanced CCD Imaging Spectrometer (ACIS) offers the capability to simultaneously acquire high-resolution images and moderate resolution spectra. The instrument can also be used in conjunction with the HETG (High Energy Transmission Grating) or LETG (Low Energy Transmission Grating) to obtain higher resolution spectra. ACIS contains 10 planar, 1024×1024 pixel CCDs; four arranged in a 2×2 array (ACIS-I) used for imaging, and six arranged in a 1×6 array (ACIS-S) used either for imaging or for a grating spectrum read-out. Two CCDs are back-illuminated (BI) and eight are front-illuminated (FI). The response of the BI devices extends to energies below that accessible to the FI chips. The chip-average energy resolution of the BI devices is better than that of the FI devices.

Swift is a first-of-its-kind multi-wavelength observatory dedicated to the study of gamma-ray burst (GRB) science. Its three instruments work together to observe GRBs and their afterglows at gamma-ray, X-ray, ultraviolet (UV), and optical wavelengths. The XRT is a narrow-field focusing X-ray telescope that localizes a GRB to approximately 2–3 arcseconds and performs imaging and spectroscopy in the 0.2 - 10 keV band (Burrows, et al. 2005, SSRv, 120, 165). It is designed to measure the fluxes, spectra, and light curves of GRBs and their afterglows over a wide dynamic range covering more than seven orders of magnitude in flux. The XRT will pinpoint GRBs to 5-arcsecond accuracy within ten seconds of target acquisition for a typical GRB, and will study the X-ray counterparts of GRBs beginning 60-80 seconds after the burst discovery and continuing for days to weeks.

The X-ray Multi-Mirror Mission, XMM-Newton, is designed specifically to investigate in detail the X-ray emission characteristics, i.e. the emission distributions, the spectra and the temporal variability, of cosmic sources down to a limiting flux of order 1E-16 erg/(s cm^2). With its high throughput and moderate angular resolution, XMM-Newton is extremely sensitive to low surface brightness X-ray emission.

The Solar Radio Observatory will use radio observations to study CO line emission from Molecular Clouds which might be interacting with SNRs. In some cases, it may be possible to study the radio emission from the SNRs themselves. The project will involve participation in the engineering design development phase to meet the requirements of the anticipated science observations, and the eventual use of the antennas for implementation of the science phase.

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