The Nonstandard Properties of a “Standard” PWN: Unveiling the Mysteries of PWN G21.5−0.9 Using Its IR and X-Ray Emission

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Abstract

The evolution of a pulsar wind nebula (PWN) depends on properties of the progenitor star, supernova, and surrounding environment. As some of these quantities are difficult to measure, reproducing the observed dynamical properties and spectral energy distribution (SED) with an evolutionary model is often the best approach to estimating their values. G21.5−0.9, powered by the pulsar J1833−1034, is a well observed PWN for which previous modeling efforts have struggled to reproduce the observed SED. In this study, we reanalyze archival infrared (IR; Herschel, Spitzer) and X-ray (Chandra, NuSTAR, Hitomi) observations. The similar morphology observed between IR line and continuum images of this source indicates that a significant portion of this emission is generated by surrounding dust and gas, and not synchrotron radiation from the PWN. Furthermore, we find that the broadband X-ray spectrum of this source is best described by a series of power laws fit over distinct energy bands. For all X-ray detectors, we find significant softening and decreasing unabsorbed flux in higher energy bands. Our model for the evolution of a PWN is able to reproduce the properties of this source when the supernova ejecta has a low initial kinetic energy $E_{\text{kin}} \approx 1.2 \times 10^{50}$ erg and the spectrum of particles injected into the PWN at the termination shock is softer at low energies. Lastly, our hydrodynamical modeling of the supernova remnant can reproduce its morphology if there is a significant increase in the density of the ambient medium ~1.8 pc north of the explosion center.

Unified Astronomy Thesaurus concepts: Supernova remnants (1667); Pulsars (1306); Infrared astronomy (786); X-ray astronomy (1810)

1. Introduction

Stars with mass $M \gtrsim 8 M_\odot$ are believed to end their lives in a core-collapse supernova event (Baade & Zwicky 1934). In many cases, this produces a highly magnetized and rapidly rotating neutron star (i.e., pulsar). Pulsars dissipate their rotational energy by powering a relativistic outflow of electrons and positrons, commonly referred to as the “pulsar wind”. The expanding magnetic bubble of particles, created by the interaction of the relativistic pulsar wind with the ambient medium, is the pulsar wind nebula (PWN). For young PWNs the ambient medium is the slowly moving supernova ejecta in the host supernova remnant (SNR), but for older PWNs it can also be the interstellar medium (ISM) after the pulsar exits the SNR (Slane 2017). The reader is directed to Slane (2017), Gaensler & Slane (2006), Chevalier (2005), Arons (2004), and Amato (2020) for detailed explanations on PWNs.

As the evolution of a PWN depends on the central neutron star, the composition of the pulsar wind, and its surrounding environment, modeling PWNs allows us to determine the physical characteristics of all components of the system—which are difficult, if not impossible, to determine by other means (e.g., Torres 2017). In addition, evolutionary models allow us to infer properties of the progenitor star and supernova. Furthermore, such models also determine the spectrum of particles accelerated inside these sources, which is needed to determine the currently unknown physical mechanism (Sironi et al. 2013) by which such objects produce some of the most energetic particles observed in the universe.

The modeling is done by generating the dynamical properties and spectral energy distribution (SED), which can be fit against measurements gathered over the entire electromagnetic spectrum. PWN G21.5−0.9 is a bright X-ray-emitting source well-suited for modeling because it has been observed by many telescopes spanning the electromagnetic spectrum. It was initially detected in 1970 (Altenhoff et al. 1970; Wilson & Altenhoff 1970) in the radio band and later observed in the X-ray band in 1981 (Becker & Szymkowiak 1981). Its central pulsar J1833−1034 was detected in 2006 (Camilo et al. 2006) and its measured period $P$ and period-derivative $\dot{P}$ suggest a high spin-down luminosity and a low characteristic age. As a PWN with a circular morphology (Figure 1) associated with a young ($\lesssim10^3$ yr) pulsar, G21.5−0.9 is appropriate for an analysis using “one-zone” models (e.g., Reynolds & Chevalier 1984, see Gelfand 2017 for a recent review).

However, previous attempts to model this system have not succeeded in simultaneously reproducing the radio and X-ray spectra (Tanaka & Takahara 2011; Torres et al. 2014; Hitomi Collaboration et al. 2018). The modeling is further complicated by the discrepant measurement of the X-ray spectrum by three observatories, Chandra, NuSTAR, and Hitomi (Nynka et al. 2014; Hitomi Collaboration et al. 2018; Guest et al. 2019). One such difference is shown in Table 1, where the parameters for the broken power-law model between NuSTAR and Hitomi are in disagreement. Furthermore, the infrared (IR) emission observed from this source (Gallant & Tuffs 1999), often
assumed to be dominated by synchrotron radiation from the PWN (e.g., Tanaka & Takahara 2011; Torres et al. 2014; Hitomi Collaboration et al. 2018), may be contaminated by emission from surrounding gas and dust. To address these concerns, we reanalyzed archival IR and X-ray observations of this source.

This paper is structured as follows. In Section 2 we describe the IR and X-ray observations and the detector-specific data reduction and analysis of PWN G21.5−0.9. In Section 3 we describe our piecewise power-law fitting approach to analyze the X-ray spectra and present our results. In Section 4 we discuss the implications of these results in our modeling for this source. We summarize our findings in Section 5.

2. Observations and Data Analysis

In this section, we describe our analysis of archival IR (Herschel, Spitzer—Section 2.1) and X-ray (Chandra—Section 2.2, NuSTAR—Section 2.3, and Hitomi—Section 2.4) observations of this source.

2.1. Infrared Observations

G21.5−0.9 was observed with the Photodetector Array Camera (PACS) Integral Field Unit (IFU) Spectrometer (Poglitsch et al. 2010) aboard the Herschel Space Observatory on 2013 April 7. The range spectroscopy mode was used to cover the [O I] 63.2 μm and 145.5 μm, [O III] 88.4 μm, and [C II] 157.7 μm emission lines. The total field of view of one IFU pointing is 47′′ × 47′′, consisting of 25 spaxels. In order to cover the entire PWN in G21.5−0.9 we obtained a 2 × 2 IFU mosaic of the source, as well as a single-pointing off-source background observation for each line. The IFU cubes were analyzed using HIPE version 15.0.1 (Ott 2010). The analysis included trimming of the spectral edges and a subtraction of the baseline continuum obtained by a two-degree polynomial fit across the line-free spectral region. While narrow background lines were detected in the baseline-subtracted and spatially integrated spectrum of the off-source IFU pointing, both narrow and broad lines were detected in the IFU cubes centered on the PWN. The broad lines have an FWHM of 850 km s⁻¹ for the [C II] 157.7 μm line and 1000 km s⁻¹ for the [O I] 63.2 μm line and likely arise from SN ejecta material. The corresponding ejecta velocities are then 425 ± 75 km s⁻¹ and 500 ± 20 km s⁻¹, respectively. If the observed line emission arises predominantly from ejecta with a low tangential velocity, the expansion velocity measured from the lines would represent a lower limit on the true velocity, which could be up to a factor of two higher, giving a range of expansion velocity between 350 and 1000 km s⁻¹. In a radiative shock, the emission that we observe likely arises from densest material at the contact discontinuity, in which case the observed velocity represents the expansion velocity of the PWN rather than the free expansion velocity of the ejecta. However, since the shock velocities that produce the IR lines are relatively low, the free expansion velocity of the ejecta material at the PWN boundary is within a similar range.

We produced emission line maps of the [O I] 63.2 μm and [C II] 157.7 μm ejecta lines by integrating the spectra across the broad-line component, while excluding the narrow line that arises from the background emission. The maps are shown in Figure 2 with the X-ray contours from the PWN overlaid in white.

Total IR flux densities of the PWN region in G21.5−0.9 were estimated from the images obtained with the Infrared Array Camera (IRAC) and Multiband Imaging Photometer (MIPS) aboard Spitzer (PID 3647, PI: Slane), and the Photodetector Array Camera and Spectrometer (PACS) and Spectral and Photometric Imaging Receiver (SPIRE) instruments aboard Herschel (ObsID 1342218642), spanning a wavelength range between 3.6 and 500 μm. For the MIPS, PACS, and SPIRE images, we extracted the total flux densities using an aperture centered on the PWN with a radius of 41′′5 and a background annulus with inner and outer radii of 41′′5 and 74′′0, respectively. The IR images and the extraction aperture are shown in Figure 3 and total flux densities are listed in Table 2. The IR background annulus slightly overlaps with the northern enhancement detected in X-rays (see Figures 1 and 4). However, as little to no IR emission is detected from this feature, its inclusion in the background annulus should not
significantly affect our analysis. The uncertainties on the flux densities in this case are dominated by the uncertainties of the local background emission. The IRAC images show very faint emission from the PWN, superposed on a dense stellar field. To make a rough estimate of the PWN emission in the IRAC bands, we estimated the surface brightness in a very small region free of stellar sources and assumed that this surface brightness is constant across the entire area of the PWN. The estimated background-subtracted surface brightness values at 3.6, 4.5, 5.8, and 8.0 μm are 0.33, 0.37, 1.6, and 4.0 MJy sr$^{-1}$. The total flux densities were estimated by multiplying by a PWN area of $8.7 \times 10^{-8}$ sr.
2.2. Chandra Observations

Chandra has regularly observed G21.5−0.9 with both its Advanced CCD Imaging Spectrometer (ACIS) and High Resolution Camera (HRC). For this study we reanalyzed ACIS-S observations where G21.5−0.9 fell on the S3 chip, the back-illuminated chip where the best imaging and energy resolution are obtained. A single ACIS chip has a field of view of $8\arcmin \times 8\arcmin$ with an imaging resolution of $\sim 1''$ over the energy range 0.2–10 keV.

Software used for this analysis includes CIAO version 4.10 (Fruscione et al. 2006) and its accompanying Sherpa version (Freeman et al. 2001; Doe et al. 2007), as well as SAOImage DS9 version 7.6 (Smithsonian Astrophysical Observatory 2000; Joye & Mandel 2003).

After querying and downloading 16 ACIS-S observations from the Chandra Data Archive where G21.5−0.9 fell on the S3 chip, error-causing subarray files (ObsIDs 1554, 3693, 10646, 14263, 16420) were deleted.

After analyzing each observation independently, we found that the results for ObsIDs 1230 and 159 deviated significantly from those for all other ObsIDs. Upon investigation, this discrepancy was attributed to these observations being taken with focal plane temperatures of $-100^\circ$C, as compared with $-110^\circ$C or $-120^\circ$C for all the other observations. The accuracy of the temperature-dependent gain correction decreases for temperatures below $-112^\circ$C, so ObsIDs 1230 and 159 were deemed too warm to provide reliable spectral results.

Spectra were extracted for the stack of all 11 remaining observations, summarized in Table 3, over the energy band 0.5–8 keV using the CIAO tool specextract. These spectra were extracted using a 35'' radius circular region covering the entire central PWN as shown in Figure 4.

2.3. NuSTAR Observations and Data Reduction

The Nuclear Spectroscopic Telescope Array (NuSTAR) is a high-energy (3–79 keV) X-ray space observatory consisting of two co-aligned telescopes with detectors placed at each of their focal plane modules (referred to as FPMA and FPMB) (Harrison et al. 2013). Each NuSTAR telescope has a field of view of $12' \times 12'$ with an FWHM of 18'' and a half-power diameter (HPD) of 58''. The FWHM spectral resolution is 400 eV at 10 keV. NuSTAR observed G21.5−0.9 on nine separate occasions for a total of $\sim 383$ ks on each of its two onboard FPM detectors (see Table 4). Of the nine observations, two of them (ObsID 10002014001, 40001016001) were taken in the STELLAR spacecraft mode, making them unsuitable for science observations due to the spacecraft roll maneuver of $\sim 1''$/day as mentioned in the NuSTAR Master Catalog. As such, we did not analyze these observations. In addition, due to

Table 3

| ObsID | Start Time     | Data Mode | Exposure (s) |
|-------|----------------|-----------|--------------|
| 1433  | 1999-11-15 22:31:18 | FAINT     | 14970        |
| 1717  | 2000-05-23 09:24:15   | FAINT     | 7540         |
| 1770  | 2000-07-05 03:42:36   | FAINT     | 7220         |
| 1838  | 2000-09-02 01:09:11   | FAINT     | 7850         |
| 2873  | 2002-09-14 01:09:17   | FAINT     | 9830         |
| 3700  | 2003-11-09 12:20:43   | VFAINT    | 9540         |
| 5159  | 2004-10-27 13:32:57   | VFAINT    | 9830         |
| 5166  | 2004-03-14 22:12:41   | VFAINT    | 10020        |
| 6071  | 2005-02-26 09:08:53   | VFAINT    | 9640         |
| 6741  | 2006-02-22 02:57:52   | VFAINT    | 9830         |
| 8372  | 2007-05-25 12:06:03   | VFAINT    | 10010        |

Figure 4. Chandra images of G21.5−0.9. Images are taken from ObsID 1433 (Table 3). Left: image showing the Chandra source region (green), the Chandra background region (red), and the IR background annulus (yellow). Right: an enlarged view of the PWN.
the short effective exposure time of ObsID 10002014006, we did not analyze this observation. Of the remaining six observations, the previous paper (Nynka et al. 2014) analyzed four (ObsID 10002014003, 10002014004, 40001016002, 40001016001) totaling ~190 ks, but did not analyze two (ObsID 10002014002, 10002014005), which would add an additional ~178 ks. We analyzed six observations, including the two previously unanalyzed, for a total exposure time of ~368 ks on each FPM. As each observation was made by both detectors on NuSTAR, we analyzed a total of 12 data sets.

For all 12 data sets we followed the standard pipeline processing (HEASoft v6.24 (NASA High Energy Astrophysics Science Archive Research Center (HEASARC), 2014) and NuSTARDAS v1.80) as explained in the NuSTAR Data Analysis Software Guide8 prior to spectral fitting. We ran the processing script nupipeline (v0.4.6) with the default options to produce the cleaned and calibrated event files, referred to as “Level 2 Data Products” in the guide. The default pipeline option does not perform any South Atlantic Anomaly (SAA) filtering (done via the command nucalcsaa). While the SAA filter may be required for fainter sources, G21.5–0.9 is a relatively bright source (>1 count per second) and therefore there is likely no need for SAA filtering as mentioned in the official NuSTAR website (Background Filtering9).

Once the cleaned and calibrated event files were created, we generated the associated redistribution/response matrix file (RMF) and ancillary response file (ARF) by running nuproducts (v0.3.3) with the option extended = yes. This option is necessary to generate the ARF appropriate for an extended source.

The source spectrum was extracted using a 177° radius circular region centered on the PWN, and the background spectra were extracted using two rectangular regions away from the source (Figure 5). This conventional background extraction method may induce small uncertainties/fluctuations in the background because the NuSTAR background is known to be nonuniform across its field of view (Wik et al. 2014). However, since G21.5–0.9 is roughly 10 times brighter than the background in most of the energy range for which we do spectral fitting, these background uncertainties should be negligible. We also see no stray light emission from nearby bright X-ray sources in the field of view (FoV) that may contribute to the background during any of the observations. We confirmed that stray light is not an issue during the observations of this source using the NuSTAR Science Operation Center’s NuSTAR constraint check page.10

2.4. Hitomi Observations and Data Reduction

During its mission’s lifetime the Hitomi X-ray observatory (Takahashi et al. 2016) observed PWN G21.5–0.9 as part of its commissioning and verification phase under the observing IDs 100050010–100050040 between 2016 March 19–23. Data were recorded to all four instruments—the Soft X-ray Imager (SXI), the Soft X-ray Spectrometer (SXS), the Hard X-ray Imager (HXI), and the Soft Gamma-ray Detector (SGD). However, during this observing run the effective area of the SXS was reduced and the two SGD detectors were either in their turn-on phase or not recording data (Hitomi Collaboration et al. 2018). Therefore, observations with these instruments are not incorporated in our analysis. We report on the reprocessing...
and reanalysis of the data obtained with the SXI and both HXI detectors in the 0.8–80 keV energy range. The data reduction was performed following the Hitomi step-by-step analysis guide version 6.1, using the Hitomi software version 6, as incorporated in version 6.26.1 of the HEAsoft tools.11 Updated calibration tools were applied using the Hitomi CALDB version 10, released on 2018 February 15. With the angular resolution of the HXI detectors of <1.7′ and that of the SXI detector of <1.5′ (Takahashi et al. 2014), PWN G21.5−0.9 is not spatially resolved and henceforward is analyzed as a point source. The HXI detectors were treated as independent instruments and the data analyzed separately. The event files from the HXI1 and HXI2 detectors were merged prior to source and background selection. Source and (off-source) background regions, as provided by the analysis guide, were inspected and applied to the data (Figure 6). Even though the Hitomi analysis guide considers that the off-source background spectrum may still include some source emission, affecting the derived flux, no non-X-ray background (NXB) spectrum is available, leaving an off-source background extraction as the sole solution. This background region comprises the entire FoV minus the source region. The SXI event data were not merged before further reduction because the Hitomi team note in the analysis guide that the cosmic-ray echo effect varies between the ObsIDs and therefore separate RMF and ARF files should be created. Accordingly, the data were reduced individually and only events detected during the non−“minus-Z day Earth (MZDYE)” were selected, so as to exclude events affected by light leakage (Nakajima et al. 2018). Subsequently, spectra and responses were co-added using the ftool addascaspec. As was done for the HXI detectors, for the SXI observations the source and background regions as provided by the analysis guide were inspected and applied to the data. For this detector this implies the background region is the full FoV excluding the calibration sources and their read-out streaks, some point sources, and the science source.

11 https://heasarc.gsfc.nasa.gov/docs/hitomi/analysis/

### 3. X-Ray Spectral Analysis

Since the source is a composite SNR, the X-ray spectrum of the PWN is superimposed on the emission arising from the SNR and central pulsar. Only Chandra, with its superior angular resolution, is capable of spatially distinguishing the emission coming from each component (see Figure 1). Recently, Guest et al. (2019) analyzed all Chandra data on this source to describe the spectrum of each substructure of the remnant. To obtain the X-ray spectrum of the PWN observed with NuSTAR and Hitomi, we therefore include the obtained parameters of each substructure observed with Chandra (see Table 5), leaving us with the “pure” PWN spectrum. Here, we first report on the general X-ray analysis performed on all data, then we present the results.

#### 3.1. X-Ray Fitting Procedure

After source extraction, each spectrum was grouped to >20 counts per bin in the low energy range (<20 keV) and to >100 counts per bin at higher energies (>20 keV). Increasing the

| Table 5 | Spectral Parameters of the Substructures Observed in the Remnant as Derived by Guest et al. (2019) |
|---------|----------------------------------------------------------------------------------|
|         | Northern Knot                                                                     | Eastern Limb                        | PSR J1833−1034 (without blackbody) | PSR J1833−1034 (with blackbody) |
| Photon index (Γ) | 2.24                                   | 2.22                               | 1.54                              | 1.35                             |
| Normalization    | 2.51 × 10⁻⁴                            | 3.76 × 10⁻⁴                        | 8.34 × 10⁻⁴                       | 6.14 × 10⁻⁴                      |
| kT (keV)         | 0.43                                   | 0.43                               | 0.43                              | 0.43                             |
| Normalization (blackbody) | 5.74 × 10⁻⁶                          |                                    |                                   | 5.74 × 10⁻⁶                      |
minimum grouping from 20 to 100 counts per bin at the higher energies had no effect on the fit parameters because of the robustness of the C statistic in dealing with bins containing few counts (Cash 1979). The spectra corrected for background and instrumental response were then analyzed using XSPEC v12.10.1m (Arnaud 1996).

To obtain the spectrum of the PWN from NuSTAR and Hitomi spectra, we fit the source spectrum including the best-fit parameters of the substructures in G21.5–0.9 reported by Guest et al. (2019). These components consist of the central pulsar PSR J1833–1034, the limb-brightened eastern limb of the remnant, and the northern knot (see Table 5 for the spectral parameters of these components). As the source region for Chandra spectra includes only the pulsar and PWN, the eastern limb and northern knot components were not needed. For the source as a whole, the hydrogen column density is found to be \( N_H = 3.237 \times 10^{22} \) cm\(^{-2}\) (Guest et al. 2019).

When fitting the pulsar component, Guest et al. (2019) find an improvement in their fit statistics when they include a blackbody component in the power-law spectrum of the pulsar. However, since this improvement is marginal, we fit for the PWN spectrum both with and without the pulsar blackbody component.

After the above-mentioned components were fixed, the PWN spectrum was fit as a pegpwrlw in which the photon index (\( \Gamma \)) and normalization remain free. We chose the power-law model pegpwrlw over the regular power-law model because it mitigates the issue of having a strong correlation between the photon index and normalization by using the unabsorbed flux between two specified energy ranges as its normalization (Yang et al. 2016). The absorption is treated using the Tübingen–Boulder ISM absorption model, incorporated in XSPEC as the tbabs procedure, with solar abundances set to wilms (Wilms et al. 2000). As mentioned at the beginning of this subsection, we set the fit statistic to cstat.

To obtain the uncertainties for the fit parameters (photon index and normalization) we opted to use XSPEC’s Markov Chain Monte Carlo (MCMC) method. We followed the XSPEC example of using the Goodman–Weare algorithm (Goodman & Weare 2010) with eight walkers and a chain length of 10,000 steps.

3.2. Piecewise Power-law Fits

Theoretical models for the radiative evolution of a PWN (Gelfand et al. 2009; Torres et al. 2014) predict that the resultant spectrum is smoothly curving in the X-ray wave band. As a result, while the broken power law commonly used to describe this curvature does a reasonable job of indicating the turnover point in the spectrum, it is not physically motivated. In addition, the location of this “break” is highly responsive to the boundaries of the observed energy range. This effect is demonstrated by the analysis of PWN G21.5–0.9 where the different X-ray observatories, covering different energy ranges, report a different break energy (see Table 1). To better explore this curvature (i.e., change in photon index over the X-ray band), we propose to fit the PWN spectrum using piecewise power laws instead of the standard broken power law. In this approach we split the total energy range we fit for into multiple contiguous and continuous energy bands. As we fit a power law in each energy band separately, we obtain a set of parameters and associated uncertainties in each energy band. We believe that in lieu of a PWN model that can accurately parameterize the smoothly curving nature of the spectrum, investigating the variation of the power-law parameters over distinct energy bands using the piecewise power-law approach is a valid and useful approach.

We approach the piecewise power-law fitting by choosing energy bands that are roughly equal in log-space, contain sufficient counts, and are defined such that comparison between instruments is feasible. We end up with the energy bands 0.8–3.0 keV (where Chandra and Hitomi SXI overlap), 3.0–8.0 keV (where Chandra, Hitomi SXI, and NuSTAR detectors overlap), 8.0–20 keV (where NuSTAR and Hitomi HXI detectors overlap), and 20–45 keV (where NuSTAR and Hitomi HXI detectors overlap).

The Chandra data were fit in the 0.8–3.0 and 3.0–8.0 keV energy bands. The spectrum from the longest observation is shown in Figure 7.

The NuSTAR data were fit in the 3.0–8.0 keV, 8–20 keV, and 20–45 keV energy bands. While NuSTAR operates in the range 3–79 keV, the spectral fitting for this source was restricted to 3–45 keV because the background dominates above 45 keV. In addition, the spectra from FPMA and FPMB were fit separately because we noticed a consistent difference in the fit parameters when performing fits for each spectrum independently. Specifically, we saw that the photon index \( \Gamma \) was higher for FPMA spectra than for FPMB spectra and that the unabsorbed flux was consistently higher for FPMB spectra than for FPMA spectra. This discrepancy between the two spectra is described in the Appendix. This issue is unrelated to the discrepancy due to a thermal blanket tear for the FPMA detector causing an excess in low-energy photons (Madsen et al. 2020) because the NuSTAR team believes the tear began in 2017, and all the observations analyzed in this study are from 2012 and 2013 (Table 4). The spectra from the longest observation are shown in Figure 8.

The data recorded by Hitomi span the combined energy range of the Chandra and NuSTAR observations. Hence the Hitomi data were fit over all specified energy bands. Given that the full energy range of Hitomi is spread over two different type of detectors, we report on the results of each energy band for the respective detector sensitive to those energies (see Tables 6–9). The observed spectra are shown in Figure 9.
indicated.

Figure 8. Wideband spectra of the NuSTAR FPMA (blue) and FPMB (orange) detectors in the 3–45 keV range. Only the spectra from the longest observation (ObsID 10002014005) are shown to prevent overcrowding the figure. The alternating unshaded and shaded bands show the different fitting energy bands: 3–8 keV, 8–20 keV, 20–45 keV.

where the detector spectrum relevant for each energy band is indicated.

### 3.3. Results

As mentioned in Section 3.1, we fit two different models to the X-ray spectra: one model incorporating a pulsar blackbody component and another without this component. We show the results of the fits for the photon index and normalization (i.e., unabsorbed flux) parameters for the PWN spectra in Figure 10, Tables 6–9, and Figure 11. Figure 10 is a collection of scatter plots showing the MCMC samples. The contours indicate regions containing 68% and 95% of the samples, respectively. The results are also tabulated in Tables 6–9. The uncertainties in the tables are the one-dimensional 90% confidence intervals. Figure 11 shows the two fit parameters separately with energy on the x-axis to highlight differences between energy bands.

As shown in Table 5, the photon index for the pulsar component is $\Gamma = 1.35$ when including the blackbody component, while $\Gamma = 1.54$ when excluding it. This increase of $\sim 0.2$ in $\Gamma$ when excluding the blackbody model assumes a softer spectrum for the pulsar component. A softer spectrum for the pulsar component implies that the pulsar’s emission is more concentrated at lower energies and does not extend to higher energies, so a larger fraction of the overall emission at higher energies is attributed to the PWN. This effect results in a harder spectrum for the PWN (i.e., smaller $\Gamma$). This difference in $\Gamma$ for the PWN component between the two models is larger for higher energies.

Figure 9. Wideband spectra of the Hitomi SXI (black) and HX1 detectors (HXI1 in blue and HXII in magenta) in the 0.8–45 keV energy range. The different fitting energy bands are indicated by the alternating shaded bands. Data that are not fitted in a given energy band are made transparent.

While the photon index $\Gamma$ from one detector does not necessarily agree with that from a different detector in the same energy band (Figure 10), overall we see a general spectral softening (i.e., increase in $\Gamma$) over the four energy bands (Figure 11). An exception to this trend is Hitomi’s HXII detector when fitting with the model that does not contain the pulsar blackbody component (Table 7) in the 20–45 keV band. However, while the best-fit photon index changes from $\Gamma = 2.27$ in the 8–20 keV band to $\Gamma = 2.18$ in the 20–45 keV band, the uncertainty in the 20–45 keV band is large enough to make a softening plausible.

Regarding the normalization (i.e., unabsorbed flux) parameter, while its values decrease for each detector as we go from lower energy bands to higher ones, similar to the photon index, the values from different detectors within the same energy band disagree.

Next, we discuss how we incorporate the uncertainties in the fit parameters, due to the disagreement between detectors and the choice to include/exclude the pulsar blackbody component, into our PWN modeling.

### 4. Discussion

Here we discuss the results of modeling the PWN while taking into consideration the above IR and X-ray analysis. In Section 4.1 we discuss the potential origin of the observed IR emission. We then use this information and our updated X-ray analysis to determine the observed properties that should be
Figure 10. Scatter plots of the MCMC samples (photon index $\Gamma$ and unabsorbed flux $F$). The contours mark the regions containing 68% and 95% of the samples. Each row shows a different energy range in increasing order from top to bottom. The left column is for the model with the pulsar blackbody component and the right column is for the model without it. The gray shaded areas are consistent within a row and their role is explained in Section 4.2.
reproduced by a physical model for the evolution of a PWN inside an SNR. In Section 4.2, we describe such an evolutionary model and the method by which we identified the combination of input parameters that best reproduces the observed properties of this system. We further discuss the implications of the derived values for the model parameters in Section 4.2, and use them to constrain structures in the surrounding ISM needed to reproduce the morphology of the surrounding SNR shell in Section 4.3.

4.1. Infrared Emission

As mentioned in Section 1, previous attempts to model the emission of this PWN were unable to simultaneously reproduce the observed IR and X-ray spectra assuming both were synchrotron emission from the PWN (e.g., Torres et al. 2014; Hitomi Collaboration et al. 2018). While the power-law spectrum for the X-ray emission derived in our analysis (Section 3.3) strongly suggests this is correct, below we evaluate whether the IR emission is also synchrotron radiation from high-energy leptons in the PWN.

The total IR flux densities of the PWN region in G21.5−0.9 are listed in Table 2 and plotted in Figure 12. Figure 12 shows the [O I] 63.2 μm and [C II] 157.7 μm line maps in the left and middle panels, as well as the MIPS 24 μm map of the PWN region in the right panel for comparison. These lines contribute to the emission seen in the Herschel PACS 70 and 160 μm
different supernova progenitors will likely have different ejecta density profiles.

2. Assume that the supernova ejecta with mass $M_\text{ej}$ and initial kinetic energy $E_\text{kin}$ is expanding into a medium with uniform density $n_\text{ISM}$. As discussed in Section 4.3, the X-ray morphology of the SNR strongly suggests a density enhancement north of the explosion site. However, as this enhancement has only impacted a small fraction of the shell—not affecting the average SNR radius $R_\text{SNR}$ used in our modeling—and has not caused the SN reverse shock to collide with any part of the PWN, this has a minimal effect on the results of our modeling.

3. Calculate the age $t_\text{age}$ and initial spin-down luminosity $\dot{E}_0$ of associated PSR J1833–1034 for a particular (assumed constant) pulsar braking index $p$ and spin-down timescale $\tau_{\text{sd}}$ using the characteristic age $t_{\text{ch}}$ and current spin-down luminosity $\dot{E}$ (given in Table 10) inferred from the measured period $P$ and period-derivative $\dot{P}$ of the pulsar (e.g., Gelfand et al. 2015):

$$t_{\text{age}} = \frac{2t_{\text{ch}}}{p - 1} - \tau_{\text{sd}}. \quad (1)$$

$$\dot{E}_0 = \dot{E} \left(1 + \frac{t_{\text{age}}}{\tau_{\text{sd}}} \right)^{\frac{p+1}{p-1}}. \quad (2)$$

Analysis of 5.5 yr of timing observations of PSR J1833–1034 recently measured the braking index of this pulsar to be $p = 1.8569 \pm 0.0006$ (Roy et al. 2012). However, the result is sensitive to the treatment of the “glitches” that occurred during this campaign. Analysis of the timing properties of this pulsar during the first ~1.5 yr of this campaign, during which no significant glitches were detected, yielded $p = 2.168 \pm 0.008$ (Roy et al. 2012). We therefore model the properties of this PWN for two cases: $p = 1.8569$ and $p$ unconstrained.

4. Assume the entire spin-down luminosity $\dot{E}$ is injected into the PWN as either magnetic fields $\dot{E}_B$ or the kinetic energy $\dot{E}_p$ of relativistic leptons ($e^\pm$), such that

$$\dot{E}_B(t) = \eta_B \dot{E}(t) = \eta_B \dot{E}_0 \left(1 + \frac{t}{\tau_{\text{sd}}} \right)^{\frac{p+1}{p-1}} \quad (3)$$

$$\dot{E}_p(t) = (1 - \eta_B) \dot{E}(t) = (1 - \eta_B) \dot{E}_0 \left(1 + \frac{t}{\tau_{\text{sd}}} \right)^{\frac{p+1}{p-1}} \quad (4)$$

where $\eta_B$ is constant with time. While the pulsed $\gamma$-ray luminosity of some pulsars can be a significant fraction of $\dot{E}$, the observed pulsed $\gamma$-ray luminosity of PSR J1833–1034 is $\approx 0.005\dot{E}$ (Abdo et al. 2013).

5. Assume that the spectrum of particles injected into the PWN is well described by a broken power law of the form

$$d\mathcal{N}_p = \begin{cases} 
N_{\text{break}} \left(\frac{E}{E_{\text{break}}}\right)^{-p_1} & E_{\text{min}} < E < E_{\text{break}} \\
N_{\text{break}} \left(\frac{E}{E_{\text{break}}}\right)^{-p_2} & E_{\text{break}} < E < E_{\text{max}} 
\end{cases} \quad (5)$$

where the five free parameters ($E_{\text{min}}, E_{\text{break}}, E_{\text{max}}, p_1$, and $p_2$) in Equation (5) are assumed to be constant with time and the normalization $N_{\text{break}}$ is calculated by requiring
that
\[ E_p = \int_{E_{\text{min}}}^{E_{\text{max}}} E \frac{dN}{dE} dE \] (6)
at all times \( t \).

6. Assume that only radiative losses suffered by particles trapped within the PWN are the result of synchrotron and inverse Compton (IC) emission. When calculating synchrotron losses, we assume that the PWN’s magnetic field has a uniform strength \( B_{\text{pwn}}(t) \) (whose evolution is calculated using the procedure described by Gelfand et al. 2009) and that the particle pitch angles (i.e., the angle between their velocity \( \vec{v} \) and the local magnetic field \( \vec{B} \)) is randomly distributed. For IC emission, we consider particles scattering photons emitted by the cosmic microwave background (temperature \( T_{\text{cmb}} = 2.7255 \) K; Fixsen 2009) as well as an additional background field that has a blackbody spectrum with temperature \( T_{\text{bb}} \) and normalization \( K_{\text{bb}} \), such that this photon field has an energy density

\[ u_{\text{bb}} = K_{\text{bb}} a_{\text{bb}} T_{\text{bb}}^4 \] (7)
where \( a_{\text{bb}} \approx 7.5657 \times 10^{-15} \) erg cm\(^{-3}\) K\(^{-4}\). We do not consider synchrotron self-Compton (SSC) emission, since previous theoretical work has found that SSC emission significantly contributes to the total IC emission only at extremely early times (e.g., Gelfand et al. 2009; Martín et al. 2012).

To convert the physical quantities predicted by our model to the observed properties of this system, we assume a distance \( d = 4.4 \) kpc—the central value derived from a recent study of its HI emission (\( d = 4.4 \pm 0.2 \) kpc; Ramasringhe & Leahy 2018).

We used a Metropolis MCMC algorithm (Metropolis et al. 1953; see Section 3.2 of Gelfand et al. 2015 for a detailed description) to identify the combination of the 13 model input parameters \( \Theta \) listed in Table 11 that best reproduce the 29 observed properties \( D \) of G21.5−0.9 listed in Table 10. This is accomplished by the maximum likelihood estimation method, in which we find the combination \( \Theta \) whose predicted values of the observed properties \( \mathcal{M} \) maximize the likelihood \( \mathcal{L}(\mathcal{D}|\Theta) \):

\[ \mathcal{L} \equiv \prod_{i=1}^{29} \mathcal{L}_i(\mathcal{D}_i|\Theta), \] (8)

\[ \ln \mathcal{L} = \sum_{i=1}^{29} \ln \mathcal{L}_i(\mathcal{D}_i|\Theta). \] (9)

As listed in Table 10, there are three types of observed quantities \( D_i \), i.e., those

1. whose measured error \( \sigma_i \) is Gaussian in nature (indicated by \( \pm \) in Table 10),
2. constrained to be below some value \( D_i < D_i^{\text{up}} \) (indicated by \( < \) in Table 10), and
3. whose true value is believed to lie within a range \( D_i^{\text{lo}} < D_i < D_i^{\text{hi}} \).

The likelihood \( \mathcal{L}_i(\mathcal{D}_i|\Theta) \) is defined differently for these three cases, as described below.

In the first case, where the errors are Gaussian, we define \( \mathcal{L}_i(\mathcal{D}_i|\Theta) \) to be

\[ \mathcal{L}_i(\mathcal{D}_i|\Theta) = \frac{1}{\sigma_i \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{D_i - \mathcal{M}_i}{\sigma_i})^2} \] (10)

\[ \ln \mathcal{L}_i(\mathcal{D}_i|\Theta) = \ln \frac{1}{\sigma_i \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{D_i - \mathcal{M}_i}{\sigma_i})^2} \] (11)

\[ \chi_i^2 = \left( \frac{D_i - \mathcal{M}_i}{\sigma_i} \right)^2 \] (12)

where \( C \equiv -\frac{1}{2} \ln(2\pi) \) and \( \mathcal{M}_i \) is the value for \( D_i \) predicted by the model for a particular combination of input parameters \( \Theta \).

For the second case, where measurements have only yielded upper limits (i.e., observable \( D_i < D_i^{\text{up}} \)), we define

\[ \mathcal{L}_i(\mathcal{D}_i|\Theta) = \left\{ \begin{array}{ll} 1 & \mathcal{M}_i < D_i^{\text{up}} \\ 1 - \frac{1}{\sigma_i \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{D_i - \mathcal{M}_i}{\sigma_i})^2} & \mathcal{M}_i > D_i^{\text{up}} \end{array} \right. \] (13)

\[ \ln \mathcal{L}_i(\mathcal{D}_i|\Theta) = \ln \left( 1 - \frac{1}{\sigma_i \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{D_i - \mathcal{M}_i}{\sigma_i})^2} \right) \] (14)

\[ \chi_i^2 = \left( \frac{D_i - \mathcal{M}_i}{\sigma_i} \right)^2 \] (15)

where \( C \equiv -\frac{1}{2} \ln(2\pi) \) and \( \sigma_i \equiv \frac{D_i^{\text{up}}}{\sqrt{2\pi}} \).

The third case is applied to the unabsorbed fluxes and photon indices of the PWN in the X-ray band. Unfortunately, measurements of these parameters are strongly dependent on the (assumed) model for the pulsar’s X-ray emission as well as the instrument used to make the measurement. As listed in Tables 6–9, the measured values for these quantities span a range \( D_i^{\text{lo}} < D_i < D_i^{\text{hi}} \) significantly larger than the statistical errors of an individual measurement (Figure 10). Since resolving these fundamentally “systematic” uncertainties is beyond the scope of this work, when determining the likelihood that the predicted value \( \mathcal{M}_i \) is consistent with measured value \( D_i \), we adopt

\[ \mathcal{L}_i(\mathcal{D}_i|\Theta) = \left\{ \begin{array}{ll} \frac{1}{\sigma_i^{\text{lo}} \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{D_i - \mathcal{M}_i}{\sigma_i^{\text{lo}}})^2} & \mathcal{M}_i < D_i^{\text{lo}} \\ 0 & \mathcal{M}_i > D_i^{\text{lo}} \end{array} \right. \] (16)

\[ \ln \mathcal{L}_i(\mathcal{D}_i|\Theta) = \ln \left( \frac{1}{\sigma_i^{\text{lo}} \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{D_i - \mathcal{M}_i}{\sigma_i^{\text{lo}}})^2} \right) \] (17)
where $\sigma_l^{no}$ is the lower error on the lowest measurement of $D_i$, $\sigma_i^{hi}$ is the upper error on the highest measurement of $D_i$, and 

$$C \equiv -\frac{1}{2} \ln(2\pi).$$

Since it is difficult to interpret the quality of a fit based on the value of $L$ or $\ln L$, we also calculate a representative $\chi^2 = \sum \chi^2_i$ defined in Equations (12), (15), and (18).

The combination of input parameters $\Theta$ that resulted in the largest $L$ of our MCMC run is given in Table 11, with the value predicted by this combination for each observable given in Table 11 and the predicted SED shown in Figure 12. For both a fixed and a variable braking index $p$, our model reproduces most of the properties of G21.5–0.9 to within $<1\sigma$ of the observed values, with the value predicted by the model deviating by $\sim 1\sigma$–3$\sigma$ from the observed values of $\theta_{\text{pwn}}$, 327 MHz flux density, 4.8 GHz flux density, and 4.49–7.86 GHz spectral index. Notably, this model successfully reproduces the unabsorbed flux and photon index measured in each of the four X-ray bands—unlike many previous attempts at modeling the SED of this source (e.g., Tanaka & Takahara 2011; Torres et al. 2014; Hitomi Collaboration et al. 2018). We note that we did not attempt to reproduce the IR flux density observed from this PWN since, as described in Section 2.1, emission from surrounding gas and dust is likely a significant contributor to this band. As shown in Figure 12, the predicted flux density of the PWN’s synchrotron emission in this band is significantly lower than the observed values (Section 2.1; Table 2). Furthermore, the expected PWN contribution is not well described by a simple power-law extrapolation of the measured radio or X-ray flux densities.

While we have not extensively sampled the possible parameter space and obtained formal uncertainties on the parameters, as done for G54.1+0.3 (Gelfand et al. 2015), the “most likely” parameters identified in our analysis can be used to derive information regarding the formation and underlying physics of this system. As indicated in Table 11, our modeling suggests that the progenitor supernova ejected $M_{ej} \approx 11 M_\odot$ of material with a rather low initial kinetic energy $E_{\text{kin}} \approx 1.2 \times 10^{50}$ erg—a situation where current simulations for core-collapse supernovae favor the creation of a stellar-mass black hole (e.g., Sukhbold et al. 2016), not a neutron star as observed here. It is important to note that we did center numerous MCMC chains (each consisting of $\approx 50,000$ samples) around a canonical supernova explosion of $M_{ej} \sim 8 M_\odot$ and $E_{\text{kin}} \sim 10^{51}$ erg and were unable to reproduce the observed properties of this system in this region of parameter space. As a result, our modeling strongly suggests that this system is the result of a low-energy, high-mass supernova explosion.

This conclusion can be tested by measuring the properties of the supernova ejecta. This is best done by thermal X-rays detected from ejecta heated by the reverse shock. Unfortunately, our results suggest that very little ejecta has interacted with the reverse shock (Section 4.3). However, as the PWN expands it sweeps up and shocks the innermost ejecta. For the most likely set of parameters given in Table 11, we find that the PWN has swept up $M_{\text{sw},\text{pwn}} \approx 0.7–0.9 M_\odot$ of ejecta, and is currently expanding ($v_{\text{pwn}} - v_0(\text{R}_{\text{pwn}}) \sim 85–90$ km s$^{-1}$ faster than its surroundings (Table 12). These predictions can be tested with future analysis of the IR emission of this source.

As listed in Table 10 and shown in Figure 12, qualitatively similar results are obtained when modeling this source by fixing the braking index of associated PSR J1833–1034 to the currently measured value ($p = 1.85690$; Roy et al. 2012) or treating it as a free parameter. Models with $p \approx 3.1$ predict higher flux densities at gigahertz frequencies and lower fluxes at X-ray energies, which improves the likelihood $L$ (and correspondingly $\chi^2$) of the fits. If this higher value of $p$ more accurately represents the time evolution of the rate at which energy is injected into the PWN by this pulsar, this suggests that its braking index may have changed over its lifetime. Such behavior has been observed from other young pulsars, e.g., PSR J1846–0258 associated with SNR/PWN Kes 75 (e.g., Livingstone et al. 2011) and PSR B0540–69 (e.g., Kim & An 2019). In fact, the spin-down inferred surface dipole magnetic field strength and ages of both PSR J1833–1034 and PSR B0540–69 are quite similar (Table 13). However, the measured braking indices of both PSRs J1846–0258 and B0540–69 are $p < 3$, suggesting that the observed spin-down is possibly the result of both magnetic dipole radiation and the particle outflow (e.g., Ou et al. 2016 and references therein), while our modeling prefers that PSR J1833–1034 has $p > 3$—inconsistent with this physical model.

The first pulsar with a braking index $p > 3$ from a phase-connected timing solution is PSR J1640–4631, which has a measured braking index $p = 3.15 \pm 0.03$ (Archibald et al. 2016). As shown in Table 13, other than age, there are very few physical similarities between these two pulsars: PSR J1833–1034 has a period $P_{\text{sd}} \sim 3 \times$ smaller than PSR J1640–4631, a spin-down luminosity $\dot{E} \sim 10^9$ larger, and a (spin-down inferred) surface dipole magnetic field strength $B_{\text{sd}} \sim 4 \times$ lower.

In addition, our modeling suggests that the age of this system is less than the pulsar’s spin-down timescale ($t_{\text{age}} < \tau_{\text{sd}}$; Tables 11 and 12), as first suggested by Camilo et al. (2006). As a result, the implied initial spin-down luminosity $E_0$ (Equation (2)) and initial period $P_0$ (e.g., Pacini & Salvati 1973; Gaensler & Slane 2006 and references therein),

$$P_0 = P \left(1 + \frac{t_{\text{age}}}{\tau_{\text{sd}}} \right)^{-\frac{1}{\gamma}},$$

are quite close to their current values (Table 12). The derived initial spin period $P_0 \approx 50$ ms is slightly longer than expected for its surface magnetic field strength by models of fallback onto the proto-neutron star during the supernova (e.g., Watts & Anderson 2002). Furthermore, the inferred initial spin-down luminosity $E_0$ is somewhat lower than the $E_0 \sim 10^{58}$--$10^{59}$ erg s$^{-1}$ derived for other systems (e.g., Tanaka & Takahara 2011; Torres et al. 2014; Gelfand et al. 2015).

The predicted injected particle spectrum in PWN G21.5–0.9 is $p_1 \approx 2.9$ and $p_2 \approx 2.5$ (see Table 11). This relationship of $p_1 > p_2$ is different than that observed in other sources because for most PWNs $p_1 < p_2$ (e.g., Torres et al. 2014; Gelfand et al. 2015). Extensive trials were conducted with $p_1 < p_2$ but were not able to reproduce the observed properties listed in Table 10. The low values of $p_1$ ($p_1 < 2$) inferred for other PWNs have been interpreted as magnetic reconnection dominating particle...
acceleration at low energies while Fermi acceleration dominates at higher energy (e.g., Sironi & Spitkovsky 2011). However, the required values of $p_1$ and $p_2$ for G21.5−0.9 (Table 11) are both consistent with Fermi acceleration, and their different values possibly suggest that particles are accelerated/injected at two sites within this PWN. If correct, this could explain the spatial variations in $\Gamma$ observed near the center of this PWN (e.g., Guest et al. 2019).

Lastly, the results of our modeling can be used to interpret features in the observed SED of this PWN (Figure 12). A particle of energy $E$ will generate synchrotron emission with a power $P_{\text{synch}}$ (e.g., Pacholczyk 1970) given by

$$P_{\text{synch}}(E) = \frac{4e^4}{9m_e^2c^7}B^2E^2,$$

where $B$ is the strength of the nebular magnetic field, $e$ and $m_e$ are respectively the charge and mass of the electron while $c$ is the speed of light, and whose spectrum will peak at a frequency $\nu_{\text{peak}}$ (e.g., Pacholczyk 1970) given by

$$\nu_{\text{peak}}(E) = 0.29 \times \frac{3}{2} \left( \frac{E}{m_ec^2} \right)^2 \frac{eB}{m_ec} \tag{20}$$

For particles with a power-law energy distribution $\frac{dN}{dE} \propto E^{-\alpha}$, the synchrotron emission is also expected to have a power-law spectrum $\frac{d\nu}{d\nu} \propto \nu^{-\Gamma}$ with

$$\alpha = \frac{1 - p_{\text{par}}}{2},$$

$$\Gamma = \frac{1 + p_{\text{par}}}{2}. \tag{23}$$

This synchrotron emission will cause a particle with energy $E$ to cool in time $t_{\text{cool}}$

$$t_{\text{cool}} \equiv \frac{E}{P_{\text{synch}}} = \frac{9m_e^4c^7}{4e^4B^2E^{-1}} \tag{24}$$

$$\approx 6.25 \left( \frac{B}{1 \mu G} \right)^{-2} \left( \frac{E}{1 \text{ GeV}} \right)^{-1} \times 10^{14} \text{ yr}, \tag{25}$$

and a break in the electron spectrum will form at the energy $E_{\text{cool}}$ whose synchrotron cooling time is equal to the age of the system:

$$E_{\text{cool}}(B, t) = \frac{9m_e^4c^7}{4e^4B^{-2}(t_{\text{age}})^{-1}} \tag{26}$$

$$\approx 1.26 \left( \frac{B}{1 \mu G} \right)^{-2} \left( \frac{t_{\text{age}}}{1 \text{ yr}} \right)^{-1} \times 10^{19} \text{ eV}. \tag{27}$$

For the age $t_{\text{age}}$ and current nebular magnetic field strength $B_{\text{pwn}}$ predicted by our most likely set of model parameters (Table 12), we have

$$E_{\text{cool}}(B_{\text{pwn}}, t_{\text{age}}) \approx 7.6 \text{ TeV} \tag{28}$$

and $\nu_{\text{peak}}(E_{\text{min}}) \approx 140 \text{ GHz}$, $\nu_{\text{peak}}(E_{\text{break}}) \approx 900 \text{ THz}$, $h\nu_{\text{peak}}(E_{\text{cool}}) \approx 0.2 \text{ keV}$, $h\nu_{\text{peak}}(E_{\text{max}}) \approx 0.1 \text{ MeV}$, where $h$ is Planck’s constant. As detailed below, we expect to see features in the observed SED at all of these frequencies.

At $\nu < \nu_{\text{peak}}(E_{\text{min}})$, the emission will be dominated by “relic particles” injected into the PWN at earlier times that have since cooled (primarily adiabatically) to lower energies. As a result, the “flat” (spectral index $\alpha \approx 0$; flux density $S_{\nu} \propto \nu^{\alpha}$) observed at GeV frequencies does not necessarily reflect the spectrum of injected particles. Beginning at $\nu_{\text{peak}}(E_{\text{min}})$, the emitting particles will be a mix of freshly injected and “relic” particles. We expect the $\alpha$ ($\Gamma$) in the observed spectrum to

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**Table 8**

| Energy Range (keV) | Chandra | Hitomi SXI | Hitomi HXI1 | Hitomi HXI2 | NuSTAR FPMA | NuSTAR FPMB |
|-------------------|---------|------------|-------------|-------------|-------------|-------------|
| 0.8–3.0           | 3.84\(^{+0.02}_{-0.02}\) | 4.57\(^{+0.05}_{-0.05}\) | ...         | ...         | ...         | ...         |
| 3–8               | 3.60\(^{+0.02}_{-0.02}\) | 3.79\(^{+0.02}_{-0.02}\) | ...         | ...         | 3.58\(^{+0.01}_{-0.01}\) | 3.82\(^{+0.01}_{-0.01}\) |
| 8–20              | ...     | ...        | 3.43\(^{+0.03}_{-0.03}\) | 3.51\(^{+0.01}_{-0.01}\) | 3.02\(^{+0.01}_{-0.01}\) | 3.31\(^{+0.02}_{-0.02}\) |
| 20–45             | ...     | ...        | 2.19\(^{+0.07}_{-0.07}\) | 2.13\(^{+0.07}_{-0.07}\) | 1.84\(^{+0.01}_{-0.01}\) | 2.45\(^{+0.06}_{-0.06}\) |

**Notes.**

a Units of 10\(^{-11}\) erg s\(^{-1}\) cm\(^{-2}\).

b Errors indicate 90% confidence intervals.

**Table 9**

| Energy Range (keV) | Chandra | Hitomi SXI | Hitomi HXI1 | Hitomi HXI2 | NuSTAR FPMA | NuSTAR FPMB |
|-------------------|---------|------------|-------------|-------------|-------------|-------------|
| 0.8–3.0           | 3.84\(^{+0.02}_{-0.02}\) | 4.57\(^{+0.05}_{-0.05}\) | ...         | ...         | ...         | ...         |
| 3–8               | 3.60\(^{+0.02}_{-0.02}\) | 3.79\(^{+0.02}_{-0.02}\) | ...         | ...         | 3.59\(^{+0.01}_{-0.01}\) | 3.82\(^{+0.01}_{-0.01}\) |
| 8–20              | ...     | ...        | 3.51\(^{+0.03}_{-0.03}\) | 3.58\(^{+0.01}_{-0.01}\) | 3.11\(^{+0.01}_{-0.01}\) | 3.39\(^{+0.02}_{-0.02}\) |
| 20–45             | ...     | ...        | 2.41\(^{+0.08}_{-0.08}\) | 2.35\(^{+0.08}_{-0.08}\) | 2.05\(^{+0.05}_{-0.05}\) | 2.65\(^{+0.06}_{-0.06}\) |

**Notes.**

a Units of 10\(^{-11}\) erg s\(^{-1}\) cm\(^{-2}\).

b Errors indicate 90% confidence intervals.
change at this point. However, \( t_{\text{cool}} \gg t_{\text{age}} \) at \( \nu_{\text{peak}}(E_{\min}) \) and \( \nu_{\text{peak}}(E_{\text{break}}) \), so previously injected particles will dominate in this energy band and the emitted spectrum will be “flatter” than that expected from the freshly injected particles:

\[
\alpha_1 = \frac{1 - p_1}{2} = -0.93 \tag{29}
\]

\[
\Gamma_1 = \frac{1 + p_1}{2} = 1.93. \tag{30}
\]

At photon energy \( h\nu \approx h\nu_{\text{peak}}(E_{\text{cool}}) \), radiation from freshly injected particles should begin to dominate the observed emission. This occurs well within the high-energy component of the injected broken power-law spectrum, and the observed synchrotron emission should have

\[
\alpha_2 \approx \frac{1 - p_2}{2} = -0.76 \tag{31}
\]

\[
\Gamma_2 \approx \frac{1 + p_2}{2} = 1.76. \tag{32}
\]

Indeed, \( \Gamma \sim 1.8-1.9 \) measured between 0.8–3.0 keV (where the emitting particles have \( t_{\text{cool}} \lesssim t_{\text{age}} \)) is similar to \( \Gamma_2 = 1.76 \). At higher photon energies, the shorter cooling time \( t_{\text{cool}} \) results in a decrease in the average age, and therefore total number, of emitting particles, resulting in a softening (increase in \( \Gamma \)) of the spectrum. However, due to the decreasing input of energy into the PWN by the pulsar, \( \Delta \Gamma = 0.5 \) as expected from standard synchrotron theory (e.g., Pacholczyk 1970). In fact, our simple

### Table 10

Observed Properties of G21.5–0.9 Used in the Modeling of This Source

| Property                      | Observed                          | “Best Fit” Values | Citation                  |
|-------------------------------|-----------------------------------|-------------------|---------------------------|
|                               |                                   | \( p \)           | \( p \equiv 1.85690 \)    |
| Current spin-down luminosity  | \( 3.37 \times 10^{37} \text{ erg s}^{-1} \) | ...               | ...                       |
| Current characteristic age 1ch| 4,850 yr                          | ...               | ...                       |
| Angular radius \( \theta_{\text{pwn}} \) | \( 40'' \pm 4'' \)         | \( 42.6'' \)     | \( 40.5'' \)              |
| Angular expansion rate \( \dot{\theta}_{\text{pwn}} \) | \( (0.11 \pm 0.02) \text{ yr}^{-1} \) | \( 0.070 \text{ yr}^{-1} \) | \( 0.070 \text{ yr}^{-1} \) |
| 327 MHz flux density          | \( 7.3 \pm 0.7 \text{ Jy} \)     | \( 5.8 \text{ Jy} \) | \( 4.9 \text{ Jy} \)       |
| 1.43 GHz flux density         | \( 7.0 \pm 0.4 \text{ Jy} \)     | \( 7.2 \text{ Jy} \) | \( 6.4 \text{ Jy} \)       |
| 4.8 GHz flux density          | \( 6.5 \pm 0.4 \text{ Jy} \)     | \( 7.5 \text{ Jy} \) | \( 6.9 \text{ Jy} \)       |
| 4.49–7.85 GHz spectral index | \( -0.12 \pm 0.03 \)          | \( -0.06 \pm 0.01 \) | \(-0.03 \pm 0.01 \)       |
| 70 GHz flux density           | \( 4.3 \pm 0.6 \text{ Jy} \)     | 3.7 Jy             | 3.7 Jy                     |
| 84.2 GHz flux density         | \( 3.9 \pm 0.7 \text{ Jy} \)     | \( 3.5 \text{ Jy} \) | \( 3.5 \text{ Jy} \)       |
| 90.7 GHz flux density         | \( 3.8 \pm 0.4 \text{ Jy} \)     | \( 3.2 \text{ Jy} \) | \( 3.3 \text{ Jy} \)       |
| 94 GHz flux density           | \( 3.5 \pm 0.4 \text{ Jy} \)     | \( 3.2 \text{ Jy} \) | \( 3.3 \text{ Jy} \)       |
| 100 GHz flux density          | \( 2.7 \pm 0.5 \text{ Jy} \)     | \( 3.0 \text{ Jy} \) | \( 3.1 \text{ Jy} \)       |
| 141.9 GHz flux density        | \( 2.5 \pm 1.2 \text{ Jy} \)     | 2.4 Jy             | 2.5 Jy                     |
| 143 GHz flux density          | \( 3.0 \pm 0.4 \text{ Jy} \)     | 2.4 Jy             | 2.5 Jy                     |
| \( 0.8–3.0 \text{ keV} \) unabsorbed flux \( b \) | \( (3.84 \pm 0.02) \times 10^{-11} \) | \( 4.46 \times 10^{-11} \) | \( 4.46 \times 10^{-11} \) |
| \( 3.0–8.0 \text{ keV} \) photon index | \( 1.78 \pm 0.02 - 1.93 \times 10^{-11} \) | \( 1.84 \pm 0.01 \) | \( 1.84 \pm 0.01 \) |
| \( 8.0–20.0 \text{ keV} \) unabsorbed flux \( b \) | \( (3.58 \pm 0.01 - 3.82 \times 10^{-11} \) | \( 3.82 \times 10^{-11} \) | \( 3.82 \times 10^{-11} \) |
| \( 8.0–20.0 \text{ keV} \) photon index | \( 1.84 \pm 0.02 - 2.04 \times 10^{-11} \) | \( 2.01 \pm 0.02 \) | \( 2.00 \pm 0.02 \) |
| \( 10–20 \text{ GeV} \) photon flux \( c \) | \( 6.5 \pm 0.2 \times 10^{-11} \) | \( 6.5 \times 10^{-11} \) | \( 6.15 \times 10^{-11} \) |
| Supernova Remnant             | \( 2.44 \pm 0.24 \text{ km s}^{-1} \) | \( 2.55 \text{ km s}^{-1} \) | \( 2.56 \text{ km s}^{-1} \) |
| Distance                      | \( 4.4 \text{ kpc} \)             | ...               | ...                       |

**Notes.** For upper limits, their statistical significance is indicated next to the Observed value. Properties with no “predicted” values were fixed in the modeling, as described in Section 4.2.

- \( a \) Spectral index \( \alpha \) is defined as flux density \( S_\nu \propto \nu^{-\alpha} \).
- \( b \) Unabsorbed flux is given in units of erg cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\).
- \( c \) Photon flux is given in units of photons cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\).
- \( d \) Flux is given in units of erg cm\(^{-2}\) s\(^{-1}\).
model for the evolution of a PWN inside an SNR does a good job of reproducing the increasingly softening spectrum in the X-ray band (Figure 12, Table 10). Lastly, we would expect little synchrotron emission at $\nu_{\text{peak}}(E_{\text{max}}) \approx 0.1$ MeV, suggesting that G21.5−0.9 should not produce much MeV emission and therefore is not a promising target for proposed missions such as AMEGO.

4.3. SNR Shell

The morphology of the SNR rim in G21.5−0.9 suggests an interaction with dense material in the north. The shell is remarkably circular until an abrupt flattening that results in brightened X-ray emission and is enhanced by knot-like structures (Figure 1). Spectral investigations by Guest et al. (2019) suggest an ejecta-rich thermal component for which the density is $\sim 45 d_{2.6}^{-1/2} f^{-1/2}$ cm$^{-3}$, where $f$ is the filling factor of the X-ray gas. We note that this value is additionally uncertain due to the unknown composition of the ejecta.

We have investigated a hydrodynamical model for the evolution of the SNR using the results from Section 4.2 (summarized in Table 11) and assuming the presence of a dramatic density increase in regions north of the explosion center. The simulation was carried out with the grid-based hydrodynamics code VH1 (see Blondin et al. 2001; Kolb et al. 2017), which utilizes the PPMLR method (Colella & Woodward 1984) to resolve shock propagation. Here we have ignored the contributions from the pulsar since the PWN has no impact on the SNR morphology at this stage of evolution. We ran the simulation to an age of 1700 yr (see Section 4.2), adjusting the position and magnitude of the density jump relative to the explosion center until the observed morphology reproduced that observed for G21.5−0.9.

We find that a reasonable representation of the SNR morphology can be obtained with a density jump by a factor of $\sim 20$ located $\sim 1.8$ pc north of the explosion center. The results are summarized in Figure 13, where we plot the density distribution from the simulation. The outermost boundary corresponds to the ambient density, and the positions of the forward shock, reverse shock, and contact discontinuity are indicated. The compression in the northern region is similar to that observed in G21.5−0.9. The white contour corresponds to the outer boundary of the PWN.

5. Summary and Conclusions

We have reanalyzed archival IR (Herschel, Spitzer; Section 2.1) and X-ray (Chandra, NuSTAR, Hitomi; Section 3.1) observations of PWN G21.5−0.9. The similar morphology observed in IR emission line and continuum maps of this source suggests that surrounding dust and gas produce much of the observed radiation (Section 4.1). Our analysis of the X-ray observations shows that while there is an overall spectral softening within this band, discrepant power-law parameter values from different detectors indicate that instrumental uncertainties should be taken into consideration when interpreting the values (Section 3.3).

To quantify the degree and shape of the spectral softening in the X-ray band, we separately fit power laws over distinct energy bands (piecewise power law fits, Section 3.2), instead of fitting a single broken power law over the entire detector energy range. This shape is consistent with what is predicted by models for the evolution of a PWN inside an SNR, which find that the continuous injection of particles into the PWN, and the changing magnetic field strength inside it, do not result in a sharp break as required by broken power-law models.
We then used a one-zone model for the evolution of a PWN inside an SNR to reproduce the observed dynamical and broadband spectral properties of G21.5—0.9, taking into consideration that the IR emission is likely not dominated by synchrotron radiation from particles inside the PWN, and the increased uncertainty in the X-ray spectrum resulting from our comparison of different instruments (Section 4.2). We found that this model can reproduce the properties of this source, but only if the supernova ejecta had a low initial kinetic energy of $E_{\text{in}} \approx 1.2 \times 10^{50} \text{erg}$ and the spectrum of particles injected into the PWN at the termination shock is softer at lower energies than at high energies ($p_1 \approx 2.9 > p_2 \approx 2.5$) — opposite to what is observed from most other PWNs. Both values are consistent with what is expected from diffusive shock acceleration, suggesting that magnetic reconnection may not play an important role in accelerating particles in this PWN, and the different values may indicate two different acceleration sites. Furthermore, we used a hydrodynamical model to determine the structure of the ambient medium needed to reproduce the morphology of the observed SNR shell (Section 4.3). We are able to do so if there is a $\sim 20 \times$ increase in density $\sim 1.8 \text{ pc}$ north of the explosion center.

As a result, we have obtained an extensive picture of the supernova, neutron star, pulsar wind, and surrounding material of this source. The derived properties are useful for understanding how neutron stars are created in core-collapse supernovae and the different ways they energize their environment. The techniques and tools presented in this study are applicable when analyzing many other PWNs, and their use may provide a more comprehensive view of the different mechanisms by which neutron stars are formed and produce some of the highest energy particles in the universe.

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Facilities: CXO, NuSTAR, Herschel, Spitzer, Hitomi.
Software: HIPE (Ott 2010), XSpec (Arnaud 1996), CIAO (v4.10; Fruscione et al. 2006), HEASoft (NASA High Energy Astrophysics Science Archive Research Center (HEASARC), 2014), Sherpa (Freeman et al. 2001; Doe et al. 2007), SAOImage DS9 (Joye & Mandel 2003; Smithsonian Astrophysical Observatory 2000), Matplotlib (Hunter 2007), NumPy (Oliphant 2006; Van Der Walt et al. 2011), SciPy (Virtanen et al. 2020).

### Appendix

#### Systematic Errors in the NuSTAR Spectrum

Here we discuss the systematic differences between FPMA and FPMB spectra. We initially fit all 12 NuSTAR spectra independently over the entire 3–45 keV range without dividing the energy ranges (Figure 14) using the model with the pulsar blackbody component (explained in Section 3.1). While we also fit the model without the pulsar blackbody component and obtained similar results, here we only report on the results of fitting the model with the pulsar blackbody component because...
we are simply trying to highlight the differences between FPMA and FPMB spectra.

We found that the photon index $\Gamma$ was consistently higher for FPMA spectra than FPMB spectra, indicating that spectra from FPMA were softer (i.e., a lower fraction of higher energy X-ray photons). The weighted average (inverse variance weighting), across observations, of the photon index for spectra from FPMA was $\Gamma_A = 2.12 \pm 0.01$ and that for spectra from FPMB was $\Gamma_B = 2.09 \pm 0.01$. The uncertainties reported here are the 1σ weighted sample standard deviations calculated with the formula $s = \sqrt{\frac{N}{N-1} \sum w_i (x_i - \bar{x})^2 \sum w_i}$, $\bar{x}$ is the weighted average, and $N = 6$ (the number of observations) in our case. The standard deviation of ±0.01 for each photon index is within what is mentioned as the approximate repeatability error of the spectral slope (±0.01) in the NuSTAR calibration paper (Madsen et al. 2015), indicating that the discrepancy across different observations from each FPM is within the calibration uncertainty. While Madsen et al. (2015) report offsets of $\Delta \Gamma \approx 0.1$ between $\Gamma_A$ and $\Gamma_B$ for the source 3C 273 during certain cross-calibration campaign observations, they do not address $\Gamma_A$ being consistently higher than $\Gamma_B$, which is what we observe for G21.5−0.9. They do note that if the signal-to-noise ratio is high enough, which could be the case for a bright source such as G21.5−0.9, the instrumental slope differences between FPMA and FPMB could be significant.

In addition to the discrepancy in the photon indices between FPMA and FPMB spectra, the unabsorbed flux values in the 3−45 keV range are also different. In units of $10^{-11}$ erg s$^{-1}$ cm$^{-2}$, we obtain $F_{A(3-45)} = 9.02 \pm 0.14$ and $F_{B(3-45)} = 9.84 \pm 0.04$. The two weighted average flux values differ by ~8%, which is slightly larger than the potential 5% flux difference mentioned in the NuSTAR calibration paper (Madsen et al. 2015). We find that the unabsorbed flux for spectra from FPMB is consistently higher than that for spectra from FPMA. As with the photon index, this consistent offset may be due to the brightness of G21.5−0.9.

We then repeated the above analysis over each energy band: 3−8 keV, 8−20 keV, and 20−45 keV (Figure 15). The photon indices $\Gamma_A$, $\Gamma_B$ agree in the 3−8 keV band and there is no consistent offset. However, while the 90% confidence intervals overlap for the 8−20 keV and 20−45 keV bands, we do see that in most cases $\Gamma_A$ is higher than $\Gamma_B$. For the unabsorbed flux we see that the value is consistently higher for FPMB spectra than for FPMA spectra in all energy bands. The 90% confidence intervals for the unabsorbed flux do not overlap in the 3−8 keV and 8−20 keV bands, and overlap slightly in the 20−45 keV band due to the large spread of values for FPMB spectra.

While there exist discrepancies in the PWN photon index and unabsorbed flux values between the spectra from FPMA

**Figure 14.** Photon index (a), normalization (b), and reduced $\chi^2$ (c) for each observation over the entire energy range (3−45 keV). The fitted model is with the blackbody component. Shaded regions indicate 90% confidence intervals.
and FPMB, the fit results between spectra from the same FPM across different observations are within the calibration uncertainty. As such, we believe the appropriate approach is to do joint fits of spectra from each FPM separately.

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**Figure 15.** Photon index, normalization, and reduced $\chi^2$ for each observation in the energy bands: 3–8 keV (a, b, c), 8–20 keV (d, e, f), 20–45 keV (g, h, i). The fitted model is with the blackbody component. Shaded regions indicate 90% confidence intervals.
