X-Ray Spectroscopy of the Highly Magnetized Pulsar PSR J1846-0258, Its Wind Nebula, and Hosting Supernova Remnant Kes 75

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Abstract

We present broadband X-ray spectroscopy of the energetic components that make up the supernova remnant (SNR) Kesteven 75 using concurrent 2017 August 17–20 XMM-Newton and NuSTAR observations, during which the pulsar PSR J1846–0258 is found to be in the quiescent state. The young remnant hosts a bright pulsar wind nebula powered by the highly energetic ($E = 8.1 \times 10^{36}$ erg s$^{-1}$) isolated, rotation-powered pulsar, with a spin-down age of only $P/2P \sim 728$ yr. Its inferred magnetic field ($B_p = 4.9 \times 10^{13}$ G) is the largest known for these objects, and is likely responsible for intervals of flare and burst activity, suggesting a transition between/to a magnetar state. The pulsed emission from PSR J1846–0258 is well-characterized in the 2–50 keV range by a power-law model with photon index $\Gamma_{\text{PSR}} = 1.24 \pm 0.09$ and a 2–10 keV unabsorbed flux of $(2.3 \pm 0.4) \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$. We find no evidence for an additional non-thermal component above 10 keV in the current state, as would be typical for a magnetar. Compared to the Chandra pulsar spectrum, the intrinsic pulsed fraction is $71 \pm 16\%$ in 2–10 keV band. A power-law spectrum for the pulsar wind nebulae (PWN) yields $\Gamma_{\text{PWN}} = 2.03 \pm 0.02$ in the 1–55 keV band, with no evidence of curvature in this range, and a 2–10 keV unabsorbed flux $(2.13 \pm 0.02) \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$. The NuSTAR data reveal evidence for a hard X-ray component dominating the SNR spectrum above 10 keV that we attribute to a dust-scattered PWN component. We model the dynamical and radiative evolution of the Kes 75 system to estimate the birth properties of the neutron star, the energetics of its progenitor, and properties of the PWN. This suggests that the progenitor of Kes 75 was originally in a binary system which transferred most of its mass to a companion before exploding.

Unified Astronomy Thesaurus concepts: Neutron stars (1108); Rotation powered pulsars (1408); Pulsars (1306); Magnetars (992); Supernova remnants (1667)

1. Introduction

To date over 2000 “ordinary” rotation-powered pulsars (RPPs) have been discovered, nearly all as radio pulsars. Their beamed emission is powered by the rotational energy loss from a radiating magnetic dipole of the neutron star (NS) as it gradually slows down (Shapiro & Teukolsky 1983). Young, energetic isolated pulsars often display radio and/or X-ray pulsar wind nebulae (PWN). It is the conversion of rotational energy into electromagnetic radiation and a particle wind that is thought to energize these synchrotron nebulae (Gaensler & Slane 2006).

In contrast, magnetars (e.g., Turolla et al. 2015) are also young, isolated NSs but they typically lack the persistent radio emission and the synchrotron nebula of the RPPs. In their quiescent state, these slowly rotating pulsars (2–12 s) emit uniquely in the X-ray band. Most notably, their thermal X-ray emission far exceed their rotational kinetic energy loss rate ($\dot{E}$) and are thought to be powered, instead, by the decay of their enormous magnetic field, above the quantum critical value of $B_{\text{QED}} = m_e c^3/\hbar e = 4.4 \times 10^{13}$ G (Duncan & Thompson 1992).

Recent exceptions to the defining properties of both the rotation-powered pulsars and the magnetars are shedding new light on their evolution and emission mechanisms: (1) over the last few years, a growing number of “low B-field” magnetars have been detected, whose magnetic fields border those of the rotation-powered pulsars (e.g., Rea 2014) (2) the so-called transient magnetars which are seen to display intermittent radio emission during their outbursts (e.g., Camilo et al. 2008), (3) recent evidence for the first detection of a wind nebula around a magnetar (Swift J1834.9–0846; Younes et al. 2016) and (4) the discovery of variability in a PWN surrounding the rotation-powered, high-B radio pulsar J1119–6127, that has shown a magnetar-like behavior (Blumer et al. 2017).

A remarkable new result is the discovery of magnetar-like millisecond bursts from PSR J1846–0258 in Kes 75 (Gavriil et al. 2008; Kumar & Safi-Harb 2008; Ng et al. 2008). This highly energetic ($\dot{E} = 8.3 \times 10^{36}$ erg s$^{-1}$), 325 ms X-ray rotation-powered pulsar (Gotthelf et al. 2000), with its bright wind nebula, is located within the core of the young supernova remnant (SNR) Kes 75 (Helfand et al. 2003; Su et al. 2009; Temim et al. 2012). Although the nominal energetics and spectral properties of PSR J1846–0258 are typical of a rotation-powered pulsar, it was caught serendipitously in a magnetar-like flaring state in 2006, with a notable softening of its spectrum and changes to its PWN morphology. And most recently, 14 yr later, on 2020 August 1, a second magnetar-like event was observed from the pulsar (Krimm et al. 2020). We might be catching a young pulsar in a unique and rare evolutionary state, possibly undergoing breakout of a buried magnetar-strength magnetic field (see Halpern & Gotthelf 2010).

We have obtained new, concurrent XMM-Newton and NuSTAR observations of the Kes 75 system in order to better study the spectral properties of its components, to infer their
interactions and evolution. In Section 2, we describe these data sets, analyzed in conjunction with archival Chandra data. We find that a simple power-law model is sufficient to characterize the spectrum of the pulsar, with no evidence for a flatter spectral component above \( \sim 10 \) keV, a characteristic of the magnetars. The spectrum of the PWN, also well-modeled by a single power law, shows no evidence of curvature. We measure a dust-scattered halo that manifests as a hard >10 keV spectral component for the SNR spectrum.

Based on these spectral results, in Section 3 we apply a dynamical and radiative evolution model to spectral energy distribution (SED) of the Kes 75 system. Finally, in Section 4, we discuss the implications of our broadband spectral and evolution modeling. The discovery of magnetar-like activity from the young rotation-powered pulsar offers a unique opportunity to study the connection between the distinct nature of rotation-powered pulsars and magnetars, their birth, and early evolution.

2. X-Ray Observations and Analysis

2.1. NuSTAR

We observed Kes 75 with NuSTAR 2017 August 17 as part of the AO3 Guest Observer programs. The nominal 100 ks exposure started at 18:56:09 UT and lasted for 208 ks, with Earth block accounting for periodic orbital time gaps. NuSTAR consists of two co-aligned X-ray telescopes, with corresponding focal plane detector modules FPMA and FPMB, each of which is composed of a 2 \( \times \) 2-node CdZnTe sensor array (Harrison et al. 2013). These are sensitive to X-rays in the 3–79 keV band, with a characteristic spectral resolution of 400 eV FWHM at 10 keV. The multi-nested foil mirrors provide 18" FWHM (58" HPD) imaging resolution over a 12/2 \( \times \) 12/2 field-of-view (FoV) (Harrison et al. 2013). The nominal timing accuracy of NuSTAR is \( \sim 2 \) ms rms, after correcting for drift of the on-board clock, with the absolute timescale shown to be better than \( <3 \) ms (Mori et al. 2014; Madsen et al. 2015). This is more than sufficient to resolve the signal from PSR J1846 –0258.

NuSTAR data were processed and analyzed using FTOOLS 09May2016_V6.19 (NUSTARDAS 14Apr16_V1.6.0) with NuSTAR Calibration Database (CALDB) files of 2016 July 6. The resulting data set provides a total of 95 ks of net good exposure time. For all subsequent analysis we merged data from the two FPM detectors. As shown in Figure 1, the small diameter SNR Kes 75 was fully imaged on the FPM detectors, centered on node-0. The pulsar is unresolved from the PWN emission, and its contribution is taken into account in the spectral analysis, using Chandra data.

2.2. XMM-Newton

We also obtained a shorter, but uninterrupted 51.4 ks XMM-Newton observation of Kes 75 on 2017 August 19 starting at 14:28:17 UT, overlapping the end of the NuSTAR observation, 1.81 days from its start. The European Photon Imaging Camera (EPIC) on-board XMM-Newton consists of three detectors, the EPIC pn detector (Strüder et al. 2001) and EPIC MOS1 and MOS2 (Turner 2001). These sit at the focal plane of co-aligned multi-nested foil mirrors with an on-axis point-spread function with FWHM of \( \sim 12''/5 \) and \( \sim 4''/3 \) at 1.5 keV, for the pn and MOS, respectively. The EPIC detectors are sensitive to X-rays in the 0.15–12 keV range with moderate energy resolution of \( E/\Delta E(\text{pn}) \approx 20–50 \).

The EPIC pn data (ObsID #0795650101) were obtained in PrimeSmallWindow mode (4/3 \( \times \) 4/4), with an increased time resolution of 6 ms, sufficient to phase-resolve PSR J1846 –0258, at the expense of a large 29% deadtime. The pulsar, PWN, and the main clumps of the SNR are imaged in the FoV (see Figure 1). To resolve possible rapid bursts from the pulsar we operated EPIC MOS2 in FastUncompressed mode, which offers 1.5 ms time resolution with 1D-imaging on the central EPIC CCD, at the expense of an increase in the background component. The MOS1 data were acquired in

Figure 1. Low resolution X-ray images of Kes 75 scaled logarithmically to highlight faint emission. Shown are the spectral extraction regions for the source (solid circles) and background (dotted circles) as described in the text. Left—the XMM-Newton EPIC pn small window mode image in the 1–10 keV band. The SNR emission is highly cut off below 1 keV. Right—the NuSTAR 3–79 keV image. The pulsar and PWN are unresolved and overlap the much fainter SNR emission in this band. The EPIC pn FoV is overlaid on the NuSTAR image (solid box).
Helfand et al. (2003) 3.96 (fixed) 1.39 ± 0.04 7.1
Ng et al. (2008) 4.0 (fixed) 1.1 ± 0.01 6.1 ± 0.03
Gavriil et al. (2008) ... 1.17±0.15 -1.12 ...
Kumar & Safi-Harb (2008) 3.96 (fixed) 1.32±0.08 -0.09 4.3 ± 0.2

Chandra 2006 data set (Flare Epoch)

Ng et al. (2008) 4.0 (fixed) 1.86 ± 0.02 37 ± 0.10
Gavriil et al. (2008) ... 1.89±0.04 -0.06 ...
Kumar & Safi-Harb (2008) 4.15±0.09 -0.12 1.97±0.05 -0.07 27±1

Chandra 2016 data set

This Work 4.0 (fixed) 1.32 ± 0.15 3.1 ± 0.1

XMM-Newton & NuSTAR 2017 data sets (Pulsed Only)

This Work 4.0 (fixed) 1.23 ± 0.09 2.2 ± 0.4

Notes. Column density is derived using the built-in XSPEC Wabs interstellar absorption model in all cases for comparison purpose. Quoted uncertainties are for the 90% C.L. for one interesting parameter.

Unabsorbed 2–10 keV flux, in units of erg cm⁻² s⁻¹.

1.8 × 1.8 PrimePartialW2 small-window mode on the central CCD with the PWN just filling the reduced FoV. The time resolution in this mode is 300 ms, useful for searching for slower flares but insufficient to resolve PSR J1846–0258.

Data were reduced and analyzed using the Standard Analysis Software (SAS) v.15 with the most up-to-date calibration files. After filtering out background flares we obtained usable live time of 50.1/36.1 ks, for the MOS/pn data.

2.3. Archival Chandra Data

To correct and verify our XMM-Newton analysis of Kes 75, we used archival Chandra data to spatially resolve in the same bandpass the pulsar, PWN, and SNR components and obtain the most accurate fluxes. Of the many Chandra observations of Kes 75 obtained over the years, we select for this work ObsID #18030, a deep observation acquired closest in time to our concurrent XMM-Newton and NuSTAR data set. This observation was carried out with the Advanced CCD Imaging Spectrometer (ACIS) on 2016 June 8 with an exposure time of 86 ks. The data were reprocessed and cleaned using standard CIAO v4.10 routines, resulting in an effective exposure time of 84.9 ks. The Chandra count rate from PSR J1846–0258 relative to the 3.14 s nominal ACIS CCD frametime results in a ~6% pileup fraction for the pulsar. This produces evident distortion in its spectrum that is mitigated by including the Chandra pileup model in all spectral fits with ACIS of the pulsar presented herein. We compare our joint fits results to those obtained using data from earlier epochs (Helfand et al. 2003; Morton et al. 2007; Kumar & Safi-Harb 2008; Ng et al. 2009; Su et al. 2009; Temim et al. 2012) as presented in Table 1.

2.4. Timing Analysis

In the following timing analysis, all photon arrival times are converted to barycentric dynamical time using the DE405 solar system ephemeris and the Chandra J2000 coordinates 18°46′24.394″ –02°58′30.1″1 (Helfand et al. 2003). We extracted photons using an aperture of radius r < 0.75 and r < 1.3 for the XMM-Newton and NuSTAR data, respectively, found to maximize the embedded pulse signal. For NuSTAR, we included photons over the full energy band but restricted our analysis to the 0.5–10 keV band for the XMM-Newton data to minimize particle contamination.

We searched for the known signal from PSR J1846–0258 using an accelerated FFT to account for the substantial frequency derivative associated with the pulsar. Photon arrival times from the long(er) NuSTAR data were binned into a 0.01 s light curve and searched at the full resolution allowed by the span of the data. A highly significant signal is recovered near the expected frequency and its derivative. We refine the strongest signal using the Z1 test (Buccheri et al. 1983), appropriate for the nearly sinusoidal pulse profile (see Figure 2). In the following phase-resolved spectroscopy, we use the best-fit period \( P = 0.32852377 \) (4) s and period derivative \( \dot{P} = 7.4(4) \times 10^{-12} \) for epoch MJD 58013.

We also searched from PSR J1846–0258 for possible millisecond bursts similar to those detected by RXTE (Gavriil et al. 2008), we examined its light curves over a range of timescales down to the 10 ms. We compared the frequency of occurrence of counts in each light curve bin to those predicted by Poisson statistics based on the mean count rate and found no significant outliers. We therefore conclude that, during the duration of our NuSTAR/XMM-Newton observation, the pulsar did not display significant temporal characteristics of a magnetar.

2.5. Spectral Analysis

For spectral fitting we use the XSPEC (12.10.1f) package (Arnaud 1996) and characterize the column density with the built-in TBabs absorption model, selecting the wilm Solar abundances (Wilms et al. 2000) and the vern photoionization cross-section (Verner et al. 1996). The \( \chi^2 \) statistic is used to evaluate the spectral fits throughout and the parameter uncertainties are quoted at the 90% confidence level (C.L.)
for one or more interesting parameters, as appropriate. Response matrices and ancillary response files were generated for each data set following the mission specific standard procedures. We note that previous spectral fits in the literature used the Wabs absorption model, a photoelectric absorption using the Wisconsin cross-sections (Morrison & McCammon 1983). Spectral fits using the newer column density model can result in a measured value that is significantly different, for the same intrinsic spectrum model.

2.5.1. PSR J1846–0258 Pulsed Spectrum

To isolate the broadband pulsed component of PSR J1846–0258 in the XMM-Newton and NuSTAR spectra, we divided the pulse profile into two phase intervals, corresponding to the peak (“on”) pulse and the valley (“off” pulse) regions. Although the valley spectrum provides a perfect representation of the unpulsed background subtracted from the peak spectrum, it necessarily includes a portion of the pulsed emission itself. For a theoretical sinusoidal signal, the flux correction factor for the background subtracted pulsed spectrum is \(\pi/2 = 1.57\). In our case, where the pulse profile is more peaked than a sine curve, the computed correction factors are 1.41 and 1.30 in the 2–10 keV band, for the XMM-Newton and NuSTAR data, respectively. This assumes that the pulse shape is essentially energy independent, for which there is no significant evidence to the contrary.

We choose source apertures of \(r < 30^{\prime}\) radius to extract the pulsar spectra for each mission to help estimate the total flux from the pulsar and to generate point-source response matrices. As the source (“on”) and background (“off”) spectra contain a similar number of counts per channel, their subtraction results in large uncertainties. With this in mind, we group all source spectra into spectral fitting channels that contain a minimum signal-to-noise of \(3\sigma\) after background subtraction.

The joint XMM-Newton and NuSTAR pulsed spectrum is well-fit to a simple absorbed power-law model in the 2–10 keV and 3–50 keV range, respectively. The column density is poorly constrained in these fits and is fixed to \(N_H = 6 \times 10^{22} \text{ cm}^{-2}\), the iterated value obtained from the final, high statistic PWN analysis (described below). The best-fit photon index is \(\Gamma = 1.24 \pm 0.09\), with a \(\chi^2_p = 0.992\) for 36 DoF (see Figure 3). The corrected 2–10 keV unabsorbed flux is \(F_\chi = 2.16_{-0.25}^{+0.26} \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}\) and \(F_\nu = 2.42_{-0.18}^{+0.29} \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}\) for the XMM-Newton and NuSTAR spectral fits, respectively. These fluxes are self-consistent within the measurement uncertainties. We note, moreover, that the mean pulsed flux of \(F_\chi = (2.25 \pm 0.35) \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}\), is fully consistent with the 2–10 keV flux predicted by the curved power-law model of Kuiper et al. (2018), \(F_\chi = 2.35 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}\), used to characterize the X-ray to gamma-ray flux.

To estimate the pulsed fraction for PSR J1846–0258, we extracted a total pulsar spectrum from the 2016 Chandra observation using a 1′/5 aperture and an 2′′ < \(r < 3′\) annular background region. A fit to an absorbed power-law in the 1–10 keV range with the column density fixed at \(N_H = 4 \times 10^{22} \text{ cm}^{-2}\) yields a best-fit \(\Gamma = 1.32 \pm 0.15\), with a \(\chi^2_p = 1.19\) for 66 DoF. The total unabsorbed flux is \(F_\chi = (3.1 \pm 0.1) \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}\), implying an intrinsic pulsed fraction of \(71 \pm 16\%\) in 2–10 keV band, assuming that the pulsar flux has been steady between the two observations, which is evidently the case, as shown in the next section.

![Figure 3. Broadband X-ray spectra of PSR J1846–0258 and its PWN in SNR Kes 75. The Chandra (blue), and concurrent XMM-Newton EPIC pn (black) and NuSTAR (red) Kes 75 PWN spectra are fitted jointly (top three curves). Similarly for the XMM-Newton EPIC pn and NuSTAR phase-resolved pulsed spectra (lower two curves). Both sets of spectra are fitted to an absorbed power-law model with independent normalizations. For the PWN spectra, the XMM-Newton model included a component to account for the pulsar emission below \(\sim 2\) keV and the NuSTAR spectrum includes a component for the pulsed emission, significant \(> 30\) keV (see the text for details). Upper Panel—the data points (crosses) are plotted along with the best-fit model (histogram) given in Table 2. Lower panels—the best-fit residuals for PWN (upper) and pulsed emission (lower) spectra in units of sigma.](image)

To compare our pulsed measurements to published results on PSR J1846–0258 obtained at earlier epochs we re-fitting these spectra using the historic XSPEC Wabs model for the interstellar absorption Helfand et al. (2003), Kumar & Safi-Harb (2008), Ng et al. (2008). These results are summarized in Table 1.

2.5.2. PSR J1846–0258 PWN Spectrum

As noted above, it is not possible to spatially isolate the PWN from the pulsar emission in the XMM-Newton and NuSTAR data sets. Instead, we fit the composite spectrum and account for the pulsar emission in the source aperture with an additional power-law component. For XMM-Newton, we estimate the pulsar contribution using the spatial resolved Chandra results, and for NuSTAR, we use the measured pulsed spectrum, both presented above. This is necessary to account for significant contamination below \(\sim 2\) keV in the XMM-Newton PWN spectrum from the pulsar and its environment, and for the pulsed emission that distorts the NuSTAR spectrum above \(\sim 30\) keV. For the XMM-Newton spectra we use an \(r < 30′\) source aperture that captures most of the PWN flux and averages over its radial-dependence spectrum. For the NuSTAR spectrum, with its poorer spatial resolution, we use a smaller \(r < 24′\) source aperture, to account for the additional blur of the PWN image in order to better match the XMM-Newton spectrum extraction region, while simultaneously minimizing possible contamination from the nearby SNR lobes. For both missions, we estimate the SNR background in...
the source aperture using a concentric annular background region $33^\circ < r < 45^\circ$. We note that background contribution is small ($<10\%$) except below $\sim2$ keV. As the PWN is poorly resolved spatially in both telescopes, we again use point-source mirror response matrices to characterize the effective area.

The spatially averaged XMM-Newton and NuSTAR PWN spectra are fitted jointly with their normalization left free to allow for systematic differences in the aperture flux. The spectrum is well-modeled by an absorbed power-law over the 1.2–50 keV span of the two data sets. This yields a column density $N_H = (6.0 \pm 0.1) \times 10^{22}$ cm$^{-2}$ and photon index $\Gamma = 2.03 \pm 0.02$, with a $\chi^2 = 0.14$ for 500 DoF. These parameters are consistent with the XMM-Newton results, suggesting no spectral change between the two epochs, and if so, the Chandra flux is considered the most accurate. It is reassuring that the details of the residuals of both spectra are effectively identical. The common systematic deviations in the spectra suggest that they are related to differences in the SNR emission between the source and background regions.

Finally, to obtain the most accurate PWN spectrum and flux measurement, we re-fitted the joint XMM-Newton and NuSTAR PWN spectra with the addition of the Chandra spectrum, again with independent normalizations. The best-fit parameters are $N_H = (6.0 \pm 0.1) \times 10^{22}$ cm$^{-2}$ and photon index $\Gamma = 2.0 \pm 0.02$, with a $\chi^2 = 1.075$ for 504 DoF. The final 2–10 keV unabsorbed PWN flux of $(2.13 \pm 0.03) \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$, is determined from the Chandra component of this fit, after allowing for the missing flux from the excluded pulsar region, a $\sim10\%$ effect. This missing flux is estimated from a spectrum of the bright northern PWN knot, extracted from an $r < 2\arcmin$ aperture. The ratio of the pulsar to the total flux (pulsar+PWN) is consistent with the observed pulsed fraction $\sim10\%$ in the 2–10 keV band. The pulsar and PWN spectra are displayed in Figure 3 along with the best-fit parameters presented in Table 2.

2.5.3. Kes 75 SNR Spectrum

We also extracted XMM-Newton and NuSTAR spectra for the SNR emission using an 0\arcmin.9 < r < 1\arcmin.8 source annulus and 2\arcmin < r < 3\arcmin background region (see Figure 1). This covers the two bright X-ray clumps labeled southeast (SE) clump and southwest (SW) clump in Helfand et al. (2003), encompassing the bulk of the remnant emission. For XMM-Newton, in small window mode, the SNR fell partially off the FoV but still includes the clumps.

The spectra of the SNR were fitted to a non-equilibrium thermal plasma model (XSPEC NEI) with variable abundances plus a power-law component (see Table 3), as indicated in the first Chandra study by Helfand et al. (2003). This model produces an excellent fit, but with parameter values notably different from those reported in the earlier Chandra studies (e.g., Helfand et al. 2003; Temim et al. 2012). This can be attributed, at least in part, to the updated ISM model used herein and to the difference in the extraction regions.

We next considered the Chandra data described in Section 2.3 to the joint XMM-Newton and NuSTAR fit, to verify XMM-Newton spectrum in their common energy range and for an improved flux measurement. We find that that: (a) a single component (XSPEC NEI) with variable abundances does model the data well, confirming the need for an additional harder component; (b) both a two-temperature NEI model and an NEI+power-law model provide an improved fit to the spectra. However, the XMM-Newton’s greater sensitivity to the hard diffuse X-ray emission, along with the expanded NuSTAR energy band allowed us to clearly select the power-law model as preferred over the thermal NEI model. The joint

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### Table 2

Spectra of the Pulsar and PWN in Kes 75

| Parameter          | Pulsar                         | PWN                          |
|--------------------|--------------------------------|-------------------------------|
| $N_H$ (10$^{22}$ cm$^{-2}$) | 6.0 (fixed)                    | 6.0 (fixed)                   |
| Photon Index $\Gamma$ | 1.24 ± 0.09                    | 2.03 ± 0.02                   |
| $F(1/3 - 10^{-4}\text{erg s}^{-1}\text{cm}^{-2})$ (abs.) | 0.18 ± 0.03 | 0.24 ± 0.01 | 1.53 ± 0.02 |
| $F(1/3 - 10^{-4}\text{erg s}^{-1}\text{cm}^{-2})$ (unabs.) | 0.23 ± 0.04 | 0.31 ± 0.01 | 2.13 ± 0.02 |
| Luminosity $L_\text{x}$ | 9.9 × 10$^{33}$ | 1.36 × 10$^{34}$ | 9.26 × 10$^{34}$ |
| $\chi^2$/DoF | 0.99(36) | 1.19(66) | 1.04(399) |

**Notes.** Quoted uncertainties are for the 90% C.L. for one or two interesting parameters, for the pulsar and PWN, respectively. The pulsar results are for a joint fit to the phase-resolved XMM-Newton/NuSTAR spectra; the total pulsar flux is determined from a fit to the Chandra data (see the text for details).

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### Table 3

Spatially Resolved Spectra of SNR Kes 75

| Region R.A. | Southeast | Southwest | Sector$^d$ |
|-------------|-----------|-----------|-----------|
| 18\arcmin.46\arcsec.22\arcsec.76 | 18\arcmin.46\arcsec.28\arcsec.57 | 18\arcmin.46\arcsec.24\arcsec.89 |
| Region decl. | −02\arcmin.59\arcsec.43\arcsec.73 | −02\arcmin.59\arcsec.09\arcsec.95 | −02\arcmin.58\arcsec.28\arcsec.73 |
| Ellipse radii | 1\arcmin.0 × 0\arcmin.4 | 0\arcmin.8 × 0\arcmin.45 | ... |
| Ellipse P.A. | 300\deg | ... | ... |
| Annulus radii | ... | ... | 0\arcmin.9 × 1\arcmin.8 |

| $N_H$ (10$^{22}$ cm$^{-2}$) | 4.11$^{+0.11}_{-0.10}$ | 4.27$^{+0.23}_{-0.31}$ | 4.14$^{+0.13}_{-0.09}$ |
| $kT$ (keV) | 1.04$^{+0.17}_{-0.10}$ | 1.18$^{+0.20}_{-0.20}$ | 0.87$^{+0.05}_{-0.06}$ |
| $\tau$ (10$^{15}$ s cm$^{-3}$) | 8.5 | 4.2 | 10.0$^{+1.2}_{-1.4}$ |
| Mg | 0.89$^{+0.09}_{-0.11}$ | 0.76$^{+0.20}_{-0.16}$ | 0.81$^{+0.08}_{-0.07}$ |
| Si | 1.26$^{+0.13}_{-0.14}$ | 1.21$^{+0.28}_{-0.28}$ | 1.27$^{+0.09}_{-0.09}$ |
| S | 0.98$^{+0.17}_{-0.16}$ | 1.0$^{+0.33}_{-0.27}$ | 1.15$^{+0.11}_{-0.11}$ |
| NEI Flux (10$^{-11}$)$^b$ | 3.0 | 1.7 | 10 |
| Photon Index $\Gamma$ | 1.73$^{+0.33}_{-0.63}$ | 2.02$^{+0.37}_{-0.92}$ | 2.02$^{+0.04}_{-0.05}$ |
| PL Flux (10$^{-11}$)$^b$ | 1.6 | 1.3 | 8.7 |
| $\chi^2$/DoF | 1.459 (452) | 1.369 (363) | 1.369 (896) |

**Notes.** See Figure 1 for the SNR clump regions. Coordinates are in the J2000 system. Quoted uncertainties are for the 90% C.L. for the parameter of interest.

$^a$ Joint fit to XMM-Newton EPIC pn, Chandra, and NuSTAR spectra, with independent normalizations.

$^b$ Unabsorbed XMM-Newton EPIC pn flux measured in the 0.5–10 keV band in units of erg s$^{-1}$ cm$^{-2}$. The first two columns correspond to the clumps fits using the XMM-Newton and Chandra data set.
fit to the SNR spectrum is displayed in Figure 4 along with the best-fit model parameters given in Table 3.

As noted above, the plasma temperature of the NEI model (softer component) differs because of the chosen TBabs with the wilms abundances. Previous works used the Anders & Grevesse (1989) abundances accounting for the lower column density and lower temperatures. We confirm this by checking against the results obtained using the early Chandra observation (Obsid 748), reprocesses with the latest calibrations.

The background for each spectrum is generally less than an order of magnitude of the source flux, up to about 20 keV, beyond which it dominates the NuSTAR spectrum. Small systematic errors in the power-law index are possible due to a difference in the size of the PSF for the two missions over the source aperture. However, this is likely to be a small effect because emission from outside the source aperture still contributes proportionally more by area to offset the losses from the larger surface brightness emission inside the aperture.

Using the XMM-Newton data alone, we also analyzed the two clump regions separately. Because of its larger PSF, the clumps are not well isolated in the NuSTAR data, and we do not attempt a joint spectral fit with the XMM-Newton data. The SNR clump extraction regions and results are presented in Table 3 and the spectral fits are shown in Figure 4. An annular (2′ < r < 3′) background region, centered at coordinates (J2000) 18°46′34.86′′ −02°58′28″3, is used for both clumps.

We have also attempted a two-temperature component fit as done in previous studies (e.g., Temim et al. 2012). We find that the spectra require temperatures of ∼0.9 keV and 4.6 keV for the cool and hotter component, respectively, of the southeast clump, and ∼0.85 and 3.2 keV for southwest clump. However, the reduced chi-squared in the 2T-component fits is higher (>1.5) than for the thermal+power-law model, and the vnei ionization timescale is too low in the 2T-component fits. We therefore again favor the power-law interpretation of the hard component. This result is consistent with the joint fit of the SNR sector with the NuSTAR data. Below, and in Section 4, we discuss the nature of the hard component and link it to a dust-scattered PWN halo.

2.6. Evidence for a Dust-scattered PWN Halo

The need for a highly significant hard continuum component to model the SNR spectra of Kes 75 has been evident since the first spatially resolved X-ray observations reported by Helfand et al. (2003), and later by Su et al. (2008), Temim et al. (2012). These authors considered several possible origins for this non-thermal emission and concluded that a dust-scattered PWN halo is the most consistent with the data. Furthermore, by comparing Chandra observations taken during and post flare epochs, Reynolds et al. (2018) found spatial evidence for a “transient halo,” likely depended on the brightness of the pulsar/PWN.

To better understand this hard component we compare broadband spectra of the SNR’s SE clump with that obtained from a mirrored region on the other side of the SNR, that lacks evidence of thermal emission, to represent the putative halo emission. For the SE SNR clump we extracted spectra from a 15″ × 30″ region, smaller then used in Section 2.5.3, to minimize the background contribution to the source region. As shown in Figure 5, the halo and the SE clump regions are equidistant from the pulsar; a background region is chosen well away from the SNR, to allow for the instrumental signature and the local Galactic ridge emission.

Figure 5 presents the joint fit to the XMM-Newton and NuSTAR spectra using the NEI plus power-law model, with the photon indices for the clump and the halo spectra linked; the thermal component is set to zero for the halo fits. The NuSTAR data is crucial to isolate the higher-energy component in a band where it is most dominant. As expected, this fit to the SE clump spectrum reproduced that reported in Table 3. Notably, the best-fit model yields a power-law index of Γ = 1.97 ± 0.09, consistent with that found for the PWN spectrum. The averaged 2−10 keV surface brightness in the halo aperture ∼1/2 away from the pulsar is 6.0 × 10³⁹ erg s⁻¹ arcsec⁻² at 6 kpc. Most importantly, the flux from the clump and the halo spectrum in the NuSTAR band is essentially the same (see Figure 5).

These results suggest that most, if not all, of the hard emission component for the SNR clumps can be attributed to a non-localized spectral component. To consider the radial
3. PWN–SNR Modeling

Currently, the best way of determining the energetics of the Kes 75 progenitor, the birth parameters of PSR J1846–0258, and for its pulsar wind, is to fit the observed properties of the PWN with a model for its dynamical and radiative evolution (see Gelfand 2017 for a recent review of such models). Following our previous analysis of Kes 75 (Gelfand et al. 2014) and similar SNR/PWN systems (e.g., G54.1+0.3, Gelfand et al. 2015; HESS J1640–465, Gotthelf et al. 2014), we use a Markoff Chain Monte Carlo code to determine the combination of input parameters of such a model (based on that described by Gelfand et al. 2009) that best reproduce (lowest $\chi^2$) the observed properties of Kes 75 listed in Table 4. The input parameters are listed in Table 5, with the age $t_{\text{age}}$ and initial spin-down luminosity $E_0$ chosen that, for a given braking index $p$ and spin-down timescale $\tau_{\text{sd}}$, reproduce the pulsar’s current characteristic age $t_{\text{ch}}$ and spin-down luminosity $E$:

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

$$E_0 = \dot{E} \left(1 + \frac{t_{\text{age}}}{\tau_{\text{sd}}}\right)^{\frac{p+1}{p}}$$

the PWN’s inverse Compton emission is the result of leptons scattering of the Cosmic Microwave Background and an additional photon field with temperature $T_{\text{ic}}$ and normalization $K_{\text{ic}}$, defined such that the energy density $u_{\text{ic}}$ of this photon field is:

$$u_{\text{ic}} = K_{\text{ic}} \alpha_{\text{bb}} T_{\text{ic}}^4$$

where $\alpha_{\text{bb}} = 7.5657 \times 10^{-15}$ erg cm$^{-3}$ K$^{-4}$, as well as assuming the spectrum of particle injected into the PWN at the

![Image](image-url)

**Figure 5.** Evidence of a dust-scattered PWN halo component in hard SNR spectra of Kes 75. Left—an XMM-Newton image of the Kes 75 SNR showing the location of mirrored source regions, situated on opposite sides of the SNR, one centered on the SE clump (left) and the other placed to sample the halo region (right), equidistant from the pulsar. The large circle shows the background region. Right—a joint fit to the concurrent XMM-Newton and NuSTAR spectra extracted from the two regions fitted with the NEI plus power-law model with their power-law indices linked. There is no evidence for excess thermal emission in the halo region and the flux from this region is sufficient to account for the hard continuum component in the SE Clump spectrum.

| Table 4: Observed and Predicted PWN–SNR Model for Kes 75 |
|----------------------------------------------------------|
| Property | Observed | Model | Reference |
| SNR |
| Radius (”) | 1.5 ± 0.15 | 1.50 | This Work |
| Distance (kpc) | 5.8$^{+0.5}_{-0.4}$ | 5.8 | Verbiest et al. (2012) |
| PWN |
| Radius (”) | 30 ± 1.67 | 30.0 | This work |
| $\theta_{\text{psn}}$ (km s$^{-1}$) | 0.249 ± 0.023 | 0.234 | Reynolds et al. (2018) |
| $S_{1.4}$ (mJy) | 348 ± 52 | 327 | Salter et al. (1989) |
| $S_{1.5}$ (mJy) | 247 ± 37 | 240 | Salter et al. (1989) |
| $S_{1.2}$ (mJy) | 172 ± 26 | 158 | Salter et al. (1989) |
| $S_{0.5}$ (mJy) | 80 ± 12 | 82 | Bock & Gaensler (2005) |
| $\Gamma$(2–55 keV) | 2.031 ± 0.025 | 2.030 | This work |
| $F$(2–10 keV)$^a$ | 2.13 ± 0.022 | 2.133 | This work |
| $\Gamma$(1–10 TeV)$^a$ | 2.41 ± 0.01 | 2.42 | H.E.S.S. Collaboration et al. (2018) |
| $F$(1–10 TeV)$^a$ | 0.160 ± 0.016 | 0.159 | H.E.S.S. Collaboration et al. (2018) |
| PSR |
| $E$ (erg s$^{-1}$) | $8.10 \times 10^{36}$ (fixed) | Livingstone et al. (2011) |
| $t_{\text{ch}}$ (yr) | 728 (fixed) | Livingstone et al. (2011) |
| $p$ | 2.65 ± 0.01 | 2.652 | Livingstone et al. (2011) |

Notes. The predicted values are for the set of model parameters which resulted in the lowest $\chi^2$. The observable timing quantities were fixed in our analysis.

$^a$ Flux in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$.  

The dependence of this component, we examined a Chandra spectrum obtained from the $33^\circ < r < 45^\circ$ annular region between the PWN and the clumps. This region is found to be an add-mixture of the thermal component and the power-law emission, with a similarly hard photon index ($\sim$2), and a surface brightness that is approximately a factor of 3 times larger than that of the western halo region. The decrease in surface brightness of the hard component away from the pulsar is consistent with a dust-scattered PWN halo interpretation, as further discussed in Section 4.
termination is well described by a broken power law:
\[
\frac{dN_\pm}{dE} = N_{\text{break}} \left( \frac{E}{E_{\text{break}}} \right)^{-p_{\pm}} E_{\text{min}} < E < E_{\text{break}} \quad (4)
\]
\[
\frac{dN_\pm}{dE} = N_{\text{break}} \left( \frac{E}{E_{\text{break}}} \right)^{-p_{\pm}} E_{\text{break}} < E < E_{\text{max}}, \quad (5)
\]
where \(N_\pm\) is the rate \(\pm\) injected into the PWN and \(N_{\text{break}}\) is calculated requiring that at all times:
\[
(1 - \eta_h)E \equiv \int_{E_{\text{min}}}^{E_{\text{max}}} E \frac{dN_\pm}{dE} dE, \quad (6)
\]
where the magnetization of the wind \(\eta_h\) is defined to be the fraction of the pulsar’s spin-down luminosity injected into the PWN as magnetic fields. In Figure 6 we show the result of modeling the Kes 75 system overlaid on the observed spectral energy distribution (SED). The best-fit parameters, presented in Table 5, give a reasonable \(\chi^2 = 0.93\), however, the number parameters is just one more than the number of observed quantities used in the fit. With this in mind, the significance and limitations of the our modeling is discussed in detail in the next section.

### 4. Discussion and Conclusions

Based on the 2016 Chandra and 2017 XMM-Newton and NuSTAR observations of PSR J1846–0258 reported herein, the pulsar had returned to its quiescent rotation-powered state following the 2006 magnetar-like event. In this state, we show that there is no evidence in the pulsed emission for an additional, flatter spectral component above 10 keV, as reported for many magnetars (e.g., den Hartog et al. 2008; see reviews by Mereghetti et al. 2015; Kaspi & Beloborodov 2017). However, during the recent, 2020 August magnetar-like burst event, the second detected, the flux from the pulsar again increased dramatically, accompanied by clear evidence of a timing glitch (Kuiper et al. 2020; Mihara et al. 2020). New spectral observations from this event will provide an important comparison with the results reported herein, in particular, if it reveals the characteristic hard (>10 keV) spectral component of a magnetar.

The pulsar is found to be highly modulated in the 2–10 keV band with a lower limit of at least 64%, not atypical for young X-ray pulsars with sinusoidal pulse profiles. The new, high quality spectral measurements confirm the relation between the power-law slopes for PSR J1846–0258 and its PWN, consistent with that predicted for other highly energetic rotation-powered pulsars (Gotthelf 2003). The flux from the PWN is consistent with that reported by Reynolds et al. (2018) and we find no evidence of curvature in its broadband 1–55 keV spectrum.

The efficiency of powering the PWN from spin-down radiative losses, \((L_\epsilon/E \approx 1\%)\), estimated from the 2–10 keV luminosity at distance of 6 kpc (Kumar & Safi-Harb 2008; Leahy & Tian 2008), is among the highest known for rotation-powered pulsars. The discovery of magnetar activity suggests that at least part of the pulsar luminosity could be from surface emission from the pulsar, however, the spectrum of the pulsar in the quiescent state, is quite distinct from that expected from a magnetar, typically characterized by a hot, 0.5 keV blackbody emission and a steep non-thermal component \(\Gamma \approx 4\) (Parmar et al. 1998; Marsden & White 2001). It is possible that some of the flux, consistent with the pulsed fraction, could be due to a cooling NS, heated during the magnetar activity. Unpulsed, soft blackbody emission could be responsible for the lower column density measured for the pulsar relative to that of the PWN, \(N_H \sim 4 \times 10^{22} \text{ cm}^{-2}\) and \(\sim 6 \times 10^{22} \text{ cm}^{-2}\), respectively. However, the high column density and instrument bandpass limits our ability to investigation this further.

The broadband X-ray spectroscopy of Kes 75 SNR reveals for the first time that the hard continuum component is dominant above 10 keV, and is clearly independent of the thermal emission. Similar non-thermal components have been detected from several SNR shells, as first discovered in the specially resolved spectroscopy of SN 1006 (Koyama et al. 1995). This emission is typically described in the X-ray band by a power-law with a steeper photon index \(\sim 2.5–3\) (Reynolds 2008) and can result in particle acceleration up to TeV energies (e.g., Reynolds 2011).
For Kes 75, the flatter spectrum and radial fall-off of the hard emission support a dust scattering halo origin for this component, that can be attributed to the bright and heavily absorbed pulsar/PWN (Helfand et al. 2003; Su et al. 2009; Temim et al. 2012). Similar halos have been discovered around magnetars or highly magnetized neutron stars that display a magnetar-like outburst (e.g., Esposito et al. 2013; Safi-Harb 2013). In the case of Kes 75, a brightening of the halo was noted following the 2006 flare (Reynolds et al. 2018). The current work shows that the halo emission is detectable even during the quiescent state of the pulsar. Such a halo has been also seen from G21.5–0.9, a similarly young, bright, and heavily absorbed PWN (e.g., Bocchino et al. 2005; Matheson & Safi-Harb 2010).

Making use of the new X-ray results for Kes 75, we re-evaluated the evolution of the PWN in the SNR using the dynamical and radiative model described in Section 3. The lack of DoFs for this model makes it difficult to draw statistically meaningful results from the fitting, however, the preferred parameters provide insight into the origin and underlying physics in this system. The results of our modeling strongly prefer Kes 75 as originated in a low energy ($E_{\text{in}} \lesssim 10^{51}$ erg), low ejecta mass ($M_{\text{ej}} < 1 M_\odot$) explosion. These quantities are determined in part by the observed high expansion rate of the PWN (Table 4), which, as discussed by Reynolds et al. (2018), implies the PWN is expanding into low density supernova ejecta. One possibility, as mentioned by Reynolds et al. (2018), is the PWN is currently embedded in a low density bubble resulting from the decay of $^{56}$Ni in the innermost ejecta (Li et al. 1993; Chevalier 2005). However, our modeling also simultaneously reproduces the observed size of the PWN and SNR, which is less dependent on the local conditions around the nebula.

Taken at face value, the low values of $E_{\text{in}}$ and $M_{\text{ej}}$ have strong implications for its progenitor. The value of $M_{\text{ej}}$ is lower than what would be expected for an isolated massive star progenitor (e.g., Sukhbold et al. 2016; Raithel et al. 2018), even when considering substantial mass-loss before exploding as a core-collapse supernova (e.g., Dessart et al. 2011). However, these values are comparable to what was found in recent three-dimensional simulations of neutrino-driven core-collapse supernovae of He cores (Müller et al. 2019)—suggesting that the progenitor of Kes 75 was originally in a binary system which transferred most its mass to a companion before exploding, indicative of a high initial mass.

The evolutionary model prefers a low temperature for the IC photon field of $T = 32$ K. This is in agreement with recent findings of dust emitting at a temperature of $T = 33 \pm 5$ K (for silicate grains) by Temim et al. (2019), which they conclude is most likely dust formed by the supernova and being shock heated by the PWN.

Furthermore, since the initial spin period $P_0$ of a pulsar can be calculated using (e.g., Pacini & Salvati 1973; Gaensler & Slane 2006; Slane 2017):

$$P_0 = P \left(1 + \frac{t_{\text{age}}}{\tau_{\text{sd}}} \right)^{-\frac{1}{2}},$$ 

the similarity between the inferred spin-down timescale $\tau_{\text{sd}}$ and $t_{\text{age}}$ from this modeling suggests that $P_0 \approx 0.618 P \approx 200$ ms (e.g., Gotthelf et al. 2000; Livingstone et al. 2011). This is considerably longer than $P_0 \approx 2$ ms needed to explain the strong, spin-down inferred dipole surface magnetic field strength $B_{\text{sd}} \approx 5 \times 10^{13}$ G if it results from an $\alpha - \Omega$ dynamo in the proto-neutron star (e.g., Thompson & Duncan 1993)—as often assumed for this and similar neutron stars (e.g., Granot et al. 2017). However, the high mass for the progenitor inferred above is consistent with the notion that such stars produce strongly magnetized neutron stars (e.g., Gaensler et al. 2005).

Lastly, the properties of the pulsar wind are somewhat atypical for this class of sources. The magnetization $\eta_{\text{b}} \sim 0.07$ inferred from this modeling is $\gtrsim 2 \times$ higher than that inferred from previous analyses of this system ($\eta_{\text{b}} \sim 0.005$; Bucciantini et al. (2011), $\eta_{\text{b}} \sim 0.008$–0.03; Torres et al. 2014), though this could be the result of a limited exploration of parameter space and reproducing a different set of observed properties than previous work. Of particular interest is the value of $E_{\text{max}}$. Current theories suggest that $E_{\text{max},\varphi} \approx e\Phi$ (e.g., Bucciantini et al. 2011), where $e$ is the charge of the electron and $\Phi$ is the voltage near the pulsar’s polar cap (e.g., Goldreich & Julian 1969; Bucciantini et al. 2011; Slane 2017):

$$\Phi = \sqrt{\frac{E_{\text{psr}}}{c}} \approx 1.66 \times 10^{13} \text{statvolt} \times \frac{299.79 \text{Volt}}{1 \text{statvolt}} \approx 4.99 \times 10^{15} \text{V},$$

or $E_{\text{max},\varphi} \approx 5$ PeV. While this value is not particularly well-constrained by our modeling, mainly due to the lack of information concerning the MeV emission from this PWN, our results suggest $E_{\text{max}}$ agrees with Bucciantini et al. (2011).

In summary, the presented X-ray observations offer a new window to study a unique pulsar-SNR system that may represent a transitional object between the rotation-powered pulsars and the magnetars. Observations during its outburst and quiescent phases will help to address questions related to its origin and what distinguishes PSR J1846–0258 from the typical pulsar in two classes of neutron stars.

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