1 Introduction

The Galactic supernova remnant (SNR) 3C 391 (G31.9+0.0), a member of the mixed-morphology class, has been observed in many different wavelengths. In this paper, we will present the analysis results of X- and gamma-ray data of 3C 391 taken with Suzaku and Fermi-LAT. The X-ray spectrum of 3C 391 was fitted to a single-temperature variable abundance non-equilibrium ionization (VNEI) model with an electron temperature of \( kT_{\text{e}} \sim 0.57 \) keV, an absorbing column density of \( N_{\text{H}} \sim 3.1 \times 10^{22} \) cm\(^{-2} \) and a very high ionization age \( (\tau > 10^{12} \) cm\(^{-3} \) s) which suggest that the plasma has reached ionization equilibrium. The spectrum shows clearly detected emission lines of Mg, Si, and S. 3C 391 was detected in GeV gamma rays with a significance of \( \sim 13 \sigma \). The spectrum was fitted with a log-parabola function, where the spectral index and beta parameters were found to be \( \alpha = 2.35 \pm 0.07 \) and \( \beta = 0.366 \pm 0.339 \). The integrated flux above 200 MeV was found as \( F = (2.34 \pm 0.37) \times 10^{-8} \) ph cm\(^{-2} \) s\(^{-1} \). These results are in agreement with the Fermi-LAT results given in the 2nd Fermi-LAT catalog.

Keywords: Supernova Remnants, Molecular Clouds, Gamma Rays, X-Rays, Fermi-LAT, Suzaku.

Studying the Supernova Remnant G31.9+0.0 in Gamma and X-Rays

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Abstract: G31.9+0.0 (3C 391) is a Galactic mixed-morphology supernova remnant observed in GeV gamma rays by Fermi Gamma Ray Space Telescope’s LAT (Fermi-LAT), as well as in the 0.3 – 10 keV X-ray band by Suzaku. In this paper, we will present the analysis results of X- and gamma-ray data of 3C 391 taken with Suzaku and Fermi-LAT. The X-ray spectrum of 3C 391 was fitted to a single-temperature variable abundance non-equilibrium ionization (VNEI) model with an electron temperature of \( kT_{\text{e}} \sim 0.57 \) keV, an absorbing column density of \( N_{\text{H}} \sim 3.1 \times 10^{22} \) cm\(^{-2} \) and a very high ionization age \( (\tau > 10^{12} \) cm\(^{-3} \) s) which suggest that the plasma has reached ionization equilibrium. The spectrum shows clearly detected emission lines of Mg, Si, and S. 3C 391 was detected in GeV gamma rays with a significance of \( \sim 13 \sigma \). The spectrum was fitted with a log-parabola function, where the spectral index and beta parameters were found to be \( \alpha = 2.35 \pm 0.07 \) and \( \beta = 0.366 \pm 0.339 \). The integrated flux above 200 MeV was found as \( F = (2.34 \pm 0.37) \times 10^{-8} \) ph cm\(^{-2} \) s\(^{-1} \). These results are in agreement with the Fermi-LAT results given in the 2nd Fermi-LAT catalog.
The spectrum for the remnant was extracted from the elliptical source region (4.85′ × 3.94′) centered at RA(J2000) = 18h49m28.6s, Dec. (J2000) = −0° 56′ 16.4″ and background spectrum was extracted from the elliptical annulus surrounding the remnant (Figure 1). The spectrum was binned to a minimum of 20 counts per bin using grppha to allow use of the $\chi^2$ statistic. We tried various combinations of spectral models. An absorbed (wabs in xspec; [21]) VNEI model, which is a model for a non-equilibrium ionization (NEI) collisional plasma with variable abundances (6) gave the best $\chi^2$ value of 950.2/659 = 1.44. During model fitting $N_H$, $kT_e$, n-e, and the abundances of Mg, Si, and S were free parameters, while the other elemental abundances were fixed to their solar values (2). We fitted the FI and BI spectra simultaneously, but only the BI (XIS1) spectra are shown for simplicity. The background-subtracted XIS1 spectrum was fitted in the 1.0–5.0 keV energy band as shown in the bottom panel of Figure 1. The best-fitting parameters (90% confidence level) are presented in Table 1.

### Table 1: Best-fitting spectral parameters of 3C 391 with corresponding errors at the 90% confidence level in the 1.0–5.0 keV band.

| Parameter | Value       | $\chi^2$/d.o.f |
|-----------|-------------|----------------|
| $N_H$ [10$^{22}$ cm$^{-2}$] | 3.1 ± 0.1    |                |
| $kT_e$ [keV] | 0.57 ± 0.01  |                |
| Mg (solar) | 1.3 ± 0.1    |                |
| Si (solar) | 0.9 ± 0.1    |                |
| S (solar)  | 0.8 ± 0.1    |                |
| $\tau$ [10$^{-5}$ cm$^{-3}$ s] | 11.7 ± 3.1 |                |
| Norm [ph cm$^{-2}$ s$^{-1}$] | 4.8 ± 0.3  | 950.2/659 = 1.44 |

The gamma-ray events in the data were binned in energy at 15 logarithmic steps between 200 MeV and 300 GeV. For the binned likelihood analysis (11), the matching energy dependent exposure maps were produced based on pointing direction, orientation, orbit location, and live-time accumulation of LAT. The large point-spread function (PSF) of LAT means that at low energies the PSF is large, the exposure map accounts for contributions from all the sources in the analysis region, exposure maps were created such that they included sources up to 10′ outside the ROI. In addition, since at low energies the PSF is large, the exposure map should be expanded by another 10′ to accommodate this additional exposure. Since the exposure map uses square pixels, to match the binning in the counts cube, we
generated an exposure map with 0.05°×0.05° bin size. For the pointlike analysis ([16]), also based on the likelihood analysis (FST-v9r31p0), the radius of the analysis region was chosen as 2° to obtain comparable results to the ones obtained by the binned likelihood analysis.

The spectral properties of the gamma-ray emission were studied by comparing the observation with models of possible sources in the ROI. Predictions were made by convolving the spatial distribution and spectrum of the source models with the instrument response function (IRF) and with the exposure of the observation. In the analysis we used the IRF version P7SOURCE_V6.

The model of the analysis region contains the diffuse background sources and all point-like sources from the 2nd Fermi-LAT catalog located at a distance ≤ 1.8° away from the center of the ROI. These point-like sources are shown in Table 2, where their positions, significances, and distances from the center of the ROI are given. The standard background model has two components: diffuse galactic emission (gal_2year7v6_v0.fits) and isotropic component (iso_p7v6source.txt), which is a sum of the extragalactic background, unresolved sources, and instrumental background, where it’s distribution is assumed to be isotropic.

The background and source modeling was done by the binned likelihood analysis using gllkt of FST. To determine the best set of spectral parameters of the fit, we vary the parameters until the maximum likelihood is maximized. In this analysis, we kept all the parameters of 2FGL J1847.2-0236 fixed, since it is relatively far away from the center of the ROI. For the rest of the point-like background sources, parameters except the normalizations were kept either fixed or free depending on the source strength and their distances from the ROI center. The detection of the source in this analysis is given by test statistics (TS) value, where larger TS values indicate that the null hypothesis (maximum likelihood value for a model without an additional source) is incorrect. This means that the source is present and its detection significance is approximately equal to the square root of TS.

Using pointlike analysis we detected 3C 391 with a significance of ~ 13 σ. We computed the best-fit position within the ROI of 3C 391, which was found as RA(J2000) = 282.360° and Dec(J2000) = −0.927°, which enhanced the TS by 2.58 σ over the position of 2FGL J1849.3-0055 in the 2nd Fermi-LAT catalog. Then the model was refitted using the best-fit position to compute the TS residual map and spectrum. Computing the TS map, we excluded 3C 391 from the model to see the full morphology of this SNR inside the ROI. Figure 2 shows the 2° × 2° TS residual map of 3C 391 and its nearby neighborhood with a bin size of 0.05°×0.05°, where the blue contours represent the Suzaku background-subtracted X-ray data from the upper panel of Figure 1, the yellow crosses and circles represent the 2nd Fermi-LAT catalog sources, and the black cross and circle is the GeV source from the 2nd Fermi-LAT catalog corresponding to SNR 3C 391. The peak value of the gamma-ray significance coincides with the X-ray remnant. The red diamonds indicate the OH maser locations reported by [10].

To check the functional form of the 3C 391 spectrum, we first tried to fit a log-parabola and then a power-law function between 200 MeV and 300 GeV:

- Log-parabola: $F(E)^{PL} = N_0 \left(\frac{E}{E_0}\right)^{(\alpha + \beta \ln(E/E_0))}$
- Power-law: $F(E)^{PL} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma}$

The log-parabola fit resulted in the spectral index and beta parameter values of $\alpha = 2.35 \pm 0.07$ and $\beta = 0.366 \pm 0.339$, respectively, for a fixed $E_0$ value of 2430 MeV. These results were in good agreement with the results in the 2nd Fermi-LAT catalog ([23]), where $\alpha = 2.35 \pm 0.16$ and $\beta = 0.308 \pm 0.099$. The power-law fit resulted in spectral index of $\Gamma = 2.28 \pm 0.03$, which is in agreement with the best-fit power-law index value given for 3C 391 in the 2nd Fermi-LAT catalog (~2.19), [23]. This result also matches to the results obtained by [17], $\Gamma = 2.33 \pm 0.11$.

The integrated flux between 200 MeV and 300 GeV was found as $F(E)^{PL} = (2.34 \pm 0.37) \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$ and $F(E)^{PL} = (8.55 \pm 0.22) \times 10^{-9}$ photons cm$^{-2}$ s$^{-1}$ for the log-parabola and power-law fits, respectively. The log-parabola fit gave a TS value of 160 for 3C 391, while the power-law fit resulted in a TS value of 146. The log-parabola fit gave a slightly higher TS value than the power-law fit, which was found to be consistent with the results in the 2nd Fermi-LAT source catalog. Figure 3 shows the GeV

| Source Name | RA ("') | Dec ("') | Distance ("') | √TS/σ |
|-------------|---------|----------|---------------|-------|
| 2FGL J1849.3-0055 | 282.33 | −0.91 | 0.02 | 8.99 |
| 2FGL J1849.3-0125c | 282.49 | −1.36 | 0.53 | 7.46 |
| 2FGL J1850.7-0014c | 282.69 | −0.248 | 0.76 | 9.18 |
| 2FGL J1848.2-0139c | 282.07 | −1.651 | 0.78 | 11.36 |
| 2FGL J1847.2-0236 | 281.81 | −2.611 | 1.77 | 13.81 |

Table 2: The point-like sources from the 2nd Fermi-LAT source catalog included in the background model of 3C 391. The source at the top of the list represents 3C 391. The distances shown are from the center of the ROI. The significances are as given in the 2nd Fermi-LAT catalog.
gamma-ray spectral data points and the statistical errors in black while the log-parabola fit is shown in red color.

3 Conclusion

In this work, we present results from a \( \sim 99.4 \) ks observation of 3C 391 with Suzaku and from almost 4-years of observations of Fermi-LAT. The X-ray spectrum of the SNR is well described by the model of a thermal plasma with electron temperature of \( \sim 0.57 \) keV, which is consistent with previous X-ray observations. We obtained a high absorbing column density of \( N_{\text{H}} \sim 3.1 \times 10^{22} \text{ cm}^{-2} \), which is consistent with the previous X-ray observations implying that it is in the Galactic plane region. For full ionization equilibrium, the ionization timescale \( (\tau_\text{n}) \), where \( n_\text{e} \) and \( \tau \) are electron density and the time since the plasma was heated, should be \( \geq 10^{12} \text{ cm}^{-3} \text{ s} \) \( (18) \). The VNEI model yields a very high ionization age (\( \tau > 10^{12} \text{ cm}^{-3} \text{ s} \)), which suggests that the plasma has reached ionization equilibrium. This is consistent with the conclusion of the ASCA \( (3, 15) \) and Chandra \( (9) \) studies. We also have analyzed the GeV gamma-ray data of 3C 391 and detected the source with a significance of \( \sim 13 \sigma \), where the position of the peak TS value of the gamma-ray emission is coincident with the X-ray location. Since the PSF of Fermi-LAT is comparable or larger than the size of 3C 391, it is not possible to resolve the SNR morphology, therefore we could not determine if the gamma rays come form the NW rim of the SNR or from the direction of the maser spots on the opposite side of the shell. The spectra shows a log-parabola type shape with spectral index of \( \alpha = 2.35 \pm 0.07 \) and beta value of \( \beta = 0.366 \pm 0.339 \). The GeV flux above 200 MeV was found to be \( \text{F}(E) = (2.34 \pm 0.37) \times 10^{-8} \text{ photons cm}^{-2} \text{ s}^{-1} \). The same spectra was also fitted with a power-law model that gave the spectral index and flux as \( \Gamma = 2.28 \pm 0.032 \) and \( \text{F}(E) = (8.55 \pm 0.22) \times 10^{-8} \text{ photons cm}^{-2} \text{ s}^{-1} \), respectively. Both models fit to the data successfully, but the log-parabola model is more favorable due to the higher significance value of the fit. The spectrum might be the result of hadronic interactions between 3C 391 and the associated molecular clouds in the vicinity. To understand if this is the case, we are going to do a detailed modeling of the spectrum to understand the possible emission mechanisms.