SUZAKU OBSERVATIONS OF $\gamma$-RAY BRIGHT RADIO GALAXIES: ORIGIN OF THE X-RAY EMISSION AND BROADBAND MODELING

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ABSTRACT

We performed a systematic X-ray study of eight nearby $\gamma$-ray bright radio galaxies with Suzaku in order to understand the origins of their X-ray emissions. The Suzaku spectra for five of those have been presented previously, while the remaining three (M87, PKS 0625−354, and 3C 78) are presented here for the first time. Based on the Fe-K line strength, X-ray variability, and X-ray power-law photon indices, and using additional information on the [O iii] line emission, we argue for a jet origin of the observed X-ray emission in these three sources. We also analyzed five years of Fermi Large Area Telescope (LAT) GeV gamma-ray data on PKS 0625−354 and 3C 78 to understand these sources within the blazar paradigm. We found significant $\gamma$-ray variability in the former object. Overall, we note that the Suzaku spectra for both PKS 0625−354 and 3C 78 are rather soft, while the LAT spectra are unusually hard when compared with other $\gamma$-ray detected low-power (FR I) radio galaxies. We demonstrate that the constructed broadband spectral energy distributions of PKS 0625−354 and 3C 78 are well described by a one-zone synchrotron/synchrotron self-Compton model. The results of the modeling indicate lower bulk Lorentz factors compared to those typically found in other BL Lacertae (BL Lac) objects, but consistent with the values inferred from modeling other LAT-detected FR I radio galaxies. Interestingly, the modeling also implies very high peak ($\sim 10^{16}$ Hz) synchrotron frequencies in the two analyzed sources, contrary to previously suggested scenarios for Fanaroff–Riley (FR) type I/BL Lac unification. We discuss the implications of our findings in the context of the FR I/BL Lac unification schemes.

Key words: galaxies: jets – gamma rays: galaxies – X-rays: galaxies

1. INTRODUCTION

Radio galaxies constitute the parent population of blazars, with low-power radio galaxies thought to be misaligned BL Lacertae (BL Lac) objects, and higher-power sources thought to be associated with flat spectrum radio quasars (FSRQs; e.g., Urry & Padovani 1995). In general, the accretion power determines the radiative properties of the direct emission of the accreting matter (i.e., the thermal continuum of the accretion disk and circumnuclear dust) and is reflected in the presence of high-excitation emission lines in the source spectrum (Hine & Longair 1979). In particular, the “low-excitation radio galaxies” (LERGs) are considered to be characterized by lower accretion rates (below ~1% in the Eddington units) and radiatively inefficient accretion flows, while “high-excitation radio galaxies” (HERGs) are believed to represent high-accretion rate sources with standard (optically thick, geometrically thin) accretion disks. The jet power, on the other hand, which generally scales with the total radio luminosity, was proposed to be related uniquely to the large-scale morphologies of radio galaxies (Fanaroff & Riley 1974), with low- and high-power jets forming Fanaroff–Riley (FR) type I and type II structures, respectively. The “FSRQs/FR II/HERGs versus BL Lacs/FR Is/LERGs” unification scenario is not without its caveats, however, as a number of BL Lacs have been found to be associated with FR II-like jets and lobes, while some FSRQs display FR I large-scale morphologies (e.g., Blundell & Rawlings 2001; Heywood et al. 2007; Landt & Bignall 2008; Chiaberge et al. 2009; Kharb et al. 2010). Also, many FR II-type radio galaxies are classified as LERGs, while some FR Is are known to be hosted by high-excitation nuclei (e.g., Harndcaste et al. 2006, 2007, 2009; Buttiglione et al. 2010; Gendre et al. 2013; Mingo et al. 2014).

Studying the core emission of radio galaxies in the aforementioned context of unification schemes for active galactic nuclei (AGNs) can be challenging, however, due to the inevitable contributions from relativistic jets, host galaxies, accretion disks, and disk coronae, any one of which may dominate the observed radiative output of a source in different frequency ranges. Hence, a detailed multifrequency analysis is needed to disentangle robustly various emission components in a number of objects before drawing any definite conclusions regarding the corresponding jet and accretion luminosities. We note that although the extended, $\gtrsim$ kiloparsec-scale jets have been resolved in the X-rays and optical for a number of sources, subkiloparsec-scale structures cannot be imaged at frequencies higher than radio, with a few exceptions (see Harris et al. 2009; Goodger et al. 2010; Worrall et al. 2010; Meyer et al. 2013). For this reason, even for the brightest radio galaxies such as Cen A and NGC 1275, the origin of the observed optical and X-ray core fluxes is still an open issue (e.g., Yamazaki et al. 2013). Often, the jet origin of the unresolved core emission is claimed based solely on the modeling of broadband spectral energy distributions (SEDs; see, e.g., Chiaberge et al. 2003 and Foschini et al. 2005 for the case of NGC 6251), and therefore the alternative possibilities, such as a disk/corona emission, cannot be ruled out.

6 See http://hea-www.harvard.edu/XJET/ and http://astro.fit.edu/jets/ for continually updated lists of large-scale jets resolved in X-rays and optical, respectively.
et al. (2013), on the other hand, concluded that the X-ray core dominant jet contribution at energies above 100 keV. Yamazaki

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The X-ray Imaging Spectrometer (XIS; Koyama et al. 2007) and the Hard X-ray Detector (HXD; Takahashi et al. 2007; Kokubun et al. 2007). The former consists of four CCD cameras. One CCD has been lost in 2006 November, and thus most of the available Suzaku data for the GeV emitting sources have already been published, as indicated in the literature. Our main conclusions are summarized in Section 5.

2. SUZAKU OBSERVATIONS

2.1. Data Reduction

Suzaku is an X-ray observatory that contains two instruments: the X-Ray Imaging Spectrometer (XIS; Koyama et al. 2007) and the Hard X-ray Detector (HXD; Takahashi et al. 2007; Kokubun et al. 2007). The former consists of four CCD cameras. One CCD has been lost in 2006 November, and thus most of the observational results shown in this paper were based on the data of three CCD cameras. The latter consists of PIN photo-diodes and GSO scintillators surrounded by active shields of BGO scintillators. All the available Suzaku data for the GeV emitting FR I radio galaxies are summarized in Table 1. Results for some of the targets have already been published, as indicated in the table; the Suzaku results for M87, PKS 0625–354, and 3C 78

In the X-ray domain, there are three pieces of evidence that can help to distinguish between thermal disk/corona emission and non-thermal radiation from an unresolved jet: variability, the Fe-K line, and, to a lesser extent, the spectral slope. Non-thermal jet emission is expected to be variable on shorter timescales and with greater magnitude than variations in an accretion disk/corona, so fast variability would be an indication of a jet origin, although a lack of such variability would not rule out a jet origin. Variability constraints were used, for example, in the Suzaku study of Cen A by Fukazawa et al. (2011b), who claimed a dominant jet contribution at energies above 100 keV. Yamazaki et al. (2013), on the other hand, concluded that the X-ray core emission from NGC 1275 is dominated by accreting matter due to a large equivalent width (70–120 eV) of the detected Fe-K line, and, to a lesser extent, the spectral slope. Non-thermal radiation from an unresolved jet: variability, the corona emission

| Source | Redshift | ObsID | Date       | Exposure | References |
|--------|----------|-------|------------|----------|------------|
| 3C 78/NGC 1218 | 0.029 | 706013010 | 2011 Aug 20 | 97 ks | This study  |
| 3C 84/NGC 1275 | 0.018 | ... | 2006–2011 | ... | Y13        |
| 3C 111 | 0.049 | 70504001-30 | 2010 Sep 2,9,14 | 170 ks | T11        |
| 3C 120 | 0.033 | 70000101-40 | 2006 Feb 3 | 147 ks | K07        |
| PKS 0625–354 | 0.055 | 706014010 | 2011 Nov 3 | 110 ks | This study |
| M87/3C 274 | 0.004 | 801038010 | 2006 Nov 29 | 98 ks | This study |
| Cen A/NGC 5128 | ... | 100005010 | 2005 Aug 19 | 94 ks | M07        |
| NGC 6251 | 0.024 | 705039010 | 2010 Dec 2 | 87 ks | E11        |

Notes.

a XIS-0 exposure.

b References: Yamazaki et al. (2013); Tombesi et al. (2011); Kataoka et al. (2007); Markowitz et al. (2007); Fukazawa et al. (2011b); Evans et al. (2011).

c Twelve pointings.

d Four pointings.

e The assumed distance 3.8 Mpc.

During the last decade, rapid developments in γ-ray astronomy have opened a new window for studying the unification of jetted AGNs. Blazars are generally bright in the γ-ray band (Hartman et al. 1999; Ackermann et al. 2011) due to relativistic beaming of the jet emission, which is expected to not be as significant for misaligned radio galaxies. Still, recent observations by the Fermi Large Area Telescope (LAT) in the high-energy (HE; 0.1–100 GeV) band, as well as by the atmospheric Cherenkov telescopes in the very high-energy (VHE; >0.1 TeV) band, have revealed that radio galaxies are HE emitters. In particular, Fermi-LAT has detected 11 radio galaxies with 15 months of sky survey data (Abdo et al. 2010b), including M87 (Abdo et al. 2009b), Cen A (Abdo et al. 2010a), and NGC 1275 (Abdo et al. 2009a). These three objects are also the only established TeV emitting radio galaxies (Aharonian et al. 2006, 2009; Aleksić et al. 2012, respectively), taking into account that the VHE-detected IC 310 (Aleksić et al. 2010) is now proposed to be re-classified as a BL Lac object (Kadler et al. 2012).

Here, we report the Suzaku (Mitsuda et al. 2007) X-ray study of eight nearby (redshifts z < 0.06) γ-ray emitting radio galaxies that are included in the 15 month Fermi-LAT “misaligned AGN” list (Abdo et al. 2010b). All these radio galaxies are of the FR I type, with the exception of 3C 111 and NGC 6251, which display classical FR II and intermediate FR I/FR II large-scale radio morphologies, respectively (e.g., Girouzzi et al. 2004; Sambruna et al. 2004; Grandi et al. 2012). The remaining three radio galaxies from the misaligned AGN sample are all distant (z > 0.25), so we do not explore them here. In Section 2, we present our original Suzaku data analysis for M87, PKS 0625–354, and 3C 78; Suzaku results for the other sources we discuss. 3C 111, 3C 120, Cen A, NGC 1275, and NGC 6251, are quoted from the literature. In Section 3, we also present the analysis of five years of Fermi-LAT data for two particularly intriguing sources, PKS 0625–354 and 3C 78. In Section 4, we discuss the origin of the X-ray emission detected with Suzaku from unresolved cores of eight analyzed radio galaxies. There, we also present for the first time the broadband SED modeling of PKS 0625–354 and 3C 78 which appear to have X-rays originating from non-thermal jet emission and have not been previously modeled. The modeling is then compared with the analogous modeling of Cen A, NGC 1275, M87, and NGC 6251 presented previously in the literature. Our main conclusions are summarized in Section 5.

Table 1

Summary of Suzaku Observations of Eight LAT-detected FR I Radio Galaxies

| Source | Redshift | ObsID | Date       | Exposure | References |
|--------|----------|-------|------------|----------|------------|
| 3C 78/NGC 1218 | 0.029 | 706013010 | 2011 Aug 20 | 97 ks | This study  |
| 3C 84/NGC 1275 | 0.018 | ... | 2006–2011 | ... | Y13        |
| 3C 111 | 0.049 | 70504001-30 | 2010 Sep 2,9,14 | 170 ks | T11        |
| 3C 120 | 0.033 | 70000101-40 | 2006 Feb 3 | 147 ks | K07        |
| PKS 0625–354 | 0.055 | 706014010 | 2011 Nov 3 | 110 ks | This study |
| M87/3C 274 | 0.004 | 801038010 | 2006 Nov 29 | 98 ks | This study |
| Cen A/NGC 5128 | ... | 100005010 | 2005 Aug 19 | 94 ks | M07        |
| NGC 6251 | 0.024 | 705039010 | 2010 Dec 2 | 87 ks | E11        |

Notes.

a XIS-0 exposure.

b References: Yamazaki et al. (2013); Tombesi et al. (2011); Kataoka et al. (2007); Markowitz et al. (2007); Fukazawa et al. (2011b); Evans et al. (2011).

c Twelve pointings.

d Four pointings.

e The assumed distance 3.8 Mpc.
are presented here for the first time. The Fe-K line equivalent widths and the X-ray luminosities of all the objects provided in Table 1 and discussed in detail below in this paper are estimated by analyzing the archival Suzaku data, including the results of Fukazawa et al. (2011a). All the observations were performed in the XIS 5 × 5 or 3 × 3 modes, and with the normal mode of the HXD. We utilized data processed with version 2.0–2.7 of the pipeline Suzaku software and performed the standard data reduction: a pointing difference of <1′:5, an elevation angle of >5° from the Earth’s rim, a geomagnetic cut-off rigidity (COR) of >6 GV, and >256 s spent in the South Atlantic Anomaly (SAA). Further selections were applied: Earth elevation angle of >20° for the XIS, COR >8 GV, and the time elapsed from the SAA (T_SAA_HXD) was selected to be >500 s for the HXD. The XIS response matrices were created with xisrmfgen and xissimarfgen (Ishisaki et al. 2007). The XIS detector background spectra were extracted 4–6 arcmin from the target object and then subtracted. We utilized the HXD responses provided by the HXD team. The “tuned” (LGFET) HXD background files (Fukazawa et al. 2009) were used, and the good time interval (GTI) was determined by taking the logical “AND” of GTIs among XIS data, HXD data, and HXD background data. For the XIS and HXD-PIN, the cosmic X-ray background was added to the background spectrum, assuming the flux and spectra in Boldt (1987), although it was negligible for the HXD-GSO.

For XIS and PIN detectors, the energy ranges of 0.45–10 keV and 17–50 keV, respectively, were used in the fitting. In addition, we ignored the 1.75–1.88 keV energy interval in the XIS spectra to avoid the response uncertainty. The X-ray spectra were binned for least \( \chi^2 \) spectral fitting so that one spectral bin contains more than 20 photons. XIS photons were accumulated within 4 arcmin of the galaxy center, with the XIS-0 and -3 data co-added for PKS 0625–354 and 3C 78. For M87, the XIS-2 CCD was utilized in the same way as above. Since M87 is embedded in the bright extended X-ray emission of the Virgo intracluster medium, we took the integration radius as 1 arcmin, the background spectrum was taken from the 1.5–2.5 arcmin ring, and we ignored the HXD-PIN data. Since the GSO signal was not significant in all the analyzed objects and the resulting upper limits above 40 keV are not constraining, we do not discuss the GSO data analysis results below. A relative normalization between the XIS-F and XIS-B was left free to vary, while that between the XIS and PIN was fixed\(^7\) to 1:1.7.

### 2.2. Results

M87, PKS 0625–354, and 3C 78 are clearly detected with the XIS below 10 keV; PKS 0625–354 is also detected with HXD-PIN above 10 keV. At first, the obtained Suzaku X-ray spectra were fit with a single power-law (PL) model multiplied by the Galactic absorption with the column densities fixed to the corresponding values provided by Kalberla et al. (2005). The spectra of all three objects showed some residuals in the soft X-ray band. These residuals could be due to the thermal emission from the hot interstellar or intracluster medium and/or absorption columns in excess of the Galactic values. Thus, one or two apec thermal plasma models were included in the second step of the fitting procedure and the absorption column densities were left free. In the cases of PKS 0625–354 and 3C 78, the metal abundance of apec was fixed to 0.3 solar, which is typical for galaxy groups (e.g., Fukazawa et al. 2004). In the case of M87, good photon statistics allowed us to leave the metal abundance free, but because the temperature structure of the M87 core region is complex (e.g., Matsushita et al. 2002), even a two-temperature apec model could not fit the soft X-ray continuum well. Since the detailed investigation of the M87 temperature structure is beyond the scope of this paper, we simply applied a two-temperature apec model to the 0.7–10 keV range, constraining the main thermal plasma parameters; then the resulting apec model parameter values were fixed during an apec + PL model fit to the 3–10 keV range. Inclusion of the additional thermal components improved the fits and are summarized in Table 2 and presented in Figure 1.

The plasma temperatures and luminosities derived for PKS 0625–354 and 3C 78 are consistent with those of interstellar and intracluster media found in elliptical galaxies and galaxy groups (e.g., Birzan et al. 2004; Fukazawa et al. 2006; Diehl & Statler 2007). We also checked the archival Chandra

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| Source | \( N_H \) (10\(^{22}\) cm\(^{-2}\)) | \( kT \) (keV) | \( Z \) (Z\(_{\odot}\)) | \( L_{0.5–10\text{keV}} \) (10\(^{42}\) erg s\(^{-1}\)) | \( \Gamma \) | \( L_{2–10\text{keV}} \) (10\(^{42}\) erg s\(^{-1}\)) | EW | \( \chi^2 / \text{dof} \) |
|--------|-----------------|----------|---------|-----------------|------|-----------------|------|-----------------|
| M87    | 10 ± 6 (1.9)    | 1.79 ± 0.02 | 1.4 ± 0.8 | 13              | 2.42 ± 0.03 | 0.7              | <13  | 674/572         |
| PKS 0625–354 | 9 ± 1 (6.36)    | 2.28 ± 0.03 | 1.4 ± 0.2 | 9.6             | 2.25 ± 0.02 | 49               | <7   | 640/486         |
| 3C 78  | 14 ± 2 (9.51)   | 0.24 ± 0.02 | 0.3(3)   | 1.0             | 2.32 ± 0.04 | 2.0               | <75  | 572/567         |
| NGC 6251 | 1.82\(^{+0.04}_{-0.05}\) | 2.86               |        |                 |      |                  |      |                 |
| 3C 111 | 1.65 ± 0.02     | 259               |        |                 |      |                  |      |                 |
| 3C 120 | 1.75\(^{+0.03}_{-0.02}\) | 100               |        |                 |      |                  |      |                 |
| NGC 1275 | 1.73 ± 0.03    | 7.7               |        |                 |      |                  |      |                 |
| Cent A | 1.73 ± 0.03     | 10                |        |                 |      |                  |      |                 |

**Notes.** (1) Source. (2) Absorption column density for phabs model; the values in the parentheses are the Galactic values \( N_H, \text{GAL} \) from Kalberla et al. (2005). (3) Temperature in the apec fits. For M87 and 3C 78, two temperatures are shown in the two apec model. (4) Abundance in the apec fit (fixed in the cases of PKS 0625–354 and 3C 78). (5) Absorption-corrected apec luminosity. (6) Photon index in the PL fit; values for bottom five objects are quoted from the corresponding references in Table 1. (7) Absorption-corrected PL luminosity. (8) Equivalent width of Fe-K line. (9) Goodness of the fit (in the case of M87, the provided \( \chi^2 / \text{dof} \) value corresponds to the PL fit to the 3–10 keV range; see Section 2.2 for details). Values for bottom five objects in Columns 7, 8, and 9 are originally derived by us.

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\(^7\) [http://www.astro.isas.jaxa.jp/suzaku/analysis/hxd/gsoarf2/]
Figure 1. Suzaku spectra of M87, PKS 0625−354, and 3C 78. The black, red, and green symbols are XIS-F, XIS-B, and HXD-PIN spectra, respectively. The solid line represents the best-fit total model, while the dashed and dotted lines are the apec and power-law model components, respectively. We include two apec models for M87 and 3C 78. The bottom panels show the residuals in units of σ.

X-ray data for PKS 0625−354 and confirmed that the X-ray appearance of the source is almost point-like with a faint extended halo due to the host elliptical/poor galaxy cluster Abell 3392. The temperatures of two apec components derived for M87 are consistent with those obtained before by Matsushita et al. (2002) based on the analysis of XMM-Newton data; the two distinct thermal components in this case are due to the projection of cool-core and hot-periphery cluster emission at the cluster center.

The absorption column densities $N_H$ for the three analyzed radio galaxies are slightly larger than the corresponding Galactic value of Kalberla et al. (2005); see Table 2. This might be due to the spectral curvature in the soft X-ray band, but we cannot rule out the uncertainty of the $N_H$ Galactic database, spectral modeling dependency of the thermal emission, and also the intrinsic absorption by the interstellar medium in host galaxies. The derived PL photon indices $\Gamma_X$, distributed within a narrow range of 2.22−2.45, are somewhat steeper but not extraordinary for coronal emission of Seyfert galaxies. They are also consistent with the X-ray photon indices of high-peaked BL Lac objects (e.g., Donato et al. 2005; Ajello et al. 2009), i.e., the aligned counterpart to FR I radio galaxies where the X-rays have a jet origin. Fluorescence Fe-K lines are common features in AGNs dominated by disk emission. However, none of the objects analyzed here show significant fluorescence Fe-K lines, except for the ionized Fe-K lines from the hot plasma around the M87 core. We obtained upper limits of the equivalent widths (EWs) of the narrow Fe-K lines at the rest-frame energy of 6.4 keV (see Table 2); these are particularly low in the cases of PKS 0625−354 and M87.

Gliozzi et al. (2008) reported on the 2005 XMM-Newton data analysis for PKS 0625−354. They found a PL X-ray component with a photon index of $2.52^{+0.02}_{-0.03}$ and a flux of $2.6 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$; the EW of the Fe-K line was constrained to be <182 eV. Trussoni et al. (1999) reported on BeppoSAX observations of PKS 0625−354 and 3C 78 from 1996−1997. Assuming a photon index of 2.3 for both sources, they derived the 1−10 keV luminosities of the PL components as $1.8 \times 10^{43}$ erg s$^{-1}$ and $1.5 \times 10^{42}$ erg s$^{-1}$, respectively. Our Suzaku observations therefore reveal a flatter spectrum and brighter (by a factor of two to three) X-ray emission of PKS 0625−354 when compared with the previous epochs. For 3C 78, the X-ray flux is almost the same as that in 1997, and we constrain the PL photon index and Fe-line EW for the first time. The Fe-K line EWs are, in general, much more strongly constrained in this study than ever before.

We also investigated the X-ray time variability of the analyzed radio galaxies during the Suzaku observations; see Figure 2. No statistically significant variability was found in the 0.45–8 keV range for 3C 78, however, most likely only due to a very low
photon statistics. PKS 0625–354, on the other hand, showed a small amount of variability with a timescale of one to two days and an amplitude of $\sim 10\%$. Significant X-ray variability of M87 detected in the acquired Suzaku data will be discussed (and compared with ongoing Chandra monitoring; see Harris et al. 2009) in the forthcoming paper.

3. FERMI-LAT OBSERVATIONS

The Fermi-LAT is a pair conversion telescope that has a field of view of about 20% of the sky from 20 MeV to over 300 GeV (Atwood et al. 2009). Since our results indicate that the X-ray spectra of PKS 0625–354 and 3C 78 are dominated by jet emission, we analyzed five years of LAT data for those two radio galaxies. As mentioned in Section 1, theSED modeling of M87 was performed by Abdo et al. (2009b).

3.1. Data Analysis and Localization

We analyzed the LAT P7REP data from 2008 August 4 to 2013 August 4, corresponding to mission elapsed time 239557420 to 397353600. Source class (evclass=2) events were selected with a zenith angle cut of $<100^\circ$ and a rocking angle cut of 52°. For the analysis, LAT Science Tools version v9r32p5 was utilized with the P7REP_SOURCE_V15 instrument response functions. Both radio galaxies are clearly visible in the 0.2 to 300 GeV LAT counts maps. We obtained a localization of the $\gamma$-ray sources associated with each galaxy with the gtfindsrc task. The resulting localizations were reduced to the 95% confidence localization error $r_{0.05} = 0.042$ centered at (R.A., decl.) = (96:785, $-35^\circ 488$) for PKS 0625–354 (NED: 96:778, $-35^\circ 488$), and $r_{0.05} = 0.089$ centered at (47:145, 4:130) for 3C 78 (NED: 47:109, 4:111). These localized positions are consistent within 0.007 and 0.046 from the center of the two targets, respectively.

3.2. Results

We extracted the data within a 12 $\times$ 12 deg$^2$ rectangular region centered on each object. The binned likelihood fitting with the gtlike tool was performed. The field background point sources within 14:5 from each source, listed in the LAT two-year catalog (Nolan et al. 2012), were included and their spectra were assumed to be PLs with the photon indices fixed to the catalog values. The standard LAT Galactic emission model was used (gll_iem_v05.fits) and the isotropic diffuse gamma-ray background and the instrumental residual background were represented as a uniform background (iso_source_v05.txt). A likelihood analysis was performed with the energy information binned logarithmically in 30 bins in the 0.2–300 GeV range for our two sources, we performed the gtlike spectral analysis for several independent energy bins, which were spaced logarithmically. Nine energy bins were analyzed for PKS 0625–354 and six energy bins for 3C 78. In order to obtain model-independent spectra in the 0.2–300 GeV range for our two sources, we performed the gtlike spectral analysis for several independent energy bins, which were spaced logarithmically. Nine energy bins were analyzed for PKS 0625–354 and six energy bins for 3C 78. In each energy bin, we fixed the PL photon index to 2.0. Figure 3 shows the resulting spectra, where we do not detect signals below 1 GeV (TS < 5) for 3C 78. Interestingly, the $\gamma$-ray detection

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**Figure 2.** Suzaku X-ray light curves of PKS 0625–354 (left) and 3C 78 (right) in the 0.45–8 keV band. The size of the time bins is 4000 s. The red data points are XIS-B, and others are XIS-F.

**Table 3**

| Source             | $\Gamma_{HE}$ | $F_{0.1–10 GeV}$ | TS     | GBMN   | IBMN   |
|--------------------|---------------|------------------|--------|--------|--------|
| PKS 0625–354       | 1.72 ± 0.06   | 6.7 × 10$^{-9}$  | 403.2  | 1.06 ± 0.02 | 1.38 ± 0.03 |
| 3C 78              | 2.01 ± 0.16   | 4.9 × 10$^{-9}$  | 61.3   | 1.04 ± 0.01 | 0.95 ± 0.03 |

**Notes.** (1) Source. (2) HE $\gamma$-ray photon index. (3) Photon flux in the units of ph cm$^{-2}$ s$^{-1}$. (4) Test statistics of the detection. (5) Galactic background model normalization. (6) Isotropic background model normalization.
is significant up to 100 GeV for both objects. In addition, the analysis indicates a break in the γ-ray spectrum of PKS 0625−354. We therefore applied the broken PL model with gtlike and found that the likelihood $L$ increased by $2\Delta \log L = 401.4$, corresponding to $20\sigma$; the resulting photon indices were then derived as $1.69 \pm 0.07$ and $4.97 \pm 1.53$ below and above the break energy $64 \pm 23$ GeV, respectively.

In order to investigate the γ-ray variability of the two analyzed radio galaxies, we binned the LAT data into 30 or 90 day bins for PKS 0625−354, and 1 yr bins for 3C 78. The gtlike analysis was performed for each time bin in the same way as the 5 yr analysis of the 0.2–300 GeV band. Figure 4 shows the resulting HE γ-ray light curves. No significant variability can be claimed for 3C 78, but PKS 0625−354 displayed a rather pronounced flare during the second year of the LAT operation. Keeping in mind the hardening in the HE γ-ray spectrum of NGC 1275 detected during the flaring state by Kataoka et al. (2010), we split the LAT data for PKS 0625−354 into the two 2.5 yr long intervals and performed the gtlike analysis for each epoch separately, but we did not find any significant spectral evolution.

$\chi^2 = 2\Delta \log L$ is distributed as $\chi^2$ for one degree of freedom.

4. DISCUSSION

4.1. Origin of the X-Ray Emission

In this section, we summarize Suzaku X-ray studies of the GeV-emitting FR I radio galaxies. Together with the new results on M87, PKS 0625−354, and 3C 78 reported in this paper, we refer to Suzaku results from publications listed in Table 1.

For most of the objects in our sample, the X-ray spectra are quite similar to those of radio-quiet (non-jetted) Seyfert galaxies, and only in a few cases do the PL photon indices seem somewhat steeper than those typically derived for Seyferts ($\Gamma_X \sim 1.5–2.1$; e.g., Perola et al. 2002). Therefore, the key feature in distinguishing between the disk/corona versus jet origin for the observed X-ray emission is a fluorescence neutral narrow Fe-K line. This line, commonly observed in Seyfert galaxies accreting at moderate and higher rates with $>10^{-2} L_{\text{edd}}$, where $L_{\text{edd}}$ is the Eddington luminosity, is believed to originate from the Compton-thick dusty torus, which subtends the accretion disk with a large solid angle as a result of reflection of coronal nuclear X-ray emission. The Fe-K line width and slow variability support the torus origin of a narrow Fe-K line (Fukazawa et al. 2011a). In the case where the X-ray emission is dominated by non-thermal jet radiation, one should not expect...
a strong Fe-K line, since the jet emission is beamed away from the disk, and so jet photons are not likely to be reflected by the torus. At the same time, sources accreting at particularly low rates with $<10^{-2} L_{\text{edd}}$ may in principle lack large amounts of circumnuclear dust or prominent coronal components, and as such may be rather weak Fe-K line emitters. Among our sample of targets, four HERGs, including Cen A, NGC 1275, 3C 120, and 3C 111, reveal clear Fe-K lines, while the objects classified as LERGs, namely M87, PKS 0625$-$354, 3C 78, and NGC 6251, do not.

Figure 5 shows the Fe-K line emission is also a meaningful indicator of pronounced disk emission, since this line is emitted by the extended gas photoionized by strong disk UV emission. Figure 6 shows a plot of the X-ray luminosity versus [O III] luminosity. The plot reveals some (weak) hints for a $L_X-L_{[\text{O III}]}$ correlation in the case of Seyferts, but it is not obvious for the analyzed radio galaxies. In particular, the three HERGs in the sample (NGC 1275, 3C 111, and 3C 120) seem to be located in the same region as Seyferts, thus obeying the correlation, while the LERGs seem to be located significantly off the track. This is in agreement with the results of Hardcastle et al. (2009) and Mingo et al. (2014), who showed that the $L_X-L_{[\text{O III}]}$ correlation persists for HERGs and is not followed by the LERGs in general. This finding can be considered as further support for the scenario for the disk/corona emission dominating the X-ray spectra in “Seyfert-like” sources NGC 1275, 3C 111, and 3C 120, and the jet emission dominating the X-ray output of the outlers such as PKS 0625$-$354. However, a caveat for this conclusion is that luminosity–luminosity correlations in flux-limited samples may not be real, but only induced by selection effects.

We have summarized the evidence for the disk/corona versus jet origin for our sample, as discussed in this Section in Table 4.

4.2. X-Ray/γ-Ray Connection

The GeV γ-ray emission from radio galaxies could originate from the parsec/subparsec-scale jet, where the likely mechanism is synchrotron self-Compton (SSC) or external Compton (EC) scattering of the dust torus or broad-line region emission. It could also originate from EC scattering of CMB photons by electrons in the 100 kpc scale jets or the radio lobes, as established for Cen A (Abdo et al. 2010b). Somewhat tentative detections of the lobes’ γ-ray emission have been reported also for the intermediate FR I/FR II sources NGC 6251 (Takeuchi et al. 2012) and Cen B (Katsuta et al. 2013), based on the spatial offset between the best-fit position of the γ-ray source and the position of the radio core or the extension of the γ-ray source aligned to the large-scale radio structure, respectively. The γ-ray emission could not be localized precisely or potentially resolved for 3C 78 or PKS 0625$-$354 due to the large position errors and a combination of relatively large source distances (when compared with those of Cen A or Cen B) and relatively small sizes of their FR I-type radio structures. The variability of PKS 0625$-$354, however, makes the parsec-scale origin much more likely for this source, and we favor this interpretation for 3C 78 as well. This also allows us to make a connection...
between the γ-rays and X-ray emission from PKS 0625–354 and 3C 78, which were established as likely being of jet origin in the previous section. We therefore model the broadband SEDs of these two sources in the framework of a standard “misaligned blazar” scenario. We combined the new X-ray and γ-ray data presented above with archival radio, optical, and X-ray data from the NASA Extragalactic Database (NED), XMM-Newton optical monitor (OM) data from Gliozzi et al. (2008) and core HST data for 3C 78 (Chiaberge et al. 2002). The thick curves denote the synchrotron/SSC model fits with two different variability timescales, as given in the legend. The solid curves include γγ absorption with the EBL model of Finke et al. (2010), while the dashed curves do not. The thin blue curves are the elliptical galaxy template from Silva et al. (1998), adjusted to the redshifts of the sources.

Figure 7. SEDs of PKS 0625–354 (left) and 3C 78 (right). Black circles indicate the Suzaku X-ray and Fermi-LAT γ-ray data presented in this paper, green diamonds are archival data from NED, and red squares are the XMM-Newton OM data for PKS 0625–354 (Gliozzi et al. 2008) and core HST data for 3C 78 (Chiaberge et al. 2002). The thick curves denote the synchrotron/SSC model fits with two different variability timescales, as given in the legend. The solid curves include γγ absorption with the EBL model of Finke et al. (2010), while the dashed curves do not. The thin blue curves are the elliptical galaxy template from Silva et al. (1998), adjusted to the redshifts of the sources.

Table 4
Summary of Evidence for Disk/Corona versus Jet Origin for X-Ray Emission

| Source          | Fe-K Line | X-ray Spectral Index | X-Ray Variability | [O m] Line | Type [Ref.] |
|-----------------|-----------|----------------------|-------------------|------------|-------------|
| 3C 78           | Jet       | Jet                  | Inconclusive      | Jet        | LERG [B10]  |
| 3C 84           | Disk/corona | Inconclusive         | Disk/corona      | HERG/HERG* |             |
| 3C 111          | Disk/corona | Inconclusive         | Disk/corona      | HERG* [E00] |             |
| 3C 120          | Disk/corona | Inconclusive         | Disk/corona      | HERG* [E00] |             |
| PKS 0625–354    | Jet       | Jet                  | Inconclusive      | Jet        | LERG [M14]  |
| M87             | Jet       | Jet                  | Jet               | Jet        | LERG [G13]  |
| Cen A           | Disk/corona | Inconclusive         | Jet               | Inconclusive | HERG [E04] |
| NGC 6251        | Jet       | Inconclusive         | Inconclusive      | Jet        | LERG [E11]  |

Notes.

a 3C 84 is diversely classified in the literature; see, e.g., Hardcastle et al. (2009), Buttiglione et al. (2010), Gendre et al. (2013).
b 3C 111 and 13C 20 are archetype examples of broad-line radio galaxies.

References. [B10, E00, M14, G13, E04, E11]; Buttiglione et al. (2010), Eracleous et al. (2000), Mingo et al. (2014), Gendre et al. (2013), Evans et al. (2004, 2011).

superposition of self-absorbed jet components unrelated to the rest of the SED (Konigl 1981) and as such should be considered as upper limits in our one-zone synchrotron/SSC modeling. The near infrared/integrated optical segments of the broadband spectra are clearly dominated by host galaxies, and therefore in our modeling, we added a template of a giant elliptical from Silva et al. (1998), adjusted to the redshifts of the analyzed sources. This template reproduces the optical data well. We assumed a relatively large jet angle to the line of sight (θ in Table 5), consistent with the sources being misaligned BL Lacs and used two variability timescales to test the robustness with respect to this poorly constrained parameter. The models with two different variability timescales are given in Table 5. Also listed in Table 5 are the results of one-zone synchrotron/SSC models applied to reproduce several other LAT-detected FR I radio galaxies from the literature. Model parameters for PKS 0625–354 and 3C 78 are consistent with those for other radio galaxies that have been modeled previously, as shown in the table. The parameters Γ and δ are lower than typically found in models of BL Lacs. We note that the black hole mass in PKS 0625–354 is estimated to be 10^7.2 M⊙ (Bettoni 2003) and in 3C 78 as 10^9.7 M⊙ (Rinn et al. 2005); these are the typical values for radio galaxies (10^7~10^9.5 M⊙; McLure et al. 2004) and BL Lac objects (10^7.3~9.2 M⊙; Barth et al. 2003).
One major difference is that the models for PKS 0625−354, 3C 78, and NGC 6251 (Migliori et al. 2011) have a higher $\gamma_{\text{brk}}$ by a factor of 10 compared to other radio galaxies in the table. The larger $\gamma_{\text{brk}}$ leads to higher peak synchrotron frequencies and lower electron jet powers compared to magnetic jet powers. For Cen A, M87, and NGC 1275, the models result in approximate equipartition between magnetic field and electron jet powers. The higher $\gamma_{\text{brk}}$ parameters for PKS 0625−354 and 3C 78 are, in turn, mainly the result of the harder $\gamma$-ray spectra and soft X-ray spectra. Cen A, NGC 6251, M87, and NGC 1275 have soft LAT spectra ($\Gamma_{\text{HE}} > 2.1$), while the LAT spectra for PKS 0625−354 and 3C 78 are harder ($\Gamma_{\text{HE}} < 2.1$), although NGC 1275 is a borderline case. As we have already noted above, PKS 0625−354 and 3C 78 were the hardest sources of the Fermi-LAT misaligned AGN list of Abdo et al. (2010c). The X-ray spectra for Cen A (Abdo et al. 2010a, a), M87 (Abdo et al. 2009b), NGC 1275 (Abdo et al. 2009a), and NGC 6251 (Migliori et al. 2011) are hard ($\Gamma_X < 2$), indicating they originate from the SSC component, although M87 likely has some synchrotron contribution as well (Abdo et al. 2009b). Assuming jet origin, the soft X-ray spectra ($\Gamma_X > 2$) for PKS 0625−354 and 3C 78 indicates the X-rays originate from synchrotron emission, implying a high peak synchrotron frequency and $\gamma_{\text{brk}}$.

Meyer et al. (2011) proposed a scenario where low-power jets (BL Lacs and FR I radio galaxies) have longitudinal bulk Lorentz factor gradients. In this scenario, when viewing more aligned jets, one observes the faster portion of the outflow resulting in high synchrotron peaked sources, while for progressively more misaligned sources, one sees progressively slower portions of the jet and progressively lower synchrotron peak frequencies. Meyer et al. also argued that such gradients are absent in high-power jets (FSRQs and FR II radio galaxies). In Figure 8, we plot the synchrotron peak luminosity ($L_{\text{peak}}$) versus the synchrotron peak frequency ($\nu_{\text{peak}}$) for the sample analyzed by Meyer et al. (see Figure 4 therein), along with the results of model fits from the literature and from this paper for $\gamma$-ray bright radio galaxies. Error bars on $\nu_{\text{peak}}$ and $L_{\text{peak}}$ were found from visual inspection of the SEDs. We do not include here NGC 1275, since its synchrotron peak is poorly constrained (Abdo et al. 2009a). The sources PKS 0625−354 and 3C 78 are found to have relatively high values of $\nu_{\text{peak}}$, not expected in the framework of the scenario of Meyer et al. (2011). This seems to disfavor their model, which states that high-peaked sources are only the most aligned jets, to some extent.

It should be emphasized here that the values of $\nu_{\text{peak}}$ and $L_{\text{peak}}$ from Meyer et al. (2011) were found from polynomial fits to radio, optical, and X-ray data, while values derived or adopted by us for $\gamma$-ray bright radio galaxies are found from a synchrotron/SSC model fit. Our model fits are more physically motivated, but also come with additional assumptions. From the point of view of the Lorentz factor gradient scenario, our models are probably preferred, since this scenario assumes synchrotron/ SSC emission. 3C 78 is included in the sample of Meyer et al. (2011), but they obtained significantly lower values for $\nu_{\text{peak}}$ than we did (see their Table 3). We believe this is for two reasons:

### Table 5

| SED Model Parameters of Radio Galaxies | PKS 0625−354 | 3C 78 | Cen A | M87 | NGC 1275 | NGC 6251 |
|--------------------------------------|--------------|-------|-------|-----|--------|--------|
| $\Gamma$ | 5.8          | 5.7   | 2.93  | 5.75| 7.0    | 2.3    |
| $\delta$ | 5.8          | 5.8   | 2.92  | 5.75| 1.0    | 1.9    |
| $\theta$ (deg) | 10       | 10    | 20    | 20  | 30     | 10     |
| $B$ (G) | 0.82         | 0.11  | 0.77  | 0.77| 0.02   | 6.2    |
| $t_v$ (Ms) | 0.1          | 1     | 0.1   | 1   | 0.1    | 1.2    |
| $R_b$ (10^{16} cm) | 1.6 | 16    | 0.85  | 17  | 0.3    | 1.4    |
| $p_1$ | 2.5          | 2.5   | 2.7   | 2.7 | 1.8    | 1.6    |
| $p_2$ | 3.5          | 3.5   | 3.7   | 3.7 | 3.6    | 3.1    |
| $\gamma_{\text{min}}$ | $6 \times 10^3$ | $6 \times 10^3$ | $1 \times 10^3$ | $1 \times 10^3$ | $3 \times 10^2$ | $8 \times 10^2$ |
| $\gamma_{\text{max}}$ | $2 \times 10^6$ | $2 \times 10^6$ | $2 \times 10^7$ | $2 \times 10^7$ | $1 \times 10^6$ | $4 \times 10^5$ |
| $\gamma_{\text{brk}}$ | $2.9 \times 10^4$ | $4.6 \times 10^4$ | $7.3 \times 10^4$ | $1.4 \times 10^5$ | $8 \times 10^4$ | $4.4 \times 10^4$ |
| $P_{\gamma,\text{e}}$ (10^{22} erg s^{-1}) | 43 | 740 | 0.3 | 2.5 | 65 | 0.02 |
| $P_{\gamma,\text{e}}$ (10^{23} erg s^{-1}) | 2 | 10 | 0.6 | 13 | 31 | 7 |

**Notes.** The model parameters are as follows: $\Gamma$ is the bulk Lorentz factor; $\delta$ is the Doppler factor; $\theta$ is the jet angle; $B$ is the magnetic field; $t_v$ is the variability timescale; and $R_b$ is the comoving blob size scale; $p_1$ and $p_2$ are the low-energy and high-energy electron spectral indices, respectively; $\gamma_{\text{min}}, \gamma_{\text{max}}, \text{and } \gamma_{\text{brk}}$ are the minimum, maximum, and break electron Lorentz factors, respectively; and $P_{\gamma,\text{e}}$ and $P_{\gamma,\text{e}}$ are the jet powers in magnetic field and electrons, respectively.

**References.** Abdo et al. (2010a, for Cen A), Abdo et al. (2009a, for M87), Abdo et al. (2010b, for NGC 1275), Migliori et al. (2011, for NGC 6251).
(1) their phenomenological model fit the radio data, while our synchrotron models do not and (2) the inclusion of the hard LAT data spectra require high values of $\gamma_{\text{brk}}$, which result in high values for $v_{\text{peak}}$. The latter indicates that LAT observations can be important for modeling the synchrotron portion of a radio loud AGNs, even though the $\gamma$-rays are not directly produced by synchrotron emission.

Finally, we note there is some ambiguity as to whether PKS 0625−345 is a BL Lac object or a radio galaxy. The optical spectrum of PKS 0625−354 resembles that of a BL Lac (Wills et al. 2004), although its radio morphology resembles an FR I radio galaxy (Ojha et al. 2010). PKS 0625−354 possesses a relatively bright unresolved core (Govoni et al. 2000), as does 3C 78 (Chiaberge et al. 2002), and all the LAT-detected radio galaxies in Table 5. They probably all have intermediate jet alignments, with $\theta$ in the range $10^\circ$−$30^\circ$.

### 5. CONCLUSIONS

We have presented Suzaku results for nearby Fermi-LAT detected low-power radio galaxies, three of which are analyzed here for the first time. Based on the Fe-K and X-ray spectral slope, X-ray variability, and [O $\text{\textsc{ii}}$] line strength, we argued for their phenomenological model fit the radio data, while our LAT observations are not directly produced from modeling the synchrotron portion of radio loud AGNs, even though the $\gamma$-rays are not directly produced by synchrotron emission.

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### REFERENCES

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009a, ApJ, 699, 31
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009b, ApJ, 707, 55
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010a, ApJ, 719, 1433
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010b, Sci, 328, 725
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010c, ApJ, 720, 912
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010d, ApJ, 715, 429
Ackermann, M., Ajello, M., Allafort, A., et al. 2011, ApJ, 743, 171
Aharonian, F., Akhperjanian, A. G., Anton, G., et al. 2009, ApJL, 695, L40
Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006, Sci, 314, 1424
Ajello, M., Costamante, L., Sambruna, R. M., et al. 2009, ApJ, 699, 603
Alexis, J., Alvarez, E. A., Antonelli, L. A., et al. 2012, A&A, 539, L2
Alexis, J., Antonelli, L. A., Antonanz, P., et al. 2010, ApJL, 723, L207
Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071
Barth, A. J., Ho, L. C., & Sargent, W. L. W. 2003, ApJ, 583, 134
Bettone, D. 2003, A&A, 399, 869
Birzan, L., Rafferty, D. A., McNamara, B. R., Wise, M. W., & Nulsen, P. E. J. 2004, ApJ, 607, 800
Blundell, K. M., & Rawlings, S. 2001, ApJL, 562, L5
Boldt, E. 1987, PhR, 146, 215
Buttiglione, S., Capetti, A., Celotti, A., et al. 2010, A&A, 509, A6
Chiaberge, M., Gilli, R., Capetti, A., & Macchetto, F. D. 2003, ApJ, 597, 166
Chiaberge, M., Macchetto, F. D., Sparks, W. B., et al. 2002, ApJ, 571, 247
Chiaberge, M., Tremblay, G., Capetti, A., et al. 2009, ApJ, 696, 1103
Dheo, S., & Statler, T. S. 2003, ApJ, 598, 150
Donato, D., Sambruna, R. M., & Gliozzi, M. 2005, A&A, 433, 1163
Eracleous, M., Sambruna, R. M., & Mushotzky, R. F. 2000, ApJ, 537, 654
Evans, D. A., Kraft, R. P., Worrall, D. M., et al. 2004, ApJ, 612, 786
Evans, D. A., Summers, A. C., Hardcastle, M. J., et al. 2011, ApJ, 744, L4
Fanaroff, B. L., & Riley, J. M. 1974, MNRAS, 167, 31P
Finke, J. D., Dermer, C. D., & Böttcher, M. 2008, ApJ, 686, 181
Finke, J. D., Razzauque, S., & Dermer, C. D. 2010, ApJ, 712, 238
Foschini, L., Chiaberge, M., Grandi, P., et al. 2005, A&A, 433, 515
Fukazawa, Y., Botoya-Nonesa, J. G., Pu, J., Ohto, A., & Kawano, N. 2006, ApJ, 636, 698
Fukazawa, Y., Makishima, K., & Ohashi, T. 2004, PASJ, 56, 965
Fukazawa, Y., Mizuno, T., Watanabe, S., et al. 2009, PASJ, 61, 17
Fukazawa, Y., Hiragi, K., Mizuno, M., et al. 2011a, ApJ, 727, 19
Fukazawa, Y., Hiragi, K., Yamazaki, S., et al. 2011b, ApJ, 743, 124
Gendre, M. A., Best, P. N., Wall, J. V., & Ker, L. M. 2013, MNRAS, 430, 3086
Gliozzi, M., Foschini, L., Sambruna, R. M., & Tavecchio, F. 2008, A&A, 478, 723
Gliozzi, M., Sambruna, R. M., Brandt, W. N., Mushotzky, R., & Eracleous, M. 2004, A&A, 413, 139
Goodger, J. L., Hardcastle, M. J., Croston, J. H., et al. 2010, ApJ, 708, 675
Govoni, F., Falomo, R., Fasano, G., & Scarpa, R. 2000, A&A, 333, 507
Grandy, P., Torresi, E., & Stanghellini, C. 2012, ApJL, 751, L3
Hardcastle, M. J., Evans, D. A., & Croston, J. H. 2006, MNRAS, 370, 1893
Hardcastle, M. J., Evans, D. A., & Croston, J. H. 2007, MNRAS, 376, 1849
Hardcastle, M. J., Evans, D. A., & Croston, J. H. 2009, MNRAS, 396, 1929
Hardcastle, M. J., & Worrall, D. M. 1999, MNRAS, 309, 969
Harris, D. E., Cheung, C. C., Stawarz, L., Biretta, J. A., & Perlman, E. S. 2009, ApJ, 699, 305
Harris, D. E., Massaro, F., Cheung, C. C., et al. 2011, ApJ, 743, 177
Hartman, R. C., Bertsch, D. L., Bloom, S. D., et al. 1999, ApJS, 123, 79
Heywood, I., Blundell, K. M., & Rawlings, S. 2007, MNRAS, 381, 1093
Hine, R. G., & Longair, M. S. 1979, MNRAS, 188, 111
Ishisaki, Y., Maeda, Y., Fujimoto, R., et al. 2007, PASJ, 59, 113
Kadler, M., Eisenacher, D., Ros, E., et al. 2012, A&A, 538, L1
Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, A&A, 440, 775
Kataoka, J., Reeves, J. N., Iwasawa, K., et al. 2007, PASJ, 59, 279
Kataoka, J., Stawarz, L., Cheung, C. C., et al. 2010, ApJ, 715, 534
Kataoka, J., Stawarz, L., Takahashi, Y., et al. 2011, ApJ, 740, 29
Katsuta, J., Tanaka, Y. T., Stawarz, L., et al. 2013, A&A, 550, A66
