MULTIWAVELENGTH VARIABILITY PROPERTIES OF FERMI BLAZAR S5 0716+714

N. H. Liao¹,²,³, J. M. Bai¹,², H. T. Liu¹,², S. S. Weng⁴, Liang Chen⁵, and F. Li¹,²

¹ Yunnan Observatories, Chinese Academy of Sciences, Kunming, Yunnan 650011, China; lianh@ynao.ac.cn, baijinming@ynao.ac.cn
² Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming, Yunnan 650011, China
³ University of Chinese Academy of Sciences, Beijing 100049, China
⁴ Department of Physics, Xiangtan University, Xiangtan 411105, China
⁵ Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China

Received 2012 November 7; accepted 2014 January 16; published 2014 February 20

ABSTRACT

S5 0716+714 is a typical BL Lacertae object. In this paper we present the analysis and results of long-term simultaneous observations in the radio, near-infrared, optical, X-ray, and γ-ray bands, together with our own photometric observations for this source. The light curves show that the variability amplitudes in γ-ray and optical bands are larger than those in the hard X-ray and radio bands and that the spectral energy distribution (SED) peaks move to shorter wavelengths when the source becomes brighter, which is similar to other blazars, i.e., more variable at wavelengths shorter than the SED peak frequencies. Analysis shows that the characteristic variability timescales in the 14.5 GHz, the optical, the X-ray, and the γ-ray bands are comparable to each other. The variations of the hard X-ray and 14.5 GHz emissions are correlated with zero lag, and so are the V band and γ-ray variations, which are consistent with the leptonic models. Coincidences of γ-ray and optical flares with a dramatic change of the optical polarization are detected. Hadronic models do not have the same natural explanation for these observations as the leptonic models. A strong optical flare correlating a γ-ray flare whose peak flux is lower than the average flux is detected. The leptonic model can explain this variability phenomenon through simultaneous SED modeling. Different leptonic models are distinguished by average SED modeling. The synchrotron plus synchrotron self-Compton (SSC) model is ruled out because of the extreme input parameters. Scattering of external seed photons, such as the hot-dust or broad-line region emission, and the SSC process are probably both needed to explain the γ-ray emission of S5 0716+714.

Key words: BL Lacertae objects: individual – galaxies: active – galaxies: jets – radiation mechanisms: non-thermal

Online-only material: color figures, machine readable table

1. INTRODUCTION

Blazars, including flat-spectrum radio quasars (FSRQs) and BL Lacertae objects (BL Lac objects), are radio-loud active galactic nuclei (AGNs; Urry & Padovani 1995, and references therein). They are characterized by the luminous, rapidly variable, and polarized nonthermal continuum emissions, extending from radio to γ-ray (GeV and TeV) energies, which are widely accepted to be produced in the relativistic jets oriented close to the line of sight (Blandford & Rees 1978; Ulrich et al. 1997). Their spectral energy distributions (SEDs) have a universal twobump structure in log νFν representation, indicating two different origins. The first bump is almost certainly caused by synchrotron emission of relativistic electrons as evidenced by its high polarization from radio through optical wavelengths, peaking at UV/X-ray bands in high-frequency peaked BL Lac objects (HBLs) (Padovani & Giommi 1995) and at IR/optical wavelengths in low-frequency peaked BL Lac objects (LBLs) and FSRQs. The second bump peaks at γ rays whose origin is less well understood.

For the second bump, there are two types of emission models that both can fit well the observational SEDs. In leptonic scenarios, the γ rays are interpreted as inverse Compton (IC) scattering of soft photons by relativistic electrons that produce the first bump through the synchrotron process. The soft photons could be synchrotron photons (the synchrotron self-Compton (SSC) model; Maraschi et al. 1992) or photons outside the jet (the external radiation Compton (ERC) models; the accretion disk radiation (Dermer & Schlickeiser 1993), UV emission from the broad-line region (BLR; Sikora et al. 1994), and infrared (IR) emission from a dust torus (Bläžejowski et al. 2000). In hadronic scenarios, if relativistic protons in a strongly magnetized environment are sufficiently accelerated, the particle–photon interaction processes, the synchrotron radiation of protons, and the proton–proton interaction processes must be taken into account (Mücke & Protheroe 2001; Aharonian 2000; Beall & Bednarek 1999).

Multiwavelength variability study provides a way to test these emission models, which make different predictions for the relative flare amplitudes and the time lags (e.g., Sambruna 2007; Marscher et al. 2008). In the leptonic models, since the same population of electrons is responsible for emitting both spectral components, correlated variations of fluxes at the low- and high-energy peaks with no lags are expected. However, in the hadronic models, no necessary correlations between the spectral components are expected. Correlated variations across SEDs observed in some blazars seem to be consistent with the leptonic models, but the so-called orphan flares observed in some TeV blazars prefer the hadronic scenarios (e.g., Bonning et al. 2012; Böttcher 2005). A long-term optical variability monitoring program for blazars has been performed at Yunnan Observatories (e.g., Bai et al. 1998). After the successful launch of the Fermi γ-ray telescope, the correlation between optical and γ-ray variations has been focused. Because it is a bright
typical BL Lac object and sometimes its synchrotron emission peaks in the optical band, S5 0716+714 has been an important target on our monitoring list.

In this paper, we present our photometric observations of S5 0716+714, together with simultaneous multiwavelength observations from radio to GeV γ rays acquired from public data archives and the literature, to investigate its variability properties and distinguish different radiation models. The outline of this paper is as follows: in the next section we give a review of the historical information on S5 0716+714; the observation and data reduction are shown in Section 3. In Section 4 we present the variability properties and their implications; in Section 5 we report the SED modeling. In Section 6 we present the discussion, and conclusions are in Section 7. Throughout this paper, we refer to a spectral index α as the energy index such that \( F_\nu \propto \nu^{-\alpha} \), corresponding to a photon index \( \Gamma_{ph} = \alpha + 1 \). We assume a ΛCDM cosmology with \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 0.27 \), \( \Omega_\Lambda = 0.73 \) (Komatsu et al. 2011).

2. HISTORICAL OBSERVATIONS OF S5 0716+714

S5 0716+714 is a famous intraday variability (IDV) source (Wagner & Witzel 1995). The IDV in radio band is possibly contributed by the synchrotron emission from the high-energy orbit, or an intermediate synchrotron peaked (Abdo et al. 2010a) blazar. Nilsson et al. (2008) derived a redshift of \( z = 0.31 \pm 0.08 \) (1σ error) by the detection of its host galaxy. The redshift was confirmed by the direct constraint from intervening absorption lines, 0.23 < \( z \) < 0.37 (99.7% confidence; Danforth et al. 2013).

S5 0716+714 is a famous intraday variability (IDV) source (Wagner & Witzel 1995). The IDV in radio band is possibly source intrinsic, rather than solely interpreted by interstellar scintillation (Wagner et al. 1996; Kraus et al. 2003). Fuhrmann et al. (2008) found that the flux densities from centimeter band to submillimeter band were correlated and the radio spectra were inverted at about 86 GHz. The atypically fast apparent speeds of jet components were from 4.5c to 16.1c (\( z = 0.3 \)) on the basis of the last 10 yr of very long baseline interferometry data of S5 0716+714 (Bach et al. 2005).

No emission lines were detected in the IR, optical, and UV spectra of S5 0716+714 (Chen & Shan 2011; Shaw et al. 2009; Danforth et al. 2013). The source is well known for almost uninterrupted variability at multiple timescales. Extreme optical variations with maximum variability rates of \( \sim 0.4 \text{ mag hr}^{-1} \) were detected (Chandra et al. 2011; Danforth et al. 2013). Not only is it a famous IDV source, but S5 0716+714 is also a source possessing variations on a timescale of years in the radio and optical bands, which may be associated with changes in the structure and/or direction of the inner jet (e.g., Raiteri et al. 2003; Nesci et al. 2005). Strong optical polarized emissions, over 20%, were observed (Takalo et al. 1994; Ikejiri et al. 2011). Larianov et al. (2008) reported a coincidence of a huge optical outburst with a 360° rotation of optical polarization angle (P.A.) in 2008 April.

Rapid X-ray flux variation with a doubling timescale of \( \sim 7000 \text{ s} \) was observed (Cappi et al. 1994). On a timescale of hours, large and rapid variations were only detected in the soft X-rays. Concave-shaped X-ray spectra of S5 0716+714 were observed, with break energies of \( \sim 3 \text{ keV} \), exhibiting a steeper-when-brighter behavior. The soft X-rays are considered to be contributed by the synchrotron emission from the high-energy tail electrons, while the hard X-rays are from the IC process of the low-energy electrons (Giommi et al. 1999; Tagliaferri et al. 2003; Zhang 2010).

The source exhibits a strong emission in the γ-ray band. It was detected by the EGRET on the Compton Gamma Ray Observatory (CGRO; Hartman et al. 1999; von Montigny et al. 1995). EGRET observation showed considerable γ-ray flux variability with the stable spectra index within the statistical uncertainty (Lin et al. 1995). In 2007 September, the γ-ray flux detected by AGILE (Tavani et al. 2008) exhibited an increase in flux by a factor of four in 3 days (Chen et al. 2008). Since the launch of Fermi, S5 0716+714 has been in the list of the Large Area Telescope (LAT; Atwood et al. 2009) Bright AGN Sample (LBAS; Abdo et al. 2009), the First LAT AGN Catalog (Abdo et al. 2010a), and the Second LAT AGN Catalog (2LAC; Ackermann et al. 2011). In the investigation of the γ-ray energy spectra of LBAS sources, a single power law gave an acceptance to S5 0716+714 (Abdo et al. 2010c). In 2LAC, a strongly caved spectrum was observed and modeled by the LogParabola function (Ackermann et al. 2011). A very high energy (VHE) γ-ray excess of S5 0716+714 was detected by MAGIC (Albert et al. 2008), and a possible correlation between the VHE γ-ray and optical emissions was suggested (Anderhub et al. 2009).

S5 0716+714 is active at all electromagnetic bands, and several papers have attempted to get insight on its properties by SED modeling (e.g., Ghisellini et al. 2010; Zhang et al. 2012). The inhomogeneous model could explain the ultrafast X-ray variation better than the homogeneous model (Ghisellini et al. 1997). Tagliaferri et al. (2003) found that the single SSC model could not explain the flat EGRET γ-ray spectrum and the scattering of the external soft photons that probably needed to be considered (e.g., BLR; accretion flow). Strongly variable optical and soft X-ray fluxes with nearly constant γ-ray flux in 2007 October were detected by GASP–WEBT–AGILE observations. This multiwavelength evolution was explained by the presence of two SSC components, one that is constant and one that is highly variable over the entire observing period (Giommi et al. 2008).

After we submitted this paper, several papers studying the variability of S5 0716+714 were published (Rani et al. 2013a, 2013b; Larianov et al. 2013). Rani et al. (2013a) also focused on the multiwavelength variability from radio to γ rays. Rani et al. (2013b) particularly concentrated on the GeV γ-ray variability. Larianov et al. (2013) analyzed the multiwavelength outburst on 2011 October through the γ-ray, optical photometric, polarimetric, and Very Long Baseline Array (VLBA) observations.

3. OBSERVATION AND DATA REDUCTION

3.1. Photometric Observation and Data Reduction

The variability of S5 0716+714 was photometrically monitored in the optical bands at Yunnan Observatories, making use of the 2.4 m telescope and the 1.02 m telescope. The 2.4 m telescope, which began working in 2008 May, is located at the Lijiang Observatory of Yunnan Observatories, where the longitude is 100°01′51″E and the latitude is 26°42′32″N, with an altitude of 3193 m. There are two photometric terminals. The PI VersArray 1300B CCD camera with 1340 × 1300 pixels covers a field of view 4′48″ × 4′40″ at the Cassegrain focus. The readout noise and gain are 6.05 electrons and 1.1 electrons ADU−1, respectively. The Yunnan Faint Object Spectrograph and Camera

6 http://www.gmg.org.cn
7 http://www1.ynao.ac.cn/~omt/
Figure 1. (a) Light curves at $I$, $R$, $V$, and $B$ bands observed by Yunnan Observatories. (b) Light curves at $K_s$, $J$, and $V$ bands of 0716+714 obtained from observations of the Kanata telescope at Higashi-Hiroshima Observatory (Ikejiri et al. 2011). (A color version of this figure is available in the online journal.)

(YFOSC) has a field of view of about $10' \times 10'$ and $2000 \times 2000$ pixels for photometric observation. Each pixel corresponds to $0.283$ of the sky. The readout noise and gain of the YFOSC CCD are 7.5 electrons and 0.33 electrons ADU$^{-1}$, respectively. The 1.02 m telescope is located at the headquarters of Yunnan Observatories and is mainly used for photometry with standard Johnson $UBV$ and Cousins $RI$ filters. An Andor CCD camera with 2048 $\times$ 2048 pixels has been installed at its Cassegrain focus since 2008 May. The readout noise and gain are 7.8 electrons and 1.1 electrons ADU$^{-1}$, respectively.

The sky flat field at dusk and dawn in good weather conditions and bias frames were taken on each observing night. Because of the negligible dark current the dark frame was skipped. Different exposure times were applied for various seeing and weather conditions. All frames were processed using bias and flat-field corrections using the task CCDRED package of the IRAF software, while the photometry was performed with the APHOT package. The magnitude of the source was calculated by differential photometry with calibration stars in the image frame (Villata et al. 1998; Ghisellini et al. 1997). The observing uncertainty of each night was the rms error of the differential magnitude between two calibration stars. At least one of them had to be fainter than or as bright as the source (Bai et al. 1999):

$$
\sigma = \sqrt{\frac{\sum \delta^2}{N-1}}, \quad i = 1, 2, \ldots, N,
$$

where $\delta = (m_2 - m_1), m_1 = m_2 - m_1, m_2 - m_1$ is the mean differential magnitude, and $N$ is the number of data points in the night. The correction for the interstellar extinction and the color excess were adopted according to Schlegel et al. (1998). Optical photometric data were converted from the magnitude system to flux in janskys (Bessell 2005). The results are plotted in Figure 1(a) and presented in Table 1.

3.2. Complementary Optical and Other Observations from the Literatures

Because of the observing time allocation, our photometric data are sparse. In order to match the data sampling of light curves at X-ray and $\gamma$-ray energies, we collected $V$-band photometric data of S5 0716+714 observed at the 1.5 m Kanata telescope of Higashi-Hiroshima observatory in Japan8 (Ikejiri et al. 2011) and the 2.3 m Bok telescope and 1.54 m Kuiper telescope at Steward Observatory of the University of Arizona (Smith et al. 2009), which were also adopted in Rani et al. (2013a), and from two published papers (Poon et al. 2009; Chandra et al. 2011). The $V$-band light curve (Figure 2(c)) thus contains 324 data points, extending from 54613.0 to 55822.0 MJD.

As mentioned in the Introduction Section, blazars are characterized by their polarized continuum emissions. High linear

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8 http://hasc.hiroshima-u.ac.jp/telescope/kanatatel-e.html
polarization from radio through optical wavelengths is common in blazars, and usually, the fractional variations in the polarized flux density are substantially larger than those in the total flux density, suggesting that polarization observation is an effective tool for investigating the emission process in blazar jets. The variability of polarization in S5 0716+714 was monitored using the Kanata 1.5 m telescope of Higashi-Hiroshima Observatory from 2008 to 2009 (Ikejiri et al. 2009) and the 2.3 m Bok telescope and 1.54 m Kuiper telescope of Steward Observatory of the University of Arizona since 2008 (Smith et al. 2009). The optical polarization, flux, and spectral data of Steward Observatory are publicly presented on their Web site, and those of Higashi-Hiroshima Observatory have been published (Ikejiri et al. 2011). These polarization data were collected. The light curves of the V-band P.A. and polarization degree (PD) data are presented in Figures 2(d) and (e), respectively.

The synchrotron peak of S5 0716+714 shifts from time to time in the near-infrared (NIR) and optical bands during different luminosity states. The J- and Ks-band photometric data of S5 0716+714 observed at Higashi-Hiroshima Observatory (Ikejiri et al. 2011) were also included in this work. The Ks-band light curve is from 54613.0 to 54839.2 MJD, and the J band light curve is from 54613.0 to 55228.0 MJD. The simultaneous light curves of the V, J, and Ks bands obtained by the Kanata telescope are presented in Figure 1(b).

The radio data were taken from the observations of the 26 m paraboloid of the University of Michigan Radio Astronomy Observatory (UMRAO; Aller et al. 1983, 1999). The light curves at 4.8, 8, and 14.5 GHz are from 54685.6 to 55917.2 MJD (Figure 2(f)). These UMRAO multiband data from 54686 to 55600 MJD have been adopted in Rani et al. (2013a).

3.3. X-Ray Data Deduction

X-ray data from the Proportional Counter Array (PCA) on RXTE and the X-ray Telescope (XRT) on Swift are accessible. The PCA observations are more continual than the XRT observations, especially for the time range from 2009 to 2010. The X-ray light curve was extracted from the PCA data. S5 0716+714 is too faint to obtain a detailed X-ray spectrum from PCA data, whose energy range is 2.6–50 keV, which is beyond the spectral concave point of about 3 keV. X-ray spectra were extracted from XRT data with an energy range of 0.3–10 keV. The X-ray data were reduced by the FTOOLS software package version 6.9.

3.3.1. RXTE/PCA

We analyzed RXTE observations taken between 2009 February 7 and 2010 December 28. We downloaded the Standard2 data from all layers of Proportional Counter Unit 2 (PCU2), which operated during all the observations. The data were filtered with the standard criteria: an Earth limb elevation angle larger than 10° and a spacecraft pointing offset less than 0.02. The background files were created using the program pcabackest and the latest faint source background model since the source intensity was <40 counts s⁻¹ per PCU (Weng & Zhang 2011). We applied the power-law model to fit the RXTE/PCA spectra over the energy range of 2.6–50.0 keV. An interstellar absorption component with the neutral hydrogen column density fixed to the Galactic value (3.05 \times 10^{20} \text{ cm}^{-2}; Murphy et al. 1996) was also included. The unabsorbed flux and its error were also calculated in the 2.6–50.0 keV range with cf1ux...
in XSPEC. The 10 day bin X-ray light curve is represented in Figure 2(b).

### 3.3.2. Swift/XRT

The initial event cleaning was performed using the `xrtpipeline` script, with the standard quality cuts (Weng & Zhang 2011). The source spectra were extracted with `xselect` from circles with a radius of 20 pixels centered at the nominal position of S5 0716+714, while the background spectra were taken from annulus regions with radii of 30 and 60 pixels. If data suffered from pileup, the annular regions were used to describe the source, and the excluded region radius depended on the current count rate.\(^{11}\) We also produced the ancillary response file with `xrtmkarf` to facilitate subsequent spectral analysis. The response files (v013) were taken from the CALDB database. Finally, the spectra were grouped to require at least 20 counts bin\(^{-1}\) to ensure valid results using \(\chi^2\) statistical analysis. The XRT spectra are given in Table 2.

### 3.4. Fermi/LAT Data Reduction

The Pass 7 \(\gamma\)-ray data were downloaded from LAT data server, in the time frame from 2008 August 4 to 2011 November 22. The LAT event photons from 0.1 to 300 GeV were selected. The LAT data analysis was performed with instrument response functions of P7SOURCE_V6 using the updated standard ScienceTools software package version v9r23p1. For the LAT background files, we used `gal_2yearp7v6_v0.fits` as the galactic diffuse model and `iso_p7v6source.txt` for the isotropic spectral template.\(^{12}\) For data preparation, `evclass=2` was adopted for `gtselect`. The maximum zenith angle was set to 100°. We used the unbinned likelihood algorithm (Mattox et al. 1996) implemented in the `gtlike` task to extract the flux and spectra. The LogParabola function was used as the spectral model. All sources from the Second Fermi/LAT catalog (2FGL; Nolan et al. 2012) within 15° of the source position were included. The flux and spectral parameters of sources within a 10° region of interest (ROI) were allowed to vary, while parameters for sources that fell outside the ROI were frozen at the 2FGL values.

For light curves, a fit of each bin was scrutinized to make sure that the fit quality was satisfactory and there was no background source with a negative test statistic (TS) value or exotic parameters. In a few low-TS cases, when the LogParabola function was not applicable, a single power-law model was used instead. There are only three fits with TS values lower than 25 in the \(\gamma\)-ray light curve analysis, and the lowest TS value is 17 (\(\geq 4\sigma\)). We did not set them as upper limits. The 10 day bin \(\gamma\)-ray light curve is shown in Figure 2(a). The Python script named `SED.scripts.v13.1` from Fermi User Contributions was used to obtain \(\gamma\)-ray spectra. In the spectral analysis, when the TS value was less than 25, flux was replaced by the 2\(\sigma\) upper limit. All errors reported in the figures or quoted in the text for \(\gamma\) rays are 1\(\sigma\) statistical errors. The estimated relative systematic uncertainties on the flux and effective area are set to 10% at 100 MeV, 5% at 500 MeV, and 20% at 10 GeV (Abdo et al. 2010b).

\(^{11}\) http://www.Swift.ac.uk/analysis/xrt/pileup.php

\(^{12}\) http://Fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

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### Table 2

Results of Swift Spectral Fits during Different States\(^a\)

| Model                | \(\Gamma_1\) | \(E_{\text{break}}\) (keV) | \(\Gamma_2\) | \(\chi^2/\text{dof}\) | Flux\(^b\) (0.3–10 keV) |
|----------------------|-------------|----------------------------|-------------|----------------------|-------------------------|
|                      |             |                           |             |                      |                         |
| 2009 Nov 30 to 2009 Dec 2 (outburst) |              |                           |             |                      |                         |
| Single power law     | 2.30\(^{+0.14}_{-0.14}\) | ...                       | ...         | 1.27/33              | 2.71                    |
|                      |             |                           |             |                      |                         |
| 2009 Dec 7 to 2009 Dec 22 (falling) |             |                           |             |                      |                         |
| Single power law     | 2.21\(^{+0.03}_{-0.03}\) | ...                       | ...         | 1.36/102             | 1.60                    |
| Broken power law     | 2.32\(^{+0.06}_{-0.06}\) | 1.27\(^{+0.34}_{-0.23}\) | 2.09\(^{+0.06}_{-0.07}\) | 1.26/100 | 1.66 |                         |
| Double power law     | 2.32\(^{+0.71}_{-0.70}\) | ...                       | 0.92\(^{+2.11}_{-0.92}\) | 1.29/100 | 1.69 |                         |
| 2009 Dec 28 to 2010 Feb 22 (quiet) |             |                           |             |                      |                         |
| Single power law     | 2.33\(^{+0.24}_{-0.23}\) | ...                       | ...         | 1.39/21              | 0.12                    |
|                      |             |                           |             |                      |                         |
| 2011 Jul 14 to 2011 Jul 16 |             |                           |             |                      |                         |
| Single power law     | 2.09\(^{+0.15}_{-0.14}\) | ...                       | ...         | 1.42/69              | 1.66                    |
| Broken power law     | 2.49\(^{+0.51}_{-0.23}\) | 3.26\(^{+0.52}_{-1.07}\) | 1.17\(^{+0.56}_{-0.44}\) | 1.20/67 | 2.30 |                         |
| Double power law     | 0.71\(^{+0.84}_{-1.79}\) | ...                       | 3.31\(^{+1.73}_{-0.84}\) | 1.18/67 | 3.76 |                         |
| 2011 Oct 25 to 2011 Oct 28 |             |                           |             |                      |                         |
| Single power law     | 2.82\(^{+0.26}_{-0.23}\) | ...                       | ...         | 1.96/46              | 1.33                    |
| Broken power law     | 3.88\(^{+0.66}_{-0.55}\) | 2.21\(^{+0.58}_{-0.35}\) | 1.85\(^{+0.43}_{-0.58}\) | 1.51/44 | 4.04 |                         |
| Double power law     | 1.40\(^{+0.71}_{-1.05}\) | ...                       | 5.06\(^{+1.84}_{-1.27}\) | 1.65/44 | 1.36 |                         |

**Notes.**

\(^a\) The fits are performed in the 0.3–10 keV band. The neutral hydrogen absorption column density is fixed to the Galactic value for the data during 2009. However, the column density is treated as a free parameter for 2011 data. All quoted errors are 90\% confidence level (\(\Delta \chi^2 = 2.706\)) for one interesting parameter. Two X-ray spectra in 2009 are used to model the simultaneous SEDs. The other three X-ray spectra are not used because of a lack of simultaneous optical data.

\(^b\) The unabsorbed flux is in units of 10\(^{-11}\) erg cm\(^{-2}\) s\(^{-1}\).
4. THE VARIABILITY PROPERTIES

4.1. Spectral and Flux Variability around SED Peaks

4.1.1. Spectral Variability in the NIR–Optical Bands

The peak frequencies and their changes of blazar SED are important to obtain the parameters of the emission model. The SEDs from NIR to optical for S5 0716+714 are obtained from simultaneous $V$, $J$, and $K_s$-band photometric data around the maximum flux at 54754.3 MJD when the flux variation is intense and the time coverage of the observations is good (see Figure 3). The data observed at 54748.3 MJD are abandoned because of the large error and peculiarly low flux in the $K_s$ band. The SEDs are characterized by the inversions around the $J$ band in the relatively low condition, which suggests that the synchrotron peak is likely close to the $J$ band at the observational frame. When the source flares, SEDs become flat between the $J$ and $V$ bands. The SED is not inverted at 54752.3 MJD, which means the frequency of the synchrotron peak is higher than the $V$ band. Similar bluer-when-brighter behavior of SED evolution of blazars (Ulrich et al. 1997). The first SED bump. The general trend that when flux increases, the peaks of the SED bumps become bluer is the classical behavior of SED evolution of blazars (Ulrich et al. 1997). The low-state spectrum and a flaring-state spectrum corresponding to the strongest flare, together with the average spectrum, are shown in Figure 4.

4.1.2. Spectral Variability at $\gamma$ Rays

The fit for 40 month LAT data is accomplished, and the result gives

$$dN/dE = (1.27 \pm 0.02) \times 10^{-10}$$

$$\times \left( \frac{E}{428.66 \text{ MeV}} \right)^{-((2.03 \pm 0.02) + (0.03 \pm 0.007) \log(\frac{E}{428.66 \text{ MeV}}))},$$

with an average flux of $(22.8 \pm 0.4) \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$, which is similar to the EGRET detection of $(2.0 \pm 0.4) \times 10^{-7}$ photons cm$^{-2}$ s$^{-1}$ (Lin et al. 1995). The 40 month LAT data are fitted by 20 energy bins. The average spectrum departs from the power law over 99% confidence tested by the spectral curvature index $C$ (Abdo et al. 2010b). A broken power law also gives an acceptable description to the spectrum, including a flat component between 0.1 and 1 GeV ($\Gamma = 2.033 \pm 0.004$) and a descent component up to higher energy ($\Gamma = 2.282 \pm 0.023$). The index of the decent part is in accordance with the nonsimultaneous TeV deabsorbed photon index of 1.8 $\pm$ 0.6 (Anderhub et al. 2009). The highest-energy photon event with a probability of 0.9998 by gtsrcprob is 207.4 GeV. It is much higher than 70 GeV for BL Lacertae objects during the first 18 month period (Abdo et al. 2011).

Simultaneous $\gamma$-ray spectra are used to study the $\gamma$-ray spectral variability of the source. The spectra of five strongest $\gamma$-ray flares, which peak at 54807.7, 55107.7, 55627.7, 55757.7, and 55857.7 MJD, correspond to the flaring state. Another spectrum is obtained using $\gamma$-ray data from 55147.7 to 55207.7 MJD when the flux is in the low state. In the energy range from 0.1 to 1 GeV, the flaring-state spectra are flat or even ascending, which are harder than the low-state spectrum. Spectral variability around the second SED bump is similar to that around the first SED bump. The general trend that when flux increases, the peaks of the SED bumps become bluer is the classical behavior of SED evolution of blazars (Ulrich et al. 1997). The low-state spectrum and a flaring-state spectrum corresponding to the strongest flare, together with the average spectrum, are shown in Figure 4.

4.1.3. The Shortest-Variability Timescale for $\gamma$ Rays

S5 0716+714 underwent three strong $\gamma$-ray flares in 2011. Their peak fluxes are almost three times the average flux. The highest daily flux is $(1.69 \pm 0.25) \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$ at 55854.2 MJD, which is lower than the AGILE detection of $(2.03 \pm 0.75) \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$ (Chen et al. 2008). The most intense variation appears when the flux increases from $(3.74 \pm 1.67) \times 10^{-7}$ photons cm$^{-2}$ s$^{-1}$ at 55853.2 MJD to $(1.69 \pm 0.25) \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$ at 55854.2 MJD. The $\gamma$-ray flux varies at roughly 4.5 times the interday timescale, which is more violent than a flux increase by a factor of four in 3 days (Chen et al. 2008). The doubling time of less than 1 day in this flare agrees with the finding of Rani et al. (2013b). Such a rapid $\gamma$-ray variation allows us to make a constraint on the Doppler factor, avoiding the heavy absorption from the $\gamma$ process (Begelman et al. 2008). The doubling time is about 21
Dondi & Ghisellini (1995), hr, and the highest-energy bin in the average γ-ray spectrum with TS \( \geq 25 \) centers at about 72 GeV. Using the equation in Dondi & Ghisellini (1995), \( \delta \geq 7.5 \). Rani et al. (2013b) use the highest photon of 207.4 GeV as the absorbed photon and make a constraint of \( \delta \geq 9.1 \).

4.2. Multiwavelength Correlations

4.2.1. Correlations of Radio/X-Ray and Optical/γ-Ray Variations

The PCA X-ray and 14.5 GHz light curves seem to be well correlated. Three flares of the 14.5 GHz band at 55186.2, 55305.9, and 55475.5 MJD correspond to the X-ray flares at 55185.6, 55302.8, and 55464.5 MJD, respectively (see the three dotted vertical lines in Figure 2). The low states between these flares in both energy bands also correspond. However, the outlines of 14.5 GHz flares are probably broader than those in the X-rays. No obvious correlation can be directly seen between other two radio bands and the PCA X-ray light curves. The flaring behaviors seem to be washed out at 4.8 and 8 GHz.

Searching for the existence of a correlation between optical and γ-ray variations had been performed for S5 0716+714 since the CGRO era (Ghisellini et al. 1997). Although the optical data in our work are limited, most optical flares have the corresponding γ-ray ones. The optical flux increases quickly during the ascent phase of the strong γ-ray flare at 55627.7 MJD (see the violet vertical line in Figure 2). Even in the extreme low state of the γ-ray, there probably exists a γ-ray flare corresponding to a strong optical flare. On the other hand, the three strongest optical flares with nearly constant optical peak fluxes correspond to three γ-ray flares with the γ-ray peak fluxes changing three times. A γ-ray flare at 54807.7 MJD with a peak flux of \((2.36 \pm 0.61) \times 10^{-7} \) photons cm\(^{-2}\) s\(^{-1}\) just above the average flux corresponds to the strongest optical flare at 54804.3 MJD. One of the strongest γ-ray flares at 55107.7 MJD, when the peak flux is \((4.41 \pm 0.45) \times 10^{-7} \) photons cm\(^{-2}\) s\(^{-1}\), correlates to a strong optical flare at 55115.3 MJD. In this case, the γ-ray peak flux is almost twice the average flux. During the long low state of the γ-ray from 55132.7 to 55222.7 MJD, another γ-ray flare at 55187.7 MJD with a peak flux of \((1.42 \pm 0.38) \times 10^{-7} \) photons cm\(^{-2}\) s\(^{-1}\) corresponds to a strong optical flare at 55185.9 MJD. The peak flux of this γ-ray flare is nearly half of the average flux.

4.2.2. Coincidence of γ-Ray Flux and Optical P.A. Variation

We find the coincidence of a γ-ray flare with a dramatic change of optical P.A. in 2011 March (see Figure 5). Within \( \sim 30 \) days, the γ-ray flux sharply increases from the low state at 55597.7 MJD to the flare peak at 55627.7 MJD. The optical P.A. sharply increases from \((19:9 \pm 0:1)\) at 55595.3 MJD to \((146:6 \pm 0:1)\) at 55599.2 MJD within 5 days and then decreases to \((22:6 \pm 0:2)\) at 55625.2 MJD within 27 days (see the two dashed vertical lines in Figure 5). Within the increasing phase of P.A., the rotation rate of P.A. is 25° per day. Within the decreasing phase of P.A., the rotation rate of P.A. is 4.6° per day. There is a flare in the V-band flux corresponding to this sharp γ-ray flare. In the increasing phase of this optical flare, the optical P.A. has a dramatic change like in the sharp γ-ray flare (see Figure 5). Larionov et al. (2013) found that a 180° rotation of the position angle of the optical linear polarization coincides with strong flares in γ-ray and optical bands in 2011 October. Actually, these similar observational phenomena have been found in two of the three strong γ-ray flares in 2011. Larionov et al. (2008) reported another coincidence of a huge optical outburst with a 360° rotation of optical P.A. in 2008 April when simultaneous γ-ray observation is missing. This

Figure 5. Coincidence of γ-ray and optical flares with a dramatic change in V-band P.A. The dark yellow circles represent the γ-ray fluxes, the purple stars are the optical fluxes, and the red squares represent the V-band P.A. Between the two vertical dashed lines, the fluxes of the γ-ray and the optical increase, while the P.A. shows the overall downward trend.

(A color version of this figure is available in the online journal.)
phenomenon seems to be a common occurrence for the source. A similar behavior was found in 3C 279 by Abdo et al. (2010e). It is suggested that the sharp γ-ray flare is correlated with the dramatic change of optical polarization, likely due to a single coherent event, rather than a superposition of multiple but causally unrelated, shorter-duration events. Cospatiality of optical and γ-ray emission regions and a highly ordered jet magnetic field are indicated (Abdo et al. 2010e).

4.2.3. Strong Optical and X-Ray Activities at the γ-Ray Low State

An interesting variability phenomenon of S5 0716+714 is that intense variations appear in the X-rays, the optical flux, and PD during the long low state of the γ rays from 55132.7 to 55222.7 MJD. The highest flux in the X-rays is (14.47 ± 2.21) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} at 55164.6 MJD, raising from (5.27 ± 1.94) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} at 55143.2 MJD. There is a strong secondary X-ray flare whose peak flux is (13.25 ± 1.98) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} at 55185.6 MJD. The flux of the X-ray becomes low for (5.00 ± 1.68) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} at 55213.0 MJD. The fluxes of the optical double peaks are both 27.4 ± 0.3 mJy at 55183.8 and 55185.9 MJD, with a maximum optical PD of (25.69 ± 0.80)% at 55183.3 MJD. The optical flux increases from 8.0 ± 0.1 mJy at 55149.9 MJD and drops to 6.2 ± 0.03 mJy at 55204.3 MJD. The lowest optical PD in this epoch is (1.69 ± 0.69)% at 55173.7 MJD. There is a flare of 14.5 GHz peaks at 55186.2 MJD. However, the duration of this radio flare is longer than flares in other bands. A γ-ray flare with a peak flux of (1.41 ± 0.38) \times 10^{-7} \text{ photons cm}^{-2} \text{ s}^{-1} at 55187.7 MJD corresponds to the optical, optical PD, and secondary X-ray flares. The peak flux of this γ-ray flare is lower than the average flux, while the corresponding peak fluxes in other bands remain constant in the high state. However, it is nearly twice the flux of (0.63 ± 0.32) \times 10^{-7} \text{ photons cm}^{-2} \text{ s}^{-1} at 55177.7 MJD and roughly 3.6 times the flux of (0.39 ± 0.25) \times 10^{-7} \text{ photons cm}^{-2} \text{ s}^{-1} at 55197.7 MJD. So the γ-ray variability amplitude is comparable to other bands. During this γ-ray low-state epoch, the TS value for each bin is larger than 25, which makes the variability amplitude reliable. The fluxes of X-rays and γ rays all vary nearly three times. The intrinsic variability amplitudes of these bands could be higher due to their 10 day average fluxes. The flux of the optical V band varies more than four times. The most violent behavior is shown as variation of more than 10 times on the optical PD. The X-ray flare at 55143.2 MJD, which leads the optical and γ-ray flares, is probably the orphan discussed in Rani et al. (2013a).

Similar work using data from Swift and AGILE satellites has been performed (Giommi et al. 2008). The multiwavelength observational results are similar to ours. However, it is claimed that the highly variable optical and soft X-ray flares are accompanied by a constant γ-ray flare, which is based on the AGILE observation with low counting statistics. The corresponding γ-ray flare may have been missed.

4.3. Statistical Analysis of Multiwavelength Light Curves

4.3.1. Time Lags

The discrete correlation function (DCF; Edelson & Krolik 1988) is a technique in time series analysis for finding time lags between different light curves utilizing a binning scheme to approximate the missing data. The z-transformed discrete correlation function (ZDCF; Alexander 1997) can estimate the cross-correlation function in the case of nonuniformly sampled light curves. The ZDCF is a binning-type method that is an improvement of the DCF technique, with the notable feature that the data are binned by equal population rather than equal bin width Δx as in the DCF. These light curves at the radio, IR, optical, and X-ray bands are sampled sparsely and unequally for S5 0716+714. Thus, as in previous research on unequally sampled light curves (Liu et al. 2008, 2011a, 2011b), time lags will be analyzed by the ZDCF. From these ZDCF profile bumps closer to the zero lag, the centroid time lags t_{centr}, which are used as the estimation of the time lag, are computed using all points with correlation coefficients r ≥ 0.8r_{max}.

The calculated ZDCFs are presented in Figures 6 for the light curves in Figures 1 and 2. Considering the bin sizes of the X-ray and γ-ray light curves, 14.5 GHz/X-ray and the optical V band/γ-ray variations appear to be zero lag. The J-band light curve (Figure 1), which is well sampled with a shorter time range than the V-band light curve, also seems to zero lag the γ-ray light curve. We also use the classic DCF method to check our correlation results. In general, the correlation results from ZDCF and DCF are in agreement. The 14.5 GHz/X-ray, the V band/γ-ray, and X-ray/γ-ray variations are all strongly correlated with an over 99.9% confidence level. Rani et al. (2013a) and Larionov et al. (2013) also suggest the optical V band/γ-ray variations are correlated with zero lag. However, we find that the relationship between the 14.5 GHz and γ-ray emissions is likely not tight. The correlation coefficient is relatively low, and the lag is not stable for different bin sizes. Rani et al. (2013a) find that the confidence levels of the correlations of γ-ray/37 GHz and γ-ray/230 GHz are lower than 3σ.

4.3.2. Fractional Variability Amplitude

In order to estimate the total variability of each light curve, we use the rms fractional variability amplitude F_{var} (e.g., Edelson et al. 2002; Vaughan et al. 2003). The fractional variability amplitude F_{var} is defined as

\[ F_{var} = \sqrt{\frac{S^2 - \langle \sigma^2_{\text{err}} \rangle}{\langle F \rangle^2}}, \]

where \( \langle F \rangle \) is the mean flux for the \( N \) points in the light curve, \( S^2 \) denotes the total variance of the light curve, and \( \langle \sigma^2_{\text{err}} \rangle \) denotes the measured mean square error of the data points:

\[ S^2 = \frac{1}{N-1} \sum_{i=1}^{N} (F_i - \langle F \rangle)^2, \]

\[ \langle \sigma^2_{\text{err}} \rangle = \frac{1}{N} \sum_{i=1}^{N} \sigma^2_{\text{err},i}. \]

The error on F_{var} is (Edelson et al. 2002)

\[ \sigma_{F_{var}} = \frac{1}{F_{var}} \sqrt{\frac{1}{2N} \langle S^2 \rangle}. \]

For light curves in Figure 2 and the J-band light curve in Figure 1, the calculated results of F_{var} are listed in Table 3. For all the light curves in Figures 1 and 2, the calculated F_{var} are presented in Figure 7. The fractional variability amplitude violently varies with the frequency. First, F_{var} increases with increasing frequency within the radio band. This trend is same as that found in 3C 273 (e.g., Soldi et al. 2008). Second, F_{var} increases from the radio to the J band, decreases to the V band.
and X-rays, and then increases to the \( \gamma \)-ray band (see Figure 7). Variability in the \( \gamma \)-ray band is the most violent. The sampling rates and time intervals of light curves significantly influence \( F_{\text{var}} \), and this is clearly shown in the light curves at the \( K_s \), \( J \), \( I \), \( R \), \( V \), and \( B \) bands (see Figure 7).

### 4.3.3. Characteristic Variability Timescale

The zero-crossing time of the autocorrelation function (ACF) of a light curve was defined as a single characteristic variability timescale (Giveon et al. 1999). It is a well-defined quantity and used as a characteristic variability timescale (e.g., Alexander 1997; Giveon et al. 1999; Netzer et al. 1996). Comparing the widths of the ACF between different bands can shed light on the relation between the mechanism and location of emission in these wave bands (Chatterjee et al. 2012). Another function used in variability studies to estimate the variability timescale is the first-order structure function (SF; e.g., Trevese et al. 1994). There is a simple relation between the ACF and the SF (see Equation (8) in Giveon et al. 1999). Therefore, only an ACF analysis is performed on our light curves. The ACF is estimated by the ZDCF (Alexander 1997). Following Giveon et al. (1999), a fifth-order polynomial least-squares procedure is used to fit the ZDCF, and this fifth-order polynomial fit is used to evaluate the zero-crossing time.

Calculated ACFs are presented in Figure 8 for the light curves in Figure 2. These characteristic variability timescales of S5 0716+714 at the 14.5 GHz, \( V \), X-ray, and \( \gamma \)-ray bands are comparable to each other, \(~60–90\) days. We also check the effect of the binning on our results. Changing the bin size

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**Table 3**

Fractional Variability Amplitudes \( F_{\text{var}} \) for Radio, Infrared, Optical, X-Ray, and \( \gamma \)-Ray Light Curves

| Frequency [Hz] | 4.8 GHz | 8 GHz | 15 GHz | J-band | V-band | X-ray | Fermi |
|---------------|--------|-------|--------|--------|--------|-------|-------|
|               | \( (1) \) | \( (2) \) | \( (3) \) | \( (4) \) | \( (5) \) | \( (6) \) | \( (7) \) |
|               | 0.25 ± 0.03 | 0.29 ± 0.03 | 0.31 ± 0.02 | 0.40 ± 0.02 | 0.38 ± 0.02 | 0.28 ± 0.05 | 0.52 ± 0.04 |
cannot significantly influence our tendency. These comparable characteristic variability timescales indicate that these emission variations likely have the same origin. However, the origin of the 14.5 GHz emission could be complicated. Since the 14.5 GHz emission is well correlated with the hard X-rays and the light curve of 14.5 GHz seems to be less rapidly variable than other three bands, the 14.5 GHz emission probably consists of two different components. One component could be more relative to the high-energy emissions and is from the compact radiation region. The other component is from an extended region and is less rapidly variable. The characteristic variability timescale of 14.5 GHz from our ACF analysis likely corresponds to the first component. Rani et al. (2013b) use the SF analysis to obtain the γ-ray variability timescale of ∼75 days. Rani et al. (2013a) find that the variability timescales of radio bands from 15 to 230 GHz are in the range of ∼60–90 days using the SF analysis. The variability timescale of the V-band light curve is suggested to be ∼60 days by Lomb–Scargle periodogram analysis (Rani et al. 2013a). Our ACF results agree with these similar variability timescale studies for S5 0716+714.

4.4. Implication of Multiwavelength Variability

Concave X-ray spectra (Table 2) with break energies of ∼3 keV based on our XRT data analysis agree with the results from the literature. The hard X-ray component is considered to be from the IC process by the low-energy electrons in the leptonic models (Giommi et al. 1999; Tagliaferri et al. 2003; Zhang 2010). Our X-ray light curve is obtained from the PCA data with an energy range of 2.6–50 keV. The radio emission of blazars is widely accepted from the synchrotron process the synchrotron emission of the low-energy electrons. If the radio and the hard X-ray emissions both come from the low-energy electrons; the 14.5 GHz and the PCA X-ray light curves should be correlated. Such a prediction is confirmed by our correlation analysis, strongly supporting the leptonic models.

A correlation with a zero lag between the optical V band and the γ-ray variations is also found, which agrees with similar works (Rani et al. 2013a; Larionov et al. 2013). With a source type similar to S5 0716+714, 3C 66A, shows a clear correlation between GeV γ-ray and optical R bands with a time lag of 10
FSRQs (Bonning et al. 2012). There are IR and between optical and light curve. Considering the strong correlation with a zero lag these four energies.

It is indicated that variations of these emissions likely have the ability timescales from SF analysis (Rani et al. 2013a, 2013b).

Such a broken power-law distribution can be the result of synchrotron self-absorption (Begelman et al. 2008). The Doppler factor can be constrained from our work, and hollow symbols are collected from the literature (radio, Fuhrmann et al. 2008; IR/optical, Chen & Shan 2011, Villata et al. 2008; X-ray, Tagliaferri et al. 2003; γ-ray, Tagliaferri et al. 2003, Giommi et al. 2008). Blue pentagons are the average fluxes of 4.8, 8, and 14.5 GHz from UMRAO. Red circles are the J- and V-band optical average fluxes. The yellow diamond is the average X-ray flux for 3–50 keV from RXTE/PCA. Cyan squares represent the 40 month average γ-ray spectrum from Fermi/LAT. The dashed line represents the calculated synchrotron emission, the dotted line corresponds to the SSC component, and the dash-dotted line is the ERC part.

(A color version of this figure is available in the online journal.)

5. SED Modeling

SED modeling is a powerful tool to test different radiation models for blazars. In this paper, a homogeneous one-zone synchrotron plus IC model is used to calculate the jet emission of S5 0716+714. The broadband electromagnetic emission comes from a compact homogeneous blob with relativistic speed with a radius of R embedded in the magnetic field. A broken power-law spectrum for particle distribution has been assumed,

\[ N(\gamma) = \begin{cases} \frac{K}{\gamma^{p_1}} & \gamma_{\min} \leq \gamma \leq \gamma_{\br} \\ \frac{K}{\gamma_{\br}^{p_1-p_2}} \gamma_{\br}^{-p_2} & \gamma_{\br} < \gamma \leq \gamma_{\max} \end{cases} \]

Such a broken power-law distribution can be the result of the balance between the particle cooling and escape in the blob. The parameters of this model include the radius R of the blob, the magnetic field strength B, electron break energy \( \gamma_{\br} \), the minimum and maximum energies, \( \gamma_{\min} \) and \( \gamma_{\max} \) of the electrons, the normalization of the particle number density K, and the indices \( p_{1,2} \) of the broken power-law particle distribution. The frequency and luminosity can be transformed from the jet frame to the observational frame as

\[ \nu = \frac{\delta \nu}{(1 + \delta)} \text{ and } L_{\nu} = \frac{\delta^4 \nu^4 L_{\nu}^*}{\text{IC}} \]

where the Doppler factor \( \delta = 1 / \sqrt{(1 - \beta \cos \theta)} \). The synchrotron self-absorption and the Klein–Nishina effect in the IC scattering are properly considered in our calculations. The detailed constraints of SED modeling can be found in Tavecchio et al. (1998) and Sikora et al. (2009).

We use the \( \chi^2 \)-minimization method to obtain the best-fitting input parameters. We make special constraints on parameters of B and \( \delta \). The values of these parameters are varied over wide ranges to calculate the corresponding values of \( \chi^2 \). Then, we obtain the probability of the fit by \( p \propto e^{-\chi^2/2} \). We plot the contours of \( p \) in the \( B - \delta \) plane and constrain the value of B and \( \delta \) at the 1σ level. A detailed SED modeling strategy can be found in Zhang et al. (2012).

5.1. Average SED Modeling

Thanks to the long accumulative observation time, the average γ-ray spectrum from 0.1 to almost 100 GeV with relatively little error provides much more information than previous observations from the EGRET and AGILE (Lin et al. 1995; Chen et al. 2008). Modeling the average SED with different models is shown in Figure 9, and the input parameters are listed in Table 4.

S5 0716+714 possesses violent variations across its broadband electromagnetic radiation. It is a famous IDV source in the radio and optical bands, with a doubling time of 7000 s at X-ray and γ-ray flux changing 4.5 times in 2 days, which are strict constraints on the emission region, \( R \approx \delta c_{\text{var}} (1 + z)^{-1} \) (Begelman et al. 2008). The Doppler factor can be constrained by rapid variations (≥5–15; Fuhrmann et al. 2008) and kinematic study (≈20–30; Bach et al. 2005). The strength of the magnetic field can be constrained by the inverted radio spectra demonstrated as a result of synchrotron self-absorption (≥0.07–0.11 G; Fuhrmann et al. 2008).

Table 4 shows that for a pure SSC model, which is usually successful for TeV blazars, the input model parameters are extreme. When the variability timescale is set to 1 day, the Doppler factor value becomes extraordinarily large, which
The Doppler factor is reduced to 39.6 $\pm$ 3.1 when the variability timescale is set to 10 days. However, the variability timescale of 10 days disagrees with the observations of fast variability from the radio to $\gamma$ rays. Meanwhile, the magnetic field $B$ is $0.006 \pm 0.001$ G, which is not harmonious with the typical value from similar SED fitting studies carried out previously (e.g., Tagliaferri et al. 2003; Giommi et al. 2008). The large frequency ratio of the SSC peak to synchrotron peak may bring out these abnormal parameters. The pure SSC model is also not favorable because of its failure to explain the extremely fast optical variability (Danforth et al. 2013).

Although no thermal components have been detected from spectroscopic observations (Chen & Shan 2011; Shaw et al. 2009; Danforth et al. 2013), scattering of weak external emissions could possibly contribute the $\gamma$-ray emission of the source. Because the synchrotron peak of S5 0716+714 locates at the NIR/optical band in the observation frame, the hot-dust emission can be heavily diluted by the strong nonthermal continuum. A prominent IR excess indicative of dust emission with 1200 K temperature from the hot-dust photons is shown in Figure 10. The values of $\delta$ are 24.5 $\pm$ 0.7 and 39.6 $\pm$ 3.1 corresponding to the hot dust and BLR emissions being the external seed photons, respectively. These values agree better with the observations than the $\delta$ value from the pure SSC model with a variability timescale of 1 day. The magnetic field intensity values are 0.24 $\pm$ 0.02 and 0.38 $\pm$ 0.06 corresponding to the hot-dust and BLR emissions being the external seed photons, respectively. Although these values are still lower than the constraint from radio spectra (Fuhrmann et al. 2008), they are more reasonable than the magnetic field intensity from the pure SSC model. The SSC+ERC models are not favorable because of their failure to explain the extreme fast optical variability (Danforth et al. 2013).

5.2. Simultaneous SED Modeling

As mentioned in Section 4.2, three strong optical flares with nearly constant optical peak fluxes correspond to three $\gamma$-ray flares with the $\gamma$-ray peak fluxes changing three times. At 55187.7 MJD, the peak flux of the $\gamma$-ray flare is even lower than the average flux, while the peak fluxes of the corresponding flares in the optical and X-ray bands remain in the high state. This seems to be abnormal for the leptonic models.

Three simultaneous SEDs are obtained for the optical and $\gamma$-ray flaring state, together with another simultaneous SED for the multiwavelength low state. For the first SED, the strongest optical flare at 54804.3 MJD corresponding to a $\gamma$-ray flare at...

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**Table 4**

| Parameters | Pure SSC | SSC+ERC(BLR) | SSC+ERC(Dust) |
|------------|----------|--------------|---------------|
| $B$(Gauss) | $6.17 \times 10^{-3}$ | $0.29_{-0.02}^{+0.02}$ | $0.24_{-0.01}^{+0.01}$ |
| $\delta$   | $39.6_{-3.1}^{+3.8}$ | $23.3_{-0.9}^{+1.9}$ | $24.5_{-0.7}^{+0.7}$ |
| $t_{var}$(day) | 10 | 1 | 1 |
| R(cm)      | $7.8 \times 10^{17}$ | $4.6 \times 10^{16}$ | $4.8 \times 10^{16}$ |
| K          | $1.2 \times 10^5$ | $1.1 \times 10^4$ | $1.0 \times 10^4$ |
| $\gamma_{ph}$ | $2.0 \times 10^4$ | $3.3 \times 10^3$ | $3.5 \times 10^3$ |
| $p_1$      | 2.4 | 2.2 | 2.2 |
| $p_2$      | 3.9 | 3.8 | 3.8 |

**Notes.**

1. Seven SEDs have been modeled in our work, and the input parameters are listed here. Three groups of parameters are obtained from modeling the average SEDs with different models. Four other groups of parameters with dates are obtained from modeling simultaneous SEDs with the synchrotron plus SSC+EC(IR) model containing three flaring states and one low state in 2010 January.

2. Detailed description of the multiwavelength variability corresponding to the four simultaneous SEDs is given in Section 5.2.

3. Input parameters are described in the first paragraph of Section 5. For all fits except the case of 2010 January, $\gamma_{min}$ is set to 10. For the fits of 2010 January $\gamma_{min}$ is chosen to be 350 due to its extremely low X-ray flux. $\gamma_{max}$ are 100 times $\gamma_{min}$ for all cases.

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![Figure 10](image_url)  
**Figure 10.** Contours of $p$ in the $B$-$\delta$ plane, where $p \propto e^{-\chi^2/2}$. Four contours correspond to $p$ of 0.05, 0.1, 0.2, and 0.26, respectively. The contour of $p = 0.2$ is drawn in red, which corresponds to the 1$\sigma$ level of the Gaussian fit for the $B$-$p$ and $\delta$-$p$ distributions. The green spot demonstrates the location of the best fit.  
(A color version of this figure is available in the online journal.)
Figure 11. Distributions of $p$ with different values of $B$ and $\delta$. The green lines are the Gaussian fits. The red horizontal lines are obtained from the 1$\sigma$ level of the Gaussian fits with a $p$ value of 0.195. The 1$\sigma$ uncertainties of the $B$ and $\delta$ are obtained from the intersections between the $B$-$p$ and $\delta$-$p$ distributions and the red horizontal lines.

(A color version of this figure is available in the online journal.)

Figure 12. Modeling the four simultaneous SEDs. Blue pentagons are the radio observations from UMRAO. Red circles are the optical and NIR photometric data. The error bars for radio and optical fluxes are too small to be seen. The yellow diamond in (b) is the interpolation by nearby RXTE/PCA observations. The X-ray spectra with yellow triangles is from Swift/XRT. The cyan squares are the Fermi/LAT observations. The dashed lines represent the calculated synchrotron emissions, the dotted lines correspond to the SSC components, and the dash-dotted lines are the ERC parts. (a) SED in 2008 December with the strongest optical flare and a $\gamma$-ray flare with medium peak flux. (b) SED in 2009 October, when both optical and $\gamma$-ray peak fluxes are in the high state. (c) Multiwavelength flaring state in 2009 December, but the peak flux of $\gamma$-ray flare is extremely low. (d) SED where all bands are in the low state in 2010 January.

(A color version of this figure is available in the online journal.)

54807.7 MJD with the peak flux just above the average flux is focused. No simultaneous X-ray observation is found. The second SED corresponds to one with the strongest $\gamma$-ray flare at 55107.7 MJD correlated with a strong optical flare at 55115.3 MJD. The X-ray constraint is the interpolation of the edges of the PCA observation blank at 55091.0 and 55136.0 MJD. Violent X-ray and optical activities have been detected during the long low $\gamma$-ray period from 55132.7 to 55222.7 MJD. Two SEDs correspond to the low and high states for highly variable X-ray and optical fluxes. An individual $\gamma$-ray spectrum for the flare at 55187.7 MJD cannot be obtained because of the shortage of $\gamma$-ray photons. So both the high- and low-state SEDs share the entire low-state $\gamma$-ray spectrum. The optical peak flux at 55185.9 MJD and the X-ray spectrum from 55172.0 to 55187.0 MJD are used for the flaring-state SED. The low optical flux at 55204.3 MJD and the X-ray spectrum from 55193.0 to 55249.0 MJD are adopted for the low-state SED. The nearest UMRAO data are used as upper limits.

We adopt only the SSC+ERC model with external seed photons from hot-dust emission. The typical variability timescale is set to 1 day. The temperature and the photon density of hot-dust emission are fixed to be consistent with the input parameters of the average SED modeling.

The input parameters from modeling the simultaneous SEDs are shown in Table 4, and the fit results are shown in Figure 12. Four simultaneous SEDs are well described by the SSC+ERC
model, which agrees with the result of similar simultaneous SED modeling work by Rani et al. (2013a). The variability phenomenon can be explained by the leptonic model. For S5 0716+714, its V-band emission is likely around the synchrotron peak, while the SSC emission peaks at about 10 MeV, which is ~1 order of magnitude lower than the energy range of Fermi/LAT, 0.1–300 GeV. When the frequencies of IC peaks become lower, the GeV γ-ray flux detected by LAT decreases quickly. However, the V-band emission cannot be influenced seriously by a small change in the synchrotron peak frequency because the SED slope is flat around the synchrotron peak. Flares at 55107.7 and 55187.7 MJD are used to make a contrast. The input parameters in Table 4 are used. Since \( v_{\text{syn}} \propto \gamma_{\text{e}}^2 B \delta \) and \( v_{\text{ssc}} \simeq \gamma_{\text{e}}^2 v_{\text{syn}} \), the frequency of the synchrotron peak in the former flare is roughly 1.2 times the latter, while for the frequencies of SSC peaks, it is about 2.8 times. This agrees with the observations that the optical peak fluxes are almost the same, but that among the three gamma-ray flares, the peak flux with the highest value is roughly three times as the peak flux with the lowest value.

The Doppler factors of three γ-ray flares tend to have higher values compared to the low state. This corresponds to the VLBA observation that the γ-ray flare always accompanies the apparent supraluminal knot ejection. The magnetic field intensities of these three γ-ray flares also tend to have higher values than the low state. The highest magnetic field intensity value is found in the flare in 2009 December when an extremely high PD of (25.69 ± 0.80)% is detected. For the three γ-ray flares, the γ-ray fluxes seem to be inversely proportional to magnetic field intensity values and proportional to the Doppler factor values. However, the latter becomes marginal because of the fitting errors. These two tendencies are similar to the findings for 3C 454.3 (Bonnoli et al. 2011) and 3C 279 (Zhang et al. 2013).

6. DISCUSSION

Because of the absence of emission lines in the optical spectra of S5 0716+714, its redshift has not been exactly determined. In the above SED modeling, we took \( z = 0.31 \pm 0.08 (1\sigma \text{ error}) \) from Nilsson et al. (2008). Different radiation models are distinguished by the input model parameters that depend on the redshift. We attempt to discuss the possible influence caused by the uncertainty of the redshift. We take the SSC+ERC model with the hot-dust emission as an example. Eleven redshift points are chosen evenly in the range of the uncertainty of redshift (0.23, 0.39). We model the 11 SEDs with different redshifts independently. The \( B \) and \( \delta \) distributions of the redshift are shown in Figure 13. The influence of 1σ uncertainty of redshift on \( B \) is comparable to the 1σ fit error. However, it is larger than the fit error on \( \delta \). We also check the redshift influence on the pure SSC model and the SSC+ERC model using BLR emission. Including the influence of 1σ uncertainty of redshift, the tendency that input parameters from the pure SSC model are more extreme than those from the SSC+ERC models is not changed.

To avoid the extreme input parameters from the pure SSC model, SSC+ERC models are used instead. On the other hand, the assumption of the existence of the external emissions cannot conflict with any observations of S5 0716+714. The luminosity of the presumed external emissions cannot exceed the nearby nonthermal jet emission. As little information on the accretion system is known, the characteristic radius scales of the dust torus

\[
R_{\text{dust}} \sim 1 \text{ pc and the BLR } R_{\text{Ly}\alpha} \sim 0.01 \text{ pc are used; then}
\]

\[
L_{\text{dust,Ly}\alpha} \simeq 4\pi R_{\text{dust,Ly}\alpha}^2 c U_{\text{dust,Ly}\alpha},
\]

where \( U_{\text{dust,Ly}\alpha} \) is the energy density of the dust or Ly\( \alpha \) line emission and \( c \) is the speed of light. The energy densities of the external field emissions are obtained from the average SED modeling, \( U_{\text{dust}} \simeq 1.1 \times 10^{-6} \text{ erg cm}^{-3} \) and \( U_{\text{Ly}\alpha} \simeq 8.6 \times 10^{-6} \text{ erg cm}^{-3} \), in the observational frame. So \( L_{\text{dust}} \) and \( L_{\text{Ly}\alpha} \) are calculated as 4.0 \( \times 10^{42} \) and 3.1 \( \times 10^{39} \) erg s\(^{-1}\), respectively. The nonthermal luminosity at the frequency of the maximum hot-dust emission is about 1.7 \( \times 10^{46} \) erg s\(^{-1}\) (Chen & Shan 2011). The constraint of the Ly\( \alpha \) line luminosity has recently been obtained, \( L(\text{Ly}\alpha) \lesssim 6.5 \times 10^{43} \) erg s\(^{-1}\) (Danforth et al. 2013). So the luminosities of the external emissions are lower than the nearby nonthermal luminosities, which makes our assumption harmonious.

Strong γ-ray emissions from S5 0716+714 have been detected by MAGIC and Fermi. If the absorptions for γ rays caused by the assumed external emissions are significant, the γ-ray photons cannot escape, which conflicts with the γ-ray observations. The optical depth of photon–photon absorption between the γ rays and the external emission can be simply calculated as (Dondi & Ghisellini 1995)

\[
\tau_{\gamma\gamma}(\mathbf{x}') = \frac{\sigma_T}{5} n'(x'_i) x'_i R',
\]

where \( \sigma_T \) is the scattering Thomson cross section, \( n'(x'_i) \) is the number density of the target photon, \( x'_i \) is the energy of the target photon in dimensionless units, and \( R' \) is the absorption length. The doubling time of 21 hr is used to constrain the distance between the black hole and the emission blob (Celotti et al. 1998). \( R' \simeq R_L = c t_{\text{doubling}}^\text{BLR} (1+z)^{-1} \). Whether the external seed photons are from the dust or the Ly\( \alpha \) line emission, the absorption opacity \( \tau_{\gamma\gamma} \lesssim 10^{-6} \ll 1 \). The absorptions are negligible. The assumptions of the external emission do not conflict with the γ-ray observations.

Synchrotron plus SSC+ERC models can describe well the broadband emission of S5 0716+714. Similar results are found
in several LBLs/intermediate-frequency peaked BL Lac objects (IBLs). For BL Lacertae objects, the prototype of the BL Lac objects shows that the SSC+ERC model using the BLR emission as seed photons is better than a two-zone SSC model, and the pure SSC model is likely to be ruled out, acting like a FSRQ (Abdo et al. 2011). The SSC+ERC model with external IR seed photons can agree with the IDV for 3C 66A (Reyes et al. 2011) and gets a more reasonable magnetic field parameter for W Comae (Acciari et al. 2009). Actually, no evidence of the thermal emission has been found for S5 0716+714 and 3C 66A. However, the external seed photons are probably necessary to explain their γ-ray emissions. LBLs/IBLs, unlike the typical HBLs, which can usually be well explained simply by the single synchrotron plus SSC model (e.g., Bartoli et al. 2012), or the FSRQs, whose γ-ray emissions are often dominated by the ERC process (e.g., Bonnoli et al. 2011), are the kind of sources for which both the SSC and ERC processes may be indispensable for their γ-ray emissions.

7. CONCLUSIONS

We present the results of the radio to γ-ray observations of S5 0716+714, together with our photometric observations at Yunnan Observatories. The variations of the 14.5 GHz and hard X-ray emissions are correlated with zero lag, which strongly supports the leptonic models. A coincidence of γ-ray and V-band flares with a dramatic change in the optical P.A. in 2011 March is detected. The γ-ray and V-band flares in 2009 December correspond to a flare of optical PD. The V-band and γ-ray flux variations are also correlated with zero lag, which is consistent with the results of Rani et al. (2013a) and Larionov et al. (2013). A close relationship between the optical and γ-ray emissions is suggested. The variability amplitudes in γ-ray and optical bands are higher than those in the hard X-ray and radio bands. The radiation cooling time of the high-energy electrons, which radiate the optical and γ-ray emissions, is much shorter than that of the low-energy electrons, which produce the hard X-ray and radio emissions. The characteristic timescales of 14.5 GHz, optical, X-ray, and γ-ray bands from our ACF analysis are comparable to each other, which is consistent with results of the SF analysis of Rani et al. (2013a, 2013b) in which the characteristic timescales of radio, optical, and γ-ray bands are ~60–90 days. The variability of these bands is likely from the same origin that causes the change in properties of the radiating electrons. Hadronic models do not have the same type of explanation for these observations as the leptonic models. By comparing the optical light curves, the orphan-γ-ray flare that supports the hadronic models is not found. However, we find a peculiar phenomenon in which a strong optical flare correlates to a γ-ray flare whose peak flux is lower than the average flux. The leptonic model can explain this variability phenomenon through simultaneous SED modeling. Conclusively, the multiwavelength emissions of S5 0716+714 are likely generated from the relativistic electrons.

Different leptonic models are distinguished by the average SED modeling. The pure SSC model is ruled out because of the extreme input parameters, agreeing with the result of Danforth et al. (2013) that the pure SSC model has difficulty explaining the extremely fast optical variability. The SSC+ERC model, whether the BLR or the hot-dust emission is used as the external emission for the IC process, can represent well the SEDs and provides reasonable input parameters. It agrees with Rani et al. (2013a), which suggests that the SSC+EC model using the BLR emission as the external photons provides a satisfactory description of the broadband SEDs. Including the influence of 1σ uncertainty of the redshift of the source, the tendency that SSC+ERC models are more favorable than the pure SSC model does not change. The luminosities of the assumed external emissions do not exceed the luminosities of nearby jet continuous emissions, and the absorptions for γ rays caused by the assumed external emissions are negligible, which makes our assumptions harmonious. Both the SSC and ERC processes are probably needed to explain the γ-ray emission of S5 0716+714.

This research has made use of data obtained from the High Energy Astrophysics Science Archive Research Center, provided by NASA/Goddard Space Flight Center. We thank Makoto Ue-mura, who provided the published Kanata optical/NIR flux and polarization data. Data from the Steward Observatory spectropolarimetric monitoring project were used. This program is supported by Fermi Guest Investigator grants NNX08AW56G, NNX09AU10G, and NNX12AO93G. We thank Paul Smith, who provided the V band flux and polarization data from Steward Observatory. This research has made use of data from the University of Michigan Radio Astronomy Observatory, which is supported by the University of Michigan and by a series of grants from the National Science Foundation, most recently AST-0607523. We thank Margo Aller, who provided the UMRAO multiband flux density data. This work is financially supported by the 973 Program (grant 2009CB824800), the National Natural Science Foundation of China (NSFC; grants 11133006, 11273052, 11233006, 11173043, 11133002, 11130302, and 11103060), and the Youth Innovation Promotion Association, CAS.

We appreciate the helpful suggestions from the anonymous referee that led to a substantial improvement of this work. We thank Jian Cheng Wang, Wei Cui, and Jin Zhang for their fruitful suggestions during different discussions. Yue Heng Xu is specially thanked for improving the quality of the English. Shao Kun li, Chuan Jun Wang, Yu Xin Xin, and Xu Liang Fan are thanked for their observations at the 1 m and 2.4 m telescopes of Yunnan Observatories. Yi Bo Wang is thanked for his suggestions of statistical analysis. The Fermi help group, especially Robin Corbet and Jeremy S. Perkins, are thanked for their advice for the data analysis of Fermi/LAT.

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