UNDERSTANDING THE NATURE OF THE BLAZAR CGRaBS J0211+1051

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ABSTRACT

The source CGRaBS J0211+1051 (MG1 J021114+1051, z = 0.20) flared up on 2011 January 23 in high-energy γ-rays as reported by the Large Area Telescope (LAT) on board Fermi. This event was followed by increased activity at the UV, optical, and radio frequencies as detected by the observing facilities worldwide. The source also showed a high and variable optical polarization based on which it was proposed to be a low-energy peaked BL Lac object (LBL). The present work reports first comprehensive multi-wavelength study of this source using data in the radio, optical, UV, X- and γ-rays, and optical polarization. Using these multi-wavelength data on the source, we have estimated various parameters and verified its classification vis-a-vis blazar sequence. Multi-wavelength light curves are used to discuss the flaring events of 2011 January in an attempt to address the nature of the source and pinpoint the possible physical processes responsible for the emission. The light curves show variations in the high-energy γ-rays to be correlated with X-ray, UV, and optical variations, perhaps indicating their co-spatial origin. Our optical data, quasi-simultaneous with UV (Swift-UVOT) and X-ray (Swift-XRT) data, enabled us to trace the low-energy (synchrotron) component of the spectral energy distribution (SED) for CGRaBS J0211+1051 for the first time. The SED shows the synchrotron peak to lie at ~1.35 × 1014 Hz, confirming that CGRaBS J0211+1051 is an LBL. Some other parameters, such as the local magnetic field (∼5.93 G) and black hole mass (~2.4 × 108 M⊙), are also estimated which are in agreement with their typical values for the blazars. Based on the present study, identification of the Fermi/LAT source, 2FGL J0211.2+1050, with its BL Lac counterpart CGRaBS J0211+1051 is confirmed.

Key words: BL Lacertae objects: individual (CGRaBS J0211+1051) – galaxies: active – methods: observational – radiation mechanisms: non-thermal – techniques: photometric – techniques: polarimetric

Online-only material: color figure

1. INTRODUCTION

Blazars are an extreme class of active galactic nuclei (AGNs). They show variable continuum emission over the entire energy spectrum along with high (≥3%) and variable polarization in the radio and the optical energy bands. According to the AGN unification model, blazars have a relativistic jet of plasma, perpendicular to the accretion disk, emanating from very close to the central black hole (BH) and aligned at a very small angle to the line of sight (≲10°) (Urry & Padovani 1995, 2000). Due to the relativistic aberration and boosting effects, emission from blazars is dominated by the jet. The variability in their emitted flux provides an important tool to study the central engine in AGNs since these remain spatially unresolved even by the current best observing facilities. The observed timescales of the flux variability provide clues to the size of the emission region and the processes responsible for the emission.

The spectral energy distribution (SED) of the blazars has a characteristic double-peaked shape with a low-frequency component peaking somewhere in the sub-millimeter to X-ray energy band and a high-frequency component peaking at the MeV–TeV energies. The low-energy component of the SED is well explained as the synchrotron emission from relativistic electrons in the jet (Urry & Mushotzky 1982), while the physics behind the high-energy component is not yet well understood. It is proposed that the high-energy flux is produced by the inverse Compton scattering of the low-energy seed photons by the highly energetic particles (electrons/positrons). The origin of these seed photons can either be the synchrotron emission itself (synchrotron self-Compton, SSC; Ghisellini et al. 1985; Bloom & Marscher 1996; Sokolov et al. 2004) or the sources external to the emission region, e.g., accretion disk, broad line region, torus, etc. (external Compton). Several models have already been proposed to explain the source of the seed photons responsible for the high-energy emission in blazars (Dermer et al. 1992; Sikora et al. 1994; Błażejowski et al. 2000; Sikora et al. 2009; Agudo et al. 2011). In order to constrain the models for the high-energy flux generation in blazars, the study of the light curves and SEDs of a sample of blazars is needed using long-term, simultaneous multi-wavelength data.

Depending upon the position of the synchrotron peak in SEDs, blazars are sub-classified into a sequence; flat spectrum radio quasars (FSRQ), radio-selected BL Lac objects (or LBL), and X-ray-selected BL Lac objects (or HBL) (Urry & Padovani 1995; Fan et al. 1997; Heidt and Nilsson 2011, and references therein). These sub-classes are known to have some intrinsically different properties. For example, their bolometric luminosity decreases from FSRQ to HBL, as does the dominance of the γ-ray emission (Fossati et al. 1998; Sambruna et al. 2009). Similarly, LBLs are reported to have, on average, a higher degree of polarization (DP) and amplitude of variation than HBLs (e.g., Andruichow et al. 2005; Tommasi et al. 2001; Fan et al. 1997; Jannuzi et al. 1993, and references therein). Fan et al. (1997) ascribe this difference in the DP to the differences in their beaming with LBLs showing stronger beaming. Recently, Heidt and Nilsson (2011) found only a marginal difference in the polarization behavior of the LBLs and the HBLs as inferred from their sample of probable blazar candidates taken from the Sloan Digital Sky Survey. However, their inference could be affected by the low statistics as they considered 8 LBLs and 37 HBLs in their sample. On the other hand, based on the studies of their samples, Andruichow et al. (2005) and Ikejiri...
et al. (2009) report that LBLs generally have a higher DP than HBLs.

In an earlier work, Chandra et al. (2012) have discussed intra-night as well as inter-night variations in DP and position angle (P.A.) for the blazar CGRABS J0211+1051. This source was detected by the Energetic Gamma Ray Experiment on board the Compton Gamma Ray Observatory as an unidentified source, 3EG J02115+1123 (R.A.= 34°00', decl. = 11°38'; Hartman et al. 1999) with a 1°8 error circle. The first and second Fermi-LAT catalogs (Abdo et al. 2010; Nolan et al. 2012) have several sources in this error circle, including the source 1FGL J0211.2+1049/2FGL J0211.2+1050, which was found to be associated with the source MGI J021114+1051 (Griffith et al. 1991) from First MIT-Green Bank 5 GHz Survey and 87GB 020832.6+103726 (1987 Green Bank Radio Survey; Gregory & Condon 1991). The source CGRABS J0211+1051 was detected in the Candidate Gamma-Ray Blazar Survey (Healey et al. 2008) and, due to its featureless optical spectrum, was categorized as a BL Lac object (Healey et al. 2007; Lawrence et al. 1986; Snellen et al. 2002). Swift (Burrows et al. 2005) detected a single X-ray source within a 1.5 radius centered at CGRABS J0211+1051. Meisner & Romani (2010) reported a redshift of 0.2 ± 0.05 for 3EG J0211+1050 (MG1 J021114+1051, 2FGL J0211.2+1050), consistent with that reported for 3EG J02115+1123. Very recently, CGRABS J0211+1051 has shown a brightening in the near infrared (H band = 11.45 mag; Carrasco et al. 2013) and high optical polarization (∼22% ± 4%; Grigoreva et al. 2013). During observations from 2011 January 30 to February 3, Chandra et al. (2012) found that the source showed a significantly high and variable (9%–21%) degree of polarization on timescales of hours. Based on that, the authors proposed that this source is an LBL or RBL. However, a true test for such classification is only provided by the location of the synchrotron peak in its SED.

In the present study, we construct the SED of CGRABS J0211+1051 using multi-wavelength data obtained during 2011 January 24 to February 3 from various observatories and we discuss the nature of the source. This paper is organized as follows. The next section discusses the observations and analysis of the data. In Section 3, we discuss the light curves and the SED of the source. We put forth the conclusions drawn from this work in Section 4.

### 2. OBSERVATIONS AND DATA ANALYSIS

In order to study the behavior of blazar CGRABS J0211+1051, we generated the light curve and SED using quasi-simultaneous data in all available energy bands. For SED, all data used are almost simultaneous, excluding a few points in radio and infrared region (WISE: http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec1_6b.html). The sub-millimeter (Ade et al. 2011) data are from 2012 observations (Ade et al. 2013). The high-energy γ- and X-ray data are taken from the Large Area Telescope (LAT; Atwood et al. 2009) and the X-Ray Telescope (XRT) on board the Fermi and Swift space-based observatories, respectively. A recent version of ScienceTools (version v9r27) is used to analyze the LAT data. The data (see Table 1 for observation dates) from the XRT (Burrows et al. 2005) and optical/ultraviolet monitor (UVOT; Roming et al. 2005) are processed and analyzed using HEASOFT version 6.12 with the calibration database as updated on 2011 August 25. For constructing the SED, the fluxes at radio frequencies (8.4 GHz, 4.85 GHz, 4.775 GHz, and 1.4 GHz) are retrieved from the NASA Extragalactic Database (NED) and do not belong to the same epoch. The 2 cm flux from the MOJAVE database (Lister et al. 2009), observed on 2011 February 27, is also used. In the following, we summarize techniques used for the analysis of various data sets.

#### 2.1. Optical Polarization and R-band Observations from MIRO

The polarimetric observations for this source were carried out using the PRL made optical photo-polarimeter (PRLPOL) as a backend instrument mounted at the f/13 Cassegrain focus of 1.2 m telescope of the Mt. Abu Infra-Red Observatory (MIRO). Detailed information about the instrument used and measurements made during the 2011 January 30 to February 3 observations are given in Chandra et al. (2012). The online data reduction provides DP, error in DP, P.A. of the polarization, and other parameters as output. The nightly averaged values of DP and P.A. along with their respective standard deviations as reported in Table 2 by Chandra et al. (2012) are plotted in Figure 1(e) and (f), respectively.

The optical observations in the R band were performed using the recently installed 0.5 m aperture optical telescope, known as the Automated Telescope for Variability Studies (ATVS), at MIRO. The field of view and plate scale of the system are 13.5 x 13.5 and 0.79 arcsec/pixel, respectively. The blazar CGRABS J0211+1051 was observed from 2011 January 30 to 31 and 2011 February 1 to 3. The field of view of the CCD is large enough to accommodate a number of comparison stars in the field of the source for differential photometry. However, in the vicinity of the source there are no known standard stars which can be used for calibration. We therefore performed aperture photometry on all the stars present in the field. The observed magnitudes of these stars are corrected using the photographic plate magnitudes from the USNO catalog after appropriate filter conversion. We tested 10 stars in the field with brightness comparable to the source for their stability in flux during the course of monitoring. Out of 10 stars, 3 are found to be appropriate to be used as standard comparison stars for the present analysis. We used one of the three, close in brightness to the source, as a comparison star and the rest as control stars to construct the differential light curves in order to check the source for variability. The observed magnitudes of CGRABS J0211+1051 were corrected using the averaged magnitudes of all the three stars. The extinction correction is performed as prescribed by Cardelli et al. (1989). The conversion of magnitude to energy flux was performed using an appropriate factor and zero point flux as described by Bessela et al. (1979). Figure 1(d) shows the R-band flux as a function of time. Table 2 presents the magnitudes derived for the source and other three comparison stars in the field.

#### 2.2. Swift Observations

We have made use of the HEASARC archival database for this source during the course of the 2011 January flaring period.
Figure 1. Multi-wavelength light curve for the blazar CGRaBS J0211+1051. (a) γ-ray flux from Fermi/LAT, averaged over three days. (b) Swift-XRT X-ray integrated flux between 2 to 10 keV. (c) Multi-band fluxes as measured by UVOT on board Swift. (d) Daily averaged R-band flux from the ATVS-MIRO measurements. (e) and (f) Degree of polarization and position angle from 2011 January 30 to February 3 (Chandra et al. 2012).

Table 2

| Date       | Time (MJD)  | S  | e_s | σ_S | C1 | σ_C1 | C2 | σ_C2 | C3 | σ_C3 |
|------------|-------------|----|-----|-----|----|------|----|------|----|------|
| 2011 Jan 29| 55591.47    | 13.23 | 0.005 | 0.039 | 13.54 | 0.037 | 12.10 | 0.033 | 12.29 | 0.039 |
| Jan 31     | 55592.45    | 13.32 | 0.004 | 0.030 | 13.54 | 0.051 | 12.10 | 0.043 | 12.28 | 0.046 |
| Feb 02     | 55594.44    | 13.31 | 0.005 | 0.063 | 13.53 | 0.059 | 12.08 | 0.059 | 12.27 | 0.063 |
| Feb 03     | 55595.44    | 13.41 | 0.003 | 0.036 | 13.53 | 0.041 | 12.09 | 0.037 | 12.28 | 0.038 |
The observation IDs of the data used for the present analysis along with their respective exposure times are listed in Table 1. *Swift* started following this source just after the report of an intense flaring activity in γ-rays by LAT on board *Fermi* (D’Ammando 2011) on 25 January 2011. The data from the instruments on board *Swift*, namely, XRT and UVOT, are downloaded from the Web site and analyzed for the present study. The latest version of the HEASOFT package (v6.12) with a calibration database updated on 25 August 2011 is used for the analysis. In the following, we describe the details of the analysis adopted for the data from various detectors on board *Swift*.

2.2.1. XRT

The level 2 cleaned event files are generated using standard procedures as recommended in the manual by instrument team. The default screening parameters are used. The PC mode grades 0–12 and WT mode grades 0–2 are selected by using Ftool *xselect*. The background light curve and spectrum are generated after using appropriate region filtering. In this case, we have taken a circular area of 15 pixel radius around the target as the source region and four source-free regions in the neighborhood of the target, each with a 45 pixel radius, as background. The required ancillary response matrix is generated by using the task xrtmkarf followed by the xrtcentroid task. The response matrix file provided with the CALDB distribution is used for further analysis. The spectrum thus obtained is then fitted to generate the light curve and SED.

The spectral fitting was done in the energy band between 0.2 to 10.0 keV using the XSPEC (version 12.7.0) package distributed with HEASOFT 6.12. The simple power law along with the Galactic absorption gives the best fit for almost all the observations of interest. The model parameters, interstellar column density, $N_{\text{H}}$, is kept fixed at a value of $5 \times 10^{20}$ cm$^{-2}$, (Kalberla et al. 2005). Table 3 summarizes the values of various parameters obtained from the spectral fitting for different epochs. We do not see any significant variation in the photon index for different observations, implying that the source remains in same spectral state during the course of monitoring. We, however, notice a variation in flux as indicated by the light curve [Figure 1(b)].

For constructing the SED, we estimated the photon flux in several small energy bins using the interactive plotting utility (IPLOT), a part of PGPLLOT, while fitting with XSPEC. The Galactic extinction correction is done in the following manner. First, modeled photon flux is calculated for all small energy bands using the IPL tool with the $nH$ parameter as described above. The same procedure is repeated with $N_{\text{H}} = 0$, which assumes no absorbing material in that particular line of sight. The ratio between the absorbed and unabsorbed model photon fluxes gives the absorption factor, which is then used to correct the observed photon flux calculated by IPL in order to obtain intrinsic photon flux. The Galactic-extinction-corrected photon fluxes respective to different energy bins are then converted into energy fluxes with appropriate conversion factors before being used to construct SED (Figure 2).

2.2.2. UVOT

UVOT snapshots with all the six available filters, V (5468 Å), B (4392 Å), U (3465 Å), UVM2 (2246 Å), and $UVW2$ (1928 Å) for all the OBSIDs (Table 1) were integrated with the *uvotimsum* task and analyzed using the *uvotsource* task, with a source region of 5”, while the background was extracted from an annular region centered on the blazar with external and internal radii of 40” and 7”, respectively (Foschini et al. 2010). The observed magnitudes from all OBSID are then corrected for extinction according to the model described in Cardelli et al. (1989). The magnitudes thus obtained are converted to energy flux (erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$) using the following equation:

$$F_\nu = FCF \times 10^{(ZPT−m)/2.5}$$

where ZPT is zero point flux, $FCF$ is the flux conversion factor (erg$^2$ cm$^{-2}$ count$^{-1}$ Å$^{-1}$), and $m$ is the observed magnitude in a particular filter. These standard values are taken from the instrument calibration database (CALDB; Poole et al. 2008). The light curves are then constructed using the flux values for the filters V, B, U, UVM2, and $UVW2$ for different OBSIDs (Figure 1(c)). The UVOT flux values averaged over the whole observing period are used to construct the SED (Figure 2).

2.3. Fermi/LAT Observations

The energy coverage of LAT on board the *Fermi* Gamma-ray observatory is broad enough ($\sim$20 MeV to $>300$ GeV) to cover the part of the blazar SED which is assumed to be mainly contributed by the inverse Compton processes in the jet. CGRABS J0211+1051 was first reported in an outburst state at 0.1–100 GeV by D’Ammando (2011). In order to investigate the high-energy emission before and after the flaring period along with the outburst state, we analyzed the data ranging from MJD 55548 to MJD 55610 (approximately two months). Only a part of this, coinciding with the high-energy emission before and after the flaring period along with the outburst state, we analyzed the data ranging from MJD 55548 to MJD 55610 (approximately two months).

| ObsID        | Start Time (UT) | $\alpha$ | $\sigma_\alpha$ | Norm | Unc. Norm | $\chi^2$/v | v |
|--------------|-----------------|----------|-----------------|------|-----------|-------------|---|
| 00399110003  | 2011 Jan 25 20:16:26 | 2.4      | 0.09            | 1.1E-03 | 1.0E-04  | 1.02        | 17 |
| 0039911004  | 2011 Jan 28 23:10:23 | 2.4      | 0.07            | 1.7E-03 | 1.2E-04  | 0.99        | 25 |
| 0039911005  | 2011 Jan 31 15:41:59 | 2.3      | 0.09            | 1.4E-03 | 1.2E-04  | 1.27        | 18 |
| 0039911006  | 2011 Feb 03 17:34:17 | 2.4      | 0.07            | 1.5E-03 | 1.1E-04  | 0.93        | 25 |

The level 2 data is used to construct SED (Figure 2).

Table 3

The Spectral Index ($\alpha$), Associated Uncertainty ($\sigma_\alpha$), and Other Parameters Obtained from the XRT Spectrum Fitting with $nH = 6.75 \times 10^{20}$ cm$^{-2}$.
available online as a contributory file, while the extragalactic one is described by a simple power law (Abdo et al. 2009).

We have adopted the methodology of Foschini et al. (2010, 2011), briefly discussed here. First, the unbinned likelihood analysis was performed on the complete data, spanning over the energy band 0.1–100 GeV in order to determine the best source model. For this event the powerlaw2 model is found to be the best-fit source model as inferred by high test statistics (530.9). The power-law index value for this fitting is 2.03 ± 0.06. The source model with the power-law index frozen to that value in the fit is used for constructing the light curve with three-day binning. The flux values with TS < 9, equivalent to σ < 3, are discarded from the final light curves.

The data corresponding to the time interval MJD 55580 to MJD 55596 are used to construct the blazar SED. For extracting SED, the event file is binned in several energy segments (e.g., 100 MeV–500 MeV, 500 MeV–1 GeV, 1 GeV–5 GeV, 5 GeV–50 GeV, 50 GeV–100 GeV, and 100 GeV–200 GeV) and a likelihood analysis is performed over each energy bin, individually, to get energy flux for the respective energy bands. The source model used for this part is similar to that used for the complete energy band except for the energy interval. For each energy bin, the source under investigation and all nearby sources in the ROI are described by one parameter representing the integral flux in that energy bin. The diffuse background components are modeled with one single parameter describing the normalization. The upper limit estimation is done for the last two energy bins as TS is always less than 9 for these bins.

The following tools provided as a part of the software distribution are used for the analysis performed here. The gtselect and gtmktime are used for event selection and live time correction, respectively. The gtlcube, gendiffrsp, and gtexpmap are used for generating the livetime cube, the Galactic diffuse response, and the exposure map, respectively. The likelihood analysis is performed using the tool gtlite. It provides the test statistics for the source model fit along with the other model parameters.

3. RESULTS AND DISCUSSION

The blazar CGRaBS J0211+1051 is an interesting source that has been brightening since 2005 (Chandra et al. 2012) from the levels of 15.5 mag in the V band (Djorgovski et al. 2011) and underwent a strong flare from 2011 January 25 to February 3. It was reported to show a bright state in almost all wavebands while Fermi γ-ray photon flux was reported to rise by 25 times the yearly averaged values (D’Ammando 2011). We used the available data on the source along with our own observations to produce light curves and SED to understand the nature of the source and to ascertain its actual classification. In the following,
we discuss the results obtained from this study and available information from the literature.

3.1. Multi-wavelength Light Curves and Optical Polarization

Figure 1 shows the multi-wavelength light curves for the blazar CGRaBS J0211+1051. Panels (a) and (b) show the $γ$-ray and X-ray flux variations, respectively. Panel (c) contains UV/optical light curves as obtained from UVOT on board Swift. Panel (d) shows the $R$-band light curve obtained from the EMCCD, mounted at ATVS, data. The last two panels, (e) and (f), show the variations in nightly averaged degrees of polarization and position angle as discussed in Chandra et al. (2012). In the following, we discuss each component individually and in relation to source behavior in other wavebands.

Visual inspection of Figure 1(f) clearly shows that emission was highly polarized (DP $\sim 21.05\%$) on MJD 55591.38 (2011 January 30), indicating a highly aligned magnetic field in the emission region. The DP gradually decreased to 10.63% on 2011 February 1 (MJD 55593.44) at a rate of 5% per day. DP then increases again at a relatively slower rate (2.42% per day) over the next two days. The P.A. follows a similar trend with a difference that it decreases on 2011 February 3. The variation in DP can be explained using intrinsic models such as shock in the jet model, fresh injection of matter in the jet, etc., depending on the timescale and nature of changes observed. The change in P.A. is unlikely to be caused in a straight, uniform axially symmetric, matter-dominated jet just by shock compression of the plasma in the emission region. The interaction with a perpendicular shock moving along a blazar jet can align the tangled magnetic field in the emission region, thus enhancing DP, but might not result in any significant change in P.A. (Abdo et al. 2010). Such a change in the P.A. (on days 1, 3, and 5) indicates either the fresh injection of material in the jet or a change in the jet geometry. The flipping nature of P.A. around MJD 55594.44 appears to be interesting because of its opposite behavior in DP. Such a trend has been noted in other blazars when DP is seen rising accompanied with sharp drops in P.A.

The $R$-band light curve (Figure 1(d)) shows that the source has seen its brightest moments before 2011 January 30 with the flux decreasing from 2011 January 30 to February 3, in agreement with the trend reported by Nesci (2011)(R $\sim 13.37$ on 2011 January 27). The $R$-band light curve also indicates a small rise in flux between MJD 55592.4 and MJD 55595.4, around which DP and P.A. show opposite behavior. This might be indicative of a small flaring activity, enhancing the $R$-band flux and DP followed by a drastic change in P.A. Since the timescale is very small ($\sim$2 days), this flare cannot be due to the global bending of the jet. It possibly favors a fresh injection of plasma in the emission zone as the cause for the change. The UV-optical light curves (Figure 1(c)) show similar behavior in all bands, albeit with a weak color dependence. A mild bluer when brighter and redder when fainter behavior seen is consistent with the shock-in-jet model. We note an about 20% increase in the $U$-band energy flux from MJD 55586.8 to MJD 55590.4 (2011 January 26–29). In all optical and UV bands, the source had maxima and minima around MJD 55590 and MJD 55595.4 with values in the $U$, $B$, and $V$ bands of 9.58, 11.2, and 14.3 mJy and 7.02, 8.1, and 10.4 mJy, respectively. The $R$-band flux peaked on MJD 55591.4 (16.67 mJy) with a minimum on MJD 55595.4 (14.14 mJy). A delay of about one day in the maxima and minima as seen in our $R$-band vis-a-vis UBV bands is possibly only due to the sampling time. As shown in Figure 1(b), the XRT- Swift X-ray energy flux increases by about 50% (from 0.18 to 0.27 mJy) within about 4 days (MJD 55586.4–55590.4) and then drops by 0.04 mJy within next 2.8 days. The X-ray (0.2–10.0 keV) light curve follows a similar trend as seen in the UV bands apart from an increase in the X-ray flux toward the end while fluxes in the $R$ and $UV$ bands decrease. The maximum (0.28 mJy) and minimum (0.16 mJy) in the X-ray light curve occur on MJD 55590.08 and MJD 55587.02, respectively.

On 2011 January 25, D’Ammando (2011) reported the source to have highest ever $γ$-ray flux on 2011 January 23. The $γ$-ray light curves shown in Figure 1(a) are obtained from Fermi/LAT observations with an inclusion of flux corresponding to TS $\geq$ 9 ($\sigma \sim 3$) and three-day binning. A significant rise around 2011 January 23 and again on 2011 January 29 was noted. The January 29 peak flux decays slowly with time reaching a minimum on MJD 55595. This flare appears to be different from that around 2011 January 23, the decaying part of which might have overlapped with the rising part of the second (January 29) flare, but the peak photon flux ($4.3 \times 10^{-7}$ photons cm$^{-2}$ s$^{-1}$) is at almost same level.

Figure 1 shows that the $γ$-ray, X-ray, $U$, and optical fluxes vary largely in unison from 2011 January 25 to February 2 with light curves in all of the bands peaking somewhere near 2011 January 29. Though there are no polarimetric observations on 2011 January 29, a polarization value of 12% on January 28 was reported by Gorbovskoy et al. (2011), followed by our measurements of $\sim$21% DP two days later on January 30. It clearly shows a trend of a rapid increase in DP from January 28 to 30 followed by equally rapid drop with January 31 recording a value of 12.8%, indicating that DP also peaked sometime on January 29. While PA follows DP from January 30 to February 2, we do not know how it behaved near the peak (January 29) as there are no measurements on January 28 for P.A. As mentioned earlier, from 2011 February 1 (MJD 55593.4), the DP increases slowly while P.A. shows an increase up to February 2 and then decreases. Interestingly, flux in the $R$ band also shows a mild rise on February 2 and then a sharp fall by about 10%, just like P.A. A slight increase in the X-ray light curve is also noticeable at this epoch. The one-day averaged Fermi/LAT flux also shows an enhancement on February 2 (MJD 55594). It might be indicative of a flicker at around MJD 55594.4 caused by the inhomogeneity in the jet, leading to an enhancement in the flux and polarization accompanied with a change in P.A. However, nothing can be said of the UVOT fluxes due to a lack of the UVOT pointed observations at this epoch.

We therefore conclude that in totality, variations in fluxes in all the bands appear to be simultaneous in nature, indicating co-spatiality of the emission at all wavebands considered here. Another important consequence of this result is that the Fermi source 2FGL J0211.1+1050, as well as its X-ray counterpart, are identified with the BL Lac object CGRaBS J0211+1051. However, one cannot miss the differences in the nature of short-term, small-scale fluctuations in the light curves for different energies, implying the presence of small-scale inhomogeneities in the physical conditions across the source.

3.2. Spectral Energy Distribution (SED)

In order to construct SED for CGRaBS J0211+1051, we used the data discussed above along with MOJAVE (2 cm) and other (8.4 GHz, 4.85 GHz, 4.775 GHz, and 1.4 GHz) radio-band data from the NED Web site. We analyzed the data for the duration of MJD 55580-MJD 55596 (2011 January 20 to February 4), which are quasi-simultaneous in nature. We combined the fluxes in the respective energy bands for the duration data that was
available for a particular band, after correcting for the Galactic extinction and other aberrations. We therefore combined 15 days of data for various UVOT/X-ray and γ-ray energy bands from *Swift* and LAT, while the R-band optical data was combined for 5 days (2011 January 30 to February 3). The SED is plotted as $vF_v v/\nu$ on a logarithmic scale in Figure 2. The filled circles in the first peak represent the fluxes in various radio bands while filled diamonds, triangles, and squares represent sub-millimeter (Ade et al. 2011), infrared (wise), and optical UV fluxes. The X-ray 0.3–10 keV fluxes from XRT and high-energy LAT/Fermi γ-ray fluxes are shown by open squares and inverted triangles.

The last two data points (open circles) are the upper limits on the γ-ray fluxes. From the nature of the spectra, it is clear that the synchrotron peak falls somewhere in optical/near IR region. To have a better estimate of the low-energy (synchrotron) peak frequency for CGRaBS J0211+1051, the following parabola was fitted to the lower-energy component of the SED:

$$\log(vL_v) = A [\log(v)]^2 + B [\log(v)] + C, \quad (2)$$

where $A$, $B$, and $C$ are constants estimated using a general nonlinear model fitting algorithm freely available in the statistical software R. The best-fit values of parameters $A$, $B$, and $C$ are $-0.23 \pm 0.04, 6.17 \pm 1.03$, and $-52.48 \pm 6.01$, respectively. The corresponding synchrotron peak energy flux and the peak position are $\sim 5.21 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ and $\sim 1.35 \times 10^{15}$ Hz, respectively. It confirms the position of the peak of the low-energy component (synchrotron) of this BL Lac object in the near infrared region, categorizing the source as “low-energy peaked (LBL)” (or RBL), supporting the suggestion made by Chandra et al. (2012) based on their polarization measurements that this source belongs to the class of low-energy peak blazars (LBL). The present study, therefore, gives credence to the idea that blazars can largely be classified based on their polarization properties.

Now, using the quantities estimated above, we can further quantify some of the other parameters for this source. Using the values of the low-energy peak flux and synchrotron peak frequency in the following expression by Böttcher (2007), one can estimate the co-moving magnetic field in the emission region.

$$B_{10} = 9D_1^{1/4} \left[ \frac{d_{27}^4 f_{-10}^2}{(1+z)^{2}\epsilon_{-6} R_{15}^2 (p-2)} \right]^{1/7} G, \quad (3)$$

with the synchrotron peak flux

$$f_{-10} = \frac{\epsilon_s}{10^{-10}} \text{erg/cm}^{-2}/\text{s}^{-1} \text{ and }$$

$$D = 10D_1 = [\Gamma(1 - \beta \cos \theta_{\text{obs}})]^{-1},$$

the synchrotron peak frequency and size of emission region

$$\epsilon_{-6} = \epsilon_s / 10^{-6}, \quad \epsilon_s = \frac{h\nu_s}{m_e c^2}, \quad R_{15} = \frac{R_B}{10^{15}} \text{ cm},$$

and the luminosity distance

$$d_{27} = \frac{d_L}{10^{27}} \text{ cm}.$$

The size of the emission region can be estimated by taking the shortest timescale of variability applying the causality arguments. For the shortest timescale, we have used $\Delta t \sim 35$ minutes, adopted from Chandra et al. (2012), which is the most probable short timescale of variations in the polarized flux observed during 2011 February 2–3. In our case, the size of the emission region $R_\delta$ is $(1.05) \times 10^{15}$ cm, taking a typical value of the Doppler factor ($\delta$) as 20. The luminosity distance is estimated by using cosmology calculators (Wright 2006) available online. For a spatially flat ΛCDM cosmology, with the most recent cosmological constants given by Ade et al. (2013) ($\Lambda_M = 0.31 \pm 0.017$, $\Lambda_\Lambda = 1 - \Lambda_M$ and $H_0 = 67.3 \pm 1.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$), the value of the luminosity distance $d_L$ is 1022.4 Mpc or 3.1552 $\times 10^{27}$ cm.

The estimated co-moving magnetic field using above prescription turns to be $11.86 D_1^{-1} e_B^{3/7}$. Here, we have obtained $p$ ($= 3.29$) from $\alpha (= (p-1)/2)$ as estimated by fitting a power law to the synchrotron part of the SED. Assuming the equipartition of energy and Doppler boosting factor as 20, the co-moving magnetic field turns out to be $\approx 5.93$ Gauss, which is a typical value of the magnetic fields in BL Lac objects (~few Gauss).

Another quantity which we have estimated from present study is the mass of the BH which is one of the most important parameters in AGNs. It controls the accretion rate and most of the features observed in the SEDs of AGNs. Two types of methods are used for estimating the mass of the BH: primary and secondary. The primary BH mass estimation methods include stellar and gas kinematics, reverberation mapping, and megamasers kinematics (e.g., Vestergaard 2004). The kinematics methods require the high spatial resolution spectroscopy of the host galaxy, the reverberation mapping method requires the detection of the broad emission lines from BLR while megamasers are only detectable in edge-on sources. Since blazars, in particular BL Lac objects, have almost featureless continuum and are nearly face-on sources, all of the methods mentioned above are not suitable for the estimation of their BH mass in principal. The so-called secondary BH mass estimation methods are also either approximations to the reverberation mapping approach that still rely on the presence of an emission line or employ well-known empirical relations between the BH mass and the velocity dispersion or mass of the host galaxy’s bulge. One method which can also be used to provide a crude estimate of the mass of BH employs a timescale of the flux variability in blazars (Abramowicz & Nobili 1982; Wiita 1985; Dai et al. 2007). The observed timescale of variability ($\Delta t$) provides an upper limit to the mass of BH with the assumption that the variation arises due to the processes occurring close to the BH. The causality condition limits the size of the emission region to $(R < \Delta t \delta / c(1+z))$. Combining this result with the expectation that the minimum size for such an emitting region is fairly closely related to the gravitational radius of the BH, $R > R_g = G M / c^2$ (Wiita 1985) BH mass can be estimated. We consider that the fast variability timescale corresponds to the perturbations in the jet plasma, at a distance of $R = 5$ Rs, where $R_s = 2GM/c^2$ is the Schwartzchild radius. Then mass of mass of the BH is (Dai et al. 2007)

$$M_{\text{BH}} = \frac{c^3 \Delta t \delta}{10G(1+z)}. \quad (4)$$

The above expression can be used for a crude estimation of the BH mass of the blazars using variability timescale as a parameter in the absence of any direct method. Using the timescale of variability considered here, the central BH mass
for this source turns out to be $\approx 2.4 \times 10^8 \, M_\odot$, which is in agreement with the typical BH masses of the BL Lac objects (Celotti 2008).

4. CONCLUSIONS

In this paper, we have used multi-wavelength observation data for the blazar CGRaBS J021+1051 to understand its behavior when it was undergoing a strong flare. The data on this source are very scant and therefore it is not straightforward to discuss its detailed behavior. We have used all available data suitable for this study in various energy regimes and found that the source shows interesting spectral behavior. Though it is a low-energy-peaked BL Lac object, its SED shows an equally strong IC component.

Based on the multi-wavelength light curves, we note presence of another flare peaking sometime on 2011 January 29, with an almost similar Fermi/LAT photon flux as reported for the 2011 January 23 flare. It appears to be a double flare when the decaying part of the first flare overlaps the rising part of the second one. The nature of the multi-wavelength light curves presented here show that they vary in unison with time, with all fluxes peaking some time on January 29. Such quasi-simultaneous trend suggests that the emissions in all energy bands are being generated in the same part of the jet, though emitting sizes might differ with frequencies. This behavior also confirms the identification of the Fermi source 2FGL J0211.2+1050 as BL Lac counterpart CGRaBS J0211+1051. That the non-thermal jet emission dominates and the magnetic field in the emission region is well ordered are confirmed by the high degree of polarization observed. It is the first detailed multi-wavelength study, including the information on the polarization on this source. Another important conclusion drawn from this work is the confirmation of this source to be an LBL, as suggested by an earlier study based on the polarization. The synchrotron peak falls in the IR region ($\nu_p \sim 1.35 \times 10^{14}$ Hz), as shown in the SED constructed. SSC processes can be used to explain the SED and various properties of the jet emission in this source. Several parameters are estimated using canonical jet model, including the co-moving magnetic field ($\sim 5.93 \, G$) in the region. We estimate the mass of the BH to be $\approx 2.4 \times 10^8 \, M_\odot$.

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