INTEGRAL AND SWIFT OBSERVATIONS OF THE Be X-RAY BINARY 4U 1036−56 (RX J1037.5−5647) AND ITS POSSIBLE RELATION WITH γ-RAY TRANSIENTS

JIAN LI1,2, DIEGO F. TORRES2,3, SHU ZHANG1, ALESSANDRO PAPITTO2, YUPENG CHEN1, and JIAN-MIN WANG1,4,5

1 Key Laboratory for Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, 19B Yuquan Road, Beijing 100049, China; jianli@ihep.ac.cn
2 Institut de Ciencies de l’Espai (IEEC-CSIC), Campus UAB, Torre CS, 2a planta, E-08193 Barcelona, Spain
3 Institució Catalana de Recerca i Estudis Avançats (ICREA), E-08010 Barcelona, Spain
4 National Astronomical Observatories of China, Chinese Academy of Sciences, 20A Datun Road, Beijing 100020, China
5 Theoretical Physics Center for Science Facilities (TPCSF), Chinese Academy of Sciences, Beijing 100049, China

Received 2012 June 11; accepted 2012 October 1; published 2012 November 21

ABSTRACT

We present timing, spectral, and long-term temporal analysis of the high-mass X-ray binary 4U 1036−56 using INTEGRAL and Swift observations. We show that it is a weak hard X-ray source spending a major fraction of the time in quiescence and only occasionally characterized by X-ray outbursts. The outburst activity we report here lasts several days, with a dynamic range spanned by the luminosity in quiescence and in outburst as high as ~30. We report the detection of pulse period at 854.75 ± 4.39 s during an outburst, which is consistent with previous measurements. Finally, we analyze the possibility of the association of 4U 1036−56 with the unidentified transient γ-ray sources AGL J1037−5708 and GRO J1036−55, as prompted by its positional correlation.

Key words: X-rays: binaries – X-rays: individuals (4U 1036−56)

Online-only material: color figures

1. INTRODUCTION

Various classes of γ-ray sources, from Galactic objects like supernova remnants, pulsar wind nebulae, and binaries to starburst galaxies and distant blazars (see, e.g., Hinton & Hofmann 2009), have been detected up to the TeV band. Among them, the class of γ-ray-emitting binaries is particularly interesting. They are X-ray binaries hosting O/B companions, which have γ-ray emission up to the high-energy regime (HE; $E > 100$ MeV) and/or very high-energy regime (VHE; $E > 100$ GeV), modulated on the orbital period. Only a handful of such binaries are known (e.g., LS 5039, LSI +61° 303, PSR B1259−63, HESS J0632+057, 1FGL J1018.6−5856, and Cyg X-3), although a larger population is expected to be discovered (see, e.g., Ackermann et al. 2012).

In recent years, a number of unidentified transient γ-ray sources were discovered in the Galactic plane, especially by $\text{AGILE}$; many of them have been suggested to have a possible binary nature (see, e.g., Sguera 2011, and references therein; Casares et al. 2012; see Torres et al. 2001 for variability studies in the EGRET era). These are shown in Table 1. All of the sources show transient behavior in γ-rays, and most of them are observed having fast and strong X-ray activities. No blazar-like candidate counterparts are found within their positional error uncertainties. Instead, all six candidates have been suggested to have a possible high-mass X-ray binary (HMXB) counterpart, four of which are confirmed supergiant fast X-ray transients (SFXTs) or candidate SFXTs. Two of the HXMB candidates are already identified as hosting a slowly rotating pulsar. The probability of finding a supergiant HMXB inside the $\text{AGILE}$ error circle by chance, for example, given the number of supergiant HMXBs detected by IBIS on the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) within the Galactic plane, is ~1%, i.e., ~0.5 chance coincidences are expected (Sguera et al. 2011).

Two γ-ray transients (AGL J1037−5708 and GRO J1036−55) are located in the same region of the sky, and with the caveat of the large positional uncertainties involved, they could perhaps be associated (see Figure 1). AGL J1037−5708 is an unidentified, transient MeV source discovered by $\text{AGILE}$ near the Galactic plane (Bulgarelli et al. 2010). $\text{AGILE}$ detected intense γ-ray emission above 100 MeV from AGL J1037−5708 between 2010 November 27 21:18 UT and 2010 November 30 14:08 UT. A maximum likelihood analysis yields a detection larger than 5σ for energies larger than 100 MeV with a flux above $300 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$.

GRO J1036−55 was discovered by the Imaging Compton Telescope ($\text{COMPTEL}$) at Compton Gamma-Ray Observatory at a significance level of 5.6σ, reaching a flux level of 350 mCrab in the 3–10 MeV band (Zhang & Collmar 2007). During $\text{COMPTEL}$’s lifetime of 9 years, GRO J1036−55 was only visible during a flare from 1996 October 3 to 1996 October 15 (MJD 50,359–MJD 50,361). An analysis of simultaneous Energetic Gamma Ray Experiment Telescope (EGRET) data at energies larger than 100 MeV did not yield any evidence for the source. The energy spectrum indicated a spectral maximum at ~4 MeV.

The HXMB 4U 1036−56 is the only X-ray source located in the region of these transients. 4U 1036−56 first appeared in the 4th Uhuru catalog (Forman et al. 1978), and it was detected by the Seventh Orbiting Solar Observatory as 1M 1022−554 (Markert et al. 1979). The first X-ray outburst from 4U 1036−56 was observed by Ariel V in 1974, from November 11 to 19 (MJD 42,362–MJD 42,370; see Warwick et al. 1981). During the ROSAT’s lifetime of 9 years, GRO J1036−55 was only visible during a flare from 1996 October 3 to 1996 October 15 (MJD 50,359–MJD 50,361). An analysis of simultaneous Energetic Gamma Ray Experiment Telescope (EGRET) data at energies larger than 100 MeV did not yield any evidence for the source. The energy spectrum indicated a spectral maximum at ~4 MeV.

The HXMB 4U 1036−56 is the only X-ray source located in the region of these transients. 4U 1036−56 first appeared in the 4th Uhuru catalog (Forman et al. 1978), and it was detected by the Seventh Orbiting Solar Observatory as 1M 1022−554 (Markert et al. 1979). The first X-ray outburst from 4U 1036−56 was observed by Ariel V in 1974, from November 11 to 19 (MJD 42,362–MJD 42,370; see Warwick et al. 1981). The maximum flux of the outburst was $2.4 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, 2.4 times the Uhuru average flux in the same energy range (2–10 keV). During the ROSAT survey, 4U 1036−56 was about 10 times dimmer than it was in 1970–1976 (Motch et al. 1997). 4U 1036−56 was later observed by Rossi $\text{X}$-ray Timing Explorer (RXTE; Reig & Roche, 1999), X-ray Multi-Mirror Mission (XMM-Newton; La Palombara et al. 2009), and Swift (see below for details) and appeared in the third and fourth IBIS catalogs (Bird et al. 2007, 2010). The flux measured by XMM-Newton is also one order of magnitude lower than the
Figure 1. Mosaic image of the 4U 1036—56 sky region, derived by combining all IBIS/ISGRI data (18–60 keV, left panel) and JEM-X data (3–20 keV, right panel). The position of the transient AGILE source AGL J1037—5708 is plotted with its 95% error region (white). Another transient source, GRO J1036—55, is shown in this sky region with its 1σ, 2σ, 3σ uncertainty location (green). The significance level is given by the color scale. Corresponding significance and color can be found in the right color bar. The X- and Y-axes are R.A. and decl. in units of degrees. (A color version of this figure is available in the online journal.)

Table 1

| Name               | Refs. | Possible X-Ray Counterpart | Possible Optical or Infrared Counterpart | Distance (kpc) | Orb. Period (days) | Refs. | Duration of Flares (Outburst) | Dynamic Range | Refs. |
|--------------------|-------|----------------------------|------------------------------------------|----------------|-------------------|-------|-------------------------------|---------------|-------|
| AGL J1734—3310     | 1, 2, 3, 4 | transient HMXB            | 2MASS                                    | ~8.5           | 1                 | 5     | ~200                          | 1, 4          |       |
| AGL J2022+3622     | 5, 6   | transient HMXB            | ?                                        | ~180 ± 0.3     | 1                 |       | 60 minutes @ 20–40 keV        | ~90           | 5     |
| ERG J1122—5946     | 5, 7, 8, 9, 10, 11, 12 | transient HMXB pulsar confirmed SFXT | HD 306414 (B1Ia) | ~6.2           | 10                | 7     | 15 minutes–2 hr (15 days) @ 1–10 keV | >1000         | 7, 8  |
| AGL J2241+4454     | 13, 14, 15 | with compact star         | MWC 656 (B3IVne+sh) | 2.6 ± 1.0      | 14                |       | 1 day @ E > 100 MeV           |               |       |
| AGL J1036—5708     | 16, 17, 18, 19 | persistent HMXB pulsar    | LS 1698 (B0IIIVe) | ~5              | 18                | 19    | (4–10 days) @ 18–60 keV       | ~30           | 21    |
| GRO J1036—55       | 20, 21, 22 | confirmed SFXT            | 2MASS                                    | ~5             | 18                | 19    | 3 days @ E > 100 MeV          |               |       |
| 3EG J1837—0423     | 23, 24, 25 | transient HMXB            | J183410043 (B1Ib) | ~5             | 18                | 19    | ~12 days @ 3–10 keV           |               |       |
| 26, 27, 28         | 24, 25   | confirmed SFXT            | ~0535465 (B1Ib) | ~5             | 18                | 19    | a few days (a few hours) @ 0.2–10 keV | ~1600         | 21    |

References. (1) Sguera et al. 2011; (2) Tomsick et al. 2009; (3) Bulgarelli et al. 2009; (4) Sguera et al. 2011; (5) Sguera 2009; (6) Chen et al. 2007; (7) Romano et al. 2009; (8) Romano et al. 2007; (9) Swank et al. 2007; (10) Masetti et al. 2006; (11) Negueruela et al. 2005; (12) Casandjian & Grenier 2008; (13) Lucarelli et al. 2010; (14) Williams et al. 2010; (15) Casares et al. 2012; (16) Bulgarelli et al. 2010; (17) Zhang & Collmar 2007; (18) Motch et al. 1997; (19) Sarty et al. 2011; (20) La Palombara et al. 2009; (21) this paper; (22) Krimm et al. 2012; (23) Tavani et al. 1997; (24) Sguera et al. 2009; (25) Bozzo et al. 2011; (26) Nespoli et al. 2008; (27) Romano et al. 2011; (28) Sguera et al. 2006.

previous average value, suggesting that 4U 1036—56 is characterized by significant variability.\(^6\) Chandra, Suzaku, and Monitor of All-sky X-ray Image have not observed 4U 1036—56 yet.

Thus, across a time interval of about 35 years, 4U 1036—56 was detected at a luminosity of \((1–3) \times 10^{35}\) erg s\(^{-1}\) between 2 and 10 keV in several instances, with some excursions to lower values (La Palombara et al. 2009). The optical counterpart of 4U 1036—56 is identified as LS 1698, a BOIII–Ve star at ~5 kpc (Motch et al. 1997). Reig & Roche (1999) performed detailed timing and spectral analysis with RXTE observations and

\(^6\) One of the ROSAT observations yielded an even lower luminosity but may possibly be inaccurate because it is derived from a count rate measurement in a different energy range and then converted into the 2–10 keV energy band (La Palombara et al. 2009).
discovered a pulsation with period $P = 860 \pm 2$ s. Based on this behavior, Reig & Roche (1999) proposed that 4U 1036–56 is a persistent, low-luminosity binary pulsar. With XMM-Newton observations, La Palombara et al. (2009) found a period of 853.4 ± 0.2, indicating an average pulsar spin-up $P \sim -2 \times 10^{-8}$ s s$^{-1}$ in the last decade.

Except for 4U 1036–56 and MWC 656 (see Table 1), the other four possible X-ray counterparts for $\gamma$-ray transients are studied in detail in the literature (see Sguera et al. 2009, 2011). But unlike MWC 656, for which few X-ray observations are available and no X-ray counterpart is identified, there are plenty of data in X-rays for 4U 1036–56 that have yet to be analyzed. In this work, we report on timing, spectrum, and long-term temporal analysis of INTEGRAL and Swift data on 4U 1036–56, examining the possibility of its association with the unidentified transient $\gamma$-ray sources AGL J1037–5708 and GRO J1036–55.

2. OBSERVATIONS AND DATA ANALYSIS

INTEGRAL (Winkler et al. 2003) is a $\gamma$-ray mission covering the energy range 15 keV–10 MeV. INTEGRAL observations are carried out in individual Science Windows (ScWs), which have a typical time duration of about 2000 s. For the INTEGRAL analysis in this paper, we use all public IBIS/ISGRI and JEM-X data for which 4U 1036–56 has an offset angle less than 9° and 5°, respectively. Our data set is composed of about 1607 ScWs for IBIS/ISGRI and 856 ScWs for JEM-X. The data cover revolutions 36–867, from 2003 January 29 to 2009 November 20 (MJD 52,668–MJD 55,155), adding up to a total exposure time of 4.42 Ms for IBIS/ISGRI and 1.02 Ms for JEM-X. (0.91 Ms from JEM-X1 and 0.1 Ms from JEM-X2). The data reduction is performed using the standard ISDC offline scientific analysis software version 9.0. IBIS/ISGRI images for each ScW are generated in the energy band of 18–60 keV. The count rate at the position of the source is extracted from all individual images to produce the long-term light curve on the ScW timescale. When 4U 1036–56 is found to be in outburst, the spectra are produced by running the pipeline from the raw data to SPE and LCR levels, following the standard steps as stated in the IBIS Analysis User Manual. In the quiescent period, the spectrum is obtained using mosaic images, as is appropriate for spectral analysis of faint sources. Using OSA 9.0, the spectrum and light curve of JEM-X during the outburst period are produced following the standard steps as stated in JEM-X Analysis User Manual.

Swift (Gehrels et al. 2004) is a $\gamma$-ray burst explorer. It carries three co-aligned detectors: the Burst Alert Telescope (BAT; Barthelmy et al. 2005), the X-Ray Telescope (XRT; Burrows et al. 2005), and the Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005). To compare with INTEGRAL results, the 65 month Swift/BAT Snapshot Survey light curve of 4U 1036–56 is also inspected. The 14–195 keV light curve covers from 2004 December 16 (MJD 53,355) to 2010 May 31 (MJD 55,347) and is produced with individual snapshot images from ~5 minute observations, corrected for off-axis effects. This light curve is rebinned to a one-day timescale to improve the signal-to-noise ratio. The total exposure time of 4U 1036–56 in this light curve is 19.4 Ms.

We have also used the data collected by the XRT instrument on board the Swift satellite (when the source was in outburst; see Krimm et al. 2012). 4U 1036–56 was first detected by the BAT in the 15–50 keV band on 2012 February 3, and its flux peaked on 2012 February 6 (MJD 55,963), remaining detectable through February 13. A 2982 s photon counting mode XRT observation was performed on 2012 February 17, for which we present timing and spectral analysis. We use archival level 2 XRT data in our analysis. The selection of event grades is 0–12 for photon counting data (see Burrows et al. 2005). To correct for the pile-up effect, we estimate the size of the point-spread function (PSF) core affected. By comparing the observed and nominal PSF (Romano et al. 2006; Vaughan et al. 2006), a radius of 4 pixels is determined, and all the data within this radius from 4U 1036–56 are excluded. Source events are accumulated within an annulus (inner radius of 4 pixels and outer radius of 30 pixels, 1 pixel ~ 2.36 arcsec), while background events are accumulated within a circular, source-free region with a radius of 60 pixels. For timing analysis, the BARYCORR task is used to perform barycentric corrections to the photon arrival times. We extract light curves with a time resolution of 2.5 s. The XRTLCORR task is used to account for the pileup correction in the background-subtracted light curves. For our spectral analysis, we extract events in the same regions as those adopted for the light-curve creation. Exposure maps are generated with the task XRTEXPMAP, and ancillary response files are generated with the task XRTMKARKF, so as to account for different extraction regions, vignetting, and PSF corrections. In order to search for a periodic signal in the Swift light curve, we use the Lomb–Scargle periodogram method (Lomb 1976; Scargle 1982). Power spectra are generated for the light curve using the PERIOD subroutine (Press & Rybicki 1989). The 99.99% white-noise significance level is estimated using Monte Carlo simulations (see, e.g., Kong et al. 1998). The 99% red-noise significance level is estimated using the REDFIT subroutine, which can provide the red-noise spectrum via fitting a first-order autoregressive process to the time series (Schulz & Muddelsee 2002; Farrell et al. 2009). All of the spectral analysis is performed using XSPEC version 12.6.0; uncertainties are given at the 1σ confidence level for one single parameter of interest.

3. RESULTS

Combining all the ISGRI data, 4U 1036–56 is detected by IBIS/ISGRI with a significance level of 11.2σ and an average intensity of 0.180 ± 0.016 counts s$^{-1}$ in the 18–60 keV band. Figure 1 (left panel) shows the IBIS/ISGRI mosaic image of the 4U 1036–56 sky region, and both panels show the position of the transient AGILE source AGL J1037–5708 (>100 MeV; Bulgarelli et al. 2010), with its 95% position uncertainty shown by the green lines. 4U 1036–56 is detected by JEM-X at 3–20 keV at a significance of 4σ (combining all data from JEM-X1 and JEM-X2), with an average intensity of 0.88 ± 0.22 × 10$^{-4}$ counts cm$^{-2}$ s$^{-1}$. The JEM-X mosaic image of this sky area is shown in Figure 1 (right panel).

We investigated the IBIS/ISGRI long-term light curve of 4U 1036–56 on the ScW timescale in the 18–60 keV band (see
Figure 2. Upper panel: long-term significance (upper panel) and light curve (lower panel) of 4U 1036−56 on ScW timescales as seen by IBIS/ISGRI in the 18–60 keV band. The highlighted periods are the INTEGRAL outburst (pink), AGILE flare (green), and Swift outburst (blue). The dotted blue and red lines in the upper panel stand for the 2σ and 4σ significance level. Lower panel: zoomed IBIS/ISGRI (upper) and JEM-X (lower) light curves on timescale of ScW. Red, blue, green, and black points stand for ScWs above 5σ, between 4σ and 5σ, between 3σ and 4σ, and below 3σ, respectively. (A color version of this figure is available in the online journal.)

Figure 2). Most of the time, 4U 1036−56 is not significantly detected by IBIS/ISGRI at the ScW level, as its significance is below 2σ (dotted blue line in Figure 2, upper panel). However, 12 ScWs have a significance larger than 4σ, and all of them are located in a period of about 5 days, between MJD 54,142 (2007 February 11) and MJD 54,147 (2007 February 16); this is highlighted, labeled, and zoomed in Figure 2. Hereafter, we refer to this period as the INTEGRAL outburst.

The recent outburst observed by Swift (Krimm et al. 2012) is also marked and labeled in Figure 2. There is no simultaneous IBIS/ISGRI observation by INTEGRAL. The time of MeV
flare from the transient γ-ray source AGL J1037−5708 is noted in Figure 2 as well. This period also lacks simultaneous observations by INTEGRAL.

Finally, we have also inspected the Swift/BAT survey light curve. In 19.4 Ms, 4U 1036−56 is detected with only 8.2σ (derived from the daily binned light curve). The average flux is $(3.03 \pm 0.37) \times 10^{-5}$ counts s$^{-1}$ in the 14–195 keV band. The significances of the daily light curve are Gaussian distributed, with a mean value of 0.172 and a deviation ($\sigma$) of 1.17. Under this distribution, and considering the 1775 points forming the daily light curve, there should be less than one observation with a single trial significance larger than 4σ. However, several such are discovered located at MJD 54,144, MJD 54,148 (right at the INTEGRAL outburst period), MJD 54,445, MJD 54,499, MJD 54,501, and MJD 54,890. Since Swift/BAT is not as sensitive as IBIS/ISGRI, the light curve is not appropriate for further analysis.

3.1. INTEGRAL Outburst and Hard X-Ray Quiescence

An outburst at MJD 54,144 is significantly detected by IBIS/ISGRI having a significance of $30.4\sigma$ and an average intensity of $2.589 \pm 0.085$ counts s$^{-1}$ in the 18–60 keV band, over a 199 ks exposure ($\sim$1/22 of the total exposure on the source). The JEM-X detection in the outburst period is significantly made at 10.1σ with an average intensity of $(0.194 \pm 0.019) \times 10^{-2}$ counts cm$^{-2}$ s$^{-1}$ in the 3–20 keV band. Out of the outburst period, 4U 1036−56 is detected by IBIS/ISGRI, but only with a significance of $5.7\sigma$ under a total exposure time of 4.4 Ms in the 18–60 keV band. The average flux is $0.094 \pm 0.018$ counts s$^{-1}$ in the 18–60 keV band (27 times dimmer than in outburst). JEM-X does not detect 4U 1036−56 during quiescence, yielding only $2.58\sigma$ in the 3–20 keV, and under a total exposure of 0.99 Ms. The mosaic images of the outburst and the quiescent period are shown in Figure 3.

In Figure 2, we show the zoomed light curve of the INTEGRAL outburst from IBIS/ISGRI and JEM-X. The count rate is extracted from the position of the source in individual images on the ScW timescale. Red, blue, green, and black points stand for ScWs with significance above 5σ, between 4σ and 5σ, between 3σ and 4σ, and below 3σ, respectively. A constant fit to the JEM-X light curve yields an average flux of $0.204 \pm 0.019$ counts $\times 10^{-2}$ cm$^{-2}$ s$^{-1}$ and a reduced $\chi^2$ of 1.3 (21 dof). Also, a constant fit to the IBIS/ISGRI light curve along the outburst yields an average flux of $2.98 \pm 0.12$ counts s$^{-1}$ and a reduced $\chi^2$ of 1.5 (70 dof). Both the JEM-X and IBIS/ISGRI light curves do not hint at variability (less than $3\sigma$), probably due to the large error bars.

Based on the significant detection of INTEGRAL outburst, we extract an energy spectrum from both JEM-X and IBIS/ISGRI and perform a simultaneous spectral analysis (see Figure 4). We use an absorbed blackbody, an absorbed power law, and an absorbed cutoff power-law model to fit the combined JEM-X and IBIS/ISGRI energy spectrum. The hydrogen column density is fixed to $3.36 \times 10^{22}$ cm$^{-2}$, following the value we have derived from the Swift observation of the 2012 outburst (see next section for detail). We have found that only an absorbed cutoff power-law model could yield an acceptable fit. Its reduced $\chi^2$ (dof) is 0.80 (8) compared with 8.587 (9) and 3.555 (9) for absorbed blackbody and power law, respectively. According to an F-test, the probability of refusing the cutoff to a simple power law is $4.78 \times 10^{-4}$, corresponding to a significance of $3.5\sigma$. The result of the fitting parameters is shown in Table 2. Based on the spectrum parameters of the INTEGRAL outburst and assuming a source distance of 5 kpc (Motch et al. 1997), the luminosity derived in the 2–10 keV band is $5.16^{+0.72}_{-0.65} \times 10^{35}$ erg s$^{-1}$.

As a result of the low significance of JEM-X detection corresponding to the out-of-outburst period, we could not extract a meaningful energy spectrum or light curve. Instead, we extracted the spectrum from IBIS/ISGRI in large energy bins directly from mosaic images. The count rate is low, but due to the long exposure time, there are enough counts accumulated to allow for a $\chi^2$ statistics fitting. Because of the limited energy bins and the low statistics, a simple power law is fitted to the spectrum (Figure 4, lower blue line). Details are given in Table 2. Since there is only 1 dof in the spectral fitting, the fitting is not good and results are only indicative. Despite the obvious caveats of the spectrum determination, the derived flux of 4U 1036−56 when in quiescence is $\sim$36 times lower than in the outburst. This is consistent with the dynamic range of $\sim$30 derived from count rate (18–60 keV). Since 4U 1036−56 is quite weak during the quiescent period, this is very likely the reason why the source was not reported in the second IBIS catalog (Bird et al. 2006), although the source was listed in the subsequent third and fourth IBIS catalogs (Bird et al. 2007, 2010) with a similar 18–60 keV average flux.

3.2. Swift Outburst

On MJD 55,960 (2012 February 3), an outburst from 4U 1036−56 was caught by Swift/BAT (Krimm et al. 2012). 4U 1036−56 was detected with a rate of $0.0040 \pm$
The Astrophysical Journal, 761:49 (9pp), 2012 December 10

Figure 4. Upper: unfolded INTEGRAL energy spectrum of the outburst (upper line) and quiescence period (lower line). The black points are from JEM-X, while red ones are from IBIS/ISGRI during outburst. The blue points are from IBIS/ISGRI during quiescence period. Lower: residual of the fit. Black and red points are from JEM-X and IBIS/ISGRI during outburst, while blue points are from IBIS/ISGRI during quiescence period.

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

Table 2
Summary of Fitting Parameters for the INTEGRAL Outburst, the Quiescent Period, and the Swift Outburst

| Period  | Hydrogen Column Density $10^{22}$ cm$^{-2}$ | Photon Index | Cutoff Energy (keV) | Blackbody Temperature (keV) | Unabsorbed Flux $(10^{-10}$ erg cm$^{-2}$ s$^{-1}$) | Reduced $\chi^2$ (dof) |
|---------|---------------------------------------------|--------------|--------------------|-----------------------------|-----------------------------------------------|-------------------------|
| Outburst | 3.36 (fixed)                                | 1.12$^{+0.25}_{-0.25}$ | 26.49$^{+7.2}_{-4.8}$ | ...                         | 2.09$^{+0.40}_{-0.35}$ | 0.80 (8) |
| Quiescence | ...                                      | 3.14$^{+0.63}_{-0.53}$ | ...                | ...                         | 0.058$^{+0.009}_{-0.009}$ | 0.03 (1) |
| Swift PL  | 3.36$^{+0.72}_{-0.53}$                      | 1.08$^{+0.23}_{-0.18}$ | ...                | ...                         | 0.868$^{+0.047}_{-0.042}$ | 0.699 (34) |
| BB       | 1.41$^{+0.41}_{-0.37}$                      | ...                         | 1.85$^{+0.16}_{-0.14}$ | ...                         | 0.698$^{+0.039}_{-0.038}$ | 0.617 (34) |

Note. PL and BB stand for power-law and blackbody models, respectively.

We have also carried out timing analysis of the Swift outburst. A 50 s binned light curve of 4U 1036−56 in the 0.3–10 keV band is shown in Figure 5. The flux shows variability that matches the pulse period. To search for a periodic signal in the light-curve data, we have generated the power spectrum. A significant signal is detected at 854.75$^{+4.39}_{-4}$ s (1$\sigma$ errors), beyond the white and the red noise (Figure 5, middle panel; since the red noise is below the white-noise component, only the white noise is shown). The derived pulse period is consistent with the 854.3±0.2 s period determined by the XMM-Newton observation (La Palombara et al. 2009). The relatively large error of pulse period and a wide peak seen in the power spectrum may be due to the limited pulse cycles (only about four) covered in the light curve, which lead to uncertainties. We fold the light curve at the 854.75 s pulse period and derive the pulse profile (Figure 5, lower panel).
that last for several days. The flux in the outburst we analyzed reached $2.09 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ (18–60 keV), implying a dynamical range of $\sim 36$.

4U 1036−56 is the only hard X-ray source in the uncertainty contour of the $\gamma$-ray transients AGL J1037−5708, as well as on the admittedly worse-localized GRO J1036−55. AGL J1037−5708 was discovered on 2010 November 27 during a flare lasting three days (Bulgarelli et al. 2010). The positional coincidence and the variability timescales make it possible to entertain the hypothesis that the HE transients and 4U 1036−56 are related. The possible association between a binary and an AGILE transient under the weight of similar exploratory arguments has been mentioned before (see Table 1 and references therein). Some of the suggested counterparts for the low number of transients found are SFXTs. These are characterized by faster X-ray flares ($\sim$hours) and larger dynamical ranges ($10^5$) than the ones found for 4U 1036−56.

Several authors proposed that it is theoretically feasible that HMXBs produce $\gamma$-ray emission during periods of X-ray activity induced by accretion (see, e.g., Bednarek 2009 for a leptonic and Romero et al. 2001 and Orellana et al. 2007 for a hadronic model). The latter has been put to the test by observations of the Be/pulsar binary 1A 0535+262 during a giant X-ray outburst (Acciari et al. 2011). Though it is beyond the scope of this paper to produce a detailed theoretical model of the source, we consider next whether it is in principle plausible that 4U 1036−56 and the AGILE flares are related. We focus here on the leptonic model.

The idea is similar to that used for propellers or $\gamma$-ray binaries that might be transitioning between a propeller and an ejector state (see, e.g., Bednarek 2009; Bednarek & Pabich 2011; Torres et al. 2012). The dense wind of a massive star can be partially captured by a neutron star inside a compact binary system. If the neutron star is rotating slowly, as is the case of 4U 1036−56, the matter from the stellar wind can penetrate the inner neutron-star magnetosphere. This matter can be directed toward the neutron surface following magnetic lines. At some distance from the neutron star, a turbulent and magnetized transition region (a distance known as the Alfvén, or magnetic, radius) is formed due to the balance between the magnetic pressure and the pressure of accreting matter. This region, the position of which can be computed as (see Bednarek 2009, and references therein)

$$R_A \sim 4 \times 10^8 B_{12}^{4/7} M_{16}^{-2/7} \text{cm},$$

where $B_{12}$ is the magnetic field at the neutron-star surface in units of $10^{12}$ G and $M_{16}$ is the accreted mass in units of $10^{16}$ g s$^{-1}$, may provide good conditions for acceleration of particles to relativistic energies. Note that the fiducial values entirely depend on the properties of the neutron star and the orbit of the binary can be significantly off the chosen scales.

For accretion to occur, three conditions must be satisfied: (1) the magnetic radius $R_A$ is inside the light cylinder $R_L = c P / 2 \pi$, where $P$ is the neutron-star period, which imposes a lower limit on $P$; (2) the rotational velocity of the magnetosphere at $R_A$ is smaller than the Keplerian velocity of the accreting matter (so no propeller is allowed); and (3) the magnetic radius is also smaller than the capture radius of the matter of the stellar wind. All three conditions are met for the known parameters of 4U 1036−56. In particular, the large pulse period found in 4U 1036−56 confirms that it is in the accreting state. By equating the electron acceleration timescales with that of the losses, particularly synchrotron losses (albeit electrons with energies lower than GeV also could be affected by significant

### Figure 5

Upper: Swift/XRT light curve of 4U 1036−56 (0.3–10 keV, 50 s bins) during the observation on 2012 February 17. Middle: power spectrum (for a 2.5 s binned light curve in 0.3–10 keV) and 99.9% white-noise level (in blue). Lower: profile folded at 854.75 s period. Phase zero is the starting time of the light curve.

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

Phase zero is arbitrarily taken as the starting time of the light curve. The pulsation exhibits a single peak profile, similar to the pulse profile in Reig & Roche (1999) and La Palombara et al. (2009). Fitting a sinusoidal function to the pulse profile yields a pulse fraction (ratio of sinusoidal amplitude to mean count rate) of 36.2% ± 6.7% (Figure 5, lower panel).

### 4. DISCUSSION

In this paper, we have reported on INTEGRAL and Swift observations of 4U 1036−56. We have found that 4U 1036−56 is a weak hard X-ray source spending most of the time in a quiescent state with an average flux of $5.8 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (18–60 keV). Occasionally, 4U 1036−56 may exhibit outbursts
where $\zeta_-$ is the acceleration efficiency, a dimensionless number in units of 0.1 (whose value is unknown; e.g., Aharonian et al. 2002 considered values of $10^{-2}$ to $10^{-4}$; Bednarek 2009 and others used the prior scale). These electrons can emit synchrotron photons of characteristic energy $\epsilon_1 = m_e c^2 (B_A / B_\circ) \gamma_{\text{max}}^2 \sim 1.9 \zeta_- 1$ MeV. Apart from the usual magnitudes of the speed of light and the mass of the electron, $B_\circ$ is the magnetic field at the position of $R_A$, obtained through the dipolar formula, and $B_A$ is the critical magnetic field $4.4 \times 10^{13}$ G. Relatively weak X-ray sources (low accretion) can accelerate particles to higher energies than the more powerful X-ray binaries. For the latter, tens of GeV can be considered as a safe upper limit for the maximum energy of the accelerated electrons. The precise values of maximal energies, we emphasize, depend on several parameters describing the neutron star and the orbit. All in all, synchrotron emission can extend to the hard X-ray regime and beyond.

In a propeller case, the maximum power available for the acceleration of electrons is limited by the energy extracted from the rotating neutron star by the infalling matter, which can be estimated as $L_{\text{rot}} \sim M_{\text{acc}}^2 v_{\text{rot}} / 2 \sim 3 \times 10^{34} B_{12}^{9/7} M_{16}^{12/7} P^{-2} \text{erg s}^{-1}$ (Bednarek 2009), with $v_{\text{rot}}$ as the rotational velocity of the magnetosphere. If we were also the case for accreting systems, the long period of 4U 1036−56 (and essentially any other neutron star in a high-mass accreting binary, for which $P' > 100$ s are common) would imply too low a power to sustain typical flare fluxes. However, in accreting scenarios, given that the rotational velocity of the magnetosphere is slower than the Keplerian velocity of the accreting matter, the gravitational energy and the specific angular momentum of the infalling matter flow from the accreting matter to the neutron star, and not vice versa. This is consistent with the observation of pulsations and with the fact that the neutron star is indeed spun up. One can then consider that the maximum power available for the acceleration of electrons is a fraction of the accretion power at $R_A$, i.e.,

$$L = G M M / R_A \sim 4.6 \times 10^{33} B_{12}^{-4/7} M_{16}^{9/7} \gamma_{\text{max}}^2.$$  \hspace{1cm} (3)

If this is the case, in a low accretion rate mode, the source barely has enough power to appear as a source in MeV observations; it shows up only as an X-ray/hard X-ray source as a result of the accretion process (i.e., when matter actually falls in the neutron-star surface). Yet, hard X-ray or higher energy X-rays may be observable only when the accretion rate increases enough (e.g., by an increase in the mass-loss rate, or accretion of a wind clump) so that the fraction of the power that can be converted into relativistic electrons at $R_A$ may lead to significant non-thermal luminosity. However, if the accretion rate increases enough, the maximum electron energies decrease, as shown above by Equation (2), actually reducing the phase space in which, for instance, an AGILE source may be detected.

Due to the AGILE energy resolution, the $E > 100$ MeV flux contains a large contribution from sub-100 MeV photons (see, e.g., Longo 2011). Actually, given that Fermi Large Area Telescope (LAT; optimized at 1 GeV) did not detect this and other AGILE transients, it is reasonable to suppose that these flares are type sub−100 MeV. Nevertheless, the photon flux of the AGL J1037−5708 flare is quite intense (Bulgarelli et al. 2010). To give some examples, assuming it corresponds to an energy range from 30 to 200 MeV and that its spectrum (which is not known) is very steep (corresponding to the fact that Fermi-LAT has not detected it), one obtains the range $(7.6 \times 10^{35}−5.8 \times 10^{34}) (1/50 \text{ kpc})^3 \text{ erg s}^{-1}$ for a power-law photon spectral index of 2.5 and 4.0, respectively. This power should only be a fraction of Equation (3), which also imposes constraints on the magnetic field and accretion rate. An example of these constraints is plotted in Figure 6 (upper panel).
it can sustain an uncertainty of 25%–50% (Motch et al. 1997). A distance of 2.5 kpc, for instance, would translate into a change of γ-ray luminosity between $1.7 \times 10^{35}$ and $1.4 \times 10^{34}$ erg s$^{-1}$ for the same range of spectral slopes. This would make the possibility of an association between 4U 1036–56 and AGL J1037–5708 more plausible. This is shown in the lower panel of Figure 6.

This work was supported by 973 program 2009CB824800 and the National Natural Science Foundation of China via NSFC-11233003, 11103020, 11133002, 11073021, and 11173023. We acknowledge the support from the grants AYA2009-07391 and SGR2009-811, as well as the Formosa program TW2010005 and iLINK program 2011-0303. We thank the anonymous referee for the constructive review. We thank A. Camero-Arranz and W. Bednarek for comments.

REFERENCES

Acciari, V. A., Aliu, E., Araya, M., et al. 2011, ApJ, 733, 96
Ackermann, M., Ajello, M., Ballet, J., et al. 2012, Science, 335, 189
Aharonian, F. A., Belyanin, A. A., Derishev, E. V., Kocharovsky, V. V., & Kocharovsky, V. V. 2002, Phys. Rev. D, 66, 023005
Barthelmy, S. D., Barbarier, L. M., Cummings, J. R., et al. 2005, Space Sci. Rev., 120, 143
Bednarek, W. 2009, A&A, 495, 919
Bednarek, W., & Pabicb, J. 2011, MNRAS, 411, 1710
Bird, A. J., Barlow, E. J., Bassani, L., et al. 2006, ApJ, 636, 765
Bird, A. J., Bassano, A., Bassani, L., et al. 2010, ApJS, 186, 1
Bird, A. J., Malizia, A., Bassani, L., et al. 2009, ApJS, 170, 175
Bozzo, E., Giunta, A., Cusumano, G., et al. 2011, A&A, 531, 130
Bulgarelli, A., Gianotti, F., Trifoglio, M., et al. 2009, ATel, 2017
Bulgarelli, A., Gianotti, F., Trifoglio, M., et al. 2010, ATel, 3059
Burrows, D. N., Hill, J. E., Nousek, J. A., et al. 2005, Space Sci. Rev., 120, 165
Casandjian, J.-M., & Grenier, I. A. 2008, A&A, 489, 849
Casares, J., Ribó, M., Ribas, I., et al. 2012, MNRAS, 421, 1103
Chen, A., Vercellone, S., Giuliani, A., et al. 2007, ATel, 1308
Farrell, S. A., Barret, D., & Skinner, G. K. 2009, MNRAS, 393, 139
Forman, W., Jones, C., Cominsky, L., et al. 1978, ApJS, 38, 357
Gehrels, N., Chincarini, G., Giommi, P., et al. 2004, ApJ, 611, 1005
Hinton, J. A., & Hofmann, W. 2009, ARA&A, 47, 523
Kong, A. K. H., Charles, P. A., & Kuulkers, E. 1998, New Astron., 3, 301
Krimm, H. A., Kennea, J. A., Holland, S. T., et al. 2012, ATel, 3936
La Palombara, N., Sidoli, L., Esposito, P., Tiengo, A., & Mereghetti, S. 2009, A&A, 505, 947
Lomb, N. R. 1976, Ap&SS, 39, 447
Longo, F., et al. (for the AGILE Collaboration) 2011, in Proceedings of Gamma-ray Astrophysics in the Multimessenger context–SciNeGHE 2010, Nuovo Cimento C, 2011, 34, 191, Published online at http://www.sif.it/ riviste/ncc/econtents/2011/034/03
Lucarelli, F., Verrecchia, F., Striani, E., et al. 2010, ATel, 2761
Markert, T. H., Laird, F. N., Clark, G. W., et al. 1979, ApJS, 39, 573
Masetti, N., Pretorius, M. L., Palazzi, E., et al. 2006, A&A, 449, 1139
Motch, C., Haberl, F., Dennerl, K., Pakull, M., & Janot-Pacheco, E. 1997, A&A, 323, 853
Negueruela, I., Smith, D. M., & Chaty, S. 2005, ATel, 470
Nespoli, E., Fabregat, J., & Mennickent, R. E. 2008, A&A, 486, 911
Orellana, M., Romero, L. P., Pellizza, L. J., & Vidrih, S. 2007, A&A, 465, 703
Press, W. H., & Rybicki, G. B. 1989, ApJ, 338, 277
Reig, P., & Roche, P. 1999, MNRAS, 306, 100
Romano, P., Campana, S., Chincarini, G., et al. 2006, A&A, 456, 917
Romano, P., Manganova, V., Cusumano, G., et al. 2011, MNRAS, 412, 30
Romano, P., Sidoli, L., Cusumano, G., et al. 2009, ApJ, 696, 2068
Romano, P., Sidoli, L., Manganova, V., Mereghetti, S., & Cusumano, G. 2007, A&A, 469, 5
Romero, G. E., Kaufman Bernadó, M. M., Combi, J. A., & Torres, D. F. 2001, A&A, 376, 599
Roming, P. W. A., Kennedy, T. E., Mason, K. O., et al. 2005, Space Sci. Rev., 120, 95
Sarty, G. E., Pilecki, B., Reichart, D. E., et al. 2011, Res. Astron. Astrophys., 11, 947
Scargle, J. D. 1982, ApJ, 263, 835
Schulz, M., & Mudelsee, M. 2002, Comput. Geosci., 28, 421
Sguera, V. 2009, PoS (Integral08) 082, Proceedings of An INTEGRAL View of Compact Objects–The 7th INTEGRAL Workshop, Published online at http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=67, id. 82
Sguera, V. 2011, PoS (Extremesky 2011) 011, Proceedings of The Extreme and Variable High Energy Sky, Published online at http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=147., id.11
Sguera, V., Bazzano, A., Bird, A. J., et al. 2006, ApJ, 646, 452
Sguera, V., Drave, S. P., Bird, A. J., et al. 2011, MNRAS, 417, 573
Sguera, V., Romero, G. E., Bazzano, A., et al. 2009, ApJ, 697, 1194
Swank, J., Smith, D., & Markwardt, C. 2007, ATel, 997
Tavani, M., Mukherjee, R., Mattos, J. R., et al. 1997, ApJ, 479, 109
Tomsick, J. A., Chaty, S., Rodriguez, J., Walter, R., & Kaaret, P. 2009, ApJ, 701, 811
Torres, D. F., Rea, N., Esposito, P., et al. 2012, ApJ, 744, 106
Torres, D. F., Romero, G. E., Combi, J. A., et al. 2001, A&A, 370, 468
Vaughan, S., Goad, M. R., Beardmore, A. P., et al. 2006, ApJ, 638, 92
Warwick, R. S., Marshall, N., Fraser, G. W., et al. 1981, MNRAS, 197, 865
Williams, S. J., Gies, D. R., Matson, R. A., et al. 2010, ApJ, 723, 93
Winkler, C., Courvoisier, T. J.-L., Di Cocco, G., et al. 2003, A&A, 411, L1
Zhang, S., & Collmar, W. 2007, ApSS, 309, 23

The Astrophysical Journal, 761:49 (9pp), 2012 December 10

LI ET AL.