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Flaring Episodes of Cyg X-3 with Korean and Japanese VLBI

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We present a 22 GHz observation of the 2007 May−June flare in Cyg X-3 performed by VLBI Exploration of Radio Astrometry (VERA), a Japanese Very Long Baseline Interferometry (VLBI) facility. The observation was carried out during a state transition from ultrasoft to hard state. A rapid mini-flare of ∼3 hr was detected in the early phase of the 2007 flare. A jet event is expected to occur during such a transition, but there has been no direct observation to support it. The model-fits indicate a structural change as an evidence of a jet ejection event, suggesting a high possibility of synchrotron flare during the mini-flare event. We present the apparent size of the source structure based on the previous VLBI observations of Cyg X-3. The KaVA (KVN and VERA Array), on-going combined array of the VLBI facilities of Korean KVN (Korea VLBI Network) and Japanese VERA, and the East Asian VLBI (EAVLBI) including the Chinese VLBI facilities, would improve the *uv* coverage to accomplish a higher resolution in the microquasar research.

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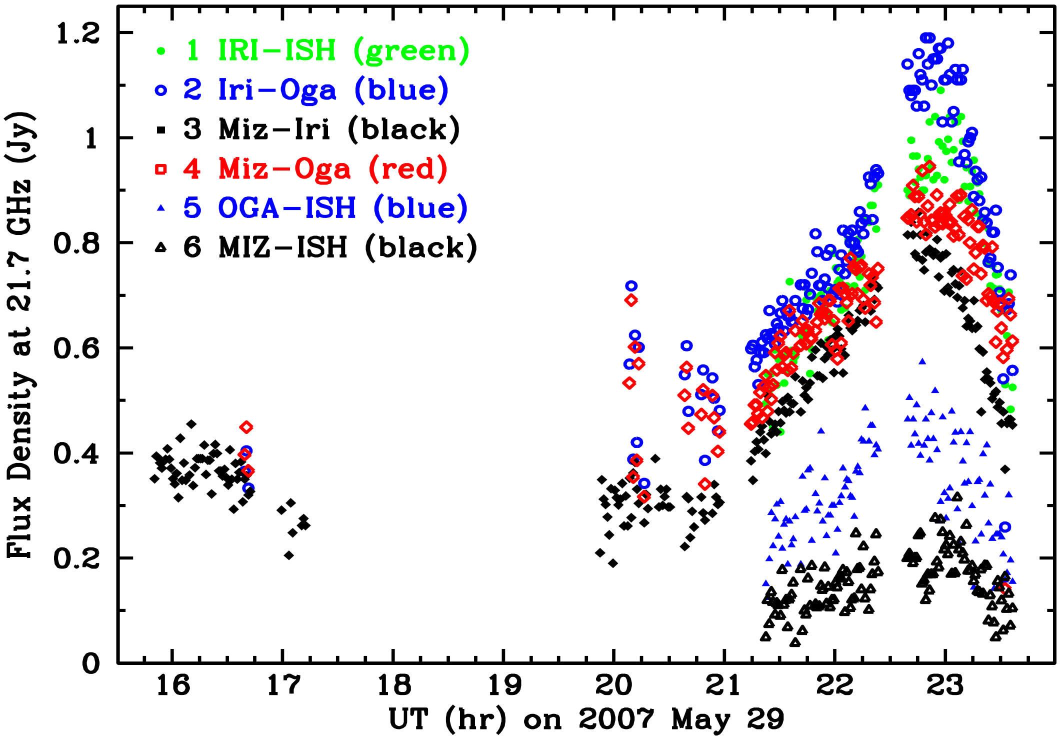

Figure 1: Visibility amplitude of Cyg X-3 observed with VERA on 2007 May 29. During ∼21−24 UT, a mini-flare was detected in all six baselines.

1. Microquasars and Cyg X-3

Microquasars are jet-ejecting X-ray binaries (e.g. Fender 2010). Cyg X-3 is a black hoe candidate with an unusual Wolf-Rayet companion, orbiting every 4.8 hr (e.g. Kim et al. 2013 and references therein). Cyg X-3 is the brightest galactic microquasar in the radio, and one of the most energetic TeV γ-ray binaries (Corbel et al. 2012 and references therein). Cyg X-3 has displayed frequent flaring activity from small (< 1Jy), intermediate (> 1 Jy) to large flares, and no real quiescence with numerous flickering states (Waltman et al. 1994). The canonical X-ray states of black hole binaries are also known in Cyg X-3: low/hard, very high, intermediate, high/soft and ultrasoft sattes. However, the X-ray spectra and hardness intensity diagram in Cyg X-3 are complex and significantly different from other X-ray binaries, and its nature has not been explored in detail (e.g. Koljonen et al. 2010).

2. Mini-flare in the early phase of 2007 event in Cyg X-3

In 2007 April, the SWIFT observations indicated that hard X-rays (15−50 keV) rapidly increased with the hardening in the soft X-rays. After a soft state since 2007 April (Krimm et al. 2007), an ultrasoft state was observed with INTEGRAL during May 21−26 (Soldi et al. 2007; Beckmann et al. 2007). During May 27−29, the onset of an X-ray state transition was observed with INTEGRAL and six days later during June 5−12 it reached a hard state (Beckmann et al. 2007). Our VLBI observation was carried out with VERA, Japanese VLBI facility, on 2007 May

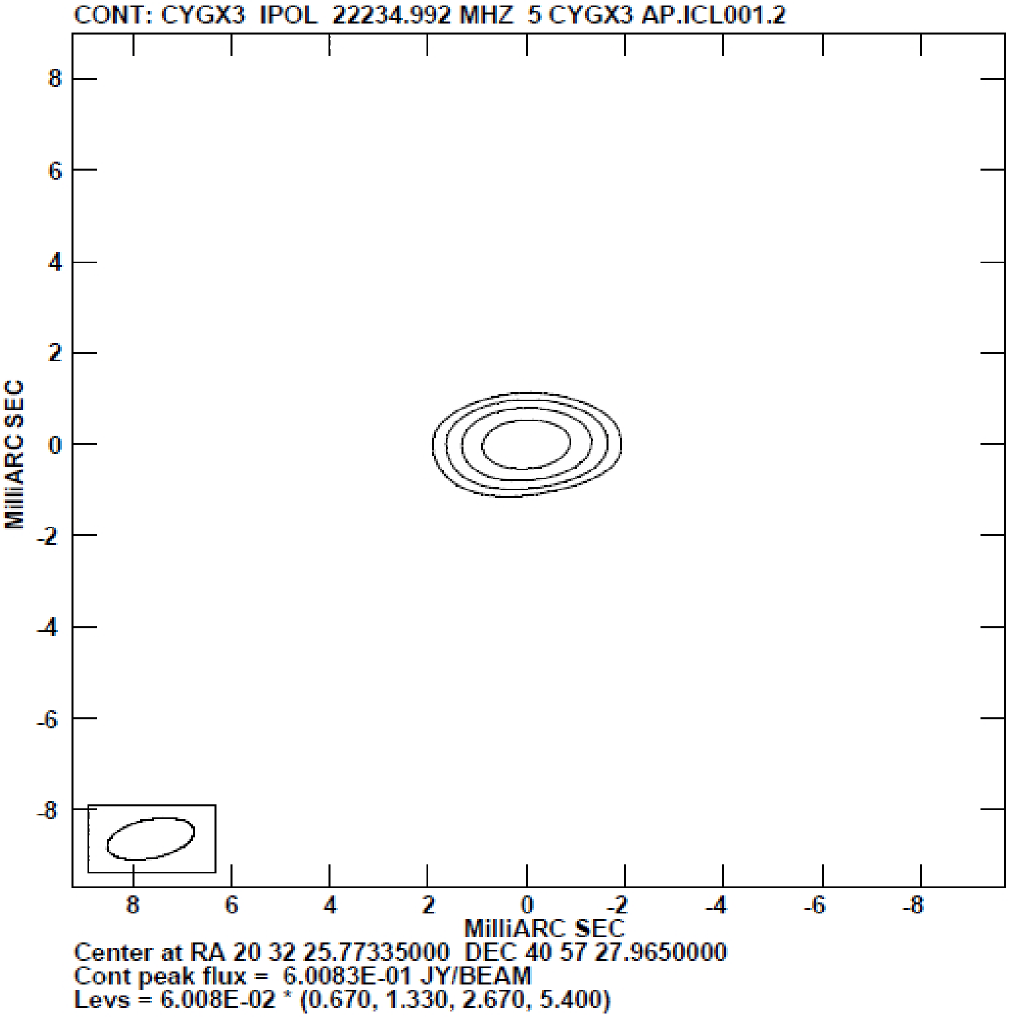

Figure 2: The 22 GHz image of Cyg X-3 observed with VERA on 2007 May 29.

29 at 22 GHz for ∼9 hr (Kim et al. 2013) during its ultrasoft state at 3−20 keV. Observations at 1−30 GHz with the RATAN-600 radio telescope showed that radio flare reached ∼1.6 Jy at 1 GHz and 3.9 Jy at 30 GHz on 2007 June 2, and declined to <1 Jy at 1−30 GHz within the next two to three days (Trushkin et al. 2007).

The detected fringes in all six baselines are presented in Figure 1, obtained with the AIPS task FRING (Figure 1). There is a short-duration flare ("mini-flare") for ∼21 − 24 UT. We confirmed that the systematic effects such as the antenna system temperature and source elevation were stable during the observation. Therefore, the mini-flare detected in all baselines indicates that it is an intrinsic phenomena of Cyg X-3 itself. The detailed discussion on testing model fits with Gaussian models to the observed visibility amplitude is discussed in Kim et al. 2013.

The 22 GHz image based on the detected fringes is presented in Figure 2, with a signal-to-noise ratio of 5 and the level of 3 σ. The image is not resolved. It is not unusual since the VLA observation at 15 and 43 GHz for the 2002 small flare of <1 day, peaked at <500 mJy did not show any extension of the structure (Miller-Jones et al. 2009).

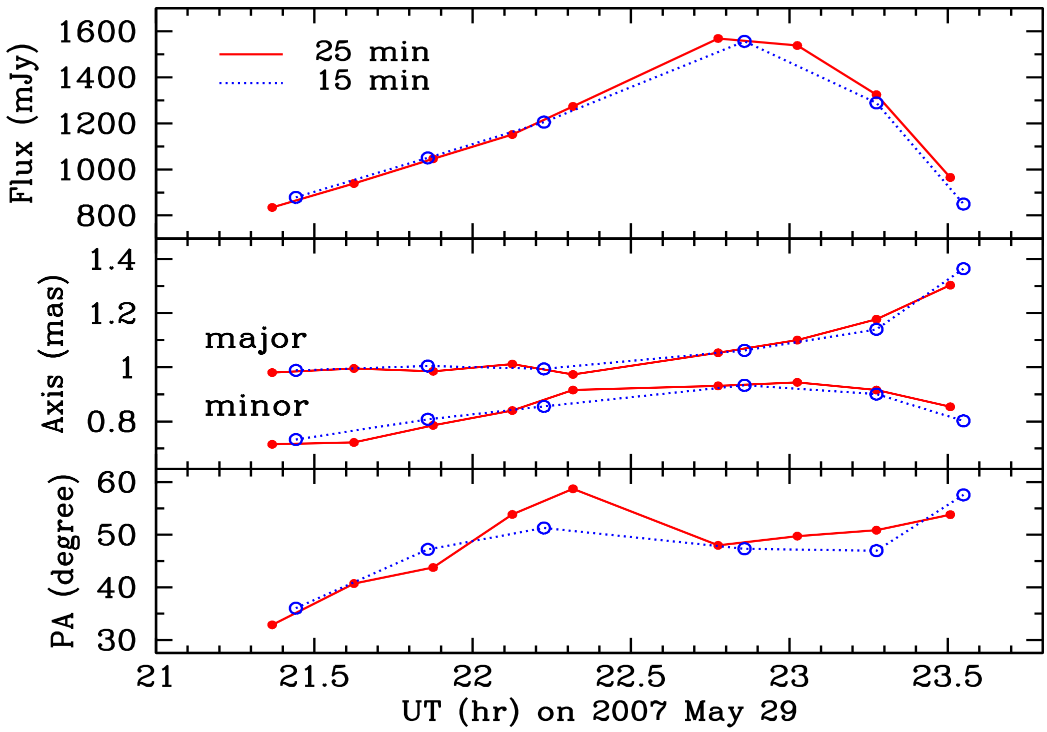

Figure 3: Model fits for the 2007 May 29 mini-flare of Cyg X-3 observed with VERA. Total flux density (top), sizes of major and minor axes (middle), and position angle (bottom panel) during the mini-flare for a single elliptical Gaussian model fits are presented with time bins of 15 and 25 minutes, designated with the blue-colored open circles and dotted lines, and the red-colored filled circles and solid lines, respectively.

The time-varying visibility amplitude in Figure 1 indicate that the detected fringes are not from a point source. Therefore, we instead tested the Gaussian models since we cannot directly produce a hybrid mapping image for a timescale short enough to trace a change of source structure with the variation of flux density due to the limitation in *uv* coverage with only six baselines. In Figure 3, we present the results of the elliptical Gaussian model-fits performed with CalTech's Difmap program: the total flux density, sizes of major and minor axes, and position angle. The single Gaussian models with time bins of 15 and 25 minutes are consistent with each other.

In Figure 3, the size of major axis kept increased since ∼22.5 UT, ∼1 hr before the peak flux density. In the two mini-flares observed in 1995 May with VLBA (Newell et al. 1998), the extended structure appeared ∼1 hr prior to the peak of each flare, proportional to the increase in flux density, and the expansion velocity of the jets are found to be $\sim 0.3c$. Therefore, similarly, the increase of the major axis size in Figure 3 may indicate a structural change, or jet ejection.

The most appropriate model to account for such rapid flares would be the so-called shock-in-jet model (Marscher & Gear 1985). The model can reproduce the time-varying radio light curves, and associated variable jet emission in microquasars (e.g. Türler & Lindfors 2007; Miller-Jones et al. 2009). Therefore, together with such observations and models for flaring activities in Cyg X-3 and other microquasars, our model fits suggest a high possibility of synchrotron flares and an associated jet ejection during the X-ray state transition from ultrasoft to hard state in the 2007

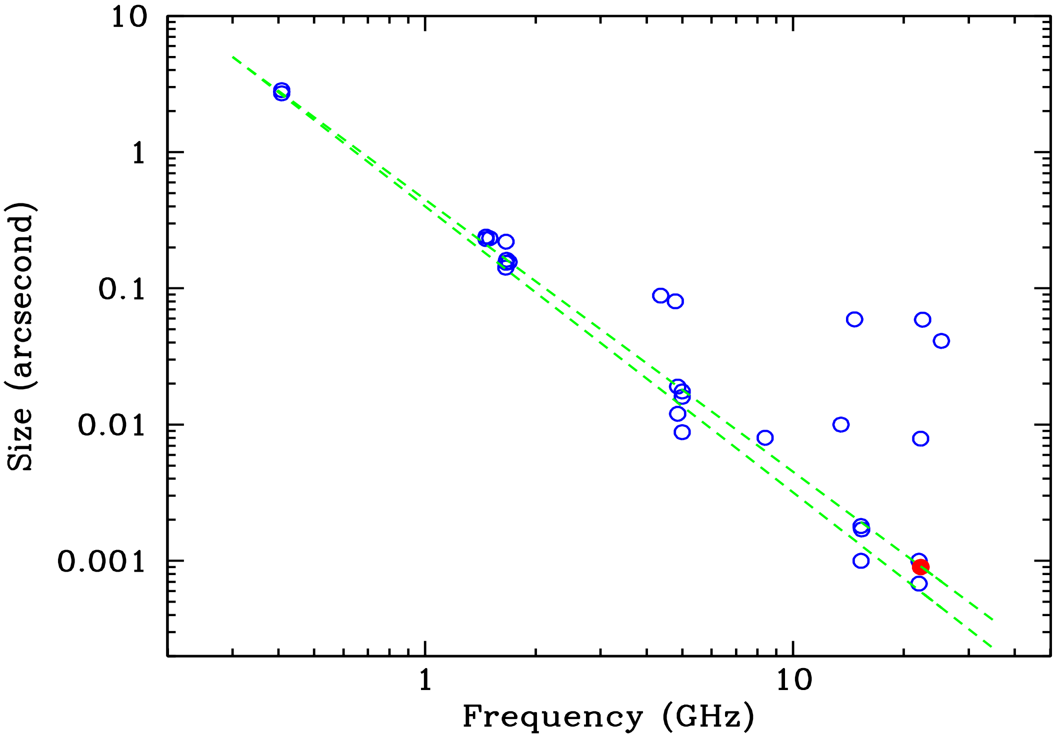

Figure 4: Reported sizes of Cyg X-3 as a function of frequency. The filled red circle is for the 2007 May 29 observation. The dashed lines are for the frequency dependence of the size ($\propto \nu^{-n}$) with $n = 2$ and 2.1. The observations are adopted from Geldzahler et al. 1983, ApJ, 273, L65; Spencer et al. 1986, ApJ, 309, 694; Schalinski et al. 1995, ApJ, 447, 752; Schalinski et al. 1998, A&A, 329, 504; Monlar et al. 1988, ApJ, 331, 494; Monlar et al. 1995, ApJ, 438, 708; Fender et al. 1995, MNRAS, 274, 633; Newell et al. 1998, 293, L17; Mioduszewski et al. 2001, ApJ, 553, 766; Marti et al. 2001, A&A, 375, 476; Tsuboi et al. 2008, PASJ, 60, 465; Tudose et al. 2007, MNRAS, 375, L11; Miller-Jones et al. 2004, ApJ, 600, 368; Kim et al. 2013, ApJ, 772, 41; Johnston et al. 1986, ApJ, 309, 707; and references therein.

May−June flare. The observation of jet activity in this particular state transition has been a long-awaited issue. We present observational evidence of such an expected jet ejection event in the state transition for the first time.

3. High resolution astronomy and microquasars

The observed apparent size of Cyg X-3 as a function of frequency is presented in Figure 4, including our 2007 VERA observation. The dashed line obeys a λ^n law with $n \sim 2$ as would be expected for scattering by electron inhomogeniety along with line of sight to the source (e.g. Spencer et al. 1986). Models for the scatter-broadened image of Cyg X-3 can be found in Wilkinson et al. (1994), with reasonable n lies between 2 and 2.2. Similar approach for the apparent size of the extragalactic compact sources (i.e. quasars and AGNs) has been performed (e.g. Krichbaum et al. 1999 in the case of *SgrA**), and $n \sim 2$ would be valid (e.g. Narayan et al. 1998). However, observations are often lies below the λ^2 extrapolation (for further discussion, e.g. Mioduszewski et al. 2001). The disagreement might be caused by cases with a single short observation, poor sensitivity, or a lack of enough number of baselines. Particularly, there has been almost no observation to test the expected minimum scattering size at frequencies higher than 22 GHz, as shown in Figure 4. The next challenge is to image the minimum scattering, or source, size with high sensitivity and appropriate number of baselines at all frequencies including poorly explored frequency higher than 22 GHz.

In the 2007 VERA observation, there were only moderately long baselines of 1000−2000 km. The combined array of KVN and VERA (KaVA) has been recently launched. In the KaVA program, the observations with frequencies higher than 22 GHz would be expected in the future. Furthermore, the East Asian VLBI (EAVLBI), the combined array including the Chinese VLBI facility together with KaVA, is in preparation. Therefore, the on-going KaVA and EAVLBI will improve the baseline problem with KVN's shorter baselines of a few hundred km, and provide better UV coverage and allow us to make snapshot images of rapidly variable sources to image the source size as well as jet ejection events.

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