THE ACCRETION FLOW–DISCRETE EJECTION CONNECTION IN GRS 1915+105

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ABSTRACT

The microquasar GRS 1915+105 is known for its spectacular discrete ejections. They occur unexpectedly, thus their inception has escaped direct observation. It has been shown that the X-ray flux increases in the hours leading up to a major ejection. In this article, we consider the serendipitous interferometric monitoring of a modest version of a discrete ejection described in Reid et al. that would have otherwise escaped detection in daily radio light curves. The observation begins ∼1 hr after the onset of the ejection, providing unprecedented accuracy on the estimate of the ejection time. The astrometric measurements allow us to determine the time of ejection as MJD 56436.274±0.016, i.e., within a precision of 41 minutes (95% confidence). Just like larger flares, we find that the X-ray luminosity increases in last 2–4 hr preceding ejection. Our finite temporal resolution indicates that this elevated X-ray flux persists within 21.8±2.6 minutes of the ejection with 95% confidence, the highest temporal precision of the X-ray–superluminal ejection connection to date. This observation provides direct evidence that the physics that launches major flares occurs on smaller scales as well (lower radio flux and shorter ejection episodes). The observation of a X-ray spike prior to a discrete ejection, although of very modest amplitude, suggests that the process linking accretion behavior to ejection is general from the smallest scales to high luminosity major superluminal flares.

Key words: accretion, accretion disks – black hole physics – X-rays: binaries

1. INTRODUCTION

One of the most striking features of Galactic black holes (GBHs) are their major radio flares. These are large increases in radio flux that appear to be rapidly moving discrete components in followup radio interferometric observations (Mirabel & Rodríguez 1994; Fender et al. 1999; Dhawan et al. 2000; Miller-Jones et al. 2005, 2012). Major flare ejections (MFEs) of rapidly moving components are rare states that occur as brief transients in some GBHs. The physics of the launching mechanism that produces these dramatic events has been the subject of much speculation. Consequently, there is a wealth of observational information from monitoring and pointed interferometer. The notion is so popular that in the highly publicized work of Marscher et al. (2002) they claimed that they detected X-ray dips preceding superluminal ejections in the active galactic nucleus of the Seyfert galaxy 3C120 and this was direct evidence of a commonality with GRS 1915+105. This is one of the most cited pieces of evidence supporting the notion of scale invariance in black hole physics from stellar massive black holes to supermassive black holes. Our detailed study of an ejection in GRS 1915+105 aims improve our understanding of the putative accretion disk–superluminal ejection connection.

In quest to understand the physics of the discrete ejections, we have been studying the X-ray time evolution immediately preceding flare production and during the ejections in GRS 1915+105 (Punsly & Rodríguez 2013a, 2013c; Punsly et al. 2014). The data being all serendipitous is not ideal, but we have reached and reaffirmed certain conclusions:

1. A conspicuous peak in X-ray flux occurs in the hours preceding the launch of the MFE.
2. During the ejection, the X-ray flux is highly variable.
3. Typically, there is a dip in the X-ray flux during the ejection, well below the pre-launch flux.
4. The time averaged X-ray flux during the ejection is correlated with the flux preceding the ejection with a similar, but slightly smaller, magnitude.
The X-ray light curve during the MFE often has large local maxima which can exceed the X-ray flux before the launch. These maxima can occur either during the ejection or immediately after the ejection episode.

The examination of these findings in the past has been hampered by crude temporal sampling. MFE ejection times have been estimated from radio light curves. There is an inherent ambiguity in that optically thick ejections will not show an increase in the light curve until they expand to become optically thin at the observing frequency. Thus, they are not precise. Historically, triggered radio interferometry initiates only after an ejection. Thus, extrapolating the trajectory of the moving plasmoids back in time for uncertainties in the ejection time. Furthermore, only the strongest MFEs (>175 mJy at 2.3 GHz) have been studied in the past since one needs a definite strong signal above the random radio fluctuations of the active source in GRS 1915 +105 in order to determine if one has a certain detection of an MFE (Dwahan et al. 2004).

We present much more accurate temporal data than has previously been available for an MFE. We also are able to extend some of the trends that were noted above to a much weaker ejection. We fortunately have multi-epoch, snapshot, Very Long Baseline Array (VLBA) observations of a slightly superluminal ejection with the data sampling beginning ~1 hr after the onset of the ejection, that were already published in Reid et al. (2014). We re-analyze here these data following a slightly different procedure. We adopt the original strategy to place this VLBA observation in a context of radio monitoring with the RATAN telescope and confront this radio flare to contemporaneous X-ray observations obtained from the MAXI all sky monitor (http://maxi.riken.jp/mxondem/). The MAXI observatory typically observes GRS 1915+105 every 1.5 hr and it can potentially provide useful spectral data in the energy range 1–20 keV (Matsuoka et al. 2009). We have downloaded the MAXI data that occurred within minutes of the ejection as well as two hours before and one hour after the ejection began. The results of our data analysis are found in Section 4.

2. RADIO MONITORING

GRS 1915+105 was observed with the RATAN-600 radio telescope at 4.8, 8.2, and 11.2 GHz as part of our 2013 monitoring campaign. The details of these observations have been described elsewhere (Trushkin et al. 2008; Punsly et al. 2014). The secondary calibrators 3C286 and PKS 1345 +12 were used for daily calibration. The temporal spacing of our monitoring program—one measurement per day—is too short to estimate the time of the major ejection that is associated with the radio flare. From Punsly & Rodriguez (2013a) and Figure 1, determination of the ejection initiation and end times require temporal resolution 100 times finer, on the order of an hour or minutes. However, strong flares are luminous for at least 1 day, so it is adequate for identifying major ejections (Rodriguez & Mirabel 1999; Miller-Jones et al. 2005). Figure 1 shows the light curve near the “suggested” time of the ejection detected with VLBA on MJD 56436.3 (Reid et al. 2014). The radio flux density is low as expected a few hours before the ejection. The increase in the low frequency flux at 4.8 GHz, 1.7 days after the ejection, is consistent with the later stages of a discrete ejection. However, the flux levels are so low for this event and the time sampling is so coarse that the identification cannot be made with certainty.

3. THE VLBA OBSERVATIONS

GRS 1915+105 was observed with VLBA at 22.2 GHz on 2013 May 24 (MJD 56436). The data from the eight continental VLBA stations were imaged in seven individual 20 minute scans. In order to track the motion of the ejection, “snapshots” were made from the VLBA observation which have ~20 interferometer (\(\nu, \nu\))-points. With the sparse \(\nu–\nu\) coverage only peak fluxes were detectable. One component was detected and its trajectory is plotted from the data in Reid et al. (2014) in Figure 2. The peak flux density at 22.2 GHz was 6.7 ± 0.8 mJy for six of the seven snapshots. The third (outlier) data point with the larger error bars was \(<2\) mJy. The core was not detected and a conservative upper limit of 3 mJy is placed on its flux density.
The trajectory provides information on the point of origin for the ejection. There are three things to consider in establishing the location of the point of origin.

1. **Accuracy of origin based on proper motion.** The expected 22.2 GHz core position based on the parallax and proper motion fitting results of Reid et al. (2014) yield the origin of the plot (which is not necessarily the point of origin of the ejection). The uncertainty associated with its location is \((\Delta \text{R.A.}, \Delta \text{decl.}) = (0.055 \text{ mas}, 0.100 \text{ mas})\).

2. **Optical depth effects.** The radio core detected in the parallax measurements is detected at high frequency (22.2 GHz) and the data have been checked for a constant flux over the observations in order to validate the application of a Fourier transformation of the interferometer data (Reid et al. 2014). The indication is that the detections are most likely the optically thick emission commonly associated with a compact jet (Klein-Wolt et al. 2002; Gallo et al. 2003; Rushton et al. 2010a). Thus, one does not see the point of origin, but the synchrotron self absorption (SSA) optical depth, \(\tau \sim 1\) surface. Modeling the source of multiple compact jets in GRS 1915+105 in Punsly & Rodríguez (2016) consistently indicated that the peak of the 15 GHz flux density was \(\approx 0.3 \text{ mas}\) from the true position of jet origin. Likewise, we expect that the peak of the 22.2 GHz emission is offset from the true point of origin for the putative compact jets detected by parallax observations. However, being much weaker than the compact jets considered in the previous models of Punsly & Rodríguez (2016), the dimensions are likely smaller. Previous jets were \(\sim 10\) times brighter than the putative compact jets monitored for the parallax measurements (Reid et al. 2014). The surface area of the \(\tau \sim 1\) surface scales with the luminosity (in a highly modeled dependent manner). Thus, we expect the magnitude of the core shift to be smaller as well. Furthermore, there is less opacity at higher frequency and highly simplified models of jets indicate that the core shifts scales like the observing frequency as \(\nu^{-1}\) (Blandford & Königl 1979). There are two effects, a smaller dimension in the weaker compact jets and an upstream shift of the core toward its true position due to less optical depth at 22.2 GHz. We incorporate this broad range of possible upstream dislocations by placing the point of jet origin, corrected for optical depth effects, to be at \(\approx 0.2 \pm 0.1 \text{ mas}\) upstream of the proper motion estimated 22 GHz peak flux density position.

3. **Statistical scatter in the fit to the trajectory.** The trajectory is estimated from a least squares fit with uncertainty in both variables. The data scatter leads to an uncertainty in the best fit trajectory.

Our first step in the determination of the ejection time is to fit the data by a linear least squares with uncertainty in both variables (Reed 1989). Unlike Reid et al. (2014), we do not exclude the outlier point. The best fit to the data scatter in Figure 2 is the solid line and the dashed lines show the 95% confidence contours of the fit. The next step is to find the radio core adjusted for optical depth effects based on points 1 and 2 above. We displace the origin 0.2 mas upstream of the point \((0, 0)\) parallel to the direction given by the slope of the trajectory obtained from our least squares fit. We find the shifted radio core location based on astrometry and the shift due to optical depth to be at \((0.15 \pm 0.09 \text{ mas}, 0.13 \pm 0.12 \text{ mas})\), where the errors are obtained by adding the errors in points 1 and 2 above in quadrature. This shifted astrometric core location is noted by the red cross in the upper right hand corner of Figure 2. The cross represents the
The uncertainty in the time measurement from the slope of the best linear fit to the end of the paragraph above. Using the speed of the ejection, the uncertainty that is associated with the point of origin noted at the centroid as the best choice for the point of origin, we find that it is located at \((0.23 \pm 0.11\text{ mas}, 0.82 \pm 0.11\text{ mas})\) with 95% confidence.

Using this estimate for the point of origin, we can compute the time of the ejection by plotting the displacement from the point of origin versus time and extrapolating backwards in time. This is done in Figure 3. The least squares fit with uncertainty in both variables is given by the solid line with the 95% contours shown as the dashed lines. The slope of the line is 0.97 mas hr\(^{-1}\). The time of origin from the fit is MJD 56436.274 \pm 0.012. However, this does not include the uncertainty that is associated with the point of origin noted at the end of the paragraph above. Using the speed of the ejection from the slope of the best linear fit to the observed relationship in Figure 3, we can translate the uncertainty in location of the point of origin to an uncertainty in time and add this uncertainty in quadrature with the uncertainty associated with the fit. We obtain a 95% confidence contour for the time of ejection,

\[
\text{EJECTION TIME} = \text{MJD 56436.274}^{\pm 0.016}_{-0.013}.
\] (1)

Because the precise timing of the X-ray variations and the ejection time is critical in order to extract the physical mechanism responsible for discrete ejections, the exercise above is necessary. The method used by Reid et al. (2014), while providing results consistent with ours, suffers from a high uncertainty on the true core position leading to slightly different times of ejection when considering the north–south and east–west ejections. Here by precisely re-setting the origin of the ejection we strengthen and refine the zero-time of the ejection. Figure 2 shows that our estimated point of origin for the jet is \(\approx 1\sigma\) from the estimated radio core position. This type of accuracy is essential for understanding the precise timing of the event.

4. MAXI OBSERVATIONS

We downloaded the data from the MAXI pipeline around the time of the ejection. The light curves of the 2.0–6.0 keV count rates and the 2.0–20 keV count rates are plotted in Figure 4. The ejection time estimated in the last section is indicated by the dotted black vertical line. The thickness represents the range of uncertainty. For more than 24 hr GRS 1915+105 is in a low X-ray state from MJD 56435.047 to MJD 56436.080. Typically, data are taken every 1.5 hr, but a key data point was missed after this. Thus, with this limitation, we note that 4 hr later the X-ray flux is at a maximum. The X-ray luminosity peak occurs on MJD 56436.259. Comparing this date to Equation (1), this elevated X-ray flux precedes the onset of the ejection by 21.8\(^{\pm 22.0}\) minutes with 95% confidence. This is the finest and most accurately determined juxtaposition in time of an X-ray spike and an MFE. We have clearly verified point 1 from the introduction. The flux and count rate in both the 2.0–6.0 keV and 2.0–20.0 keV windows increases by \(\gtrsim 100\%\) in \(\leq 4.3\) hr (Table 1 and Figure 3). It is uncertain if the ejection is still taking place during the next MAXI observation on MJD 56436.323.

Based on our estimate of the ejection time above, we use the MAXI spectral data to look for spectral evolution before and during ejection. The sensitivity of MAXI is low (low effective area), and we needed to bin the data over the quiescent period preceding the flare in order to better constrain the spectral fits. This was acceptable because the source was slowly varying in time. Our spectral fits are based on an absorbed powerlaw model (\texttt{tbabs*powerlaw} in XSPEC terminology) with abundances obtained from Wilms et al. (2000). The absorbed powerlaw models applied to the MAXI data from 1 to 20 keV are described in Table 1. The first column gives the date of the
observation. The next column is the fitted column density of hydrogen, \( N_{\text{H}} \). The third column is the photon index of the powerlaw fit to the data, \( \Gamma \). Columns four and five are the absorbed flux and the unabsorbed (intrinsic) flux that results from removing the absorbing effects of \( N_{\text{H}} \), respectively. The last column is the reduced \( \chi^2 \) of the fit. The errors on the fitted parameters are at 90% confidence. There are some evident trends in Table 1 for the 56436.27 flare. Obviously, the luminosity increases before the ejection. But, we also see that \( \Gamma \) steepens preceding the flare. This was observed in MFEs previously observed with MAXI (Punsly et al. 2014). The uncertainty in the photon index in Table 1 makes this phenomenon less than statistically significant. We do not see an increase in \( N_{\text{H}} \) immediately before the flare as previously observed with MAXI (Punsly et al. 2014). The combination of a weak flare and the low sensitivity of MAXI makes the spectral analysis difficult and it might be that for such a weak flare that trends are undetectable with any significance. We also note a few limitations of the data. First, the fit to the last data entry in Table 1 is poor. There are just not enough counts to get good spectral information. Binning or combining observations is unfortunately not possible here, there is only the one widely spaced observation (shown in Figure 4) over the next two days. Furthermore, the changes are so rapid and the fluxes so low for this flare that it has poor statistics.

In this article, we re-examined a VLBA observation beginning \( \sim 1 \) hr after the onset of the ejection of a plasmoid of modest luminosity in order to explore the disk–jet connection for superluminal ejections with unprecedented accuracy. We used this fortunate circumstance in combination with X-ray monitoring with MAXI to verify that an increase in X-ray luminosity preceded the ejection. We were able to verify that the X-ray flux begins to increase 2–4 hr before the ejection and the elevated flux persists within \( \pm 2 \) minutes of the onset of the ejection with 95% confidence. This is one of the five X-ray properties (listed in the Introduction) detected before in larger MFEs with coarse time resolution of X-ray coverage and much coarser estimates of the times of ejection. The other four properties noted in the Introduction could not be verified, due to the fact that the ejection was relatively weak and brief and the MAXI time resolution and sensitivity were not adequate. The most interesting aspect eluded us due to insufficient time sampling of the X-ray data: when does the rise in X-ray luminosity end relative to the ejection time? We performed time resolved spectroscopy with MAXI even though the count rates were generally small to moderate. We did see a trend (although not statistically significant with the low number of counts) previously detected with MAXI that the spectral index of the X-ray powerlaw steepens when the X-ray luminosity increases before ejection (Punsly et al. 2014).

### Table 1

| Date MJD | \( N_{\text{H}} \) | \( \Gamma \) | Observed Flux 1–10 keV \( (10^{-8} \text{erg s}^{-1}\text{cm}^{-2}) \) | Intrinsic Flux 1–10 keV \( (10^{-8} \text{erg s}^{-1}\text{cm}^{-2}) \) | Reduced \( \chi^2 \) (dof) |
|----------|-----------------|-------------|----------------------------------------|---------------------------------------------|------------------------------|
| 56436.05 ± 0.04 | \( 7.2^{+3.0}_{-1.5} \) | 2.4 ± 0.2 | 1.0 | 2.7 | 0.69(26) |
| 56436.18 ± 0.02 | \( 8.8^{+3.7}_{-2.1} \) | 2.8 ± 0.3 | 1.5 | 5.4 | 0.89(20) |
| 56436.26 ± 0.01 | \( 8.1^{+2.8}_{-1.8} \) | 2.7 ± 0.2 | 2.0 | 6.4 | 1.15(25) |
| 56436.65 ± 0.01 | \( 6.2^{+2.5}_{-1.1} \) | 2.4 ± 0.3 | 1.5 | 3.7 | 0.3(20) |

5. DISCUSSION
Our results suggest a possible link between weak radio “bubbles” and MFEs. First, weak radio “bubbles” with flux densities of 10–60 mJy at 15 GHz have been associated with X-ray cycles in X-ray classes $\nu$, $\lambda$, $\kappa$ and $\beta$ (Rodriguez et al. 2008a, 2008b). X-ray spikes occur on the order of seconds to minutes before an increase in radio flux occurs. The spikes are accompanied by a softening of the X-ray spectrum similar to the spectral steepening seen here and in other MAXI observations of MFEs (Punsly et al. 2014). The discrete ejection observed here is $\approx$45 mJy at 8.2 GHz (1.7 days after the ejection according to Figure 1) and forms a possible example of a common ejection mechanism that straddles the luminosity gap between the fainter “bubbles” ejections and the brighter MFEs. Furthermore, the phenomena of an X-ray spike preceding ejections seems to extend to stronger radio emission, up to 120 mJy in other quasi-periodic cycles (Prat et al. 2010). However, we note that no discrete ejections were monitored.

The unification of these phenomenon has some significant discrepancies. The single discrete ejection discussed here and MFEs are temporally different from quasi-periodic episodes described in (Dhawan et al. 2000; Rodriguez et al. 2008a, 2008b; Prat et al. 2010). There is no cycle, the event happened once. Also, the timescale for the X-ray spike to grow is much larger for the one time discrete ejections than for quasi-periodic cycles (Prat et al. 2010). Furthermore, strong quasi-periodic radio states showed no discrete components in VLBA monitoring (Dhawan et al. 2000). The radio image is morphologically similar to a blow-torch flame with no concentrations of intensity. This might be an artifact of blurring from multiple ejections moving a beam width in $\sim$1 hr and poor $u$–$v$ coverage from only 10 antennas.

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