Evidence for a Disk-Jet Interaction in the Microquasar GRS 1915+105

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We report simultaneous X-ray and infrared (IR) observations of the Galactic microquasar GRS1915+105 using XTE and the Palomar 200-inch telescope on August 13-15, 1997 UTC. During the last two nights, the microquasar GRS 1915+105 exhibited quasi-regular X-ray/infrared (IR) flares with a spacing of ~ 30 minutes. While the physical mechanism triggering the flares is currently unknown, the one-to-one correspondence and consistent time offset between the X-ray and IR flares establish a close link between the two. At late times in the flares the X-ray and IR bands appear to “decouple”, with the X-ray band showing large-amplitude fast oscillations while the IR shows a much smoother, more symmetrical decline. In at least three cases, the IR flare has returned to near its minimum while the X-rays continue in the elevated oscillatory state, ruling out thermal reprocessing of the X-ray flux as the source of IR flare. Furthermore, observations of similar IR and radio flares by Fender et al. (1997) imply that the source of the IR flux in such flares is synchrotron emission. The common rise and subsequent decoupling of the X-ray and IR flux and probable synchrotron origin of the IR emission is consistent with a scenario wherein the IR flux originates in a relativistic plasma which has been ejected from the inner accretion disk. In that case, these simultaneous X-ray/IR flares from a black-hole/relativistic-jet system are the first clear observational evidence linking of the time-dependent interaction of the jet and the inner disk in decades of quasar and microquasar studies.

Subject headings: infrared: stars – Xrays: stars – black hole physics – stars: individual: GRS 1915+105
1. Introduction

The galactic microquasar GRS1915+105 is one of the most fascinating objects in astrophysics today. Discovered as a transient hard X-ray source (Castro-Tirado et al., 1992), GRS1915+105 is best-known as the first Galactic source of superluminal jets (Mirabel and Rodríguez, 1994). The other known Galactic source of superluminal jets, GRO1655-40, has been shown to harbor a compact object of mass $\sim 7M_\odot$ (Orosz and Bailyn, 1997), implying that both GRO1655-40 and GRS1915+105 are powered by accretion onto a black hole. The combination of relativistic jets and a central black hole has in turn earned these two objects the name "microquasar", as they seem to be the stellar-mass analogs of the massive black hole systems in quasars and AGN.

The microquasars offer an exciting opportunity to study the physics of the black-hole/relativistic-jet interaction in ways that are impossible in "normal" quasars. In particular, the fact that Galactic microquasars are much smaller than quasars means that they can vary on much faster timescales – fractions of a second to days rather than weeks to years – and the fact that they are closer by orders of magnitude means that relatively fainter features can be observed. While Harmon et al. (1997) have shown a long-term correlation between hard X-ray flux and jet activity in a microquasar, the hard X-ray instruments lacked the sensitivity to study any fast variability which might reveal the details of the interaction between the jets and accretion. Well-collimated outflows have also been observed in a large variety of nonrelativistic systems, including young stellar objects, planetary nebulae and accreting white dwarf supersoft sources (see Livio 1997 for a recent review). All of these systems have jet velocities comparable to the escape velocity from the central object, which strongly suggests the jet must somehow tap accretion energy being liberated in the very inner disk. However, the actual mechanism which launches the jet is poorly understood, and no detailed time-dependent correlation between the disk
activity and jet variability has ever been observed. In the following sections, we present X-ray and infrared (IR) observations of GRS1915+105 revealing such fast variability which may have important implications for both quasars and microquasars. We then discuss the overall characteristics of this variability, possible interpretations of this behavior, and its ramifications for the black-hole/relativistic-jet interaction. We will give a more detailed analysis of the data and possible theoretical interpretations in a forthcoming paper (Eikenberry et al., in preparation). Finally we present the conclusions drawn from these observations.

2. Observations and Data Reduction

We observed GRS 1915+105 on the nights of 13-15 August 1997 UTC using the Palomar Observatory 200-inch telescope and the Cassegrain near-infrared array camera in the K (2.2μm) band. We configured the camera for high-speed operation, taking 64x64-pixel (8x8-arcsec) images at a rate of 10 frames per second. Absolute timing was provided by a WWV-B receiver with ~ 1 ms accuracy. The camera computer system limited us to 4000 consecutive frames before restarting the integration. We observed GRS 1915+105 in this mode for approximately 5 hours each night, obtaining ~ 1.5 x 10^5 frames per night. The field of view in this mode was large enough to capture both GRS 1915+105 and a nearby field star, Star A, which has a magnitude of $K = 13.3$ mag (Eikenberry and Fazio, 1996; Fender et al., 1997). For each frame, we subtracted an averaged sky frame to remove the array bias features which dominate the short exposures, and then divided the result by a flat field. For each star (GRS 1915+105 and Star A), we then calculated the flux within a ~ 1-arcsec-radius software aperture, and subtracted the sky flux from a surrounding annulus. We used the measured flux from Star A as a reference, smoothing it with a 5-second boxcar filter to increase signal-to-noise ratio, dividing it into the GRS 1915+105
flux, and then multiplying the result by the 3.1 mJy flux density of Star A at 2.2μm. We present the resulting flux density for GRS 1915+105 on Aug. 14-15 UTC with 1-second time-resolution in Figure 1. We obtained X-ray observations on the same nights using the PCA instrument on the Rossi X-ray Timing Explorer (RXTE - see Greiner, Morgan, and Remillard (1996) and references therein for further details regarding the instrument and data modes). Due to unfavorable Earth-Sun-GRS 1915 geometry at the time of the observations, only a limited fraction of the IR observations had simultaneous X-ray coverage. We present the segments of data with significant (> 500 sec) simultaneous coverage in Figure 2.

3. Discussion

3.1. Flaring Behavior

The most obvious features in Figures 1 and 2 are the large amplitude X-ray/IR flares, which appear with a quasi-periodicity of ~ 30 minutes on both August 14th and 15th. Similar behavior has been observed previously in the X-rays (Greiner, Morgan, and Remillard, 1996), radio (Rodriguez and Mirabel, 1997; Pooley and Fender, 1997), and in the IR (Fender et al., 1997). However, simultaneous coverage in both the X-rays and IR has never been obtained until now. The overlapping coverage here allows us to establish that there is a one-to-one correspondence between the X-ray and IR flares – for every X-ray flare (of 7) there is a corresponding IR flare, and vice versa. While this could certainly be expected from previous observations, this is the first conclusive evidence that the X-ray and IR flares are caused by the same events.

Except for the ubiquitous X-ray precursor spike, both the X-ray and IR flare rises are relatively smooth and have essentially monotonic rising edges. In Figure 2, the IR flare peak is offset in time relative to the X-ray flare peak. Table 1 gives the time offsets of the IR
peak relative to the X-ray peak for the flares in Figure 2 that have sufficient simultaneous coverage. In all 6 cases the time offset between the peaks is consistent with a value of $\sim 300$ seconds, and a $1/\sigma^2$-weighted combination of the measured time offsets gives an average time offset between the peaks of $310 \pm 20$ seconds. The time offset between the X-ray peak and the X-ray precursor as well as the time offset between the beginning of the X-ray rise and the X-ray peak are also constant within the uncertainties given in Table 1. Thus, the data do not support any particular interpretation of the the value of the time offset between the peaks (such as associating it with the light travel time between the X-ray and IR-emitting regions). Furthermore, it is interesting to note that the X-ray precursor spikes appear to be coincident with the beginning of the IR flares, suggesting that the spikes may be associated with the initiation of the IR flares. However, the constancy of this offset and the one-to-one correspondence of the flares are compelling evidence that the rising edges of the X-ray and IR flares are closely linked, and possibly triggered by the same event.

Such a linkage is not present, however, in the latter stages of the flares. After reaching its peak flux, the X-ray flare enters a wildly oscillating high state, with rapid large-amplitude variability (changes of near 80% of maximum flux on timescales of $\sim 10$ seconds). These oscillations continue for several hundred to several thousand seconds before the return to the X-ray low-state. The IR flares, on the other hand, appear to show decaying phases very similar in their smoothness and timescale to the rising phases. In particular, no large amplitude oscillations are present in the IR. Smaller amplitude ($\sim 10 - 30\%$) IR variability on $\sim 10$-second timescales is present in some flares (e.g. the flare $\sim 9000$ seconds after MJD 50674.125 in Figure 1). We will discuss these “sub-flares” in detail elsewhere, and only note here that this variability is not seen in every flare (in contrast to the X-ray oscillations), and when present it is not correlated with the X-ray variability in any obvious way.

We can also see that oscillations similar to those seen in the X-rays are not simply
“smeared out” in the IR by examining the simultaneous observations near $t \sim 10000$ seconds and $t \sim 17500$ seconds after MJD 50674.125 and $t \sim 10000 - 12000$ seconds after MJD 50675.125. In all three cases, the X-ray oscillations continue with a time-averaged flux near one-half of the flare maximum while the IR flux has returned to near minimum. To show this more clearly, we took the X-ray and IR data from $t = 16000 - 18000$ seconds after MJD 50674.125, subtracted the baseline from both bands, and divided by the maximum flux level, resulting in the normalized flare shown in Figure 3. This figure clearly shows that the IR flux has declined to near its minimum level while the X-rays remain in the elevated oscillatory state. Thus, we conclude that the X-ray and IR emissions do indeed “decouple” from one another during the decay phases of the flares.

### 3.2. Interpretation of the Flares

This behavior is inconsistent with a scenario wherein the majority of the IR flux arises from thermal reprocessing of a fraction of the X-ray flux on structures near the black hole (the disk and/or companion star). In such a scenario, radiative delays are negligible, but light travel time effects cause both delay and smearing of the reprocessed flux as compared to the X-ray, as is seen in the optical counterparts of X-ray bursts from X-ray binaries (Pedersen et al., 1982). This is in direct opposition to the observed behavior in Figure 3, where the IR flare continues to drop while the X-rays oscillate around a high average value. Simultaneous X-ray/IR observations on Aug. 13 1997 UT also contradict the thermal reprocessing scenario, having high X-ray count rates of $\sim 3 \times 10^4$ s$^{-1}$ but IR flux densities of $\sim 5$ mJy — only slightly above the minimum seen here. Thus, we conclude that thermal reprocessing of the X-ray flux cannot be the primary source of IR flux during the flares.

On the other hand, the observed behavior of the X-ray/IR flares is consistent with a scenario wherein the IR flux arises from ejected synchrotron-emitting plasma. As noted
above, the one-to-one correspondence between the X-ray/IR flares and the constant time offset between the X-ray/IR peaks indicate that the same event triggers both flares, and thus imply that the IR- and X-ray-emitting regions are initially physically close to each other. The subsequent decoupling of the IR emission from the X-rays implies that a significant separation between the IR-emitting and X-ray-emitting regions develops at later times. Since the post-flare X-ray oscillations continue to show peak luminosities of $\sim 10^{39}$ ergs/s, the X-ray emission region must remain very close to the compact object, and is very likely the inner disk. Therefore, we conclude that the IR-emitting plasma arises from the inner disk and is ejected from the system.

This scenario is also supported by same-day IR and radio observations of previous IR flares from GRS 1915+105 (Fender et al., 1997). The high brightness temperature of the radio flares ($\sim 10^{10}$ K) rules out a thermal origin. This fact, together with the flat radio spectrum of the flares (pooley and Fender, 1997), and the linear polarization of the source during flaring activity ($\sim 1\%$; Rodriguez and Mirabel, 1997) strongly implies a synchrotron origin for the flares. The decay timescales are similar for both the radio and IR flares, implying that adiabatic expansion may be the dominant cooling mechanism. Thus, these observations also favor the interpretation of the IR flares as emission from ejected plasma. Further radio observations (Pooley and Fender, 1997) revealed wavelength-dependent delays in the peaks of the radio flares. If the IR-radio flares are due to expanding ejecta, it is tempting to explain such a delay as the transition from optically thick to optically thin synchrotron emission at longer and longer wavelengths. Such an interpretation might also explain why the X-ray/IR time offset between the peaks here is 300 seconds, while at other times the X-ray/radio peak separation appears to be closer to $\sim 800$ seconds (Pooley and Fender, 1997). However, while this explanation agrees qualitatively with the observations, it is not clear that the observed time offset scaling versus frequency is compatible with such a transition in an adiabatically-expanding plasma.
The plasma ejection scenario is by no means the only possible explanation for the behavior shown above. The salient features are that the X-ray and IR flares are triggered by the same event, but are clearly decoupled from one another at late times in the flare. However, given that GRS 1915+105 is known to eject synchrotron-emitting blobs of relativistic plasma (Mirabel and Rodriguez, 1994), the ejection hypothesis seems the most likely and natural explanation for the behavior observed here. We note, however, that even if the flares are due to plasma ejection, they are NOT identical to the superluminal events observed from GRS 1915+105. The timescales of the flares, on the order of 2000 seconds (see Figure 1), is significantly faster than the several-day timescale seen during superluminal ejections (Mirabel and Rodriguez, 1994). Furthermore, the radio fluxes of flares similar to those in Figure 1 are lower than the major ejections by an order of magnitude (Fender et al., 1997). Thus, any plasma ejection taking place in the 14-15 August 1997 observations can at most be a “baby jet” analog to the much larger superluminal ejection events.

4. Conclusion

We have seen simultaneous X-ray/IR flares from GRS 1915+105 with a quasi-regular spacing of ∼ 30 minutes. The one-to-one correspondence of the X-ray flares with the IR flares, and the constant time offset between them establishes that both flares originate from the same event. At late times in the flare, the X-ray and IR flares appear to decouple, ruling out thermal reprocessing of the X-rays as the source of the IR flares. This behavior is consistent with ejection of an IR-emitting plasma from the system during increased activity in the inner accretion disk.

If the simultaneous X-ray/IR flares are indeed the signatures of plasma ejection in GRS 1915+105, then they are giving us insights into the “central engine” of a black-hole/relativistic-jet system. Despite the fact that quasar and AGN jets have been studied
for decades, no observations of the central jet engine have been possible due to the great
distances to the quasars. Since microquasars are much smaller, closer, and vary faster than
the extragalactic systems, they have been considered as potential “laboratories” for the
study of the physics of black-hole/relativistic-jet systems. From the observations reported
here, it appears that the microquasars have lived up to this potential. In particular, these
observations intimately link the apparent plasma ejection to activity in the inner accretion
disk – an important constraint for the multitude of theoretical models attempting to
describe black-hole/relativistic-jet systems. More detailed analyses of this rich data set and
further multi-wavelength observations of GRS 1915+105 will undoubtedly yield even more
insight into the physical characteristics and behaviors of the central engines.

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REFERENCES


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Table 1. Time offsets between the X-ray peaks and IR peaks for the flares shown in Figure 2. The X-ray and IR time series were rebinned to 10-second resolution (to smooth over the rapid small-scale variability), and peaks determined as the time when the flare reaches maximum flux. The uncertainty in this value is determined by the time span over which the flux is equal to the maximum within the statistical uncertainties (see Figures 1 and 2), and thus depends on both the sharpness of the flare peak and the statistical uncertainties in the flux measurements.

<table>
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<tr>
<th>MJD</th>
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<th>Offset (s)</th>
<th>Unc. (s)</th>
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<td>400</td>
<td>$\pm 50$</td>
</tr>
<tr>
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<td>305</td>
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</tr>
<tr>
<td>50675</td>
<td>17000</td>
<td>255</td>
<td>$\pm 160$</td>
</tr>
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</table>

$^a$Approximate start of the X-ray flare as measured from 3 UTC on given date (= MJD + 0.125).
Fig. 1.— Infrared flux density from GRS 1915+105 measured with 1-second time-resolution in the K (2.2μm) band from the Palomar 200-inch telescope. Typical uncertainties (±1σ) are shown - they are dominated by the uncertainty in the reference flux density from Star A, and are calculated by taking the standard deviation in that flux density and multiplying by the ratio of the GRS 1915+105 flux density to the reference flux density.
Fig. 2.— Simultaneous X-ray and infrared observations of GRS 1915+105 at 1-second time-resolution. X-ray flux is in PCA counts/s, IR flux density is in milliJansky. Typical uncertainties are shown for the IR. The X-ray uncertainties are assumed to be Poissonian, and are too small to be seen on this scale.
Fig. 3.— Simultaneous observations of a flare in the (a) X-ray, (b) IR. Both bands have a constant baseline subtracted and are normalized to a maximum amplitude of 1.0. Note that the IR flare has returned to near its baseline level, while the X-rays continue to oscillate wildly with a time-averaged flux near one-half of the flare maximum. This behavior rules out thermal reprocessing of the X-rays as the primary source of IR flux in the flare.