EVIDENCE FOR A DISK-JET INTERACTION IN THE MICROQUASAR GRS 1915+105

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ABSTRACT

We report simultaneous X-ray and infrared (IR) observations of the Galactic microquasar GRS 1915+105 using the Rossi X-Ray Timing Explorer and the Palomar 5 m telescope on 1997 August 13–15 UTC. During the last two nights, the microquasar GRS 1915+105 exhibited quasi-regular X-ray/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 the IR flares. Furthermore, observations of similar IR and radio flares by Fender et al. 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 are consistent with a scenario wherein the IR flux originates in a relativistic plasma that 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 revealing the time-dependent interaction of the jet and the inner disk in decades of quasar and microquasar studies.

Subject heading: black hole physics — infrared: stars — stars: individual (GRS 1915+105) — X-rays: stars

1. INTRODUCTION

The Galactic microquasar GRS 1915+105 is one of the most fascinating objects in astrophysics today. Discovered as a transient hard X-ray source (Castro-Tirado, Brandt, & Lund 1992; Castro-Tirado et al. 1995), GRS 1915+105 is best known as the first Galactic source of superluminal jets (Mirabel & Rodriguez 1994). The other known Galactic source of superluminal jets, GRO 1655−40, has been shown to harbor a compact object of mass ~7 M☉ (Orosz & Bailyn 1997), implying that both GRO 1655−40 and GRS 1915+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 “microquasars,” as they seem to be the stellar mass analogs of the massive black hole systems in quasars and active galactic nuclei (AGNs).

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 that might reveal the details of the interaction between 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 that the jet must somehow tap accretion energy being liberated in the very inner disk. However, the actual mechanism that launches the jet is poorly understood, and no detailed time-dependent correlation between disk activity and jet variability has ever been observed. In the following sections, we present X-ray and infrared (IR) observations of GRS 1915+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. 1998).

Finally, we present the conclusions drawn from these observations.

2. OBSERVATIONS AND DATA REDUCTION

We observed GRS 1915+105 on the nights of 1997 August 13–15 UTC using the Palomar Observatory 5 m telescope and the Cassegrain near-infrared array camera in the K (2.2 μm) band. We configured the camera for high-speed operation, taking 64 × 64 pixel (8' × 8') images at a rate of 10 frames per second. Absolute timing was provided by a WWVB 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 hr each night, obtaining ~1.5 × 10^3 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 & Fazio 1997; Fender et al. 1997). For each frame, we subtracted an averaged sky frame to remove the array bias features that 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 an ~1' 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 s boxcar filter to increase the 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 2.2 \( \mu m \). We present the resulting flux density for GRS 1915+105 on August 14–15 UTC with 1 s 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, & Remillard 1996 and references therein for further details regarding the instrument and data modes). Owing 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 s) 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 \( \sim 30 \) minutes on both August 14 and 15. Similar behavior has been observed previously in the X-rays (Greiner et al. 1996), radio (Rodriguez & Mirabel 1997; Pooley & Fender 1997), and in the IR (Fender et al. 1997). However, simultaneous coverage in both the X-rays and the 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 seven), 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 six cases, the time offset between the peaks is consistent with
a value of \( \sim 300 \) s, and a \( 1/\sigma^2 \)-weighted combination of the measured time offsets gives an average time offset between the peaks of \( 310 \pm 20 \) s. 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 value of the time offset between the peaks (such as associating it with the light-travel time between the X-ray-emitting 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 \( \sim 10 \) s). 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. The observed behavior of the X-ray/IR flares is consistent 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 with 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 1997 August 13 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.

### 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 with 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 1997 August 13 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-emitting 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 postflare X-ray oscillations continue to show peak luminosities of \( \sim 10^{39} \) ergs s\(^{-1} \), 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-

**Table 1**

| MJD   | Flare Time\(^a\) (s) | Offset (s) | Uncertainty (s) |
|-------|----------------------|-----------|-----------------|
| 50674 | 4000                 | 400       | +50, ±110       |
| 11000 | 345                  |           | ±30             |
| 16000 | 285                  |           | ±30             |
| 50675 | 4000                 | 220       | ±160            |
| 15500 | 305                  |           | +20, ±70        |
| 17000 | 255                  |           | ±160            |

*Approximate start of the X-ray flare as measured from 3 UTC on given date (=MJD +0.125).*

**Fig. 3.—**Simultaneous observations of a flare in the (a) X-ray and (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.
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 (∼10^{10} K) rules out a thermal origin. This fact, together with the flat radio spectrum of the flares (Pooley & Fender 1997) and the linear polarization of the source during flaring activity (∼1%; Rodríguez & 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 & 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/Radio time offset between the peaks here is 300 s, while at other times the X-ray/Radio peak separation appears to be closer to ∼800 s (Pooley & 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 & Rodríguez 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 s (see Fig. 1), are significantly faster than the several-day timescale seen during superluminal ejections (Mirabel & Rodríguez 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 1997 August 14–15 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 because of 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 multiwavelength observations of GRS 1915+105 will undoubtedly yield even more insight into the physical characteristics and behaviors of the central engines.

The authors wish to thank G. Neugebauer for useful discussions of these observations. S. E. acknowledges the support of a Sherman Fairchild Postdoctoral Fellowship in Physics.

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