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The Radius Dilemma: A brief look at the QPO Frequency-Inner Disk Radius Connection in GRS 1915+105

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We examine the evolution of the color radius and GRS 1915+105 and compare that to predictions made by the Magnetic Flood Model. This model applies a linear correction to associate the Low Frequency QPO to the Keplerian frequency. Because spectral fits to the X-ray data using XSpec often produce erroneously low color radius results, the quantity is often ignored, but the trend is assumed to be a valid trace of the inner disk radius. We show that, if the radius *trend* established by the X-ray spectral fits can be believed, then no monotonic solution can rectify the QPO frequency to the Keplerian radius. We discuss various caveats and analases that may be performed to further test the Magnetic Flood model.

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1. Introduction

Our story begins as most do, with the arrival of a mysterious stranger. Just 14 years ago, GRS 1915+105 appeared in the X-ray sky and unlike most other X-ray transients known before it, GRS 1915+105 never faded. In fact, it revealed itself to be a mystifying X-ray binary that accreted matter from its companion star and ejected it at near the speed of light. The superluminal radio jet ejections earned GRS 1915+105 the name of 'microquasar' [5].

GRS 1915+105 reveals its complexity through a broad display of multi-wavelength behavior, only some of which is relevant here. (For a more complete review, see [1, 2, 6, 7].) To summarize, GRS 1915+105 has wild X-ray variability and several distinct X-ray light-curve classes with unique (but repeatable) appearance, count rate, and color. There are at least 12 light-curve classes [1], but for this particular analysis, we focus on three: β, α, and θ.

All of these have spectrally hard dips followed by soft X-ray flares and infrared flares. We use several *Rossi X-ray Timing Explorer* (RXTE) observations of GRS 1915+105 (see Table 1). For more complete review of the associated X-ray and infrared behavior, see [2], [4], and [7]. The IR flares associated with each are ~ 100 mJy for the β-class, ~ 10 mJy for the α-class, and ~ 5 mJy for the θ-class. In all cases, the infrared flare begins as the X-ray hard dip ends.

During these spectrally hard dips a low-frequency quasi-periodic oscillation (LFQPO) appears. It is believed that the LFQPO's frequency and evolution can tell us about the processes leading to the disruption of the accretion disk and subsequent jet ejection. QPO models tend to tie the LFQPO to a magnetoacoustical frequency (e.g., [9]) or a Keplerian frequency (e.g., [3]). The general problem with the latter is that the LFQPO is too low to be a Keplerian frequency without some scaling. For a complete description on the XSpec spectral analysis and QPO frequency detection methods used herein, see [4].

2. The Magnetic Flood Model and the Radius Dilemma

A model that has recently come into favor is the Magnetic Flood model, which ties the LFQPO to an Accretion-Ejection Instability frequency [8]. Using a single spiral arm model, the source of the AEI is associated outward to a co-rotation radius which is (in some magentic regimes) associated with the Keplerian Frequency (and hence Keplerian radius). This would mean the the QPO frequency and the radius are directly connected, which according to early literature they are, somewhat [6]. However, according to [4], the radius is very poorly correlated to the LFQPO, as compared to other spectral features. Thus, either the LFQPO is not tracing the Keplerian frequency or the color radius is not tracing the inner disk radius. I refer to this contradiction as the Radius Dilemma.

The dissociation of the color radius and the inner disk radius is not a surprising contributer to this dilemma. When we fit the X-ray spectra using XSpec 11.3, the blackbody normalization reveals a radius too small to be the innermost stable orbit. In fact, most of the time, the measured radius is inside the Schwarzschild radius. This is a known problem that seems to be often ignored. In fact, [3] did a reliability study using XSpec. They created a series of model X-ray spectra, added noise and accounted for detection quirks, and found that the XSpec radius fits were inherently

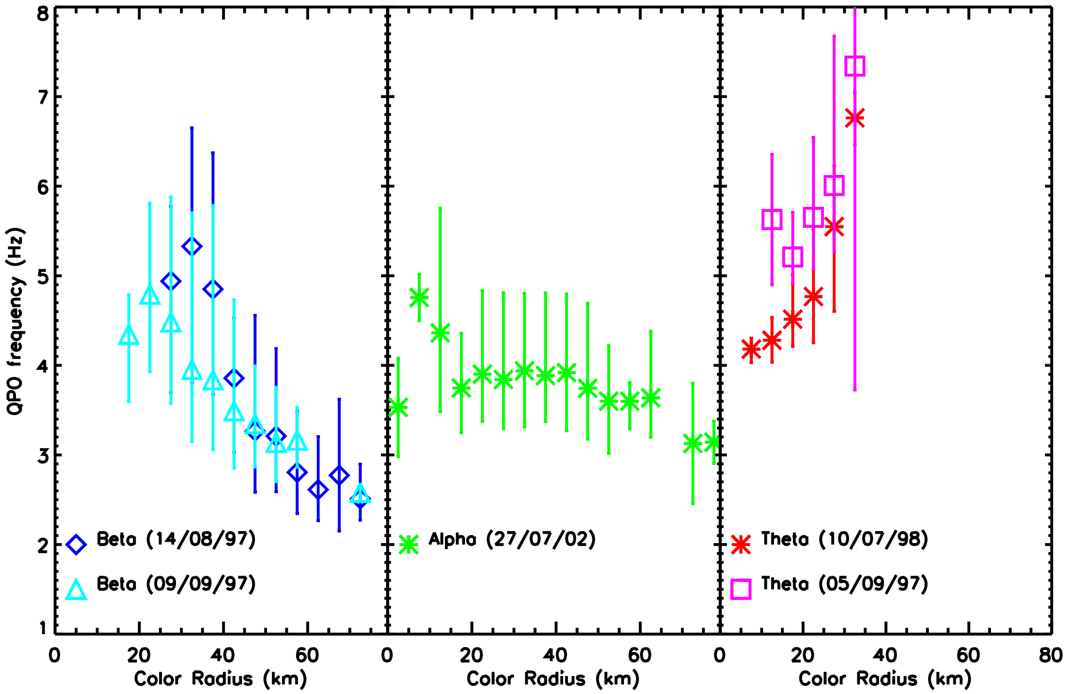

Figure 1: The color radius vs. QPO frequency. The bars on these points represent the dispersion of frequencies observed in each radius bin. Although the average points for the β-class suggest a trend reminiscent of Keplerian, there is high dispersion at the lower radii. The α-class shows no apparent trend between color radius and QPO frequency. The θ-class shows an inverted relationship. These points represent averages among 17 different hard dip events.

unreliable. They also found that there is no single correction factor that can be applied to correct the measured radius to the true radius, especially in a volatile system.

Despite the known caveats, the belief persists that the LFQPO and the color radius can be associated to the common ground of the Keplerian frequency. This is in part because in a subset of observations, the LFQPO and the color radius show an apparent trend of $\nu_{QPO} \propto R_{col}^{-3/2}$. Of the 17 light-curves we examine for this work, only three show this apparent trend. In Table 1, we have fit the LFQPO and the color radius. We restrict ourselves to the first 200s of each dip, as the blackbody flux is still relatively strong here and the trace of the blackbody normalization is probably more reliable. In examining 9 β-class light curves, three α-class light-curves, and five θ-class light curves, we find that the only time an apparent "Keplerian" relationship exists between the LFQPO and color radius is in the β-class. Even then, it is inconsistent. Both the α- and θ-class show relatively flat relationships. In fact, when considering the entire dip, the θ-class shows a relationship inverse of what one would expect. In Figure 1, we plot the relationship of the color radius to the LFQPO when considering the full length of the dip. We see that the radius relationship is inverted in the θ-class.

It is worth noting that since all of these are spectrally hard states, we are in a terrible position for distinguishing blackbody flux from the total flux. One may think it is simply not worth believing contradictions in such an unreliable statistic. But we do know that other parameters like total flux, blackbody flux, blackbody temperature, and powerlaw flux show trends with QPO frequency that are consistent between the three classes.

At this juncture, our options are two-fold. First, we can assume that the model is wrong and that Keplerian frequency is not tied to the QPO frequency. Second, we can assume that the model is right and that the problem lies in our ability to observe the blackbody and measure the radius.

The first option is not necessarily the case because there exists a regime in the AEI model where the LFQPO-radius relation exhibits an inversion [10]. It would not be unreasonable to assume that the magnetic field conditions are sufficiently different between the three clases so as to push us onto different regimes of this curve. We are currently testing this hypothesis.

Despite the existence of a turnover, we should probably expect that within a certain class, we can operate within a single regime of the model. Because we know that the β-class falls within the "Keplerian" regime, we perform the following test of the second hypothesis. First, using a β-class light curve, we have found the QPO frequency as a function of time. Then using the scaling factor of 2.5 Hz:58 km (based on data fitting), we have calculated a theoretical blackbody normalization based on the QPO frequency. We allow for an error of 0.6 Hz based on the standard scatter of the QPO frequency. We then use XSpec to fit our spectra using this stricter constraint on the blackbody normalization parameter. Attempts to absolutely fix the blackbody normalization parameters yielded no good fits. Even allowing for the error associated with 0.6 Hz and a loose restriction of $\chi^2 < 8$, we find that 50% of our spectra failed to make any fit. In contrast, when allowing the color radius to be completely free and placing a tighter constraint of $\chi^2 < 2$, we find good fits for 90% of the spectra. We compare the results of the two spectral fits in Figure 2. This preliminary test suggests that the color radius cannot be forcibly conformed to the predictions of the Magnetic Flood model in the β-class. We intend to repeat this experiment with other data sets in order to test this result.

3. Discussion and Conclusions

The Radius Dilemma, as we have called it, is a multi-layer dilemma arising from attempts to associate the poorly understood LFQPO with the better understood Keplerian frequency. Here, we have sought to reiterate a few oft-looked over issues and point out a few more caveats that need to be addressed when modeling the QPO. In summary, we have shown:

1. XSpec produces erroniously low radius fits. [3] have previously studied this and shown that the radius fits cannot be monotonically adjusted to an associated inner disk radius.

2. If the radius trend traces the inner disk radius, then no monotonic scaling factor can rectify the LFQPO to the Keplerian frequency.

3. The Magnetic Flood model does have a potential solution for the inverted LFQPO-radius relation seen in the θ-class. However, attempts to constrain the color radius in XSpec fits using the Magnetic Flood model yields poor fits for half of the data. This suggests that a true Keplerian relationship does not exist between QPO frequency and color radius.

Our general dilemma is enhanced because of problems inherent to the data we have collected. First, being in a spectrally hard state, it is difficult to accurately detect the blackbody contribution

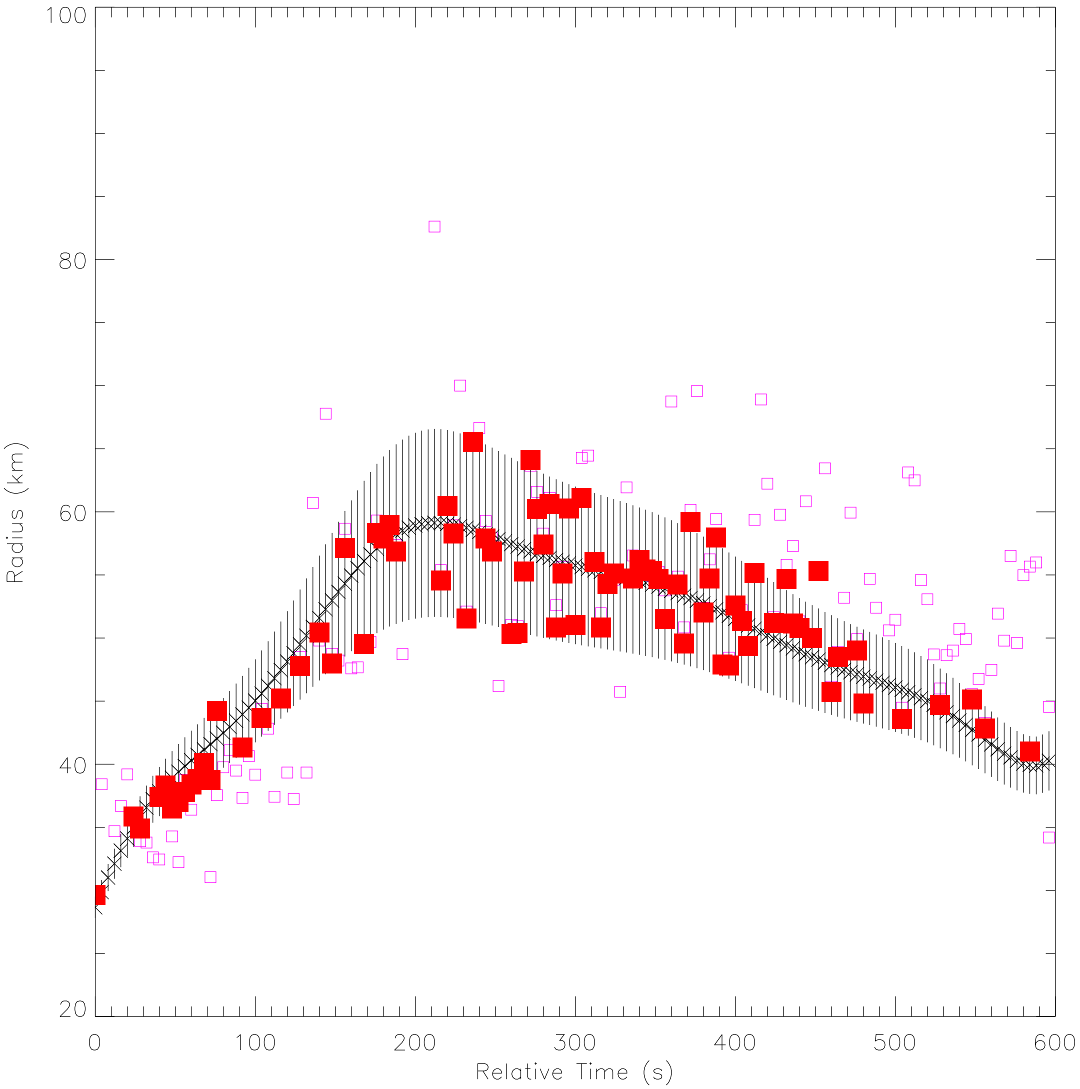

Figure 2: Radius fits for the β-2 event. The open squares are the original radius fits with XSpec 11.3 ($\chi^2 < 2$, radius is a free parameter). The black lines are theoretical estimates based on the Magnetic Flood Model and allowing for a 0.6 Hz frequency error. The filled squares are the revised XSpec fits using the restricted theoretical radius. In order to get a reasonable number of fits at all, we allowed $\chi^2 < 8$. Even with the relaxed restricion of χ^2, only 54% of the spectra can be fit (compared to our original criteria which fit 90% of the spectra).

Set ID	RXTE DATA ID	Date Observed	Start Time	Power Law Index
β-1	20186-03-03-01	1997 Aug 14	04:20:52	-1.40
β-2	20186-03-03-01	1997 Aug 14	05:50:52	-1.42
β-3	20186-03-03-01	1997 Aug 14	07:17:12	-0.98
β-4	20186-03-03-01	1997 Aug 14	09:18:56	-0.69
β-5	20186-03-03-02	1997 Aug 15	07:33:36	-1.53
β-6	20402-01-45-03	1997 Sep 09	06:15:32	-0.92
β-7	20402-01-45-03	1997 Sep 09	08:04:28	-0.74
β-8	20402-01-45-03	1997 Sep 09	09:21:28	-0.48
β-9	20402-01-45-03	1997 Sep 09	09:50:36	-0.29
α-10	50125-01-04-00	2002 Jul 27	07:30:50	+0.26
α-11	50125-01-04-00	2002 Jul 27	10:24:48	-0.21
α-12	50125-01-05-00	2002 Jul 28	06:57:37	-0.02
θ-13	30182-01-03-00	1998 Jul 10	05:05:57	+0.106
θ-14	30182-01-03-00	1998 Jul 10	05:46:27	+0.24
θ-15	30182-01-03-00	1998 Jul 10	08:55:27	+0.09
θ-16	30182-01-03-00	1998 Jul 10	05:15:15	—
θ-17	20402-01-45-02	1997 Sep 05	05:02:37	+0.06

Table 1: QPO frequency- Radius Fits Observation IDs and dates of the 17 epochs. The Start Time indicates where spectral fitting began. The IDs are based on the [1] classifications. We fit the QPO-Frequency and the color radius with a power law. In a Keplerian case, the Power Law Index would be -1.5. These fits only consider the first 200 seconds of the dip where the correlation of the QPO frequency and blackbody features are more certain (see [4]). No value is given for θ-16 because the start of the dip is not visible. Note how the α and θ classes appear relatively flat here.

of the spectrum. Also, in these particular states, we believe that the accretion disk is undergoing serious disruption, so there is no reason to assume a blackbody will work. It is also possible that the entire Blackbody plus power-law model that we use to fit the data is too simplistic to convey real information. Finally, XSpec is known to return erroneous outputs depending on the current behavior of the system [3]. These caveats make it difficult to say confidently that the QPO frequency is not associated to the Keplerian frequency. However, we can show that if the radius trend revealed by XSpec is accurate, then no monotonic solution can rectify the QPO frequency to the Keplerian frequency. With this constraint, we may be able to eliminate LFQPO models that invoke Keplerian orbits. We will discuss our continued tests of the Magnetic Flood model in a forthcoming paper.

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PoS(MQW6)021