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Using *INTEGRAL* and *RXTE* to explore the Spreading Layer of GX 9+9

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GX 9+9 is a persistently bright atoll-type Low-Mass X-ray Binary. We fitted its *INTEGRAL* and *RXTE* spectra from 2002–2007 with a two-component model: a multi-temperature accretion disc blackbody, plus another blackbody representing the spreading layer (SL), an extended accretion zone on the neutron star surface. The results were mostly consistent with SL theory, although the SL temperature seemed to increase at low SL luminosities, while the approximate angular extent had a nearly linear luminosity dependency. Partial Comptonization of the SL blackbody was not required to fit the spectra. Together with the upper bound of inclination imposed by the lack of eclipses, the best-fit normalization of the accretion disc component implies a distance of ~ 10 kpc, instead of the usually quoted 5 kpc.

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1. Introduction

The Galactic X-ray source GX 9+9 was discovered by a sounding rocket flight performed in 1967 [1], in the direction of Ophiuchus. It is one of the brightest neutron star Low-Mass X-ray Binaries of the atoll-type, so called for their distinctive tracks in colour-colour diagrams. GX 9+9 has a 4.2 hour modulation period that has been detected in both X-rays [2] and the optical [3], which is assumed to be the orbital period. The modulation and the lack of eclipses imply a somewhat less than 70° inclination angle to the axis of rotation. The companion star is thought to be a 0.2–0.45 $M_{\odot}$ early M-class dwarf [2, 3]. Single-component blackbody, power law or bremsstrahlung models have been shown to be inadequate to describe the spectrum [4], but several different two-component models have been fit more or less successfully [5]. The distance is commonly quoted as 5 kpc [6], but we show in this paper that it could in fact be $\sim$ 10 kpc.

In the following sections we first describe the spreading layer theory, then present our observations and modelling method in Sections 3 and 4 respectively, discuss the source distance in Section 5, and present the results followed by the conclusions in Sections 6 and 7.

2. Spreading layers

The spreading layer (SL) theory [7] is an alternative approach to the intermediate area between an accretion disc and a neutron star surface, where the infalling plasma loses about half of its energy while slowing down. In the older boundary layer model (see e.g. [8] and the references therein), the boundary layer is an extension of the geometrically thin accretion disc into a radial flow. In the spreading layer model, the matter starts spreading towards the poles as it approaches the surface, and loses energy due to turbulent friction with the underlying layers.

The width and thickness of the layer are expected to increase with the accretion rate and the luminosity. The model turns out to have luminosity maxima near the outer edges of the radiating zone, while at the disc plane there is a minimum. The optically thick spreading layer produces a spectrum with the shape of a diluted blackbody, which includes reprocessed emission from below the spreading flow. This shape depends very little on the vertical structure of the layer, the inclination angle of the system, or the luminosity [9].

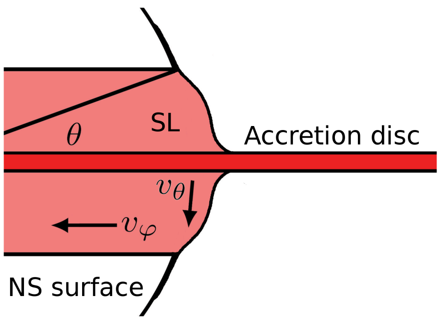

Figure 1: The spreading layer (SL) geometry. Matter flows from the accretion disc onto the neutron star surface and forms the SL, defined as the faster-rotating, radiating part of the spreading flow. θ is the boundary angle of this zone, v_θ is the latitudinal velocity and v_φ the rotational velocity.

Church et al. [10] compared the spreading layer theory and the boundary layer theory with the results of a survey of LMXBs. They found good agreement with the former at low luminosities, but at higher luminosities the blackbody emission exceeded predictions by a factor of two to four, suggesting that radial flow dominated the emitting area. Revnivtsev & Gilfanov [11] found that the shapes of their Fourier frequency resolved spectra of luminous LMXBs were luminosity-independent, which was consistent with the radiation pressure supported spreading layer model. Suleimanov & Poutanen [9] developed the theory further and compared it to some spectra from [11], finding a soft excess possibly related to classical boundary layer emission.

Vilhu et al. [12] examined GX 9+9 spectra from 2003 and 2004 in light of the spreading layer theory. The results on the whole supported the SL theory, except for possible unexpected effects at low SL luminosities. This work has been a continuation of [12], to confirm or rule out its findings with a larger long term data set (and see Savolainen et al. (2008, submitted) for a more extensive report).

3. Observations

For our data set, we sought out all available pointed observations of GX 9+9 by the INTErnational Gamma-Ray Astrophysics Laboratory (*INTEGRAL*) [13] and Rossi X-ray Timing Explorer (*RXTE*) [14] satellites. For the former, the instruments used were the Joint European X-ray Monitors (JEM-X) [15] 1 and 2 and the *INTEGRAL* Soft Gamma-Ray Imager (ISGRI) [16]) – the low energy detector of the Imager on Board the *INTEGRAL* Satellite (IBIS) [17]. For *RXTE*, we used the Proportional Counter Array (PCA) [18] and the High Energy X-ray Timing Experiment (HEXTE) [19]. *INTEGRAL* spectra were extracted over one Science Window and *RXTE* spectra over a single orbit, producing a time resolution of ~ 3200 seconds. In the end, we reduced and analysed 196 spectra, spanning 2002 May 1 to 2007 July 4.

4. Modelling

The spectral modelling was done in XSPEC, using the two-component model sometimes called the Eastern model: the multi-temperature blackbody `diskbb` [20], [21] for the accretion disc component and the partially Comptonized blackbody `compbb` [22] for the harder component, in this case interpreted as the spreading layer. We also included Galactic absorption with the neutral Hydrogen column density fixed at the LAB survey [23] value of $0.196 \cdot 10^{22}\,\mathrm{cm}^{-2}$, and a variable energy-constant factor for instrument cross-calibrations.

Before fitting the individual spectra, averaged spectra for the different instruments were fitted together to establish a general picture and fix some of the parameters. HEXTE and ISGRI values were tied to the corresponding simultaneous PCA and JEM-X values, respectively. Fig. 2 shows the averaged spectra, folded with the model, and the data to model ratios, while Fig. 3 has the unfolded model for the average PCA spectrum with its components. The reduced χ^2 was about 0.93 for the averaged spectra, and on average about 0.96 for the individual spectra, using 2% systematic errors for *RXTE* and 3% for *INTEGRAL*.

In the `diskbb` component, the inner disc temperatures T_{in} were left free, while the N_{disc} normalizations were tied to the most restrictive instrument, the PCA, to establish a single value.

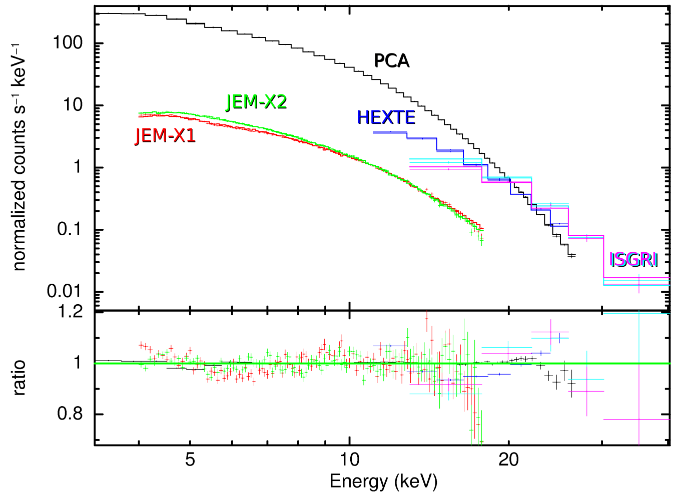

Figure 2: Average spectra, folded `const` $*$ `wabs`(`diskbb` + `compbb`) model, and data/model ratios.

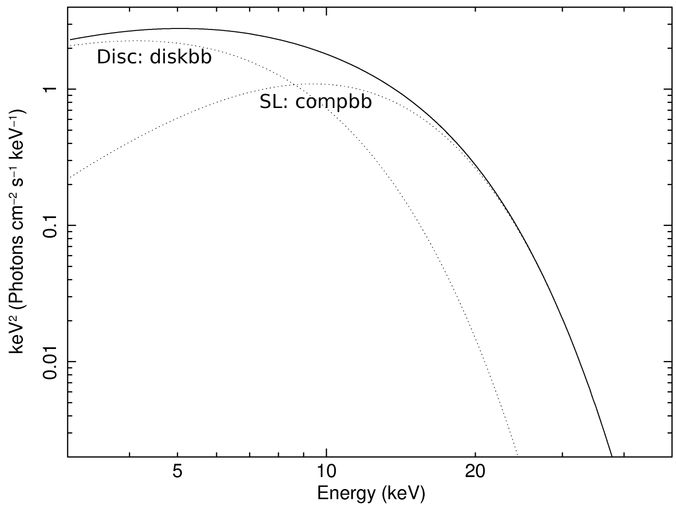

Figure 3: Unfolded model fitted to the average PCA spectrum.

	$T_{\rm in}$ [keV]	$N_{\rm Disc}$	kT, k$T_{\rm e}$ [keV]	τ	$N_{\rm SL}$
PCA+HEXTE	$1.76^{+0.01}_{-0.02}$	36^{+1}_{-2}	$2.42^{+0.02}_{-0.02}$	$0.0^{+0.1}_{-0.0}$	$5.9^{+0.9}_{-0.0}$
JEM-X1+ISGRI	$0.97^{+0.01}_{-0.02}$	Tied to PCA	$1.691^{+0.010}_{-0.011}$	$2.18^{+0.11}_{-0.11}$	12^{+1}_{-1}
JEM-X2+ISGRI	$1.29^{+0.07}_{-0.06}$	Tied to PCA	$1.699^{+0.011}_{-0.014}$	$2.21^{+0.11}_{-0.12}$	46^{+2}_{-4}
Individual fits	$1.787^{+0.005}_{-0.005}$	Fixed to 36^{+1}_{-2}	$2.50^{+0.02}_{-0.02}$	Fixed to 0.0	$5.5^{+0.2}_{-0.2}$

Table 1: Best-fit parameters of the average spectra, and averages of the best-fit values of the individual fits (bottom line). $T_{\rm in}$ and kT are the inner accretion disc and spreading layer temperatures, respectively, while $N_{\rm Disc}$ and $N_{\rm SL}$ are the corresponding normalizations.

This is because we assumed the inner accretion disc radius to stay constant, and equal the neutron star radius.

In the `compbb` component, the spreading layer colour temperatures kT, normalizations $N_{\rm SL}$ and Comptonization optical thicknesses τ were left free, but as the PCA spectra strongly favoured pure blackbody shapes with no additional Comptonization, τ was fixed to zero in the individual fits, effectively rendering `compbb` into a basic area-normalized blackbody. The Comptonizing electron temperature k$T_{\rm e}$ was set to equal the blackbody temperature, as both Comptonization parameters couldn't be meaningfully constrained simultaneously.

As can be seen in Table 1, the *INTEGRAL* spectra favoured rather different values than the *RXTE* spectra, which were used to fix the values because of their tighter confidence limits.

5. NS / inner disc radius and the distance of GX 9+9

To calculate luminosities, we have to assume a value for the distance. We can estimate this from the normalization we get for the accretion disc component, 36^{+1}_{-2}. Fig. 4 (a) shows the distance-inclination relation for these values, for three different inner accretion disc / neutron star radii. One can see that the commonly assumed distance of 5 kpc is inconsistent with the absolute upper limit imposed on the inclination by the lack of eclipses, 74–77°. Schaefer [3] further reasons that the lack of significant dips in the light curve implies an inclination less than $\sim 70°$.

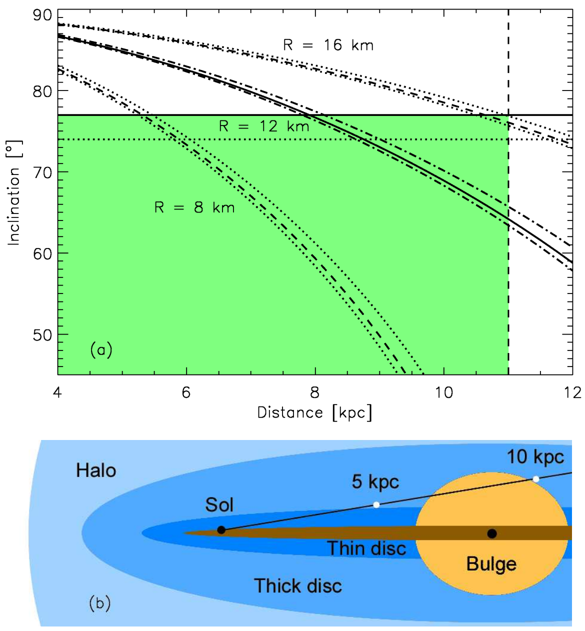

Figure 4: (a) Inclination versus distance for $N_{\rm Disc} = (R_{\rm in}/D_{10})^2 \cos i = 36^{+1}_{-2}$ at three different values of $R \approx 1.19 R_{\rm in}$ (curves). The horizontal lines are the maximum inclinations in the case of a 0.2 or 0.45 $M_\odot$ secondary, 77˙ and 74˙, while the vertical dashed line denotes the distance of ~ 11 kpc, where the high end of the luminosity distribution calculated from the model fluxes surpasses the Eddington limit. The region of acceptability is shaded; (b) Suggested locations of GX 9+9 along the line of sight (white dots) and a cross section of the Galactic environment [24].

On the other hand, distances larger than 11 kpc are increasingly unlikely, as the binary would be further and further away from the Galactic bulge, and its luminosities increasingly above the Eddington limit. Therefore, we assume a distance of 10 kpc. Fig. 4 (b) shows roughly where these distances would put GX 9+9 in the Galactic environment.

6. Results

Fig. 5 is a colour-colour diagram of GX 9+9, showing it consistently occupies the so-called banana state. The earliest of our *RXTE* observations, from 2002 May and June, show the strongest correlation. The grey area represents the atoll source data in [25], and is shown to illustrate general atoll source behaviour.

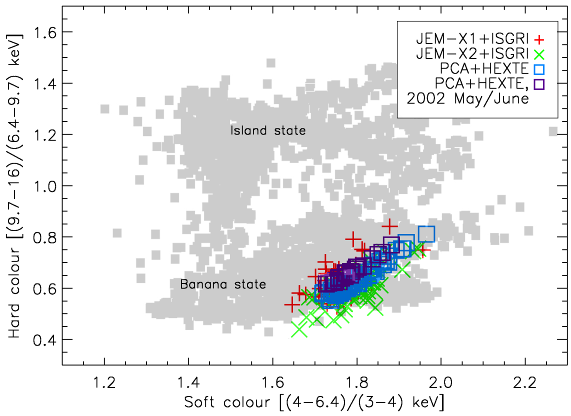

Figure 5: A colour-colour diagram of GX 9+9. The grey background is adapted from [25], and illustrates general atoll source behaviour.

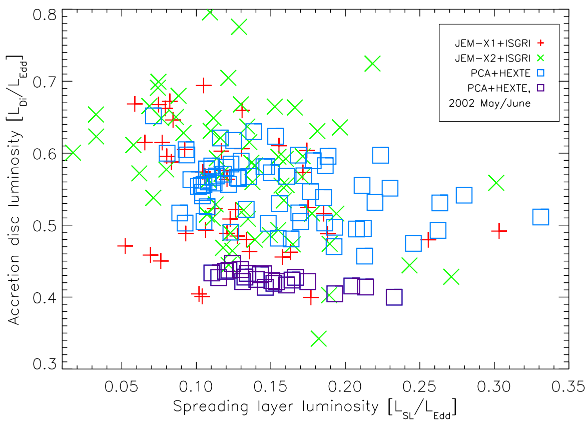

Figure 6: Luminosities of the model components.

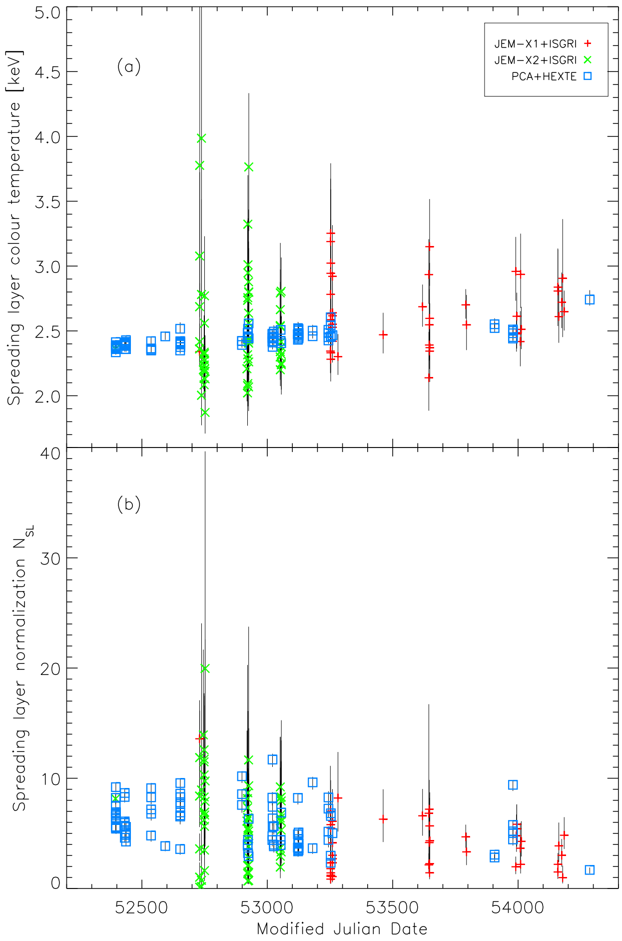

Figure 7: Best-fit spreading layer parameter values vs. time (MJD). (a) kT, (b) N_SL.

Fig. 6 shows the relative luminosities of the two model components. The correlation is drowned out by variations in the total luminosity, for a smaller part due to orbital modulation. An exception are the earliest *RXTE* observations from 2002 May and June, where the disc luminosity was almost constant.

Fig. 7 illustrates the temporal evolution of the spreading layer parameters. kT stayed at ~ 2.5 keV all the way from 2002 May to 2007 July. The tighter confidence limits of the *RXTE* results (mostly within the symbols) imply that there was significantly less variability than the *INTEGRAL* results would suggest. $N_{\rm SL}$ showed more short-term variability even in the *RXTE* results. Any possible long-term trend is blotted out.

Fig. 8 shows the observed SL temperature as a function of the SL luminosity. For the most part, it stays rather constant at a level comparable to the Eddington temperature, which is ~ 1.9 keV for a 12 km, 1.4 $M_\odot$ neutron star. This is what we would expect from spreading layer theory, and also consistent with observational findings for other sources, such as in [11] and preceding papers.

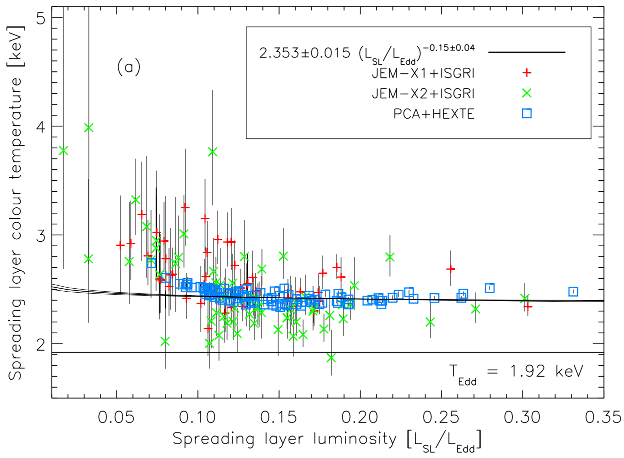

Figure 8: Observed SL colour temperature vs. SL luminosity. Also shown are best-fit power laws ($\chi^2/dof \approx 2.7$) and the Eddington temperature for spherical emission.

However, there is indication of a rise toward lower luminosities that is not accounted for by the theory, and which was also seen in [12]. It's not as strong as some of the *INTEGRAL* points would suggest, but the best-fit power law curve may underestimate it.

We also estimated the angular extent of the spreading layer as a function of its luminosity, using the observed normalization. As shown in Fig. 9, the best-fit power law index that we get is close to unity, as opposed to ~ 0.8 predicted by theory [7]. However, this should be considered inconclusive due to the approximations used. The normalization gives us the projected area of the visible radiating zone; from this alone we couldn't deduce both an upper and a lower boundary angle, but had to assume the radiating zone starts from the disc plane, even though most of the radiation should come from near the outer edges. We also didn't account for relativistic light bending, which allows us to see some angular distance into the far hemisphere.

The geometry of the approximation is depicted in Fig. 10. The projected area $A_{\rm SL}$, in red in Fig. 10 (b), is found at higher inclinations i and moderate SL angles θ to be close to

$$A_{\rm SL} = \frac{\pi R^2}{2} - \left(\frac{\pi - 2\theta \sin i}{2\pi}\pi R^2 - 2\left(\frac{1}{2} R \sin\theta \sin i \frac{R \sin\theta \sin i}{\tan(\theta \sin i)}\right)\right)$$

$$+ \frac{\pi R^2}{2}\cos i - \frac{\pi R^2}{2}\frac{R \sin\theta \sin i}{\tan(\theta \sin i)}\cos\theta \cos i$$

Using this, $N_{\rm SL}$ was solved to single decimal accuracy and compared to observations to find θ:

$$N_{\rm SL} = \frac{R^2}{D_{10}^2}\left(\frac{\theta \sin i}{\pi} + \frac{\sin^2\theta \sin^2 i}{\pi \tan(\theta \sin i)} + \frac{\cos i}{2} - \frac{\sin\theta \sin i}{2\tan(\theta \sin i)}\cos\theta \cos i\right)$$

$R = 12$ (km), $D_{10} = 1.0$ (= 10 kpc) and $i = 69.0$ (°) were used for the calculations.

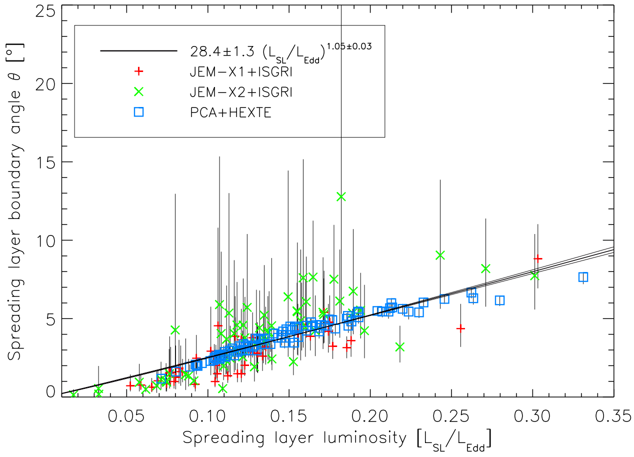

Figure 9: Approximate SL boundary angle vs. luminosity and best-fit power law ($\chi^2/dof \approx 1.5$).

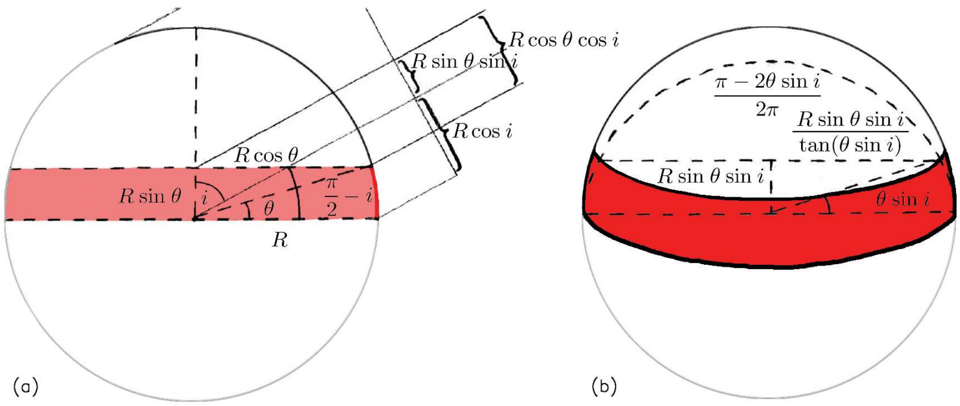

Figure 10: The geometry of the projected visible spreading layer area approximation. (a) cross-section side view; (b) observer view.

7. Conclusions

Presuming that the model is valid, GX 9+9 may be twice as distant as previously thought, of the order of 10 kpc instead of 5 kpc. The Comptonization parameters were found to be unnecessary, the hard spreading layer component of GX 9+9 could be fitted with a basic blackbody. The SL blackbody parameters varied on time scales of a few hours or days, but showed no clear long term trends.

There was an apparent increase in the observed SL temperature at low SL luminosities, unaccounted for by theory. The possible causes are an actual rise in the effective temperature due to effects not taken into account in the theory, an increase in the hardness factor, which is the ratio between the observed and effective temperatures, or perhaps a breakdown of one or more of the basic assumptions at the lowest luminosities reached by the source. Otherwise the results are consistent with the spreading layer scenario, but this work does not rule out other alternatives.

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