Modelling the *RXTE* and *INTEGRAL* Spectra of GX 9+9

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GX 9+9 is a persistently bright atoll-type Low-Mass X-ray Binary with a neutron star primary. The neutron star is assumed to have an accretion disc extending close to the surface, where it has a dynamic continuation in the form of either a simple, thin boundary layer or a spreading layer, i.e. a wider zone of matter settling towards the poles. Both *RXTE* and *INTEGRAL* have observed GX 9+9 on numerous occasions. The spectra from 2002–2007 were fitted with a model consisting of two modified blackbodies, one representing the accretion disc and the other the spreading layer (SL). The SL temperature was seen to increase towards low SL luminosities, while the approximate angular extent had a linear luminosity dependency. We also compared parameter time evolution to a trend and modulation seen in the long-term light curve.

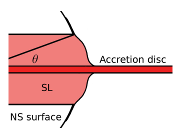
Introduction

GX 9+9 is an atoll-type neutron star (NS) binary in a persistent banana state (Hasinger & van der Klis, 1989). The companion is likely an early M-class dwarf of 0.2–0.45 $M_\odot$ (Hertz & Wood, 1988; Schaefer, 1990). A 4.2-hour orbital modulation has been observed in both X-rays (Hertz & Wood, 1988) and the optical (Schaefer, 1990). The distance estimate most often used is 5 kpc from Christian & Swank (1997).

Recently Vilhu et al. (2007) studied *INTEGRAL* and *RXTE* spectra of GX 9+9 from 2003 and 2004 in the framework of the spreading layer (SL) theory (Inogamov & Sunyaev, 1999). We have continued this work, starting with all *INTEGRAL* and *RXTE* observations from 2002 to 2007. The final data set consisted of 48 JEM-X1+ISGRI, 61 JEM-X2+ISGRI and 92 PCA+HEXTE spectra, 201 in total.

In non-pulsating NS LMXBs, the magnetic field is weak enough for the accretion disc to extend to the surface. If the star rotates slower than the infalling matter, the difference in kinetic energy must be radiated in a boundary layer between the disc and the surface. Inogamov & Sunyaev (1999) introduced a model where the principal friction mechanism is the turbulent viscosity between the matter spreading on the surface and the slowly moving dense matter below.

Suleimanov & Poutanen (2006) calculated the spectra produced by a spreading layer at different luminosities, and seen from different inclination angles; the dependence on these was slight. The SL spectrum was found to be close to a diluted blackbody.



The SL geometry. θ is the boundary angle of the rotating, radiating part of the spreading layer (light red). The width of the SL increases with the accretion rate and the luminosity. The SL has luminosity maxima near its outer latitudes and a minimum at the equator.

The model and fitting method

Modelling was done with XSPEC v.12.4.0, using the same model as Vilhu et al. (2007), defined as $\texttt{const} * (\texttt{diskbb} + \texttt{compbb})$.

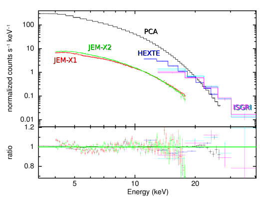
Averaged spectra for the different instruments were first fitted together with all the `diskbb` normalizations $N_{\rm Disc}$ and `compbb` optical thicknesses τ tied to the PCA ones (best-fit values 36^{+6}_{-4} and $0.03^{+0.07}_{-0.03}$, respectively), and the rest of the ISGRI and HEXTE parameters tied to the corresponding JEM-X and PCA parameters. Best-fit values for these are given in the table below. $kT_{\rm e}$ was frozen to 10 keV. $\chi^2/dof = 282.31/279 \approx 1.01$.

Instruments	$T_{\rm in}$ [keV]	kT [keV]	$N_{\rm SL}$
PCA+HEXTE	$1.76^{+0.06}_{-0.07}$	$2.41^{+0.03}_{-0.06}$	6^{+2}_{-1}
JEM-X1+ISGRI	$1.91^{+0.05}_{-0.06}$	$2.84^{+0.13}_{-0.13}$	$2.3^{+1.0}_{-0.4}$
JEM-X2+ISGRI	$2.11^{+0.03}_{-0.03}$	$3.42^{+0.16}_{-0.16}$	$0.6^{+0.3}_{-0.2}$

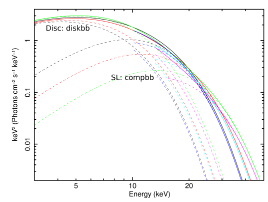
Having $N_{\rm Disc} = (R_{\rm in}/D_{10})^2 \cos i = 36^{+6}_{-4}$, $R_{\rm in}$ as the NS radius ~10 km and inclination $i < 70^\circ$ because of the lack of eclipses leads us to assume a distance of 10 kpc.

The individual spectra were then fitted with the same model, freezing $N_{\rm Disc}$ and τ to the values of the average spectra. The means for the free parameters in the individual fits are listed below.

Disc temperature $T_{\rm in}$	1.775 ± 0.005 keV
SL temperature kT	2.46 ± 0.02 keV
SL normalization $N_{\rm SL}$	6.0 ± 0.2

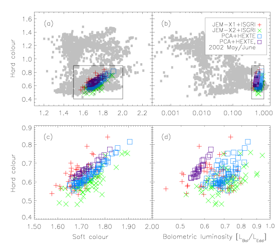


Average spectra for the instruments, folded model, and the data to model ratios.



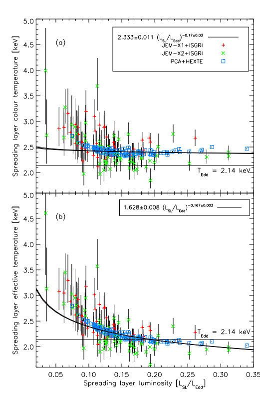
Unfolded model corresponding to the previous figure. The lower-energy family of component curves represents the accretion disc component (`diskbb`) and higher-energy family the spreading layer component (`compbb`).

Fluxes, colours and luminosities



(a) A colour-colour diagram of GX 9+9. Soft colour is the flux ratio (4-6.4)/(3-4) keV and hard colour (9.7-16)/(6.4-9.7) keV. The grey area is adapted from Gladstone et al. (2007) and represents all the atoll source data; (b) corresponding colour-luminosity diagram, assuming a distance of 10 kpc and a mass of 1.4 $M_\odot$; (c) the boxed area of (a); (d) the boxed area of (b). The source is consistently in the banana state. The PCA+HEXTE observations from 2002 May/June (purple squares) form their own distinct track.

Spreading layer temperature



(a) Observed SL colour temperature kT vs. luminosity; (b) effective SL temperature as calculated from (a) by dividing with the hardness factor $f_{\rm c}$, having the luminosity dependence used in Suleimanov & Poutanen (2006). The *RXTE*/PCA+HEXTE error bars are mostly within the symbols. Also shown are best-fit power laws ($\chi^2/dof = 4.1$) and the estimated Eddington temperature $T_{\rm Edd}$.

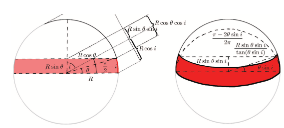
In the models of Suleimanov & Poutanen (2006), the effective SL temperature $T_{\rm eff}$ decreases slightly with decreasing SL luminosity. The observed colour temperature (k$T = T_{\rm c} = f_{\rm c} T_{\rm eff}$) results in the previous figure show an opposite trend.

This may be due to an actual increase of $T_{\rm eff}$ from some low accretion rate factor not properly considered in the theory. In order to account for the increase by the hardness factor $f_{\rm c} = T_{\rm c}/T_{\rm eff}$, it should have a stronger low-luminosity increase. The formula quoted by Suleimanov & Poutanen (2006) instead gives a strong decrease at luminosities below $0.1\ L_{\rm Edd}$:

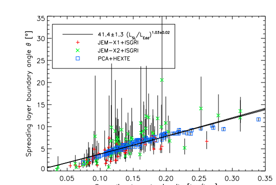
$$f_{\rm c} = \left(0.15 \ln\left(\frac{3+5X}{1-L}\right) + 0.59\right)^{-\frac{4}{5}} \left(\frac{3+5X}{1-L}\right)^{\frac{2}{15}} L^{\frac{3}{20}}$$

where X is the hydrogen mass fraction and the luminosity L is expressed in Eddington units. This formula has been successful in describing luminous ($> 0.9\ L_{\rm Edd}$) X-ray burst spectra (Pavlov et al., 1991), but may be incorrect in the low-luminosity domain where it has not been extensively tested.

Spreading layer boundary angle

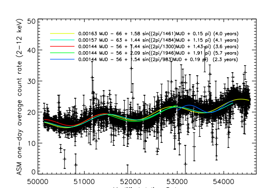


The geometry of the projected visible spreading layer area approximation. (a) cross-section side view; (b) observer view. We ignore relativistic light bending, which causes the far hemisphere to be visible up to an angle of ~20–40° beyond the classical horizon. The SL is further approximated by a spherical zone extending from the plane of the accretion disc to the boundary angle θ; the accretion disc hides the other side. The results agree well with those of Monte Carlo simulations, and assuming an inclination of 65°, are also close to the 90° case with small values of $N_{\rm SL}$ and θ.

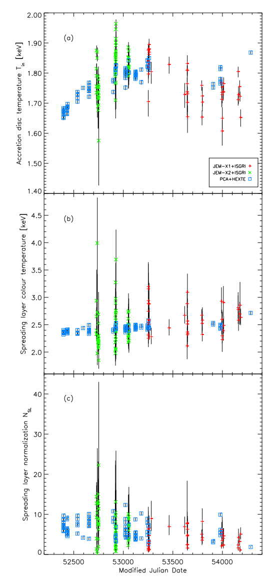


Approximate spreading layer boundary angle, calculated from the SL normalization $N_{\rm SL}$, vs. luminosity and best-fit power law ($\chi^2/dof = 2.2$). The best-fit power law dependency is close to linear, as opposed to the theoretically predicted index of ~ 0.8. Without proper relativistic corrections, the implications on theory remain unclear.

Time evolution



Noticing a rising trend and an apparent long-term periodicity, we have also been analyzing the light curve of GX 9+9 collected by *RXTE*/ASM over the last 12 years. The seemingly linear + sinusoidal form is the most pronounced in the sum band (2-12 keV) daily average data in this figure, but such a simple model doesn't fit the data quite well enough, as can be seen from the best-fit curves to different intervals ($\chi^2/dof \approx 4-6$).



Best-fit parameters vs. time (MJD). The accretion disc temperature (a) seems to correlate with the long-term trend of the ASM light curve in the previous figure. The SL temperature (b) and normalization (c) show no clear long-term trends.

Conclusions

- Assuming the model of an accretion disc constantly reaching the neutron star surface is valid, GX 9+9 may be twice as distant as previously thought, on the order of 10 kpc. The distance is constrained by the observed normalization of the soft spectral component identified with the accretion disc (36^{+6}_{-4}), together with the upper limit imposed on the system inclination ($\sim 65^\circ$) by the lack of eclipses. This distance corresponds to a luminosity range of ~0.5–0.9 $L_{\rm Edd}$.
- Colour ratios showed that GX 9+9 remained in the banana state.
- There was an increase in the colour temperature of the SL at low SL luminosities, either due to an effective temperature increase from some low accretion rate factor not considered in the theory, or incorrect theoretical low-luminosity values for the hardness factor $f_{\rm c}$.
- The long-term modulation and trend are real phenomena, at least first of which seems to be connected to the accretion disc temperature.

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