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Radio and X-rays from GRS 1915+105 - Close correlations of the third kind

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Abstract. We have examined a decade's worth of radio data from the Ryle telescopes and *RXTE* on the microquasar GRS1915+105 and found 3 basic kinds of correlation: the well known low-hard state, the radio flaring state, and a new one - a long term variation combining both states. There is a close correlation during the low/hard state over periods of a few weeks, suggesting either an improbably close connection between accretion rate and radio emission, or that a large fraction of the X-ray emission is via the synchrotron process in the jets.

Key words. Binary Stars: Jets – Stars X-rays, Radio

1. Introduction

Microquasars are galactic objects which have a relatively normal star orbiting a compact object such as a black hole or neutron star. Accretion via an accretion disk around the compact object gives intense X-ray emission. The inflow, probably combined with magneto-hydrodynamics in a strong gravitational field, can give rise to the explosive formation of relativistic jets, in processes which are in many ways analogous to those in the much more powerful and distant quasars. Recent studies of microquasars have shown close relationships between X-ray characteristics and radio emission, giving very good evidence that the formation of relativistic jets is associated with the accretion process. GRS 1915+105 is a strong X-ray emitter in our Galaxy with a variety of X-ray states which also has variable radio emission including transient relativistic jets. There are clear relationships between X-ray states and the radio emission (Mirabel & Rodriguez, 1994; Rushton et al., 2010b). Simultaneous radio and X-ray observations can be of direct help in understanding the inflow-outflow mechanisms around the black hole (Fender & Belloni, 2004).

Some changes in the X-ray state are directly related to the ejection of knots of radio emission moving away from the binary system at relativistic velocities (Fender et al., 1999). These can produce large scale structures which dominate the radio emission, over timescales of days or weeks. However, we expect the core of the radio source to be more directly associated with accretion activity, over shorter

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timescales. VLBI observations (Dhawan et al., 2000) have shown the size of this region to be only a few light hours in size. Furthermore there are periods when the radio emission tends to be steady over periods of days to weeks, with a flat spectrum (i.e. suggesting emission from a compact jet) combined with a relatively hard X-ray state with low flux. This state is known as the plateau state and referred to as class χ by Belloni et al. (2000).

Thus there are two relatively well known radio-X-ray associations – the variable transition state between low/hard to soft X-ray state accompanied by the ejection of large scale relativistic jets (Fender et al., 1999) and the low/hard plateau state with reasonable strong (~50 mJy) steady radio emission (see discussion by Rushton et al., 2010b). We describe a possible third association, occurring over much longer timescales, found by a long series of joint radio and X-ray observations.

2. Observations

The Ryle Telescope (RT) has been used extensively for monitoring of microquasars over many years (e.g. Pooley & Fender, 1997). Daily observations of GRS1915+105 at 15 GHz have been taken from 1995 to 2006 at sensitivities of ~ 2 mJy. At X-ray wavelengths data from the Rossi Timing Explorer (*RXTE*) by the All Sky Monitor (ASM) in the 2-12 keV range enable fluxes and a simple spectral indicator – the hardness ratio (HR2) – measured between the 5-12 kev and 1.5-3 keV energy bands. This ratio can easily indicate when the source is in the low/hard state.

Study of the spectra during the full period of observations shows that a diagram of X-ray intensity versus hardness has 3 dominant modes of X-ray emission: weak-very soft with count rates of <20 /sec and HR2<1, highly variable-soft with counts between 2–200 /sec and 1< HR2<1.5, and persistent-hard with flux at 30–50 counts/sec and HR2>1.5. When the source is in this last state for more than a few days it always has strong radio emission – i.e. when GRS 1915+105 is in X-ray spectral class χ a compact radio jet is always present.

Figure 1 shows a plot of X-ray counts *vs* hardness ratio. The head of the flying bird is where the X-ray are hard with intermediate counts – and is clearly where the radio emission occurs.

Figure 2 shows a plot comparing radio and X-ray intensity for the period April 2001 – June 2006, where 5 long periods of radio outburst occurred. The radio flaring is associated with relatively steady periods of X-ray emission – with counts in the 30 to 50 /sec range and corresponding to the persistent-hard state as also shown in figure 1. Figure 2 also shows that the radio emission has a rapid rise from a quiescent state to levels of ~ 100 mJy, followed by decay over several months. This latter long term behaviour was not so noticeable in previous data. Here we can see that it takes place on several occasions.

The X-ray emission during the persistent –hard state also varies though not in such a strong way – in fact a plot of radio *vs* X-ray flux (figure 3) shows a good correlation with a slope of 1.7 ± 0.3. This can be compared with the radio/X-ray correlation for galactic black hole X-ray binaries in the low/hard or plateau state as a whole (Gallo et al., 2003) where $L_{radio} \propto L_X^{0.7}$ when scaled to a common distance of 1 kpc.

Also shown in figure 2 is a plot of the ratio of the log of the radio emission to the log of the X-ray emission. Five periods where the source is in the plateau state / class χ can be seen during the radio outbursts; however, the deep quenching immediately before the radio outburst is made clear. This seems to be due more to a decrease in the radio emission rather than a rise in X-rays as the ASM counts also appear to be low in this phase. A period of rapid variability in the ratio occurs after the plateau state, primarily due to rapid X-ray variability when in the variable- soft state before the whole sequence is repeated. There thus seems to be systematic repeated behaviour with a duration for each cycle of around 1 to 1.5 years.

3. Discussion

Radiatively efficient thin-disk models successfully describe the basic accretion properties

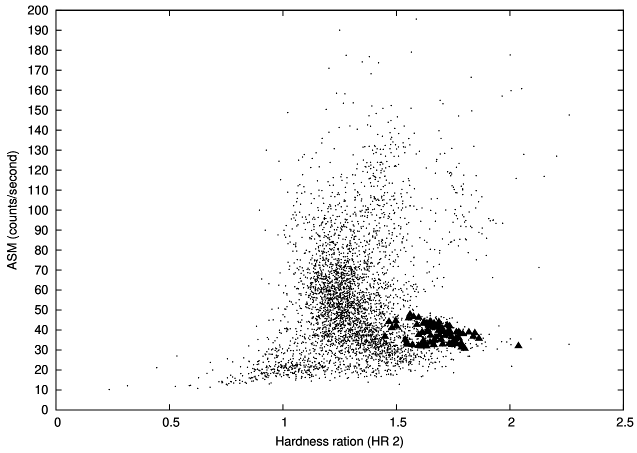

Fig. 1. Hardness intensity diagram of GRS 1915+105 between 1996 and 2008, showing the one day average intensity, between 2-12 keV, plotted as a function of the hardness radio, HR2 ($\frac{5\text{–}12\ \text{keV}}{2\text{–}5\ \text{keV}}$). The triangles represent *persistent radio emission* associated with the X-rays known as class χ by Belloni et al. (2000) and the 'plateau' state by Pooley & Fender (1997).

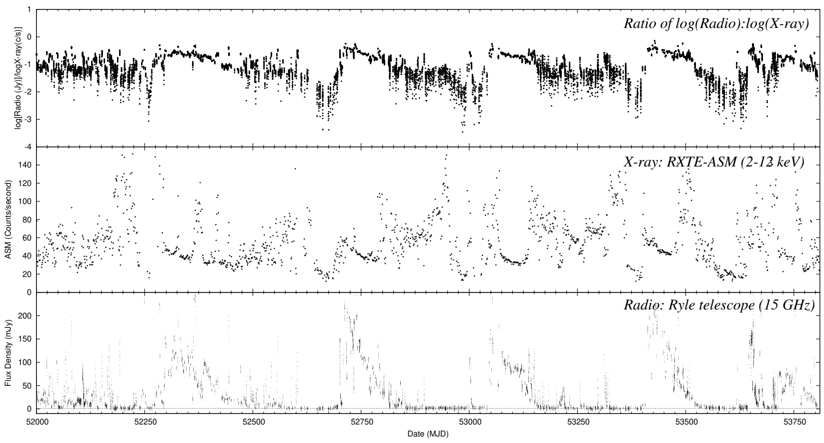

Fig. 2. The radio and X-ray lightcurves (bottom and middle respectively) of five long periods of outburst. The top graph represents the ratio of log(radio)/ log(X − ray), clearly showing direct relationship between the two bands.

of thermally dominated disks. However these models break down when the gas pressure is low. Recent models for radiatively inefficient flows can more successfully explain accretion onto black holes, in particular the low hard state (McClintock & Remillard, 2006). The inflow can from a geometrically thick disk and in advection dominated accretion flow (ADAF) models much of the energy which would normally appear as viscous dissipation in the disk is advected into the black hole, Such sources would be under-luminous for their accretion rate.

The close correlation between X-ray and radio luminosity implies that the accretion rate is related to the power in the jet, though

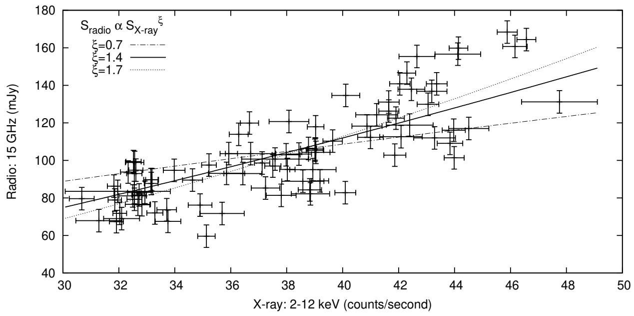

Fig. 3. X-ray/radio correlation in the hard state of GRS 1915+1915 (i.e. plateau state). The dotted line represents a 'best-fit' of $\xi \sim 1.7 \pm 0.3$, the solid line represent a model of $\xi \sim 1.4$ and the dashed-dotted line represents a model of $\xi \sim 0.7$, where $S_{\rm radio} \propto S_{\rm X-ray}^{\xi}$.

the exact details of how scale-free relativistic jets are formed by accretion is unclear. However ADAF flows are expected to produce an X-ray luminosity proportional to the square of the mass accretion rate. For a partially self-absorbed compact jet this results in $L_{radio} \propto L_X^{0.7}$ as observed for black hole candidate microquasars. We find a much higher slope in the plateau state / class χ of GRS 1915+105 – as would be obtained if we do not assume an advective dominated flow. If there is instead radiatively efficient flow with a linear relationship between luminosity and mass accretion rate as in the standard thin disk model then the expected relation becomes $L_{radio} \propto L_X^{1.4}$ which could be consistent with our results.

Alternatively much of the X-ray emission could be due to synchrotron radiation from the inner, high field, high energy density part of the jets (e.g. Markoff et al., 2001). This would naturally produce a close relationship between the X-rays and radio. It is interesting to note that both the radio and X-ray fluxes tend to decrease through the plateau state, as we might expect as energy losses take place as jets expand. However the radio seems to decreases more rapidly than the X-rays – opposite to what one expect form synchrotron losses, though no doubt an expansion model could be contrived where the large scale radio emission expands more and has higher adiabatic expansion losses. Further details on these ideas are published in the full write up of this work (Rushton et al., 2010a).

What still remains a mystery is the relatively coherent long term behaviour over long time scales: the third kind of correlation. This occurs over periods much greater than thermal or dynamical time scales for an accretion disk. A possible explanation is the presence of a 3^{rd} body interfering with accretion as it proceeds in orbit around the black body, but we would perhaps expect a constant period for the phenomenon here. Also it is worth noting that the long term behaviour is not as clear in the earlier 1996-2001 section of the data. Obviously further data is required – let's hope *RXTE* can continue for several more years.

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