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Rapid X-ray variability of the superluminal source GRS1915+105.

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Abstract. The superluminal X-ray transient source GRS 1915+105 was observed during July 20-29, 1996 with the Indian X-ray Astronomy Experiment (IXAE) on the Indian satellite IRS-P3 launched on March 21, 1996 from Shriharikota Range in India. During our observations covering the energy band 2-18 keV, we have seen strong erratic intensity variations on time scale of 0.1s - 10s. Quasi Periodic Oscillations (QPOs) in a frequency range of 0.62 to 0.82 Hz were detected with a rms fraction of about 9%. The rapid X-ray intensity variations in GRS1915+105 are similar to those observed in some other black hole binaries and thus provide further support for the hypothesis that this source is likely to be a black hole. We discuss the possible emission region and mechanism of the observed quasi-periodic oscillations. Comparing the observed QPOs with the ones observed in other neutron star and black-hole systems, we argue that GRS1915+105 is possibly a black-hole.

Key words: accretion, accretion disks - black hole physics - X-rays: stars - stars: individual - GRS 1915+105

1. Introduction

The Transient X-ray source GRS1915+105 was discovered with the WATCH instrument onboard the GRANAT Observatory in 1992 (Castro-Tirado et al. 1994). Hard X-ray studies in 20-100 keV band have shown erratic intensity variations on time scales of days and months (Foster et al. 1996; Sazonov et al. 1994). The source has been identified with a superluminal radio source (Rodriguez & Mirabel 1993) which undergoes frequent flaring on a variety of time scales. Based on its peculiar radio characteristics and superluminal motion, it has been termed as a micro-quasar (Mirabel & Rodriguez 1994). An infrared source with a jet at the same position angle as seen in the radio counterpart, has also been identified with this object (Sams et al. 1996). Based on its X-ray luminosity which greatly exceeds the Eddington limit and radio characteristics which are similar to those of the radio loud quasars, it has been suggested to be a black hole. We have observed this source with the Indian X-ray Astronomy Experiment (IXAE) and have detected erratic intensity variations on time scale of 0.1s - 10s. Strong Quasi Periodic Oscillations (QPOs) in a frequency range of 0.62 to 0.82 Hz were also detected unambiguously (Agrawal et al. 1996b). In this letter we discuss the possible emission region and mechanism of the observed quasi-periodic oscillations. The strong and erratic intensity variations are identical to the variations seen in other black-hole candidate X-ray sources. The QPOs seen in GRS 1915+105 are compared with the same in other black hole candidates and neutron star binaries.

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2. The IXAE and Observations

The X-ray observations were made with the IXAE which was launched onboard the Indian Remote Sensing satellite-P3 (IRS-P3) using the Polar Satellite Launch Vehicle (PSLV) on March 21, 1996 from Shriharikota Range in India. The satellite is in a circular orbit at an altitude of 830 km and inclination of 98°. The IXAE includes three collimated Pointed Proportional Counters (PPCs) with an effective area of about 1200 cm^2 filled with P-10 gas at a pressure of 800 torr. Each PPC is a multi-anode, multi-layer detector with 54 anode cells of size 11 mm x 11 mm arranged in 3 layers with a wall-less geometry. The end cells of each layer and the third layer are joined together to form a veto layer for rejection of charged particles and background produced by Compton scattering of gamma-rays. The odd and even cells of the first and second layers, which detect X-rays, are connected together and operated in mutual anticoincidence to further reduce

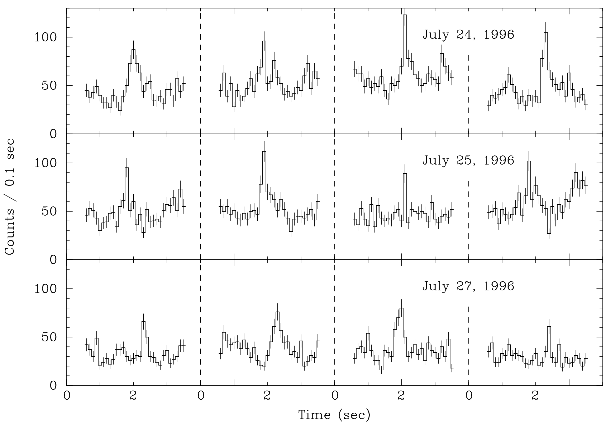

Fig. 1. The subsecond flux variations seen in GRS1915+105 with the Indian X-ray Astronomy Experiment (IXAE). Observations were made with 100 msec time resolution during 24-27 July 1996. Similar bursts were seen in all the detectors and the combined data are plotted here. Each panel shows a few of the flares seen on the days mentioned in the figure. Data of 3 seconds are plotted with a bin size of 100 msec around the flares. A factor of 2 or more increase in the X-ray flux is seen for a duration of about 100 to 400 msec.

the non-cosmic X-ray background. A sandwich of 25 micron thick aluminized mylar and 25 micron thick uncoated polypropylene serves as the X-ray entrance window. The collimators with a field of view of $2.3^\circ \times 2.3^\circ$ are made from honeycomb shaped aluminum coated on both sides with a 6 micron thick layer of silver. The detectors and associated electronics are so designed that each PPC has a modular structure with its associated high voltage unit, signal processing electronics, 8086 microprocessor and a memory of 4 MB. In the normal mode of operation count rates are recorded from the first layer in 2-6 keV and 2-18 keV bands, from the second layer in 2-18 keV band and all count in the veto layer above 2 keV with an integration time of 1 sec. The integration time can, however, be changed by command to .01, 0.1 or 10s. The gas gain of each detector is measured by continuously monitoring the pulse height due to 22.2 keV X-rays from a collimated Cadmium-109 radioactive source which irradiates only the end cells of the veto layer. A more detailed description of IXAE has been given by Agrawal et al. (1997).

Since the satellite is in a polar orbit and most of the orbits pass through the South Atlantic Anomaly (SAA) region, the useful data are obtained only when the satellite is usually in the latitude range of 50° N to 30° S outside the SAA region. The IRS-P3 is a three-axes stabilized satellite with an onboard star tracker which is used for acquisition and pointing at a given X-ray source.

The X-ray instrument was first switched-on on May 2, 1996 and its performance was verified by observing Cyg X-1 during May 2 - 9 period. The observed count rate for Cyg X-1 was about 500 counts per second indicating that it was in a low intensity state. Subsequent pointing at Cyg X-1 during July 4-10, when it had made a transition to a bright state, showed a count rate of about 1000 counts per sec. Preliminary results on Cyg X-1 describing erratic variability on time scales of sub-second to second are described by Agrawal et al. (1996a). Observation of GRS 1915+105 were conducted during July 20-29, 1996. The target acquisition accuracy was better than 0.1°. The background of the PPCs was measured by pointing at a source-free region near GRS1915+105. The total background count rate in 2-18 keV energy band from the three detectors is about 45 counts per second.

Table 1. IXAE observations and results of GRS1915+105

Day of 1996 July	From hh mm (UT)	To hh mm (UT)	Useful time (sec)	Cnts per sec	QPO freq (Hz)	rms %
23	18 15	18 19	240	760		
24	11 16	11 21	120	704	0.68	8.29
24	12 43	13 02	1080	664	0.70	8.52
24	14 27	14 43	900	631	0.70	9.13
25	12 33	12 39	380	755	0.62	8.89
25	14 01	14 20	1080	734	0.62	9.21
25	15 44	16 02	1090	779	0.66	9.97
25	19 15	19 22	420	712	0.70	9.44
25	20 59	21 12	240	707	0.62	8.42
27	11 37	11 56	1080	519	0.74	9.00
27	13 21	13 37	1080	467	0.74	9.01
27	15 03	15 20	1140	476	0.82	9.43

3. Results

Even though GRS1915+105 was observed in the pointed-mode for 4 days during the period July 20-29, 1996 the useful data are for about 8850 seconds due to various operational constraints. Almost all the count rates were acquired with an integration time of 0.1 sec. The X-ray light curve for the entire period of useful observations showed no large scale intensity variations on time scale of a minute or longer. This is unlike the results reported in the higher energy band (Castro-Tirado et al. 1994; Sazonov et al. 1994). Analysis of data on shorter time scale, however, shows pronounced variations on time scale of a second and less. A few typical light curves showing sub-second intensity variations are shown in figure 1. These variations were detected independently in each detector with similar count rate profiles. Further the veto layer count rates do not exhibit this kind of variability. It will be noticed from the light curves that GRS 1915+105 shows frequent flaring activity on time scales of less than a second and occasionally over 0.1 sec. During the flares the

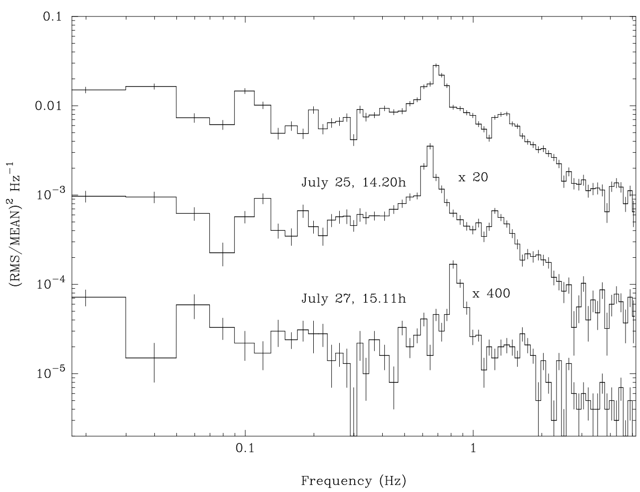

Fig. 2. The Power density spectrum of the X-ray source GRS1915+105 observed with the Indian X-ray Astronomy Experiment (IXAE). The power density spectra of 130 independent data sets with 512 data points each, with a bin size of 100 msec were added to generate the plot at the top. A strong peak at a frequency of 0.7 Hz is clearly visible. In the two plots below that two power density spectra with peak at frequencies 0.62 Hz and 0.82 Hz respectively show the frequency variation in the QPO peak. The times of observations are given in the figure. The first harmonic at a frequency of twice that of the main peak is seen in all the three plots

intensity varies by a factor of upto 3 in less than a second. From analysis of the flare frequency in GRS1915+105 and Cyg X-1, we find that flare occurrence in GRS1915+105 is less common than that in Cyg X-1. Details of flaring activity in Cyg X-1 will be reported in a separate paper (Rao et al. 1997). During the sporadic intensity variations, the light curves of the two sources exhibit remarkable similarity at time scale of 0.1 to 1 second. Power density spectrum and Fast Fourier Transform (FFT) analysis showed no variability with a fixed period indicating that the source is not an X-ray pulsar. However, strong Quasi- Periodic Oscillation (QPOs) were detected from GRS1915+105 in all the data. The periodogram is shown in figure 2. The QPOs are clearly detected independently at the same frequency in the data of each PPC as well as in the summed data. The QPO frequency however varies in an erratic manner from day to day. A summary of the observations and QPO characteristics is given in table I. It will be noticed that the QPO frequency varied from 0.62 to 0.82 Hz. The rms fraction in QPO is typically about 10%. Besides the 0.7 Hz peak the summed power spectrum also shows another less prominent peak at $\approx$ 1.4 Hz, which can be the first harmonic of the main peak. The power spectrum is nearly flat between 0.02 to 0.5 Hz with a power law index of -0.26 and becomes steep above the QPO frequency with a power law index of -1.26 in the 2 to 5 Hz range.

Anticorrelation between the total intensity and hardness ratio (6-18 keV to 2-6 keV) is seen at very small time scale. Details of the analysis will be reported in a separate paper.

4. Discussion

The only reported low energy observations (below 20 keV) are the one by Nagase et al. using the ASCA satellite (Nagase et al. 1994) and by Greiner using the ROSAT satellite (Greiner et al. 1993). Recently, observations using PCA and ASM onboard the RXTE satellite have shown intensity variation on a variety of time scales (Greiner et al. 1996). The maximum X-ray luminosity for an assumed distance of 12.5 kpc (Mirabel & Rodriguez 1994), is more than 10^{39} erg s^{-1} (Sazonov et al. 1994). This greatly exceeds the limiting Eddington luminosity for emission from a neutron star surface of reasonable mass (Lang 1980). No coherent pulsations in the frequency range 0.001 to 0.1 Hz were detected (Finoguenov et al. 1994). Radio outbursts seen with the Green Bank Interferometer (GBI) are found to be correlated with the X-ray flaring seen by the BATSE onboard the CGRO (Foster et al. 1996) during a previous outburst of the source. The long time light curve of the source as seen by the All Sky Monitor (ASM) on the RXTE after its recent outburst in January 1996, shows very strong variability during May 15 to 30 June 1996 and August 15 to very recent time and almost constant intensity between July 1 and August 15 1996 (http://space.mit.edu/XTE/ASM_lc.html). Our observations were made during the period of July 20-29 when ASM count rate shows no significant intensity variations. Though the source was found to be bright in radio during the current outburst too (Fender et al. 1996), there is no reported radio observation during the rarely occuring constant intensity state reported here.

The subsecond time variability seen in GRS1915+105 indicates that the emission is from a compact region of size much smaller than a light second. But the total X-ray intensity greatly exceeds the Eddington luminosity from a neutron star with permitted mass limit. Therefore the most likely place for the radiation to come from is the accretion disk. In neutron star binaries, even a small magnetic field of 10^8 gauss is sufficient to keep the inner disk away from the neutron star surface (Frank et al. 1992). Hence the subsecond variability that is seen in GRS1915+105 indicates that the compact object in this system is likely to be a black hole. The observed quasi-periodic oscillations when compared to QPOs seen in other black hole X-ray binaries also support the black hole picture.

The stability of the QPO frequency over 4 days indicates that the intensity oscillations are generated in an annular region in the disk. If the QPOs were to arise due to blob of material orbiting in the disk, the

QPO frequency should have increased systematically with time as the blob of material spirals towards the inner part of the disk. If the inner disk is superheated it can emit very high energy radiation upto gamma rays. Such an emission process is needed for the plasmoids to be thrown away by the compact object in the form of jets by radiation pressure along the axis of the system (Liang & Li 1995). While calculating the emission pattern from a disk around a black-hole two factors are to be considered, the gravitational redshift experienced by the radiation from the innermost disk and for super Eddington luminosity systems like GRS1915+105 and the effect of radiation pressure in the inner disk structure. If the radiation pressure is efficient in reducing the effective gravity the radial structure of the disk can be very different from that of an ordinary thin disk. These two factors, can lead to the fact that the efficient radiation zone in a disk around a black-hole can be somewhat further away from the event horizon. The observed QPOs of 0.7 Hz and even smaller frequencies as seen by PCA (http://heasarc.gsfc.nasa.gov/docs/xte/SOF/toonews.html) can then be from the most efficient zone of radiation in the disk whose radius changes because of various disk instabilities.

In low mass X-ray binaries usually two types of QPOs are seen, the nominal branch QPOs with a narrow frequency peak around 6 Hz with rms variation of 1-3% and the horizontal branch and flaring branch QPO peak in the frequency range 15 - 50 Hz and somewhat larger rms variation. Quasi-periodic oscillations are also seen in some of the pulsars but at a lower frequency of 0.02 to 0.2 Hz and these can be explained using the beat frequency model (van der Klis 1995). If the compact object in GRS1915+105 is a neutron star, the QPOs seen in this source are not like the ones in any of the other neutron star sources. In many Black Hole Candidates (BHC) QPOs associated with low frequency noise are seen at different frequencies in the range of 0.04 to 6 Hz. The type of QPOs seen in GRS1915+105 are similar to those seen in GX 339-4 (Grebenev et al. 1991).

Very strong subsecond intensity variations similar to GRS1915+105 are also seen in other black-hole candidates like Cyg X-1 and GX 339-4 (van der Klis 1995). Some neutron star sources like Cir X-1 (Toor 1977), 4U 1608-52 (van der Klis 1995), V0332+53 (Tanaka et al. 1983) also have shown subsecond variability but of smaller magnitude. So the short time variability seen in the present observation alone does not prove that GRS1915+105 is a black-hole source. However the Quasi-periodic oscillations at a frequency of 0.7 Hz and its first harmonic brings out the remarkable similarity of the power density spectrum (PSD) of this source with that of Cyg X-1 and GS 1124-68 in their very high state (van der Klis 1995). The flatness of the PSD below the QPO peak and the steep fall above the QPO frequency is also similar to that of other black-hole candidates in their very high state. So the identical nature of the PSD of GRS 1915+105 to that of Cyg X-1 and GS 1124-68 and subsecond intensity variations by a factor of 2 or more makes a strong case for this source to be a black hole. The hard X-ray tail of the spectrum of GRS1915+105 also supports its black-hole nature. Simultaneous observations in low and high energy X-rays in future will help in finding the true nature of this source.

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