OPTICAL AND X-RAY OBSERVATIONS OF IGR J00291+5934 IN QUIESCENCE

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ABSTRACT

We report on optical and X-ray observations of the accretion powered ms pulsar IGR J00291+5934 in quiescence. Time resolved $I$-band photometry has been obtained with the 4.2 m William Herschel Telescope, while a 3 ks Chandra observation provided contemporaneous X-ray coverage. We found an unabsorbed 0.5–10 keV X-ray flux of $1 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ which implies that the source was in quiescence at the time of the optical observations. Nevertheless, the optical $I$-band light curve of IGR J00291+5934 shows evidence for strong flaring. After removal of the strongest flares, we find evidence for an orbital modulation in the phase folded $I$-band light curve. The overall modulation can be described by effects resulting from the presence of a superhump. Comparing our lightcurve with that reported recently we find evidence for a change in the quiescent base level. Similar changes have now been reported for 4 soft X-ray transients implying that they may be a common feature of such systems in quiescence. Furthermore, the maximum in our folded lightcurve occurs at a different phase than observed before.

Subject headings: stars: individual (IGR J00291+5934) — accretion: accretion discs — binaries: close — stars: neutron — X-rays: binaries

1. INTRODUCTION

Low–mass X–ray binaries (LMXBs) consist of a compact object, either a neutron star or a black hole, that accretes from a late type companion star. The companion star typically has a mass $\lesssim 1$ M$_\odot$. Stellar evolution theory predicts that neutron star LMXBs are the predecessors of the recycled millisecond radio pulsars (Radhakrishnan & Srinivasan 1982; Alpar et al. 1982). This link between the neutron star LMXBs, their transient cousins, the X-ray transients, and the millisecond radio pulsars has been established by the discovery of the first accretion powered millisecond X–ray pulsar in 1998 (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998).

Subsequently, more of these systems have been found. At the time of writing there are ten accretion powered millisecond X–ray pulsars known. In three of these sources pulsations are detected only intermittently (the transients HETE J1900.1–2455, Aql X–1 and SAX J1748.9-2021 in the globular cluster NGC 6440; Galloway et al. 2007; Casella et al. 2007; Altamirano et al. 2007). To date all of them are found in globular clusters (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998).

In quiescence these systems are very faint in the optical. The counterpart can often not be detected (e.g. XTE J1751–305 the optical counterpart was not discovered in outburst nor in quiescence; Jonker et al. 2003). There are two noticeable exceptions; SAX J1808.4–3658 (Homer et al. 2001) and IGR J00921+5934 (Fox & Kulkarni 2004; Roelofs et al. 2004; Steeghs et al. 2004; Bikmaev et al. 2007). For a comprehensive overview of the outburst and initial quiescence observations of IGR J00921+5934 see Torres et al. 2007. D’Avanzo et al. (2007) recently reported multi-band quiescent optical and near–infrared observations of IGR J00921+5934.
Using optical observations of SAX J1808.4–3658 in quiescence, Homer et al. (2001) found evidence for a 9–15 per cent semi–amplitude modulation (the observed amplitude depends on the photometric band that is used for the observations). Those authors proposed that this would be due to X–ray irradiation from the neutron star. However, as pointed out by Burderi et al. (2003), assuming that SAX J1808.4–3658 was indeed in quiescence at the time of the optical observations, the quiescent X–ray flux of SAX J1808.4–3658 is too low by two orders of magnitude to explain the modulation in terms of X–ray heating. The absence of a double–humped morphology rules out that the modulation is due to ellipsoidal variations. Burderi et al. (2003) proposed that the irradiation is caused by a turned–on radio pulsar instead of the quiescent X–ray emission. Evidence for a turned–on radio pulsar, albeit indirect in this case (see Campina et al. 2004), would reinforce the link between the LMXBs and the millisecond radio pulsars. Furthermore, a turned–on radio pulsar would have an important effect on the evolution of the mass–losing donor star, altering the evolutionary path of the binary (Ruderman et al. 1989). Due to the absence of pointed X–ray observations at the time of the optical observations of Homer et al. (2004) and Campana et al. (2004), low level X–ray activity could have remained unnoticed in X–rays but would heat the side of the companion star facing the neutron star, providing an alternative explanation for the observed optical modulations. However, simultaneous X–ray and optical observations of SAX J1808.4–3658 reported by Heinke et al. (2004) forgo this possibility.

In this Manuscript, we present phase resolved photometric observations of the optical counterpart of IGR J00291+5934 in quiescence obtained with the 4.2 m William Herschel Telescope (WHT). In addition we present our analysis of a short contemporaneous Chandra observation of IGR J00291+5934 obtained with the aim to determine the contemporaneous X–ray flux.

2. OBSERVATIONS, ANALYSIS, AND RESULTS

2.1. Chandra X–ray observations

We have observed IGR J00291+5934 with the back–illuminated S3 CCD–chip of the Advanced CCD Imaging Spectrometer (ACIS) detector on board the Chandra satellite. The observation started on Sept. 13, 2006 at 13:33 (UTC; MJD 53991). The data telemetry mode was set to very faint to allow for a thorough background subtraction. Due to windowing of the ACIS–S CCD a frame time of 0.4104 s has been used. We have reprocessed and analysed the data using the CIAO 3.4 software developed by the Chandra X–ray Center using CALDB version 3.3.0.1 to take full advantage of the very faint data mode. In our analysis we have selected events only if their energy falls in the 0.3–7 keV range. The 0.3–7 keV background count rate was always lower than 0.4 counts s−1 during our observation. The net on–source exposure time is 2.88 ks.

Using wavdetect we detected two sources CXC J00291+593420 and IGR J00291+5934. We detect 22 photons from IGR J00291+5934 during the 2.88 ks observation, leading to a source count rate of 7.6×10−3 counts s−1. Using xspec version 11.3.2p (Arnaud 1996) we have fitted the spectrum of IGR J00291+5934 using Cash statistics (Cash 1979) to

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an absorbed powerlaw model. We held fixed the interstellar extinction to the value of 4.6×1021 cm−2 favored by Torres et al. (2007) and the powerlaw index to 2. We derive an absorbed 0.5–10 keV source flux of 7×10−14 erg cm−2 s−1 and an unabsorbed 0.5–10 keV flux of 1×10−13 erg cm−2 s−1. The source flux is consistent with that derived previously by Jonker et al. (2003) and Torres et al. (2007). We searched for variability in the rate of arrival of the photons but we found none. A Kolmogorov–Smirnov (Press et al. 1992) test showed that the probability that the data are consistent with the null–hypothesis of a constant photon arrival rate is 63%. We conclude that the source was in quiescence during our optical observations.

2.2. WHT optical observations

We obtained Harris J–band images using the Auxiliary Port Imager (AUX) instrument mounted on the 4.2 m WHT telescope at the Roque de Los Muchachos Observatory, La Palma, Spain. On September 13 and 14, 2006 (MJD 53991 and 53992 UTC) observations with an exposure time of 600 s, totalling 10.7 hours of data, were obtained. The observing conditions were good with a seeing of 0.7–1 arcsec during our optical observations. Those authors proposed that this would be due to X–ray irradiation from the neutron star. However, as pointed out by Burderi et al. (2003), assuming that SAX J1808.4–3658 was indeed in quiescence at the time of the optical observations, the quiescent X–ray flux of SAX J1808.4–3658 is too low by two orders of magnitude to explain the modulation in terms of X–ray heating. The absence of a double–humped morphology rules out that the modulation is due to ellipsoidal variations. Burderi et al. (2003) proposed that the irradiation is caused by a turned–on radio pulsar instead of the quiescent X–ray emission. Evidence for a turned–on radio pulsar, albeit indirect in this case (see Campina et al. 2004), would reinforce the link between the LMXBs and the millisecond radio pulsars. Furthermore, a turned–on radio pulsar would have an important effect on the evolution of the mass–losing donor star, altering the evolutionary path of the binary (Ruderman et al. 1989). Due to the absence of pointed X–ray observations at the time of the optical observations of Homer et al. (2004) and Campina et al. (2004), low level X–ray activity could have remained unnoticed in X–rays but would heat the side of the companion star facing the neutron star, providing an alternative explanation for the observed optical modulations. However, simultaneous X–ray and optical observations of SAX J1808.4–3658 reported by Heinke et al. (2004) forgo this possibility.

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calibration of the field was performed by observing two Landolt standard stars and differential photometry was used to derive the source flux variability as a function of time. The photometric results given here are with respect to the four field stars shown in Figure 1. These are the brightest isolated stars available in the unvignetted field of view of AUX that were recorded in the linear regime of the CCD.

We plot the I-band magnitude of IGR J00291+5934 (crosses) and those of a nearby comparison star of similar brightness (open circles; star C5) observed in quiescence on Sept. 13 and 14, 2006 in Figure 2 folded on the orbital period of IGR J00291+5934. We have used the pulsar ephemeris of Galloway et al. (2005). The error in propagating the orbital ephemeris to the time of our observations is \( \approx 0.01 \) phase. Phase zero is superior conjunction of the neutron star (i.e. the epoch of 90° mean longitude). The brightness of the comparison star (star C5 on Figure 1) is consistent with being constant. In contrast, the folded light-curve of IGR J00291+5934 displays several large flares (see also Figure 3). These are the brightest isolated stars available in the field of view of AUX that were recorded in the linear regime of the CCD.

In an attempt to determine whether there are variations in the quiescent optical brightness due to a change in aspect of the Roche–lobe filling companion star as a function of the orbital phase, we have removed flares from the light-curve of both nights. In order to come to a definition of a flare we have varied the magnitude threshold above which we identify a data point as a flare. Next, for a range of potential magnitude thresholds we fold and average the data in 10 orbital phase bins and we determine the \( \chi^2 \) and the number of degrees of freedom (d.o.f.) of a fit of a sinusoid plus a constant to the folded data. We show the results of this in Figure 4. It is clear that the \( \chi^2 \) strongly decreases when more and more stringent magnitude thresholds are taken. The reduction in \( \chi^2 \) levels off around a threshold magnitude of 21.75 (see Table 1).

For more stringent magnitude limits the decrease in \( \chi^2 \) is proportional to the reduction in the number of degrees of freedom as indicated by the straight dashed line in Figure 4. Such behavior is expected when clipping data points that are not flares.

Using 21.75 as our magnitude threshold above which we define data points as flares, the average I-band magnitude and the variance therein becomes 21.90 and 0.09 magnitudes, respectively. The variance is slightly higher than \( \approx 0.05 \) which is found for several stars of similar brightness that do not vary, implying that variability due to intrinsic variations is still present in the light-curve of IGR J00291+5934. The resultant folded light curve is shown in Figure 4. The most striking feature is the presence of a clear orbital modulation. In order to quantify the modulation we have fit the folded light-curve with a fit function consisting of a constant plus a sinusoid. An F-test gives that the improvement of a fit of a constant plus sinusoid has a probability of 2% to occur due to chance. We derive \( (6 \pm 1) \times 10^{-2} \) magnitudes and 0.34± 0.03 for the semi–amplitude and phase of the sinusoid, respectively. The value of the constant is 21.91±0.01 magnitudes. In addition to the sinusoidal variation there is suggestive evidence for an increase in source brightness at phase 0.9. In principle, an

| Magnitude limit | \( \chi^2_{\text{red}} \) | \( \chi^2 \) | D.o.f. |
|-----------------|-----------------|---------|------|
| 21.95           | 1.1             | 13.2    | 20   |
| 21.90           | 1.77            | 35.4    | 20   |
| 21.85           | 2.44            | 73.2    | 30   |
| 21.825          | 2.82            | 98.7    | 35   |
| 21.80           | 3.05            | 134.4   | 44   |
| 21.775          | 3.23            | 152     | 47   |
| 21.75           | 3.29            | 161     | 49   |
| 21.725          | 3.43            | 175     | 51   |
| 21.70           | 3.56            | 185     | 52   |
| 21.65           | 4.23            | 224     | 53   |
| 21.60           | 4.95            | 272     | 55   |
| 21.55           | 5.82            | 326     | 56   |

Fig. 2.— Optical I-band folded light curve of IGR J00291+5934 (stars) obtained with the 4.2 m WHT on Sept. 13 and 14, 2006. Strong flaring of IGR J00291+5934 can be seen. The strong flaring precludes the detection of clear trends in the I-band magnitude as a function of orbital phase. The open circles shows the I-band magnitude of a nearby star of comparable brightness (star C5 in Figure 1) measured simultaneously. The points for star C5 have been scaled down by 0.5 magnitude for display purposes. Phase zero corresponds to the epoch of 90° mean longitude as given by Galloway et al. (2005).

Fig. 3.— The image corresponding to the strongest flare visible in Figure 4 is displayed on the left. On the right is the image taken 20 minutes after the flare. North is up East to the left.
Fig. 4.— The $\chi^2$ of the fit of a constant plus sinusoid to the phase folded light curve of IGR J00291+5934 plotted against the number of degrees of freedom (d.o.f.) in the fit for the various magnitude thresholds that we investigated (see Table 1). The drawn line is the linear correlation described by the data points below d.o.f. = 50. The transition between the linear correlation and a more steep correlation occurs around magnitude 21.75.

Fig. 5.— Phase folded optical $I$–band light curve of IGR J00291+5934 after excluding flares in the light curve (i.e. data points with $I < 21.75$). The dashed line is the best–fitting model of a sinusoid plus a constant. The sinusoid reaches a maximum at phase $0.34 \pm 0.03$. For clarity two orbital cycles are plotted. Alignment of small flares in the phase bin centered on phase 0.9 can have caused an increase above the sinusoidal modulation. Ellipsoidal modulations due to the Roche–lobe filling companion star are not detected.

3. DISCUSSION

Comparing the source X–ray flux during a 3 ks–long Chandra observation of IGR J00291+5934 with that observed on previous occasions when the source was in quiescence, we conclude that IGR J00291+5934 was in quiescence on Sept. 13, 2006. Optical $I$–band observations acquired with the 4.2 m WHT telescope on Sept. 13 and 14, 2006 reveal strong variability with flares of $\sim 1$ magnitude on timescales of tens of minutes. After removal of flares we have phase folded our data. A clear sinusoidal variation is present. In our data set the orbital phase at which the source brightness is maximal is $0.34 \pm 0.03$. D’Avanzo et al. (2007) report a maximum consistent with phase 0.5. Furthermore, their average $I$–band magnitude of 22.4$\pm$0.2 for IGR J00291+5934 is 0.50$\pm$0.22 lower than our average magnitude (after removal of flares larger than $I = 21.75$). Hence, the brightening is only significant at the 2.3 $\sigma$ level and D’Avanzo et al. (2007) obtained the $I$–band observations under non–photometric conditions. Interestingly, D’Avanzo et al. (2007) do not report evidence for flaring. The lack of flaring together with the lower average brightness suggests that the source showed activity at the time of our optical observations above that found by D’Avanzo et al. (2007).

In order to investigate the nature of the flares and the observed variability in the phase folded optical light curve, we compared the quiescent properties of IGR J00291+5934 observed by us with those reported by Torres et al. (2007) and D’Avanzo et al. (2007) and with those reported for several other sources, most notably Cen X–4 (Chevalier et al. 1989, Shahbaz et al. 1993). Optical flares similar to those observed in IGR J00291+5934 in quiescence have been reported for several sources (e.g. Chevalier et al. 1989, Zurita et al. 2003, Hynes et al. 2003). However, flares as large as the largest that we observe in IGR J00291+5934 have not been reported to our knowledge. In addition, we note that a variation of about half a magnitude in the average brightness similar to that mentioned above for IGR J00291+5934 has been reported for Cen X–4, XTE J2123–058 and the black hole X–ray transient A 0620–00 (Chevalier et al. 1989, Tomsick et al. 2004, Cantrell et al. 2008, respectively).

Strong flares of similar duration (tens of minutes) have been observed in mid and late M dwarfs (e.g. see Rockenfeller et al. 2006 and references therein). However, Hynes et al. (2003) showed that the flares in quiescent LMXBs are associated with the accretion disk. Indeed, the combination of strong flaring and the lack of clear ellipsoidal variations in the phase folded light curve (this work as well as D’Avanzo et al. 2007), imply that the quiescent light is not dominated by a Roche lobe filling, but otherwise unperturbed donor star. If the flares are from the donor star their amplitude must be larger still. Instead, (superhumps from) a residual accretion disk, the accretion stream, and/or effects from an irradiated donor star are potentially important contributors to the quiescent $I$–band light. Torres et al. (2007) derive a similar conclusion on the basis of the quiescent intrinsic $R – K$ color and constraints on the donor star from the pulsar mass function.

The absence of ellipsoidal variations in the phase folded light curves of both IGR J00291+5934 as well as SAX J1808.4–3658 is consistent with the very low contribution of a (non–irradiated) brown dwarf to the optical light. Overall, the phase folded quiescent $I$–band light curve of IGR J00291+5934 that we find resembles that of the average quiescent $V$–band light curve of Cen X–
4 observed by Chevalier et al. (1989) in 1984–1988 (see their figure 7). Chevalier et al. (1989) show that a model where a large fraction of the optical light comes from the heated hemi–sphere of the companion star or an accretion disk attenuated by electron scattering in an accretion wake can describe the data well. In particular such a model can explain the lower brightness at orbital phases 0.5–0.7. The heating of the companion star in ms X–ray pulsars in quiescence has been ascribed to the turn–on of an active radio pulsar (Burderi et al. 2003).

Such an effect might be underlying the folded lightcurve of IGR J00291+5934, however, due to the (likely) higher level of activity during our observations additional effects seem to be important. An important clue comes from the phase difference between the maximum of the sinusoidal modulation reported by D’Avanzo et al. (2007) and that reported in this work. This suggests the presence of a modulation that has a period unequal to the orbital period, such as a superhump. Potentially, the overall morphology of our folded lightcurve can indeed be described by effects originating in a superhump. Superhumps have been detected in the black hole candidate XTE J1118+480 while near quiescence (Zurita et al. 2002). As explained in Whitehurst & King (1991), superhumps can occur in systems when the ratio between the companion star and the compact object mass is $\lesssim 0.3$. An accretion stream that perturbs the outer disk facilitates the excitation of tidal torques that are setting off the superhump resonance (Whitehurst & King 1991).

The hint for a brightening of the source around phase 0.9 visible in Figure 5 can be explained by the presence of an accretion stream and hot–spot while the mass ratio is very likely (much) lower than 0.3. However, from studies of Cataclysmic Variables it is known that the superhump only develops during outburst, most likely since the mass and hence angular momentum transfer rate through the disk in quiescence is too low to allow for a large extent of the disk. Hence, it is not clear whether all the conditions necessary for the occurrence of superhumps are fulfilled in IGR J00291+5934 during our observations. Interestingly, Neilsen et al. (2007) also found evidence for the presence of an eccentric, precessing disk in the black hole candidate A 0620–000 in quiescence. As superhumps can potentially explain the overall variability observed in the optical in several systems while in quiescence, further investigation is necessary to test whether during phases of (enhanced) mass transfer in quiescence a superhump can develop in quiescent LMXBs with mass ratios less than 0.3.

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