A BEPPOSAX-WFC VIEWPOINT OF NEW INTEGRAL SOURCES, PARTICULARLY IGR J17544-2619

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ABSTRACT

Of the 21 new sources that INTEGRAL discovered up to Feb. 1, 2004, 5 were detected with the BeppoSAX Wide Field Cameras at earlier times. IGR J16320-4751 appears to be a persistently active X-ray source which hints at a supergiant Roche-lobe overflowing companion star in this proposed high-mass X-ray binary. IGR J17091-3624 is a transient source that was detected in 1996 and 2001 with a maximum flux of 20 mCrab (2-28 keV). It is either a Be X-ray binary or a low mass X-ray binary transient. IGR J18483-0311 may be a high-mass X-ray binary, because it is located in a region rich of such objects, just like IGR J19140+098. IGR J17544-2619 appears to be a frequently active X-ray source whose hours-long flares, of which WFC detected five, are reminiscent of the stellar black hole source V4641 Sgr. We discuss this source in detail.

Key words: X-rays: binaries – Gamma rays: observations – accretion.

1. INTRODUCTION

Up to Feb. 1, 2004, 21 new sources were detected with INTEGRAL according to reports in the literature, see Table 1. They are all within 7 degrees from the Galactic plane and it is likely that most are located in the Galaxy. Some are obscured in the classical 2-10 keV band by thick absorption columns ($N_H > 10^{23}$ cm$^{-2}$), others are quick transients with activity periods of less than a day. Both kinds are interesting. If they are X-ray binaries, this suggests deviations from pure Roche-lobe overflow which is the standard in low-mass X-ray binaries. The thick local absorption columns could be indicative of massive in or outflows outside the accretion disk plane (if eclipses nor dips are present), while the short durations are reminiscent of the black hole transient V4641 Sgr.

A fraction of the new sources has been detected in earlier observations with instruments on ASCA, BeppoSAX and RXTE. We here discuss the earlier detections with the BeppoSAX Wide Field Cameras. Thanks to its large field of view ($40^\circ \times 40^\circ$ with 5' angular resolution, similar to IBIS) and a bandpass that extends to the unobscured > 10 keV part, the contribution of the WFCs to the understanding of these transients may be relevant. For instance, an accurate flux history of these hard sources will provide strong constraints on the suggested transient nature of some sources.

The WFCs were operational between June 1996 and April 2002, in other words in the six years preceding the launch of INTEGRAL. The WFC data archive has a substantial coverage over large parts of the sky. Along the Galactic plane, the exposure time is always in excess of 1 million seconds. The peak of the coverage coincides with the Galactic center where 6 million seconds of net exposure time was obtained. Typical sensitivities are a few mCrab for months-long observation times. For a recent review of these observations, we refer to In ’t Zand et al. (2004).

2. WFC ANALYSIS

We have gone through all WFC data of the 21 IGR sources and searched for detections on time scales of 1.5 hr, 1 d, 6 months and 6 years and in energy bands 2-10 and 10-25 keV. The total exposure time checked ranges from 1 to 4 million seconds. Per source this is up to 30% less exposure than present in the archive. This is due to conservative data filter thresholds, to avoid any complication due to partly obscuration by the earth of the field of view. Table 1 provides the average fluxes of all 21 sources. We found detections in 5 cases. In all other cases the upper limits over all observations combined are between 0.7 and 2.4 mCrab (2-28 keV).

In the following we discuss some results on the five detected sources. In particular, we discuss the 2-28 keV flux history. Beforehand we note that none of these 5 sources exhibited type-I X-ray bursts.
I  

| IGR Name and ref. | Alternative name | Follow up‡ | WFC detection? | WFC average flux† | Remark |
|------------------|------------------|-----------|--------------|------------------|--------|
| J06074+2205¹     |                  |           |              |                  |        |
| J15479-4529²     | 1RXS J154814.5-452845 |           |              |                  |        |
| J16316-4028³     |                  |           |              |                  |        |
| J16318-4848⁴     |                  |           |              |                  |        |
| J16320-4751⁵     | AX J1631.9-4752 | R,X       | y            | 3.3±0.2 (1.9)    |        |
| J16358-4726⁶     |                  |           |              |                  |        |
| J16393-4643⁷     |                  |           |              |                  |        |
| J16418-4532²     |                  |           |              |                  |        |
| J16479-4514⁴     |                  |           |              |                  |        |
| J17091-3624⁹     | 1SAX J1709-36   | y         |              |                  |        |
| J17391-3021²     | XTE J1739-302   |           |              |                  |        |
| J17456-2901       |                  |           |              |                  |        |
| J17464-3213       | H1743-322       | C,R       |              | 1.6 (4.0)        | BH transient |
| J17475-2822       |                  |           |              |                  |        |
| J17544-2619⁴⁺     |                  |           |              |                  |        |
| J17597-2201⁴      | XTE J1759-220   | R         |              | 2.0 (3.3)        | Burster, 1-3 hr orbit |
| J18027-2017       | SAX J1802.7-2017|           |              | 17 (3.3)         | Pulsar in HMXB close to GX 9+1 |
| J18325-0756⁶⁺     |                  |           |              |                  |        |
| J18483-0311      | 1RXH J184817.3-031017 |           |              | 2.2±0.3 (0.9)    |        |
| J18539+0727      |                  |           |              |                  |        |
| J19140+098⁹⁺     | EXO 1912+097    | R         |              | 1.0±0.1 (1.5)    |        |

¹Chevzez et al. 2004; ²Tomsick et al. 2004; ³Rodriguez et al. 2003a; ⁴Courvoisier et al. 2003; ⁵Tomsick et al. 2003; ⁶Revnivtsev et al. 2003c; ⁷Malizia et al. 2004; ⁸Molkov et al. 2003; ⁹Kuulkers et al. 2003; ¹⁰Sunyaev et al. 2003a; ¹¹Belanger et al. 2004; ¹²Revnivtsev et al. 2003a; ¹³Revnivtsev et al. 2004; ¹⁴Sunyaev et al. 2003b; ¹⁵Lutovinov et al. 2003a; ¹⁶Lutovinov et al. 2003b; ¹⁷Chernyakova et al. 2003; ¹⁸Lutovinov et al. 2003c; ¹⁹Hannikainen et al. 2003, Cabanac et al. 2004a,b and Schulz et al. 2004
²These are the 6-year average fluxes (mCrab in 2-28 keV). Between parentheses are indicated the exposure times checked, in Msec. The sensitivity also depends on the off-axis angle.
³X-ray follow-up activity up to Feb. 1, 2004 (X=XMM-Newton, R=RXTE, C=Chandra)

2.1. IGR J16320-4751

IGR J16320-4751 = AX J1631.9-4752 (Tomsick et al. 2003) was consistently detected with the WFCs during 1996-2002, at a flux that varied between 10 and 16 mCrab (5-10 keV; 2-month averages); with the ASCA detection, this suggests that the source has been persistently active for at least 8 years. Based on three broad channels (2-5, 5-10, and 10-28 keV) and averaged over all data, an absorbed power law model describes the data well with a photon index of 2.5 ± 0.3 and $N_H = (2±1) \times 10^{23}$ cm$^{-2}$. The average unabsorbed 0.7-10 keV flux is $4 \times 10^{-10}$ erg cm$^{-2}$s$^{-1}$. If the source is indeed a high-mass X-ray binary (HMXB), as suggested by Rodriguez et al. (2003b), the persistently bright emission would be more in line with the mass donor being a (super)giant than a Be star. The position in the combined WFC data is $\alpha_{2000.0} = 16^h32^m05.4^s$, $\delta_{2000.0} = -47^\circ52'07''$ (error radius 1.7; all WFC positional accuracies are given at 99-percent-confidence), which is 1.1 from AX J1631.9-4752 (ref TBD) and 1.1' from IGR J16320-4751. The analysis of an XMM spectrum by Rodriguez et al. (2003b) is in general agreement with the WFC measurements, but ASCA measurements show a much harder spectrum with an index of 0.5.

2.2. IGR J17091-3624

During Sept. 20.7–21.7 and Sept. 29.8 through Oct. 1.1, 2001 (UT), the WFCs detected a source which coincides with IGR J17091-3624. From combined data taken during August-October 2001, the source was localized to $\alpha_{2000} = 17^h09^m06^s$, $\delta_{2000} = -36^\circ24'39''$, with an error radius of 1.5'. The position is 0.03' from the INTEGRAL centroid (Kuulkers et al. 2003), 0.5' from the COMIS-TTM centroid (Revnivtsev et al. 2003b), and 1.3' from the reported radio source (Rupen et al. 2003). The flux
was 14 mCrab and 20 mCrab (2-10 keV) during the two observations. The spectrum is consistent with a 3.0±0.4 photon-index power law or $kT=4.3±1.4$ keV for thermal bremsstrahlung; $N_H$ was constrained to upper limits of 5 and $2 \times 10^{22}$ cm$^{-2}$, respectively (90% confidence). A search through the WFC archive revealed a weak detection five years earlier, in the combined data of the 1996 August-Oct WFC campaign of the Galactic center. In 650 ksec of data, the source was detected at an average flux of about 5 mCrab. All X-ray data combined imply that IGR J17091-3624 is a moderately bright variable X-ray source which flared in Oct. 1994 (Mircomis/TTM; Revnivtsev et al. 2003b), Sept. 1996 (BeppoSAX-WFC), Sep. 2001 (BeppoSAX-WFC), and April 2003 (INTEGRAL-IBIS) and most likely is an X-ray binary. The spectrum is fairly soft and no X-ray bursts were detected which marginally hints at a black hole transient at a relatively far distance. We note that the source was followed up by the BeppoSAX Narrow-Field Instruments on Sept. 25, 2001, after the first real-time detection. Therefore, it is listed in the SAX observation catalog under 1SAX J1709-36. Unfortunately, this observation was terminated before useful data could be taken due to problems with the satellite attitude control.

2.3. IGR J17544-2619

IGR J17544-2619 is a flaring source which was first detected with INTEGRAL on Sep. 17, 2003, when it exhibited two flares (Sunyaev et al. 2003b Grebenev et al. 2003) and a second time on Mar. 8, 2004 (Grebenev et al. 2004). The first detection was accompanied by two XMM-Newton observations which revealed further strong, flaring-like, activity at flux levels one to two orders of magnitude fainter (Gonzalez-Riestra et al. 2003, 2004). The nature of the source is thus far undetermined. However, there is the suggestion from the strong variability and the small angular distance to the Galactic center (37′3) that it is a compact object in our Galaxy.

Actually, IGR J17544-2619 was detected by the WFCs already in August 1996. The detection lasted just a few hours with a peak flux of about 50 mCrab (Fig. 1). The combination of duration and peak flux prevented real-time searches from finding the source and it was only noticed during more sensitive offline searches weeks later. By that time it was obviously too late for a target of opportunity observation. The source was tentatively identified with a ROSAT source detected during the all-sky survey, 1RXS J175428.3-262033, as was also done after the first INTEGRAL detection (Sunyaev et al. 2003b) by Wijnands (2003). The source was detected a further 4 times and each time it was only noticed weeks to months later during offline searches. Due to its presumed association with the ROSAT source (see Fig. 3) and in anticipation of a number of pending follow-up requests it was not reported. Only due to the INTEGRAL detection and the subse-
The spectrum of flares 3 and 4 cannot be modeled within 20 d from each other. Flares 2/3 and 4/5 are appear clustered in time. Flares 2/3 and 4/5 are not the only good model. An absorbed power law with a high-energy cutoff fits just as well and the extrapolated fluxes in the two INTEGRAL bands do not differ by more than 30%.

There are several data sets that support the notion that even outside large flares, the flux also appears to vary violently. There are the two XMM-Newton observations on Sep. 11 and 17, 2003, when for instance the flux increased from $8.8 \times 10^{-13}$ to $4.0 \times 10^{-11}$ erg cm$^{-2}$s$^{-1}$ (0.5-10 keV) in a matter of ~10 minutes (Gonzalez-Riestra et al. 2004). Furthermore, the source was not detected during a serendipitous XMM-Newton observation in March 2003 with an upper limit of $5 \times 10^{-14}$ erg cm$^{-2}$s$^{-1}$. Then there are the semi-weekly flux measurements through scans with the RXTE Proportional Counter Array of the Galactic bulge (Swank & Markwardt 2001), see Fig. 4. During the 5 years that these measurements have persisted so far, IGR J17544-2619 flared up above the 1.5 mCrab detection threshold (about $10^{-13}$ erg cm$^{-2}$s$^{-1}$ in 2-10 keV) 16 non-consecutive times. This points to a duty cycle above that level of about 5%. Finally, there are measurements with the RXTE All-Sky Monitor, which occasionally show fluxes up to 0.4 Crab (2-12 keV) during 90-s dwells.

In conclusion, IGR J17544-2619 is a source which appears to be active for a large portion of the time with strong variability between an upper limit of $5 \times 10^{-14}$ erg cm$^{-2}$s$^{-1}$ and a peak flux of $\sim 10^{-9}$ erg cm$^{-2}$s$^{-1}$. No X-ray bursts were ever detected. This kind of behavior is quite reminiscent of V4641 Sgr=SAX J1819.3-2525=3TE J1819-254 (Wijnands & van der Klis 2000, In ’t Zand et al. 2000, Hjellming et al. 2000) which is a dynamically established black hole candidate (Orosz et al. 2001). In that object also strong variability was detected with hours-long flare activity that culminated in one of the brightest X-ray flares ever observed (12 Crab units). Therefore, perhaps this is a black hole candidate, as was also recently suggested by Gonzalez-Riestra et al. (2004). The variability would then be due to an atypical companion star. Optical follow-up may bring the solution. A fairly bright O-type candidate has been identified by Rodriguez (2003) and Gonzalez-Riestra et al. (2004). A search for orbital Doppler shifts will likely provide constraints on the mass of the compact object.

We note that the list of similar fast X-ray transients without obvious optical counterparts such as RS CVn stars, BY Dra flare stars, or pre-main sequence objects, is slowly growing. To our knowledge, it now consists of five objects: IGR J17544-2619, XTE J1739-302 (Smith et al. 1998), V4641 Sgr (In ’t Zand et al. 2000; Orosz et al. 2001), XTE J1901+014 (Remillard & Smith 2002), and SAX J1818.6-1703 (In ’t Zand et al. 1998). The latter source was seen only once with the WFCs, but an investigation of the RXTE/ASM light curve (Fig. 5) shows at least 3 more flares above 100 mCrab (2-12 keV). Therefore, all these sources exhibit multiple hours-long flares with peak fluxes around $10^{-9}$ erg cm$^{-2}$s$^{-1}$. For the first three systems there is now evidence that the strong variability may be due to a high-mass companion star which may feed the compact object for a significant part through a wind instead of an accretion disk (like in many high-mass X-ray binaries).
Table 2. Flares from IGR J17544-2619.

| Time (MJD) | Peak flux (WFC \(c \text{s}^{-1}\text{cm}^{-2}\)) | Duration\(^{\dagger}\) (hr) |
|------------|---------------------------------|------------------|
| 50320.6    | 0.38                            | 3.3 ± 0.2        |
| 51229.7    | 0.31                            | 0.2 ± 0.2        |
| 51248.8    | 0.20                            | 0.4 ± 0.2        |
| 51807.5    | 0.25                            | 8.3 ± 0.2        |
| 51825.1    | 0.38                            | 1.0 ± 0.2        |

\(^{\dagger}\) time when flux is in excess of 0.1 times the peak value.

None of the systems exhibited X-ray bursts. When taking into account that the WFC exposure of these sources is a few million seconds, this provides further evidence that the compact objects are black hole candidates. There is a subtle non-uniformity in this group: V4641 Sgr, the only dynamically confirmed black hole candidate, is not continuously active with a small duty cycle, but intermittently with a high duty cycle. The key to understanding these systems is optical follow up (see above).

2.4. IGR J18483-0311

The coverage of BeppoSAX-WFC on IGR J18483-0311 is limited due to frequent large off-axis angles. The maximum flux observed with BeppoSAX-WFC is 0.03 c s\(^{-1}\) cm\(^{-2}\) (2-28 keV), or 15 mCrab, on April 26, 1997, and the lowest flux 1.5 mCrab for the combined data of Jul-Dec 1996 (257 ks exposure). All upper limits are worse than the lowest detected flux. The 6-year average is 2.2 ± 0.3 mCrab. Since it is located in the Scutum arm of our Galaxy where many HMXBs were detected in the past (cf Koyama et al. 1990; see Fig. 3), it may also be a HMXB.

IGR J19140+098 was detected in IBIS in March 2003 (Hannikainen et al. 2003) and May 2003 (Cabanac et al. 2004a). The peak flux was 0.1 Crab (13-100 keV). A brief (3 ksec) follow-up observation was performed by RXTE in March 2003 when it peaked at about 10 mCrab in 2-10 keV (Swank & Markwardt 2003). The spectrum is variable with a transient Fe-K emission line complex (with equivalent width 550 eV during the RXTE observation) and a power law with photon index between 1.7 and 3. The source shows significant variability on time scales longer than 100 s.

This source also has limited coverage by the BeppoSAX WFCs. All 1-d WFC detections cluster around 10 mCrab (similar to what was observed with RXTE), and the 6-month averages vary between an upper limit of 1 mCrab (3\(\sigma\)) and a detection of 5.0 ± 0.5 mCrab (for Jan-Jun 1998). The position is \(\alpha_{2000,0} = 19^h13^m09^s5, \delta_{2000,0} = +9^\circ52'37''\) (error radius 2'). The 6-year average is 1.0±0.1 mCrab (exposure time 1.5 Msec; see Fig. 4). All WFC detections are insufficient to provide meaningful constraints on pulse signal amplitudes or spectra.

Based on coordinates extracted from the Simbad database at CDS Strasbourg, we identified this source with a EXO 1912+097. This is a source which was identified in EXOSAT data in the nineties through a new detection algorithm by Lu et al.
(1997). However, investigation of the Lu et al. paper, which is written in Chinese, yielded that the error circle of EXO 1912+097 is actually shifted by such an amount that the WFC and INTEGRAL source positions are on the edge of the error circle. Therefore, it is slightly questionable whether the EXOSAT source is related to the WFC and INTEGRAL sources. For details, see Fig. 11.

The source was often detected with WFC and INTEGRAL, but at flux levels close to the detection limit. Therefore, it is feasible that the source is strongly variable but persistent. A determination of its physical nature would benefit from high-spatial-resolution observations at X-ray and optical wavelengths, also to confirm the tentative identification with a radio counterpart (Schulz et al. 2004; Pandey et al. 2004).

3. SUMMARY

BeppoSAX-WFC provided detections of 5 out of 21 of the new INTEGRAL sources in the classical X-ray band. The flux levels of these detections are all except one below $10^{-10}$ erg cm$^{-2}$s$^{-1}$. The one exception is a clear transient which goes into outburst for a few hours at least once a year. One other source shows the hallmarks of a classical though faint transient: IGR J17091-3624. The other three sources exhibit detections in the combined 6-year WFC data which, for fluxes which were rarely measured to be above a factor of 10 of the 6-year averages, implies that they are most likely low-flux persistent sources. The two transients are very likely X-ray binaries in our galaxy. The nature of the three fainter but possibly persistent sources is less well constrained, but probably also X-ray binaries in the Galaxy.

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