Czech Participation in INTEGRAL: 1996–2011

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Abstract

The European Space Agency ESA INTEGRAL satellite launched in October 2002 is the first astrophysical satellite of the European Space Agency (ESA) with Czech participation. The results of the first 8 years of investigations of various scientific targets are briefly presented and discussed here, with emphasis on cataclysmic variables and blazars with the ESA INTEGRAL satellite with Czech participation.

1 Introduction

There is a long tradition of involvement of Czech scientists in high-energy space projects, starting nearly 40 years ago with Czech involvement in various satellite experiments within the INTERKOSMOS programme. Collaboration with the European Space Agency (ESA) started soon after the political changes in Czechoslovakia in 1989. The ESA INTEGRAL project was the first ESA project in space astronomy with official Czech participation based on a collaboration agreement between ESA and the Czech Republic, i.e. prior to full membership of the Czech Republic in ESA. The INTEGRAL (International Gamma-Ray Astrophysics Laboratory) satellite has now been in orbit for more than 8 years, and some general conclusions may be drawn at this point.

Fig. 1: OMC Test Device (providing real test images) operated at AI Ondrejov prior to the launch of INTEGRAL. BART Wide Field CCD camera, FOV 6×7 degrees, lim mag 15.5, identical with INTEGRAL OMC Test Device (18 arcsec/pixel)

There are four co-aligned instruments on board INTEGRAL: (1) an IBIS gamma-ray imager (15 keV to 10 MeV, full coded field of view (FOV) 8.3×8 deg, 12 arc min FWHM), (2) an SPI gamma-ray spectrometer (12 keV–8 MeV, full coded FOV 16×16 deg), (3) a JEM-X X-ray monitor (3–35 keV, fully illuminated FOV diameter 4.8 deg), and (4) an OMC optical monitoring camera (Johnson V filter, FOV 5×5 deg) (Winkler et al. 2003). These experiments enable simultaneous observation in the optical, medium X-ray, hard X-ray, and gamma spectral region (or at least a suitable upper limit) for each object, assuming that it is inside the field of view. The basic observation codes are as follows: (a) Regular (weekly) Galactic Plane Scans (GPS) (-14 deg $< b_{II} < +14$ deg), (b) Pointed observations (AO), (c) Targets of opportunity (ToO).

In this paper, we deal with examples of observations and analyses of INTEGRAL data with Czech participation, focusing on two categories of objects, namely cataclysmic variables (CVs) and blazars.

2 Czech involvement in the INTEGRAL Project

Czech involvement in the ESA INTEGRAL project started in 1996, when Rene Hudec was invited to join the OMC and ISDC consortia, on the basis of a collaboration agreement between ESA and the Czech Republic. At that time, our participation focused on ISDC and OMC.

In OMC (Optical Monitoring Camera), our participation focused on various software packages, such as OMC PS (OMC Pointing Software) for Integral ISOC, and also on the design, development and operation of OMC TD (Test Device), a ground-based camera with output analogous (pixel size 18 arcsec) with the real OMC.

For ISDC (Integral Science and Data Center), located in Versoix, Switzerland, the main part of our contribution involved providing manpower, i.e. one person working within the team, with various responsibilities and involvements in the ISDC operations. As for the scientific responsibilities, Rene Hudec was delegated to lead the study of cataclysmic variables, and he was later also a member of the working groups on gamma-ray bursts (GRBs) and AGNs. In this paper, we very briefly summarize the scientific achievements in these fields. In addition, we have participated in the development and operation of dedicated robotic telescopes, considered as the ground-based segment of the project, and in delivering supplementary optical data for satellite triggers. This work has been done mainly by young research fellows and by students.

The Czech scientific participation focused on topics allocated by INTEGRAL bodies, mostly cataclysmic variables but also blazars and some other objects, such as Gamma-Ray Bursts (GRBs).

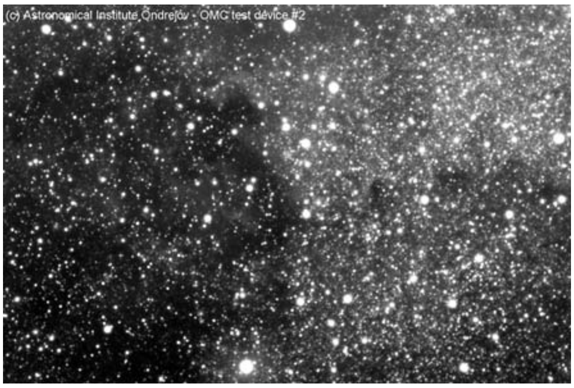

Fig. 2: Test image provided by the OMC Test Device operated at the Ondrejov Observatory (FOV 6 × 7 deg, lim mag 15.5, pixel size 18 arcsec identical with the real OMC camera)

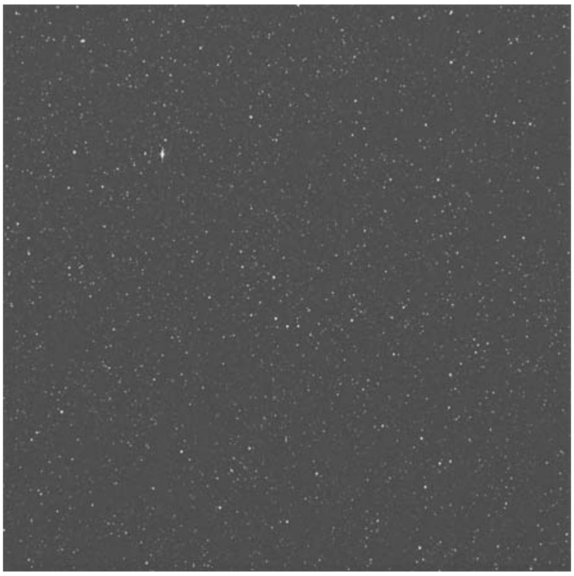

Fig. 3: Example of an OMC image from space

3 Cataclysmic variables

Responsibility for the category of cataclysmic variables (CVs) and related objects was delegated to Rene Hudec. The results of hard X-ray detections of these binary galactic objects were surprising. The soft X-ray emission of the group was already known in advance, but the hard X-ray extension to (in some cases) more than 80 keV was a new discovery. These findings have even led to the idea that CVs may make a contribution to the galactic X-ray background.

In total, 32 cataclysmic variables (CVs) have been detected by the INTEGRAL IBIS gamma-ray telescope (this is more than had been expected before launch, and represents almost 10 percent of INTEGRAL detections). 22 CVs have been seen by IBIS and found by the IBIS survey team (Barlow et al. 2006, Bird et al. 2007, Galis 2008), based on a correlation of the IBIS data and the Downes CV catalogue (Downes et al. 2001). Four sources are CV candidates revealed by optical spectroscopy of IGR sources (Masetti et al. 2006), i.e. new CVs, not in the Downes catalogue. They are mainly magnetic systems: 22 were confirmed or probable IPs, 4 probable magnetic CVs, 3 polars, 2 dwarf novae, 1 unknown. The vast majority have an orbital period $P_{\rm orb} > 3$ hr, i.e. above the period gap (only one has $P_{\rm orb} < 3$ hr), but 5 objects are long-period systems with $P_{\rm orb} > 7$ hr.

The long lifetime of the INTEGRAL satellite (> 10 years) has enabled long-term variability studies, albeit limited by observation sampling. At least in some cases, the hard X-ray fluxes of CVs seen by INTEGRAL exhibit time variations, very probably related to the activity/inactivity states of the objects. The spectra of the CVs observed by IBIS are in most cases similar. A power law or thermal bremsstrahlung model compares well with the previous high-energy spectral fits (de Martino et al. 2004, Suleimanov et al. 2005, Barlow et al. 2006).

Another surprise is that while the group of IPs represents only ~2 percent of the catalogued CVs, it dominates the group of CVs detected by IBIS. More such detections and new identifications can therefore be expected, as confirmed by our search for IPs in the IBIS data, which provided 6 new detections (Galis et al. 2008). Many CVs covered by the Core Program (CP) remain unobservable by IBIS because of short exposure time, but new CVs have been discovered. IBIS tends to detect IPs and asynchronous polars: in hard X-rays, these objects seem to be more luminous (up to a factor of 10) than synchronous polars. Detection of CVs by IBIS typically requires 150–250 ksec of exposure time or more, but some of them remained invisible even after 500 ksec., at least in some cases. However, this can be related to the activity state of

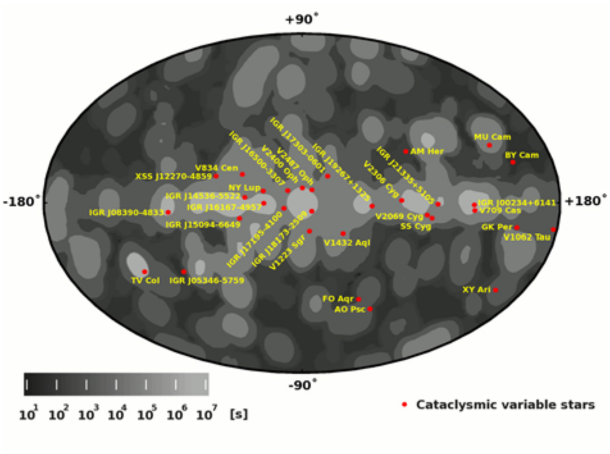

Fig. 4: Preview of 32 CVs observed by INTEGRAL–INTEGRAL IBIS sky coverage (up to March 2009)

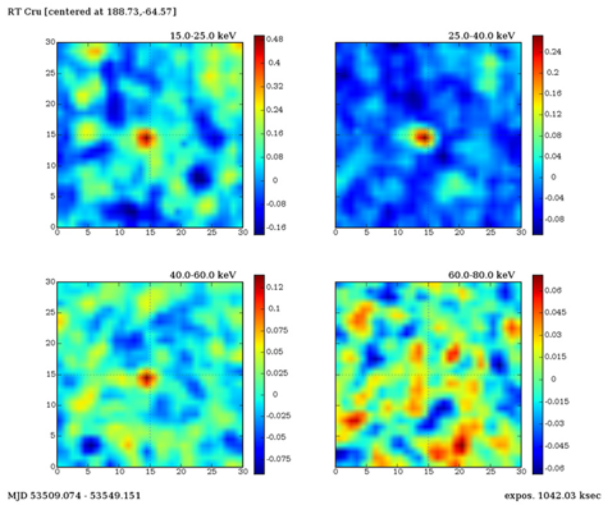

Fig. 5: Symbiotic star RT Cru observed as an IBIS source up to energy 60 keV. The detection of symbiotic stars in hard X-rays by INTEGRAL was a surprise

the sources — the hard X-ray activity is temporary or variable.

Detecting hard X-ray flaring activity is another important issue. There is an indication for a hard X-ray flare in a CV system, namely V1223 Sgr, seen by IBIS (a flare lasting for > 3.5 hr during revolution 61 (MJD 52743), with the peak flux > 3 times above the average (Barlow et al. 2006)). These flares had already been seen in the optical in the past by a ground-based instrument (duration of several hours) (van Amerongen & van Paradijs 1989). This confirms the importance of the OMC-like instrument (preferably with the same FOV as a gamma-ray telescope) on board gamma-ray satellites: even with the V limiting mag 15, this can provide valuable optical simultaneous data for gamma-ray observations. Analogous flares are also known for other IPs in the optical, but not in hard X-rays. TV Col (Hudec et al. 2005) can serve as an example: in this system, 12 optical flares have been observed so far, five of them on archival plates from the Bamberg Observatory, and the remaining flares by others observers. TV Col is an IP, and the optical counterpart of the X-ray source 2A0526–328 (Cooke et al. 1978). This system is the first CV discovered through its X-ray emission, newly confirmed as an INTEGRAL source. The physics behind the outbursts in IPs is either the instability of the disk or an increase in the mass transfer from the secondary.

4 Blazars

Another category of INTEGRAL targets that we have investigated is a special class of AGN (Active Galactic Nuclei), known as blazars. These objects belong to the most important and also optically most violently variable extragalactic high-energy objects. We focus on objects found by data mining in the INTEGRAL archive for faint and hidden objects. For more details on blazar analyses with INTEGRAL, see Hudec et al. (2007). In addition, successful blazar observations have been performed mostly in the ToO regime. The extensive collaboration led by E. Pian serves as an example (Pian et al. 2007). We have developed procedures for accessing faint blazars in the IBIS database. Blazar 1ES 1959 + 650 can serve as an example. This blazar is a gamma-ray loud variable object visible by IBIS in 2006 only, invisible in total mosaics and/or other periods. The optical light curve available for this blazar confirms the relation of active gamma-ray and the active optical state.

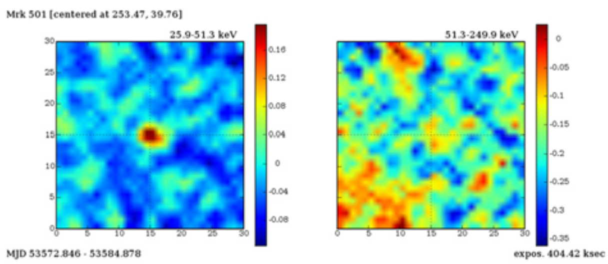

Fig. 6: The most significant result of the IBIS data mining procedure for faint sources. The flux corresponding to the excess in the lower spectral band for Mrk 501 is (1.57 ± 0.24) 10–11 erg/cm^2/s. The coordinates of the images are given in pixels, one pixel being 4.9 arcmin; the mosaics are centered on the catalogue position of the source

5 OMC

The small optical camera on board the INTEGRAL OMC satellite delivered a great amount of valuable simultaneous optical data for observations of gamma-ray and hard X-ray sources. However, for gamma-ray bursts (GRBs) this is the case only for a few triggers, as the field of view (FOV) of OMC is much smaller than the FOV of the most widely-used instrument on INTEGRAL, namely IBIS (5 vs. 8 degrees). However, OMC proved to be an efficient tool for optical objects without gamma–ray counterparts, such as eclipsing binaries. For these objects, the uninterrupted nature (no day/night cycles) of space-based observations was found to be positive for studying the light curves and for determining the times of the minima.

6 ISDC

The Czech involvement focused on direct participation in the operation and activities of the Integral Science and Data Center (ISDC), including providing one person continuously working directly within the ISDC team (as well as other persons occasionally visiting ISDC). The person at ISDC participated in the service work of Center (especially by contributing to ISDC operations), and also in scientific analyses. Participation in the scientific programme has involved observations, data analyses, data archiving, data interpretation, and scientific evaluations.

In addition, we have worked on transferring ISDC s/w packages, further development of tools for effective and interactive scientific analyses and the use of INTEGRAL data, further improving the quality of astrometry and photometry, and on operating the second (local) ISDC center/office (Ondrejov Integral Data Center, OIDC) at the Ondrejov Astronomical Institute, enabling the astronomical community in the Czech Republic and in Central and East Europe to participate in scientific activities related to INTEGRAL, data evaluation, data archiving, and interpretation. The scientific activities have focused on allocated scientific tasks, especially Cataclysmic Variables and white dwarfs, Gamma ray Bursts, and Blazars-AGNs.

Czech participation in ISDC (INTEGRAL Science and Data Centre) in Versoix has included the following tasks, which are listed below as examples.

idx_merge tool. Idx_merge is a tool program developed at ISDC, which was used in archive processing for merging two FITS indices. Petr Kubanek carried out benchmark tests to provide information about possible speed-up in this program. The tests identified the fast-merge patch as the best possible solution. A fast-merge patch was developed by Petr Kubanek, tests for this patch were made, and the patch was delivered to ISDC. The patch significantly speeded up archive processing.

ISR – Integral Source Results web pages. Based on discussions with Mathias Beck, Mohamed Meherga and Roland Walter, Petr Kubanek created the Integral Source Results web pages. These enabled users not familiar with OSA (Offline Scientific Analysis, a software package used for analysing INTEGRAL data) to access data products from standard OSA runs, which are executed at ISDC (Kubanek and Hudec, 2007). The web pages were later further developed by the ISDC staff.

The web pages enabled access to light-curves, spectra and IBIS and JEM-X processed images of objects. They contained processed data for all public observations of sources that were flagged as detected in the INTEGRAL Source Results catalogue, version 15. ISDC repeatably reprocessed this data with new OSA releases, which provided better results on this quick-look page. A user guide for ISR was written, and also a description of ISR for the ISDC Newsletter. The ISR Perl source code was fully documented and delivered as the ISDC SW package.

lc_extract tools. Based on discussions with Filip Munz, Petr Kubanek developed lc_extract tools, which were tested for extracting the countrates of weak sources from the INTEGRAL IBIS detector. lc_extract uses a variant of the pure open/close mask element method to detect weak sources inside the IBIS field of view.

VO – Virtual Observatory at ISDC

Almost all facilities dealing with astronomical data archiving contribute to the development of Virtual Observatory. Virtual Observatory can be used for quick multispectral analysis of various sources, and for computer-driven data mining and processing. It can help researchers to gain quick access to information that they need in a format that they can use, so that they can focus on validating their theories rather than on learning various methods for processing data from various Earth and space based observatories.

We contributed significantly to the development of Virtual Observatory by conforming access to INTEGRAL data. Petr Kubanek prepared the environment for enabling Virtual Observatory to provide access to INTEGRAL data. This work included installing and configuring the Apache Tomcat server on the ISDC Solaris computers. He decided to implement VO services at ISDC as a set of Java Servlets. The main reason for this was his experience with Java Servlets, which he found superior to the Perl::CGI approach. Object-oriented programming (OOP), which forms the basis of Java language, allows better design of complex programs. At the cost of a longer design phase, it enables better growth of initial small code subsets to full feature services and then procedural programming. It also promotes separation of code to small subsets with clearly defined interfaces. Thanks to this approach, the code can be reused.

It should be noted that OOP was also introduced to Perl, but since Perl was not invented for OOP,

OOP implementation in it is introduced at the cost of various design requirements, which layer OOP over the original Perl procedural language.

Java also introduced JavaDoc for writing documentation directly in code. This enables better and more up-to-date documentation than writing separate programming documentation.

After deciding on the target enviroment (Java Servlet Container - Tomcat from the Apache Foundation), Petr Kubanek implemented VO access to the INTEGRAL catalogue. This first servlet was used as the prototype for developing of another servlet, which handles FITS images search and extraction.

We developed a prototype for VO access to INTEGRAL IBIS mosaics. The advanced VO access was later offered by the ISDC staff to the world astronomical community, after further development of VO access, taking it from a prototype to production status, and including other high-level products in the VO database for all INTEGRAL instruments.

As various VO developers have pointed out, the only currently available pure Java library to access FITS files, nom.tam.fits library, has significant drawbacks. These include bugs in reading big gzipped files, resulting in inability to read most of the INTEGRAL data, and lack of support for WCS (World Coordinate Systems) extensions (which are used for storing information about the part of the sky that the image contains). Petr Kubanek patched the nom.tam.fits library so the he can use it in his VO servlets. However, on the basis of discussions with other VO developers, he decided to recode the Java FITS access library, so that it will not suffer from the drawbacks noted during its use. He has also made changes to the UK Starlink Starjava package, so that he can use it to quickly generate pages used for VO access. These efforts have been further developed by the ISDC staff.

7 Ground based segment

The optical camera (OMC) onboard INTEGRAL has delivered valuable data, but there are some limits on magnitude, on accuracy, and on available FOV. There is an obvious need to provide additional optical data for simultaneous analyses of astrophysical objects detected by the onboard hard-energy experiments, above all IBIS. A similar procedure is considered for the ESA Gaia satellite, since the photometric sampling of the Gaia photometry will not be optimal in many cases.

For this reason we have from the beginning laid emphasis not only on space experiments but also on the related ground based segment, namely optical ground-based experiments, with emphasis on robotic telescopes. The RTS2 dedicated control program has been designed and developed.

RTS2 was installed and runs on (nowaday) numerous robotics telescopes, which are spread around the globe. RTS2 was originally developed for conducting observations of gamma-ray burst error boxes in an optical window, but it has evolved to a full-featured package for any robotic telescope (http://rts2.org).

On the basis of experience gained from developing RTS1, RTS2 is layered to an abstract, device-independent communication layer, and drivers for various devices. Thanks to this layering, new devices can be integrated smoothly and very rapidly into RTS2.

Members of the Czech Integral group have continued to develop RTS2 (Remote Telescope System, 2nd version). A major change involved separating the execution and selection logic, which had previously been handled by a single RTS2 component (planc), into two independent componets (rts2-executor, and rts2-selector). This separation enabled us to better fulfil the different requirements for different scheduling algorithms for different telescopes (http://rts2.org).

RTS2 was installed e.g. in the 60 cm BIR (Bootes Infra-Rocho) telescope. BIR is located at the Instituto de Astrofisica de Andalucia (IAA) Observatorio de Sierra Nevada (OSN). RTS2 has also been installed in the FRAM telescope at the Pierre-Auger Observatory in Argentina. It is used for monitoring the atmospheric conditions above the Pierre-Auger optical detectors. RTS2 has also been installed in the Watcher 1 telescope, located at the Boyden Observatory in South Africa. As RTS2 is released under GNU licence, the University College of Dublin members who built Watcher downloaded it, customized it to fit their purpose and installed it in their telescope. Members of our group helped them with the installation process, and provided help in customizing RTS2.

RTS2 was also customized for use in the MARK telescope, which is located in the Prague Stefanik Observatory, and we are running prelimary tests on RTS2 at this site. Thanks to the MARK tests, RTS2 acquired the ability to control observations setups with a copula. This ability will be very important for the use of RTS2 in larger telescopes. It is currently under negotiation for various telescopes (more than 1m in diameter). RTS2 uses the libnova library to carry various astronomical calculations. Petr Kubanek, who co-maintains libnova, has futher patched and developed libnova.

8 Other works

The secondary science centre in Ondrejov has been put into operation. Various versions of OSA data analysis software have been transferred and successfully installed. Data for the most promising sources has been reprocessed with the OSA software packages and organized into a local archive in a way that enables any combination of SCWs to be constructed on demand.

Source database. Considerable time has been spent on developing a web interface for INTEGRAL working groups, devoted to studies of blazars (http://altamira.asu.cas.cz/iblwg) and cataclysmic variable (CV) stars (http://altamira.asu.cas.cz/icvwg). Most of the features of these pages were supplied by a common code written in PHP with the underlying MySQL database. This database is filled with information from the ISDC archive (position and quality of individual pointings), and also with available HE data on the sources to predict their possible detection using INTEGRAL instruments. We still lack information on the X-ray spectra of CVs (only a small collection of about 20 spectra from ASCA observations is available above 1 keV).

More recently, a large new set of possible blazar positions (about 700, half of them corresponding to Veron-Cetty AGN locations) from *astro-ph/0506720* has been included. We are currently checking the candidates with highest exposures.

An important feature of these web pages is a scheduler that uses data from the ISOC pages (a complex script for retrieval of scheduled pointings and for importing them into the database was written by Jiri Polcar). This allows us to plan simultaneous observations with optical telescopes in advance, not just to react to GCN alerts about new INTEGRAL pointings (more suitable for robotic telescopes). In some cases, a given source is below the horizon at the time of INTEGRAL observation, so optical monitoring should be performed before the alert is issued.

Weak source analysis. Our basic tool for extracting physical data from reconstructed images is mosaic_spec, a small program in C intended originally as an alternative to standard spectral analysis (started at ISDC with Roland Walter in 2004). While the old version is currently employed by the INTEGRAL Source Result web interface to ISDC archive, the Czech team members have added some new features that allow us to obtain more information about the shape of the analysed peak in an IBIS image, the properties of the background (to sort out most of the false detections), and finally to retrieve a cutout from a large mosaic. This latter feature allows us significantly to reduce (by several orders of magnitude) the amount of data that needs to be transferred from ISDC when analyzing large mosaics (either available directly for pre-defined observation groups — OGs — or constructed from selected SCWs using the ii_skyimage mosaicking capability). Since the energy binning of reconstructed IBIS images in the ISDC archive (revision 2) is too fine for a search of weak sources, mosaic_spec can also sum-up several energy bins together to improve the statistics. The cut-outs should soon be available (once the bitmap conversion has been mastered).

The analysis of short-time pre-defined OGs (up to 3 days in length) is well suited for studies of blazars (whose flares can appear at these time scales) but not so well suited for a search of cataclysmic variables (whose variability has a more periodic nature). Where their basic periods (orbital, rotation or beat of these two) are known, we could employ phase resolved analysis. A new tool called lc_extract has been developed for this purpose by Petr Kubanek. It uses a pixel illumination factor (PIF) method similar to the standard IBIS light curve extraction process, but it should be less sensitive to variations of fluxes of strong sources in the field of view (which is the case for CVs close to the Galactic bulge). The production version of this tool script includes GTI and noisy pixel treatment.

More recently, we have participated in the efforts at ISDC to further develop ISDC into a more general scientific and data centre for space astronomy.

In addition, data from astronomical plate archives has also been analysed for some of the targets, adding additional time dimensions to the investigations, identification and classification of INTEGRAL sources.

Not only the long-term evolution of optical light curves of objects (in some cases for up to 100 years) can be studied this way. Low-dispersion spectra (for various time epochs) can also be extracted and analysed.

9 Conclusions

The Czech INTEGRAL team has contributed to various fields of INTEGRAL science. Only a few examples have been given in this paper. In general, the INTEGRAL satellite opens a new 10–100 keV X-ray observational window to which there had previously been only very limited access. The X-ray emisssion of some CVs and SSs extends to 80 keV. Our results confirm that the INTEGRAL satellite is an effective tool for finding new CVs, mainly IPs.

The contribution of the Czech participants in the ESA INTEGRAL project has focused on the onboard OMC camera, on work at ISDC, and on INTEGRAL science, with emphasis on cataclysmic variables and blazars. The INTEGRAL satellite is clearly an effective tool for analyzing both CVs and blazars. So far, 21 blazars, 32 CVs and 3 symbiotics have been detected, and the number is increasing with time. The successful observations of CVs using INTEGRAL provide proof that CVs can be successfully detected and observed in hard X-rays with INTEGRAL (for most CVs, these are considerably harder passbands than had been possible previously). These results show that more CVs (in harder passbands) will be detectable with increasing integration time. There is also an increasing probability of detecting objects in outbursts, high and low states, etc. Simultaneous hard X-ray and optical monitoring of CVs and blazars (or at least suitable upper limits) can provide valuable inputs for better understanding of the physical processes that are involved.

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