Chin. J. Astron. Astrophys. Vol. 5 (2005), **Suppl.**, 1–6
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

Exploring the *INTEGRAL* Sources in Search for New Microquasars

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Abstract Here we present a search for new microquasars among the sources detected with the *INTEGRAL* satellite (IGR sources). We focus on radio emitting IGR sources and report the discovery of two new probable extragalactic sources behind the galactic plane, as well as the detection at higher energies of the *ASCA* source AX J1639.0−4642, probably a new microquasar in the Galaxy and coincident with a high-energy gamma-ray emitting EGRET source.

Key words: X-rays: binaries — X-rays: galaxies — X-rays: individual: (AX J1639.0−4642, IGR J16393−4643, IGR J18027−1455, IGR J21247+5058)

1 INTRODUCTION

The INTErnational Gamma-Ray Astrophysics Laboratory (*INTEGRAL*), launched on 2002 October 17, carries out different instruments covering the electromagnetic spectrum from the optical to the soft gamma-rays (Winkler et al. 2003). Among them, the combination of the IBIS imager (Ubertini et al. 2003) with the ISGRI detector working in the energy range 15–1000 keV (Lebrun et al. 2003) is able to provide a resolution of 12 arcmin FWHM. This effectively means a position accuracy in the range 1–3 arcmin for sources detected at a level in the range 20–6σ with a 90% confidence (Gros et al. 2003). This combination, hence, provides the best astrometric accuracy for hard X-ray sources up to date, and allows us a relatively easy search for soft X-ray/radio counterparts, from which the search for optical and near infrared counterparts can be performed. These capabilities encouraged us to search for new microquasars among the IBIS/ISGRI sources (see Mirabel & Rodríguez 1999 and Fender **?** for reviews on microquasars).

Bird et al. (2004), have recently reported data of 123 sources detected with IBIS/ISGRI in cumulative observations within the mission Core Programme conducted between 2003 February 28 and October 10. Among them, there are 27 new sources or re-detected sources poorly studied

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in the past (discovered with *ASCA*, *RXTE*, etc.), which have the denomination IGR. Moreover, other sources have been discovered by different groups in pointed observations. In total, since the beginning of observations in 2003 November until the time of writing (middle July 2004), the IBIS/ISGRI instrument has detected up to 42 X-ray/γ-ray new or poorly studied sources in the energy range from 20 to 100 keV (a regularly updated list is kept by J. Rodríguez at `http://isdc.unige.ch/~rodrigue/html/igrsources.html`).

An inspection of the published data of these sources reveals the presence of 8 X-ray binaries (including 2 confirmed and 2 suspected High Mass X-ray Binaries (HMXBs), 3 low mass X-ray binaries, 1 black hole candidate), 4 X-ray binary candidates (including 3 HMBX candidates), possibly Sgr A* (Bélanger et al. 2003) and 3 suspected AGN, while there remain 26 completely unidentified sources. Clearly, multi-wavelength observations are necessary to discern their unknown nature. Interestingly, huge hydrogen column densities of $N_{\rm H} > 10^{23}\,{\rm cm}^{-2}$ towards some of these sources have been inferred by means of soft X-ray observations performed with the *ASCA* and *XMM-Newton* satellites (e.g., IGR J16318−4848 by Revnivtsev et al. 2003, Matt & Guainazzi 2003 and Walter et al. 2003, and IGR J16320−4751 by Rodriguez et al. 2003). Basically, *INTEGRAL* allows us to look at highly obscured sources in the galactic plane, including galactic and extragalactic sources.

We have performed a search for non-thermal radio counterparts, a signature of relativistic jet emission from microquasars and AGN, among the IGR sources by means of publicly available surveys, like the 1.4 GHz NRAO VLA Sky Survey (NVSS, Condon et al. 1998) and the 843 MHz Molonglo Galactic Plane Survey (MGPS, Green et al. 1999). Here we present updated multiwavelength studies of three sources: the probable extragalactic sources IGR J18027−1455 and IGR J21247+5058 and the probable galactic source IGR J16393−4643/AX J1639.0−4642, which turns out to be the best microquasar candidate discovered by *INTEGRAL*.

2 IGR J18027−1455

The discovery of IGR J18027−1455 was reported by Walter et al. (2004), and soon after that Combi et al. (2004a) presented a preliminary analysis. According to Bird et al. (2004), this source was detected with a significance of 8.9σ in the energy range from 20 to 100 keV during 769 ks of observations. The obtained fluxes are $F_{(20-40~{\rm keV})}$=2.6±0.2 mCrab and $F_{(40-100~{\rm keV})}$=3.0±0.4 mCrab. Well within its 2 arcmin-radius position error circle (at 90% confidence), centered at $(\alpha,\delta)_{\rm J2000.0} = (18^{\rm h}02^{\rm m}45\overset{\rm s}{.}8, -14^\circ54'11'')$, we have found the faint *ROSAT* X-ray source 1RXS J180245.5−145432 (Voges et al. 2000). Within its 2σ position error circle there is the weak radio source NVSS J180247−145451, with an estimated position of $(\alpha,\delta)_{\rm J2000.0} = (18^{\rm h}02^{\rm m}47\overset{\rm s}{.}37 \pm 0\overset{\rm s}{.}13, -14^\circ54'51\overset{''}{.}6 \pm 2\overset{''}{.}2)$, and a flux density of 10.5±0.6 mJy (see Fig. 1).

Inside the 2σ position error ellipse of this radio source, it is located an extended Near InfraRed (NIR) source from the 2 Micron All Sky Survey catalog (2MASS, Cutri et al. 2003), 2MASXi J1802473−145454 (see Fig. 2), which has coordinates $(\alpha,\delta)_{\rm J2000.0} = (18^{\rm h}02^{\rm m}47\overset{\rm s}{.}370 \pm 0\overset{\rm s}{.}002, -14^\circ54'54\overset{''}{.}76 \pm 0\overset{''}{.}03)$ and magnitudes J=13.18±0.07, H=12.02±0.09, $K_{\rm s}$=10.94±0.04. The optical counterpart of this NIR source has average magnitudes B=19.3±1.0, R=14.9±0.8 and I=13.8±0.5 in the USNO-B1.0 catalog (Monet et al. 2003). The obtained NIR/optical color indexes are not compatible with a pure stellar spectrum. This fact, together with the extended nature of the NIR source suggest that IGR J18027−1455 is an extragalactic object.

Photometric and spectroscopic observations of the proposed optical/NIR counterpart have recently been performed, and further radio and soft X-ray ones are also planned.

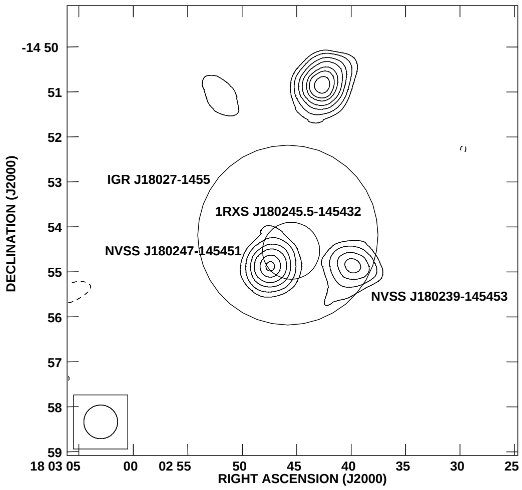

Fig. 1 NVSS radio contours of the field around IGR J18027−1455 showing the presence of two possible counterparts. The center of the source NVSS J180247−145451 falls within the 2σ uncertainty error circle of a *ROSAT* source.

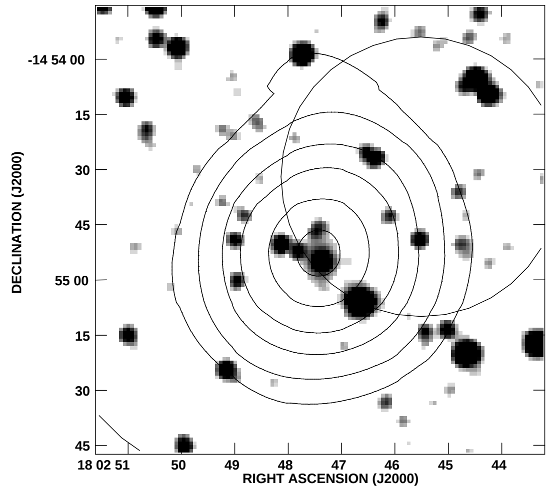

Fig. 2 Enlargement of Fig. 1 around NVSS J180247−145451, where we plot in greyscale the 2MASS K_s-band image. The extended NIR source 2MASXi J1802473−145454 is clearly visible in a position compatible with the peak of the radio source.

3 IGR J21247+5058

The discovery of IGR J21247+5058 was reported by Walter et al. (2004), and soon after that Ribó et al. (2004) presented a preliminary analysis. According to Bird et al. (2004), this source was detected with a significance of 6.5σ in the energy range from 20 to 100 keV during only 70 ks of observations. The obtained fluxes are $F_{(20-40\ \mathrm{keV})}$=5.4±0.7 mCrab and $F_{(40-100\ \mathrm{keV})}$=9.3±1.4 mCrab, showing that the source is significantly hard. Inside its 2 arcmin-radius position error circle (at 90% confidence), centered at $(\alpha,\delta)_{\mathrm{J2000.0}}$ = $(21^{\mathrm{h}}24^{\mathrm{m}}42\overset{\mathrm{s}}{.}0, +50°58'48'')$ there is located the core of the bright radio source 4C 50.55 (see Fig. 3), also known as GPSR 93.3194+0.394, KR2, NRAO 659 or BG 2122+50, among other names. The core has a flat radio spectrum with a peak flux density of 237 mJy beam^{-1} at 1.4 GHz. It is at the center of an elongated structure of 10×3 arcmin (see Fig. 3) that ends in two optically thin large radio lobes (Mantovani et al. 1982). The morphology of 4C 50.55 is typical of a radio galaxy, and the comparison among published radio data shows no significant changes in flux and morphology during the last 30 years (see, e.g. Fanti et al. 1981).

The estimated position of the radio core from archival VLA data is $(\alpha,\delta)_{\mathrm{J2000.0}}$ = $(21^{\mathrm{h}}24^{\mathrm{m}}39\overset{\mathrm{s}}{.}35 \pm 0\overset{\mathrm{s}}{.}03, +50°58'25\overset{''}{.}8 \pm 0\overset{''}{.}2)$ (1σ uncertainty). Coincident with this position there is the NIR source 2MASS J21243932+5058259 (see Fig. 4), with coordinates $(\alpha,\delta)_{\mathrm{J2000.0}}$ = $(21^{\mathrm{h}}24^{\mathrm{m}}39\overset{\mathrm{s}}{.}328 \pm 0\overset{\mathrm{s}}{.}003, +50°58'25\overset{''}{.}93 \pm 0\overset{''}{.}03)$ (1σ), and magnitudes J=13.27±0.04, H=12.38±0.06, K_s=11.37±0.04. The optical counterpart of this NIR source has average magnitudes B=16.9±0.2 and R=15.1±0.2 in the USNO-B1.0 catalog (Monet et al. 2003). The obtained NIR/optical color indexes are not compatible with a pure stellar spectrum.

All these properties are consistent with an extragalactic source, although, to our knowledge, no conclusive optical counterpart of a galaxy host has ever been reported, probably due to its location close to the galactic plane (l=93.32°, b=+0.39°). Photometric and spectroscopic observations in the optical have recently been performed to unveil the nature of the source, and soft X-ray ones are also planned.

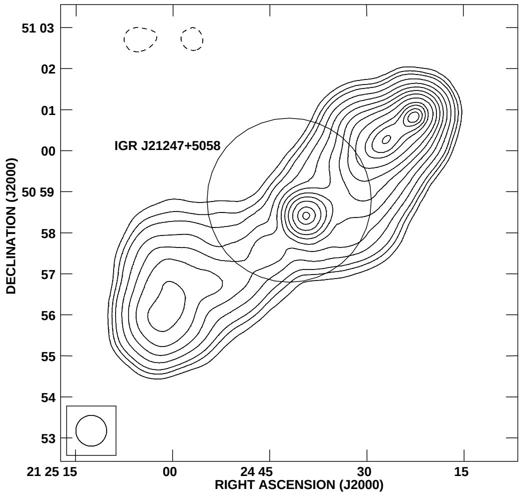

Fig. 3 NVSS radio contours of the field around IGR J21247+5058. showing the presence of the core of the radio source 4C 50.55 well within the 90% uncertainty error circle of the IGR source.

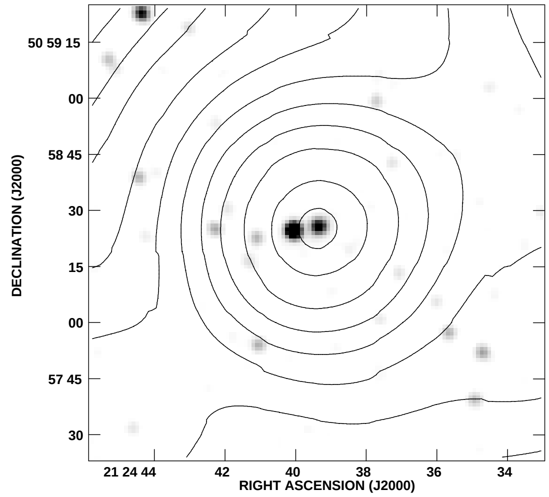

Fig. 4 Enlargement of Fig. 3 around the core of 4C 50.55, where we plot in greyscale the 2MASS $K_{\rm s}$-band image showing the proposed NIR counterpart, coincident with the radio peak.

4 IGR J16393−4643 / AX J1639.0−4642

The discovery of IGR J16393−4643 was reported by Malizia et al. (2004) while at the same time Combi et al. (2004b) presented a multiwavelength study of the unidentified X-ray source AX J1639.0−4642, with a position in agreement with IGR J16393−4643. AX J1639.0−4642 had been discovered by the *ASCA* satellite in the 0.7–10 keV energy range, and presented as a possible HMXB (Sugizaki et al. 2001). Its measured flux was $F_{(0.7-10~{\rm keV})} \simeq 2\times10^{-11}\,{\rm erg\,cm^{-2}\,s^{-1}}$, and it showed variable X-ray emission with a confidence $\geq$ 99 %. Combi et al. (2004b) reanalyzed these data and found evidences for variability on timescales of hours, supporting a HMXB. Moreover, Malizia et al (2004) report that IGR J16393−4643 has an average flux of $F_{(20-100~{\rm keV})} \simeq 5\times10^{-11}\,{\rm erg\,cm^{-2}\,s^{-1}}$, and presents a factor of 2–3 flux variability on timescales of months, supporting again a HMXB.

An inspection among the MGPS data reveals the presence of a point-like radio source (see Fig. 5), dubbed MOST J1639.0−4642, well within the error box of the X-ray source, with a flux density of 136 ± 18 mJy. Although this radio source was not inside the error box in position of IGR J16393−4643 reported preliminary by Malizia et al. (2004), it is inside the new error box in position reported in the final catalog by Bird et al. (2004).

There are 10 NIR sources from the 2MASS within the 3σ error circle in position of MOST J1639.0−4642, some of them visible in the $K_{\rm s}$-band image shown in Fig. 6. At the far infrared part of the spectrum, from 12 to 100 microns, the source IRAS 16353−4636 lies inside the error box of the X-ray source. This IRAS source overlaps the southern part of the 3σ position error circle of MOST J1639.0−4642, and its uncertainty ellipse in position contains several 2MASS sources, as can be seen in Fig. 6.

Combi et al. (2004b) pointed out that AX J1639.0−4642 lies inside the 95% location contour of the unidentified γ-ray source 3EG J1639−4702 (Hartman et al. 1999). Its γ-ray flux is $(2.6\pm0.4)\times10^{-10}$ erg cm^{-2} s^{-1}, presents a steep γ-ray spectral index of $\Gamma = 2.5\pm0.18$ and has a variability index of $I = 1.95$. Although Torres et al. (2001)

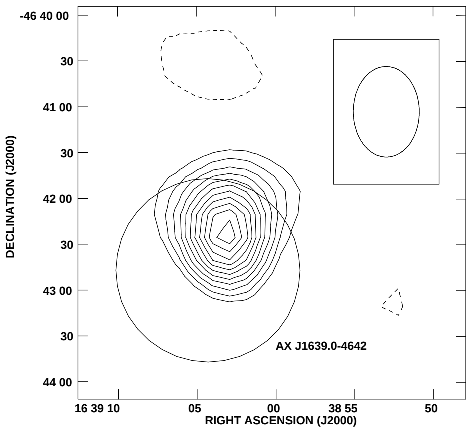

Fig. 5 MGPS radio contours of the field around AX J1639.0−4642, showing the radio source MOST J1639.0−4642 well within the 90% uncertainty error circle of the *ASCA* source.

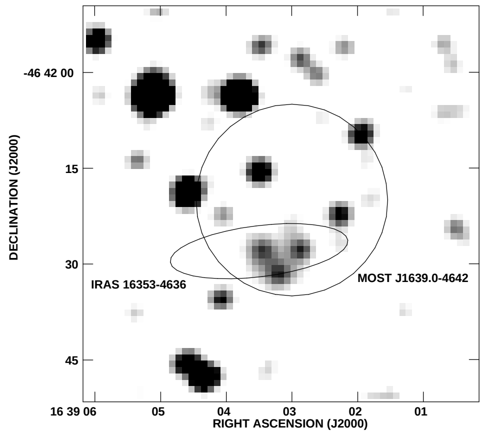

Fig. 6 2MASS K_s-band image of the environment of MOST J1639.0−4642 (3σ position error circle). The far infrared source IRAS 16353−4636 2σ position error ellipse is also plotted.

found three radio pulsars inside the 95% confidence contour of the γ-ray source, its possible variability and steep photon index do not seem to agree, in principle, with a pulsar origin. Similarly, these properties would rule out an association with the three SNRs found within the 95% confidence contour (Torres et al. 2003). Moreover, no identified blazar has been found within the γ-ray contours. Therefore, Combi et al. (2004b) suggested that the microquasar candidate IGR J16393−4643/AX J1639.0−4642/MOST J1639.0−4642 is the counterpart of 3EG J1639−4702. Radio observations with ATCA and NIR/optical photometric and spectroscopic observations are in progress to unveil the nature of this source.

5 DISCUSSION AND CONCLUSIONS

Although *INTEGRAL* was designed basically to explore the Galaxy, its capability to detect high-energy unabsorbed X-ray photons has allowed us to discover the probable background extragalactic sources IGR J18027−1455 and IGR J21247+5058. In this context, Bassani et al. (2004), have presented a study of extragalactic sources detected by *INTEGRAL* during its first year of observations. These authors have found 10 AGN and one cluster of galaxies, but the expected number of detected extragalactic sources is around 20, indicating that some of the still unidentified IBIS/ISGRI sources are probably extragalactic, as we (and they) suggest for IGR J18027−1455 and IGR J21247+5058.

On the other hand, IGR J16393−4643/AX J1639.0−4642 appears as one of the most promising microquasar candidates among all IGR sources. Interestingly, the multi-wavelength properties of this system are similar to those of the well-known microquasars LS 5039 and LS I +61 303, also associated to unidentified EGRET sources (see Paredes et al. 2000 and Massi et al. 2004). A detailed comparison reveals that all of them are compatible with HMXBs containing neutron stars as compact objects (Combi et al. 2004b). This suggests that HMXB/NS microquasars are good candidates to be the counterparts of some of the still unidentified EGRET sources close to the galactic plane. *INTEGRAL* has not yet allowed us to unambiguously discover a new microquasar, but it is clear that this search is revealing unexpected and interesting results.

Acknowledgements We thank Sylvain Chaty, Paula Benaglia, Gustavo E. Romero, Josep M. Paredes, Josep Martí, Valentí Bosch-Ramon and Rob Fender for useful discussions. M. R. acknowledges support by a Marie Curie Fellowship of the European Community programme Improving Human Potential under contract number HPMF-CT-2002-02053. M.R. also acknowledges partial support by DGI of the Ministerio de Ciencia y Tecnología (Spain) under grant AYA2001-3092, as well as partial support by the European Regional Development Fund (ERDF/FEDER). J.A.C. is a researcher of the programme *Ramón y Cajal* funded by the Spanish Ministery of Science and Technology and the University of Jaén. J.A.C. was supported by CONICET (under grant PEI 6384/03).

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