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IGR J11014-6103: a newly discovered pulsar wind nebula?

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IGR J11014-6103 is an hard X-ray *INTEGRAL* source, reported for the first time in the 4th IBIS/ISGRI catalog as an unidentified source. In this proceeding we report on our investigation of the nature of IGR J11014-6103 carried out through the analysis of public observations performed in the direction of the source from radio up to X- and γ-rays energy domains. Our analysis revealed that, in the X-ray energy band, IGR J11014-6103 is comprised of three different regions: a cometary like "tail" (~4 arcmin) and two compact sources, of which one is genuinely point-like, while the other has a modest extension (~ 8 arcsec). These two sources are only 22 arcsec apart one from the other, and located at one end of the "tail". No clear signs of timing variability were detected from the entire X-ray structure. A compact radio source positionally coincident with the head of the X-ray tail was also identified. Based on the discussed results, and comparison with other similar and known systems, we suggest that the emission from IGR J11014-6103 is generated by a pulsar wind nebula produced by a neutron star escaped from its supernova remnant and moving at very high velocity in the interstellar medium. IGR J11014-6103 might be the first of these systems detected with *INTEGRAL* IBIS/ISGRI.

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1. Introduction

Bow-shock pulsar wind nebulae (bsPWN) are elongated cometary-like objects that form when a pulsar escapes from the associated supernova remnant and moves at very high velocity through the interstellar medium (typically hundreds of km/s, i.e. orders of magnitude higher than the velocities of the cold and warm components of the interstellar medium, see e.g. Roberts et al. 2005, and references therein). Close to the pulsar, the relativistic wind of the compact object usually gives rise to a sub-luminous cavity in X-rays surrounded by a termination shock. In this region, particles are thermalized and accelerated, thus producing a conspicuous X-ray and radio emission (through synchrotron processes due to the interaction with the local magnetic field). As the pulsar is moving, a bow shock is formed in front of it and the flow of material advects the emitting particles back along the direction of motion, leading to the formation of an elongated cometary structure (see e.g. Gaensler & Slane 2006, for a detailed discussion). In a few cases, deep X-ray observations with the ACIS telescope on-board *Chandra* permitted to clearly disentangle the different contributions to the total X-ray and radio emission produced by the structures around a bsPWN (see e.g. the case of the PWN G359.23-0.82; Gaensler et al. 2004).

IGR J11014-6103 is a hard *INTEGRAL* source detected in the IBIS/ISGRI mosaic at a significance level of 5.4 σ (20-100 keV). The best determined *INTEGRAL* position of the source is at *RA*=165.341 deg, *Dec*=-61.056 deg (J2000, ±4.3 arcmin). The averaged source fluxes in the 20-40 keV and 40-100 keV energy band are $(3.0 \pm 0.8)\times10^{-12}$ and $(5.6 \pm 2)\times10^{-12}$ erg cm^{-2} s^{-1} respectively. The light curve of the source, obtained from the online tool Heavens (Walter et al. 2010), does not show evidence of variability. A counterpart to IGR J11014-6103 in the soft X-ray (0.3-10 keV) domain was identified by Malizia et al. (2011) using pointed *Swift* observations. In the *Swift*/XRT field of view (FOV) around IGR J11014-6103, they detected a single source inside the *INTEGRAL* error region of IGR J11014-6103 at *RA*=165.44 deg, *Dec*=-61.022 deg (associated uncertainty ~6").

Here we report on the results obtained from multiwavelength analysis of public data in the *INTEGRAL* error region around IGR J11014-6103. The details of the analysis and an extended discussion on the nature of IGR J11014-6103 can be found in Pavan et al. (2011).

2. Results

2.1 X-ray observations: *XMM-Newton*

We analysed two *XMM-Newton* observations with standard XMM/SAS (v.10.0) analysis and the latest available calibration files. From the deeper observation (ID. 0152570101, ~60 ks, performed in 2003) the source detected in *Swift* by Malizia et al. (2011) was clearly resolved into 2-components (see Fig. 1), separated by only $\sim 22''$, of which one purely point-like (hereafter source S) and the other displaying a mild extension ($\sim 8''$, hereafter source N). The same observation besides revealed the presence of an extended cometary-like tail ($\sim 4'$) departing from the two sources.

The spectra of these components could be fit with a simple absorbed powerlaw model. From a contour plot in the $N_H - \Gamma$ plane, the two compact sources (N and S) showed marginal evidence of different spectral parameters (see Fig. 2). The photon index Γ of the powerlaw fitted to the

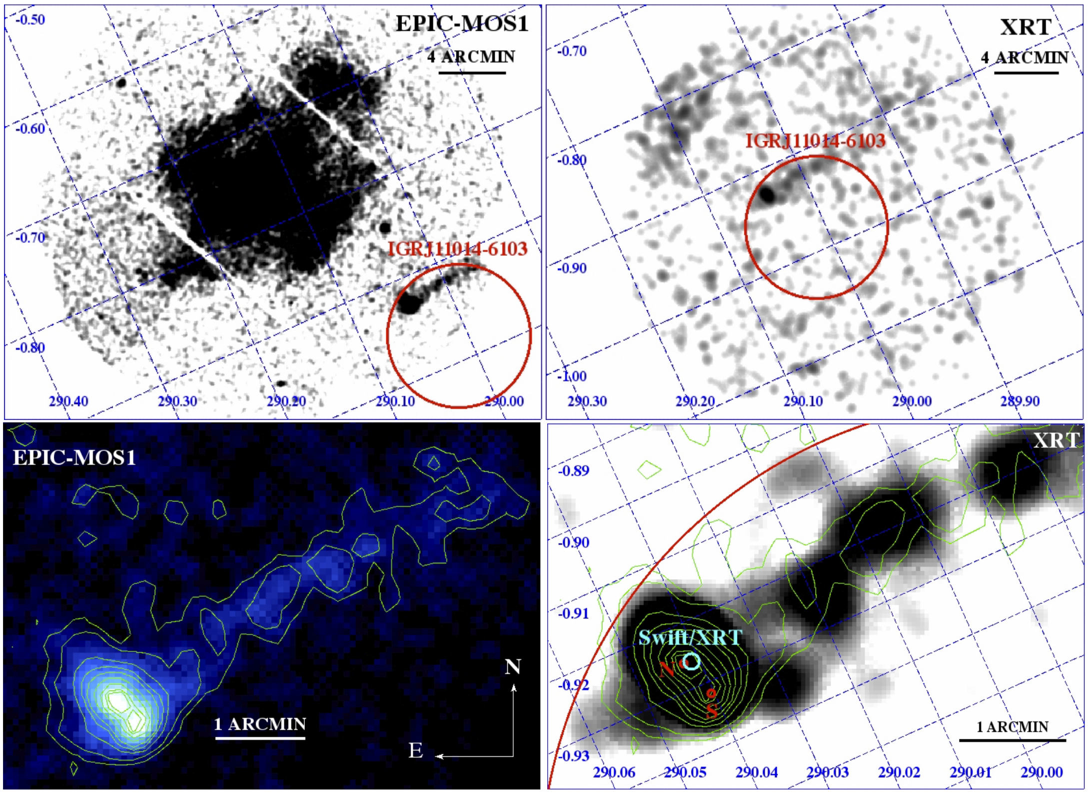

Figure 1: *Upper left*: FOV around IGR J11014-6103 as observed by EPIC-MOS1 on-board *XMM-Newton* (0.5-12 keV). *Upper right*: *Swift*/XRT FOV around IGR J11014-6103 (1-9 keV). *Bottom left*: zoom of the EPIC-MOS1 FOV. In this case we kept the colours and removed the coordinate grid and the error circles around the detected sources for clarity. *Bottom right*: zoom of the XRT FOV. In this figure we marked the source detected with *Swift* (uncertainty of 4.4" at 90% c.l.), and sources N and S detected with *XMM-Newton* (uncertainty of 2" at 90% c.l.). The contours determined from the *XMM-Newton* observations are also overplotted (in green), together with the error circle representing the *INTEGRAL* position of IGR J11014-6103 (in red). The intensity scale, here and in the following images, is logarithmic and the grid is in galactic coordinates.

three regions was 2.0 ± 0.3 (source N), 1.3 ± 0.4 (source S) and 2.2 ± 0.8 (tail). The 2–10 keV flux (not corrected for absorption) was estimated in $1.2^{+0.2}_{-0.5} \times 10^{-13}$ erg cm^{-2} s^{-1} (source N), $0.8^{+0.2}_{-0.4} \times 10^{-13}$ erg cm^{-2} s^{-1} (source S) and $1.9^{+0.3}_{-1.0} \times 10^{-13}$ erg cm^{-2} s^{-1} for the tail. The spectra extracted from the shorter observation (ID. 0111210201, ~11 ks, performed in 2000) provided compatible results and did not indicate any variation between the two epochs.

The *XMM-Newton* spectrum could also be fitted jointly with the *INTEGRAL*/ISGRI one (see Fig. 2). The entire 1–60 keV spectrum could be fit with a simple powerlaw model, with an inter-calibration constant between the two instruments ~ 1. This, besides strengthening the association between the X-ray source and the *INTEGRAL* source IGR J11014-6103, suggests that IGR J11014-6103 is a persistent X-ray emitter and hard source, with best-fit $\Gamma = 1.5 \pm 0.2$. Similar spectral properties, hardness and flux stability, has already been measured e.g. in the case of the young pulsar+PWN AX J1838-0655 (Malizia et al. 2005; Gotthelf & Halpern 2008).

A timing analysis of the two compact sources N and S was performed to search for time

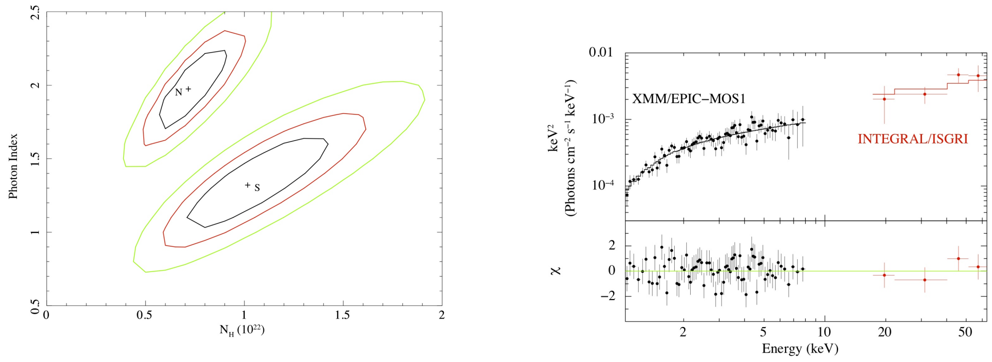

Figure 2: *Left*: Contour plot of the absorption column density ($N_{\rm H}$) and power law photon index (Γ) derived from the EPIC-MOS1 data for sources N and S in observation ID. 0152570101. The contours correspond to 68%, 90% and 99% confidence levels. *Right*: Unfolded *XMM-Newton* and IBIS/ISGRI spectrum of IGR J11014-6103. We fitted both spectra with a single absorbed power-law model (solid line). In the bottom panel we show the residuals from this fit.

variability on time scales of seconds to hours and/or periodicity in the signal, both of which have not been detected. By following the approach of Leahy et al. (1983) and adopting an epoch-folding technique with 16 phase bins, we determined an upper limit on the pulsed fraction for a sinusoidal signal from sources N and S (the signal from the two sources has been analysed together to maximize the number of utilized photons) of 71% (at 90% c.l.) in the 0.001 to 500 Hz frequency range, and 33% (at 90% c.l.) in the range 0.001–0.2 Hz.

The morphology and emission properties of the 4 arcmin extended X-ray tail in IGR J11014-6103 might resemble the elongated features observed in the case of PSR B2224+65 (“the Guitar” nebula, Hui & Becker 2007) and PSR J0357+3205 (De Luca et al. 2011). In both cases a pulsar has been firmly detected at one end of the elongated structures, and the cometary-like tails have been tentatively explained under the “bow-shock pulsar wind nebulae” scenario. If the structures detected in IGR J11014-6103 are indeed originating from the pulsar wind, the X-ray tail can be interpreted as being due to relic electrons spread along the direction of motion of the pulsar. According to this interpretation, source N, extended in X-rays, would represent the compact PWN (with possible contribution coming also from the bow-shock). The association of source S to this region is less straightforward. In case source S is not physically related to the X-ray tail, it might just by chance be located along the line of sight to the extended structure. The pulsar responsible for the formation of the compact and relic PWNe, might, in this case, be unresolved and comprised in the emission detected from source N. In case, instead, that source S, the point-like source, is physically connected to the PWN, it would be reasonable to associate it to the pulsar generating the X-ray structures. Under this scenario the misalignment between the direction of the 4 arcmin tail and the axis between sources N and S would imply a significant tilt between the proper motion of the pulsar and the position of the compact PWN (a similar misalignment, however, was already observed in e.g. PSR B2224+65, and ascribed to the strong interaction between the fast-moving pulsar and its dense surrounding environment; Hui & Becker 2007). Indeed, as for the case of PSR B2224+65, also the environment around IGR J11014-6103 was found to be a complex and dense region, characterized by the presence of several background and foreground molecular clouds (Filipović et al. 2005, and references therein).

2.1.1 *ROSAT* and *ASCA*

The source has been detected also in *ROSAT* and *ASCA* observations. In *ROSAT*/HRI observations, only the relatively brigth head of the source, containing sources N and S, have been detected. This is not surprising, given the limited spatial resolution, sensitivity and energy coverage of the *ROSAT*/HRI with respect to the *XMM-Newton*/EPIC cameras. The *ASCA* observations instead revealed only the extended emission. Again, this might be expected due to the lower spatial resolution but higher sensitivity and broader energy coverage (0.5-10 keV) of the instrument compared with the *ROSAT*/HRI camera.
The spectra extracted from these observations are compatible with the ones obtained from *XMM-Newton*. All these results suggest that IGR J11014-6103 is a persistent X-ray emitter that displayed in the past ~31 years only marginal variations (if any) in the 0.3-100 keV energy band. The stability of the flux and spectral parameters is in agreement with the PWN interpretation of the source.

2.2 Counterparts at different energies

At higher energies the *EGRET* source 3EG J1102-6103 is spatially coincident with IGR J11014-6103 (with a positional uncertainty of 0.6 deg). However we were unable to confirm this association because of other possible counterparts located within the EGRET error circle of 3EG J1102-6103, SNR MSH 11-61A and the young energetic pulsar PSR J1105-6107 (Kaspi et al. 1997), among others.

The improved X-ray positions of sources N and S permitted also to search for possible counterparts in the optical (USNO B1.0) and infra-red (2MASS) domain, but the closest objects to sources N and S lie just outside the 90% c.l. positional error region determined from *XMM-Newton*.

In the radio domain the compact source MGPS J110149-610104 (from the MGPS-2nd epoch archive Murphy et al. 2007) match reasonably well with the head of the X-ray emission (see Fig. 3). The detection of a radio source close to X-ray source N might support the PWN scenario, since under this hypothesis radio synchrotron emission is expected from particles accelerated at the termination shock.

Further observations with an X-ray telescope characterized by a finer spatial resolution (i.e. the ACIS on-board *Chandra*) and increased spectral and timing statistics are required to solve the issues above and firmly establish the real nature of IGR J11014-6103. In case these observations will confirm that IGR J11014-6103 is a newly discovered PWN generated by a high-velocity pulsar, this would be the first detection with *INTEGRAL* of one of these systems (to the best of our knowledge).

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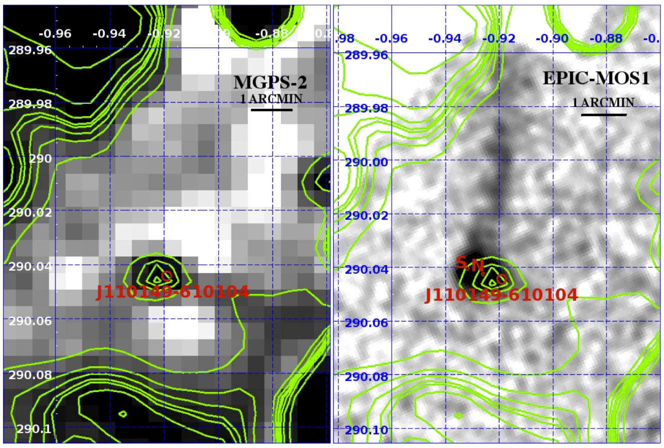

Figure 3: *Left*: radio image (and contours) at 843 MHz around the position of IGR J11014-6103 retrieved from the MGPS-2 archive. We mark in red the position of the source MGPS2 J110149-610104. *Right:* EPIC-MOS1 image from observation ID. 0152570101. We overplot on the image the radio contours derived from the MGPS-2 data in green and marked in red the position of the radio source J110149-610104 and the two *XMM-Newton* sources N and S.

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