Is the INTEGRAL/IBIS source IGR J17204−3554 a $\gamma$-ray emitting galaxy hidden behind the molecular cloud NGC 6334?\(^1\)

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1. Introduction

Giant Molecular Clouds (GMC) are the coolest (10-20K) and densest portions (about $10^{12}$ particles per cubic meter) of the interstellar medium: stretching typically over 100 light-years and containing several hundred thousand solar masses of material, they are the largest known objects in the Universe made of molecular material. Observations of these sky regions are made difficult by the large amount of gas and dust which prevents direct optical view. The only source of information on objects inside or behind GMCs is provided at longer wavelengths such as radio and infrared where the emission is free from absorption. Although high energy measurements can also be extremely efficient in probing deeply into these regions, only a handful of GMC have so far been observed in X-rays (Garmire et al. 2000, Hofner et al. 2002, Kohno, Koyama & Hamaguchi 2002) and virtually none in gamma-rays. To probe GMC regions in gamma-rays, the imager on board INTEGRAL (IBIS) is a powerful instrument: it allows source detection above 20 keV with a mCrab ($\sim10^{-11}$ erg cm$^{-2}$ s$^{-1}$) sensitivity in well exposed regions, an angular resolution of 12$^\prime$ (thus covering the full extension of a GMC) and a point source location accuracy of 1$^\prime$-2$^\prime$ for moderately bright sources (Ubertini et al. 2003). Furthermore, INTEGRAL has regularly observed the entire galactic plane during the first two and half years in orbit providing, at these energies, a galactic survey with unprecedented sensitivity (Bird et al. 2004). A second catalogue, resulting from greater sky coverage and deeper exposures, is now completed (Bird et al. 2005): within this catalogue two sources are spatially coincident with molecular clouds, IGR J17475−2822 and IGR J17204−3554. The first object is fully discussed by Revnivtsev et al. (2004) who interpreted the X/soft-gamma ray emission as Compton scattered and reprocessed radiation emitted in the past by our Galaxy Center (Sgr A*) and mirrored by the SGR B2 molecular cloud complex. In this paper, we report, instead, on the identification of the second object which is associated with NGC6334. Our deep analysis of the region indicates that this new IBIS source is probably a background AGN seen through the cloud.

\(^1\)Based on observations obtained with the ESA science mission INTEGRAL
2. NGC6334

NGC6334 is a prominent HII region/molecular cloud complex located in the Sagittarius arm of the Milky Way at a photometric distance of 1.7 kpc (Neckel 1978). The complex contains several recent and current star-forming sites which are embedded in an elongated GMC extending over about 45′ (Dickel, Dickel & Wilson 1977; Kraemer & Jackson 1999). The morphology of the region is complex, and, unfortunately, this is reflected in the nomenclature of the different sources and components. In the scheme that has evolved in time, letter designations correspond to centimeter radio sources, while roman numeral designations are used for millimeter and infrared sources. Radio continuum observations have identified five major components denoted as NGC 6334 A to F (Rodríguez, Cantó, & Moran 1982) while far-infrared (FIR) observations have detected six major sources that are denoted NGC 6334 I to VI, increasing in the opposite direction relative to the radio data (McBreen et al. 1979). In radio, all sources are HII regions, with the exception of NGC6334B, which is probably an extragalactic object seen through the cloud (Moran et al. 1990). Each of the far-infrared cores is instead due to the combined emission of young massive stars embedded in the cloud star-forming regions (Rodríguez, Cantó, & Moran 1982). Although most of the reported cores are detected both at radio and far-infrared wavelengths, not all radio sources have corresponding FIR emission and vice versa (Kraemer & Jackson 1999).

X-ray emission has been detected by ASCA from NGC6334 (Sekimoto et al. 2000). Due to the limited angular resolution ($\geq 4′$) of the instrument it was not possible to separate the blurred extended emission into single sources although five FIR cores were indicated as being responsible for the emission above 2 keV (NGC6334 I to V) while at softer energies the radiation was found to be mostly absorbed except for core III, located at the center of the cloud. Northwest of NGC6334 a bright object was also detected: this corresponds to an emission line star of type BO.5 (CD−3511482). The combined ASCA spectrum was reported to be thermal with a temperature of $\sim$9 keV, a metal abundance about half the solar value, a column density of $9\times10^{21}$ cm$^{-2}$ (close to the galactic value in the source direction) and an unabsorbed flux of $\sim2\times10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the 0.5-10 keV band. The high temperature observed is not easily reconciled with emission from young stellar objects which are known to populate the cloud, so that alternative explanations were proposed by the authors, none of which were convincing enough to explain the high temperature seen by ASCA.
3. Unveiling the Nature of IGR J17204−3554

3.1. Step 1: INTEGRAL/ASCA data

Data reported here belong to the Core Program (i.e. were collected as part of the INTEGRAL Galactic Plane Survey and Galactic Center Deep Exposure) as well as to public Open Time observations and span from revolution 46 (February 2003) to revolution 202 (September 2004); the total exposure of the region containing IGR J17204−3554 is 1.36 Msec. In the present paper, we refer to data collected by the imager (IBIS) on board INTEGRAL (Ubertini et al. 2003) and in particular to detection by the first layer (ISGRI) of the instrument (Lebrun et al. 2003). A detailed description of the source extraction criteria can be found in Bird et al. (2005). Figure 1 shows the 20-100 keV band image of the region surrounding IGR J17204−3554: the source is detected with a significance of \( \sim 13\sigma \) at a position corresponding to R.A.(2000)=17\text{h} 20\text{m} 24\text{s} 96 and Dec(2000)=-35\text{°} 54' 00" 00 with a positional uncertainty of \( \leq 1.5 \) (90% confidence, Gros et al. 2003). Superposition of the INTEGRAL/IBIS positional uncertainty on the ASCA/GIS image (figure 2) indicates that the IBIS emission is located between infrared Cores III and IV. Given the morphology of the region, we cannot exclude at this stage that we are detecting diffuse and/or multiple source emission.

In view of its angular resolution, IBIS/ISGRI is not able to separate the various contributions: in this case the emission from the whole region, including the stellar object at the northwest side of the cloud, is detected by INTEGRAL. The flux of IGR J17204−3554 detected in each individual pointing was also used to generate the source light curve: no flares are visible nor does the source show periodicities and/or pulsations. Fluxes for spectral analysis were extracted from narrow band mosaics of all revolutions added together. A simple power law provides a good fit to the IBIS data \( (\chi^2=6.4/4) \), a flat photon index \( (\Gamma=1.43^{+0.26}_{-0.25}) \) and a 20-100 keV flux of \( 3 \times 10^{-11} \) erg cm\(^{-2}\) s\(^{-1}\). Quoted errors here and in the following correspond to 90% confidence level for one interesting parameter.

Next we analysed the combined ASCA/GIS and INTEGRAL/IBIS data over the 2-100 keV band; the ASCA data refer to a region of 4' centered on the cloud. The combined data are well fitted \( (\chi^2=162.5/143) \) by an absorbed power law having a photon index of \( \Gamma=1.43^{+0.05}_{-0.04} \) and a column density of \( N_H=7.5\pm0.9\times10^{21} \) cm\(^{-2}\). To account for a cross calibration mismatch between the two instruments and/or source variability between the two observing periods, we have introduced a free constant in the fit; when left free to vary it provides a value of 1.3\pm0.3. A thermal model could also be a good fit but results in an unacceptably high temperature of 130 keV; if the temperature is constrained to the value originally proposed by ASCA, the fit is unacceptable implying that a thermal model is unable to explain
the soft gamma-ray emission detected by INTEGRAL.

3.2. Step 2: Swift/Chandra data

In order to understand what powers the gamma-rays seen from NGC6334 by INTEGRAL, a ToO observation with Swift (Gehrels et al. 2004) was immediately requested and granted. The observation was performed on July 12, 2005 and the source observed for 1.5 ks with the XRT in Photon Counting mode (Hill et al. 2004). Data reduction was performed using the XRTDAS v2.0 standard data pipeline package. Two sources were readily detected in the region: source 1 at R.A.(2000)=17h20m31.88 and Dec(2000)=-35°51′04″63 and source 2 at R.A.(2000)=17h20m26.00 and Dec(2000)=-35°43′58″80 with a positional uncertainty of 7 and 10 arcsec respectively. Both sources are quite weak in X-rays with 0.5-10 keV fluxes of 2.7 and 1.3×10^{-12} erg cm^{-2} s^{-1} respectively. The first source (also named 2E1717.1-3548) coincides with [SHM89] FIR-III-13, a zero age main sequence star of type O7 which is thought to ionize the HII region NGC 6334C/Core III (Straw, Hayland & McGregor 1989); the second is coincident with the emission line star CD-3511482 also seen by ASCA. Only source 1 is close to the ISGRI error box, although outside its border but it is too weak to be associated with the ISGRI source unless it is strongly absorbed. However, this is the source associated with core III which is the only one seen by ASCA at soft energies suggesting therefore weak absorption. Despite the interesting result of pinpointing X-ray emission from the star ionizing a compact HII region, the Swift observation was too short to be able to solve the ISGRI source enigma and to answer the question of what is producing gamma-rays in a molecular cloud.

A search of the HEASARC archive provided 2 Chandra observations on 31-08-2002 (OP1) and 02-09-2002 (OP2). These measurements, made with the ACIS instrument, lasted 40 ks each and were pointed at R.A.(2000)=17h20m01.8, Dec(2000)=-35°56′07″(OP1) and R.A.(2000)=17h20m54.8, Dec(2000)=-35°47′04″(OP2) respectively. They each cover a portion of the cloud and OP1 in particular also completely covered the ISGRI error box. The Chandra data were reduced following standard procedures and using CIAO v3.2. A quick-look analysis of these data indicates that the emission in the region of interest is resolved into many point sources, including source 1 (seen in OP1/OP2 and shown in figure 3) and source 2 (seen in OP1 only). The Chandra position and location accuracy (≤1″) confirm the Swift identification for source 1 and further provide information on sources inside the ISGRI error box: many X-ray emitting objects are detected, but they are too X-ray weak for detection by ISGRI except for source 3 located at R.A.(2000)=17h20m21.81 and Dec(2000)=-35°52′48″25 (uncertainty ≤1″). Figure 3, which shows Chandra images in two different
wavebands (0.5-2keV and above 2 keV), clearly indicates that this source is very hard (heavily absorbed and/or spectrally flat) as it is not seen below 2 keV but it is quite bright above this energy compared to source 1 which is visible in both wavebands. In fact spectral analysis of Chandra data indicates that source 1 is very soft and only slightly absorbed ($\Gamma=2.36\pm0.12$, $N_H=7.4\pm0.8\times10^{21}$ cm$^{-2}$, $\chi^2=147/123$ d.o.f.) while source 3 is flat and heavily absorbed ($\Gamma=1.6\pm0.4$, $N_H=1.6\pm0.3\times10^{23}$ cm$^{-2}$, $\chi^2=97/101$). This was the clue to the solution of the knotty problem of NGC6334 by identifying source 3 as that responsible for the soft gamma-ray emission. In fact a combined analysis of ISGRI and Chandra data of this source provides a good fit ($\chi^2=109/107$, figure 4) with the following spectral parameters: $\Gamma=1.2\pm0.1$, $N_H=1.4\pm0.1\times10^{23}$ cm$^{-2}$ and a cross calibration constant fixed to 1; if left free to vary the constant is $1.8^{+0.8}_{-0.6}$ and the spectrum is softer ($1.5\pm0.3$) while the absorption remains the same. The flux corrected for absorption is $0.5\times10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the 2-10 band.

3.3. Step 3: The nature of source 3

Having found the source responsible for the X/gamma-ray emission in NGC6334, we next need to understand its nature. The Chandra position coincides with NGC6334B (also G351.28+0.68), the only radio source possibly not associated with the molecular cloud but likely to be a background active galaxy. This conclusion is based on a number of observations: its brightness temperature at 6cm is far in excess of the value expected from HII regions; it is not closely associated with other sources of star formation (in fact it is not a FIR core); it has the largest scattering disk of any known source (implying plasma scattering from the nearby NGC6334A HII region) and it is time variable at radio frequencies (Moran et al. 1990). Also, measurements of HI indicate the presence of additional absorption toward NGC6334B with respect to the cloud and therefore a larger distance ($\geq 6$ Kpc, Moran et al. 1990).

Within the Chandra error box there is no optical/infrared source listed in the USNO B1 or 2MASS catalogues (Monet et al. 2003, Cutri et al. 2003), although there is slight evidence of very faint emission (magnitude $\sim$15) in the 2MASS K-band image. Correcting for measured X-ray absorption, this corresponds to an intrinsic brightness of $7^{th}$ magnitude, similar to active galaxies in the local universe ($D \leq 15$ Mpc). Clearly follow up optical spectroscopy will better classify the source type and redshift, however, the extra absorption found suggests that it might be a type 2 active galaxy. Alternatively, the column density in excess to the cloud value might be related to material located between the cloud and the galaxy. In either case, NGC6334B is a source concealed behind the molecular cloud and further hidden from view by extra gas and dust: a real conspiracy to prevent its detection.
4. Conclusions

Following a difficult and challenging path, we were able to identify the newly discovered source, IGR J17204-3554, as a background galaxy. While revealing the true nature of this IBIS/ISGRI object, we have also solved some of the mysteries related to the X-ray emission from NGC6334. First we can firmly state that the radiation measured by ASCA is resolved into many weak point sources likely to be young massive stars embedded in their forming regions as already observed in a number of molecular clouds (Garmire et al. 2000, Hofner et al. 2002, Kohno, Koyama and Hamaguchi 2002). Analysis of their X-ray characteristics is beyond the scope of the present paper but already we can assess that they cannot provide the 9 keV temperature reported by ASCA. Instead this is due to the convolution of many soft X-ray spectra contaminated at high energies by the emission from IGR J17204-3554.

We can further conclude that the X-ray emission from NGC6334 is dominated by 3 bright sources: an emission line star (CD-3511482), the ionizing star of the ultracompact HII region NGC6334C ([SHM89] FIR-III-13) and an active galaxy located behind the molecular cloud. The radiation from this active galaxy, besides being hidden by the cloud, is also absorbed by material located in the galaxy itself or in between IGR J17204-3554 and the cloud. Clearly, everything was conspiring to prevent identification of this soft gamma-ray source and only the combination of 3 powerful instruments (INTEGRAL, Swift and Chandra) has allowed us to finally solve the NGC6334 enigma.

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Fig. 1.— IBIS/ISGRI 20-100 keV image with 2 sources detected: the HMXB EXO 1722−363 and the unidentified source IGR J17204−3554.
Fig. 2.— ASCA/GIS (2-10 keV) image: crosses mark the positions of FIR cores I to V and corresponding radio sources. The circle corresponds to the IBIS/ISGRI error box.
Fig. 3.— Chandra images in two energy bands. The circle indicates the ISGRI error box. Source 1, seen also by Swift, is soft and unabsorbed while source 3 is hard and absorbed.
Fig. 4.— Combined Chandra-ACIS/IBIS-ISGRI spectrum of source 3 = NGC6334B.