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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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ABSTRACT

We report on the identification of a soft gamma-ray source, IGR J17204−3554, detected with IBIS, the Imager on Board the *INTEGRAL* Satellite. The source has a 20–100 keV flux of $\sim 3 \times 10^{-11}$ ergs cm^{-2} s^{-1} and is spatially coincident with NGC 6334, a molecular cloud located in the Sagittarius arm of the Milky Way. Diffuse X-ray emission has been reported from this region by *ASCA* and interpreted as coming from five far-infrared cores located in the cloud. However, the combined *ASCA* spectrum with a 9 keV temperature was difficult to explain in terms of emission from young pre–main-sequence stars known to be embedded in the star-forming regions. Detection of gamma rays makes this interpretation even more unrealistic and suggests the presence of a high-energy source in or behind the cloud. Follow-up observations with *Swift* and archival *Chandra* data allow us to disentangle the NGC 6334 enigma by locating an extragalactic object with the proper spectral characteristics to explain the gamma-ray emission. The combined *Chandra*-IBIS spectrum is well fitted by an absorbed power law with $\Gamma = 1.2 \pm 0.1$, $N_{\rm H} = (1.4 \pm 0.1) \times 10^{23}$ cm^{-2}, and an unabsorbed 2–10 keV flux of 0.5×10^{-11} ergs cm^{-2} s^{-1}. This column density is in excess of the Galactic value, implying that we are detecting a background galaxy concealed by the molecular cloud and further hidden by material located either in the galaxy itself or between IGR J17204−3554 and the cloud.

Subject headings: galaxies: active — gamma rays: observations — ISM: clouds — X-rays: general

Online material: color figures

1. INTRODUCTION

Giant molecular clouds (GMCs) are the coolest (10–20 K) 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 2002), and virtually none in gamma rays. To probe GMC regions in gamma rays, the IBIS imager on board the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*) is a powerful instrument: it allows source detection above 20 keV with millicrab ($\sim 10^{-11}$ ergs cm^{-2} s^{-1}) sensitivity in well-exposed regions, an angular resolution of 12′ (thus covering the full extension of a GMC) and a point-source location accuracy of 1′–2′ for moderately bright sources (Ubertini et al. 2003). Furthermore, *INTEGRAL* has regularly observed the entire Galactic plane during its first $2\frac{1}{2}$ years in orbit, providing, at these energies, a Galactic survey with unprecedented sensitivity (Bird et al. 2004). A second catalog, resulting from greater sky coverage and deeper exposures, is now completed (Bird et al. 2005); within this catalog, 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-ray and soft gamma-ray emission as Compton-scattered and reprocessed radiation emitted in the past by our Galaxy's center (Sgr A*) and mirrored by the Sgr B2 molecular cloud complex. In this Letter, we report instead on the identification of the second object, which is associated with NGC 6334. Our deep analysis of the region indicates that this new IBIS source is probably a background active galactic nucleus seen through the cloud.

2. NGC 6334

NGC 6334 is a prominent H II 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 et al. 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 over 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 NGC 6334 A–F (Rodríguez et al. 1982) while far-infrared (FIR) observations have detected six major sources

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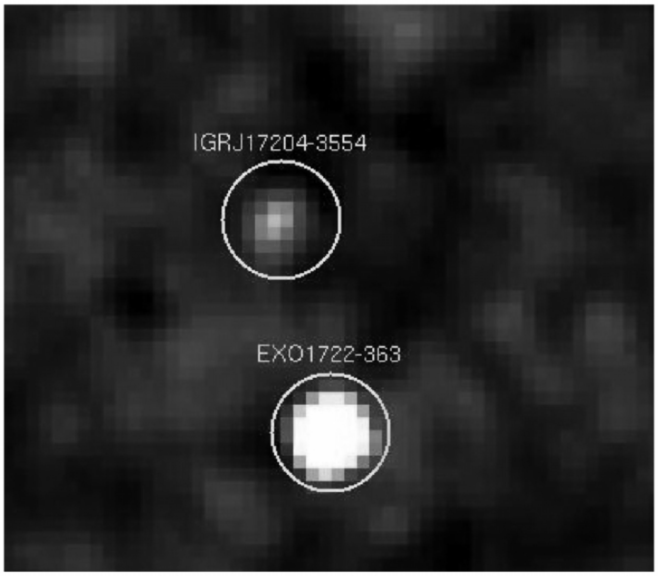

FIG. 1.—IBIS/ISGRI 20–100 keV image with two sources detected: the high-mass X-ray binary EXO 1722−363 and the unidentified source IGR J17204−3554. [*See the electronic edition of the Journal for a color version of this figure.*]

that are denoted NGC 6334 I–VI, increasing in the opposite direction relative to the radio data (McBreen et al. 1979). In radio, all sources are H II regions with the exception of NGC 6334B, which is probably an extragalactic object seen through the cloud (Moran et al. 1990). Each of the FIR cores is instead due to the combined emission of young massive stars embedded in the cloud's star-forming regions (Rodríguez et al. 1982). Although most of the reported cores are detected at both 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 the *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*) from NGC 6334 (Sekimoto et al. 2000). Because of the limited angular resolution (≥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 (NGC 6334 I–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 NGC 6334, a bright object was also detected: this corresponds to an emission-line star of type B0.5 (CD −35 11482). The combined *ASCA* spectrum was reported to be thermal, with a temperature of ∼9 keV, a metal abundance about half the solar value, a column density of 9×10^{21} cm^{-2} (close to the Galactic value of 1×10^{22} cm^{-2} [Dickey & Lockman 1990] in the source direction), and an unabsorbed flux of $\sim 2 \times 10^{-11}$ ergs cm^{-2} s^{-1} in the 0.5–10 keV band. The high temperature observed is not easily reconciled with emission from the young stellar objects that are known to populate the cloud, and so 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 and ASCA Data*

The data reported here belong to the Core Programme (i.e., they were collected as part of the *INTEGRAL* Galactic Plane

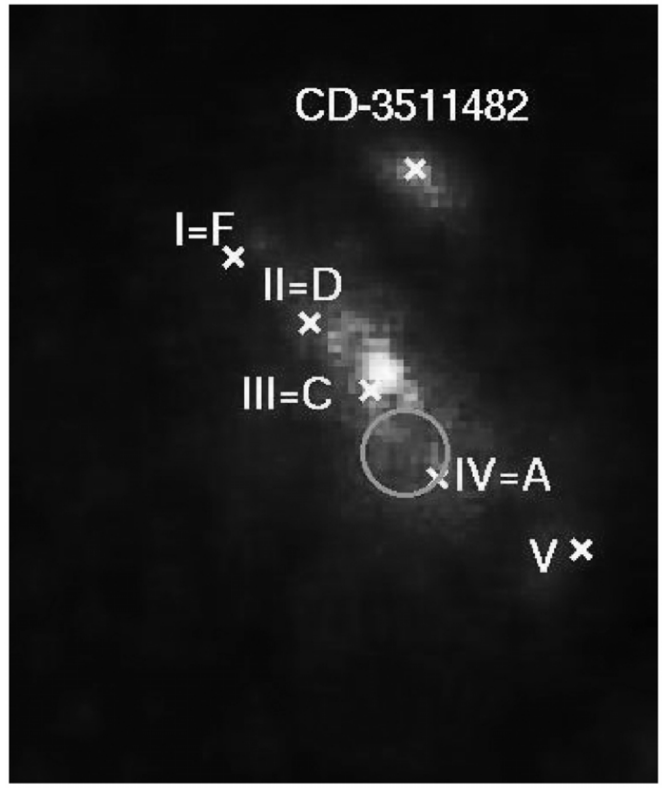

FIG. 2.—*ASCA* GIS (2–10 keV) image: crosses mark the positions of FIR cores I to V and corresponding radio sources. The circle corresponds to the IBIS/ISGRI error box. [*See the electronic edition of the Journal for a color version of this figure.*]

Survey and Galactic Centre Deep Exposure), as well as to public open-time observations, and they span from revolution 46 (2003 February) to revolution 202 (2004 September); the total exposure of the region containing IGR J17204−3554 is 1.36 Ms. In the present Letter, 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. = $17^{h}20^{m}24.^{s}96$ and decl. = $-35°54'00''.00$ (J2000) with a positional uncertainty of $\leq 1'.5$ (90% confidence; Gros et al. 2003). Superposition of the *INTEGRAL* IBIS positional uncertainty on the *ASCA* Gas Imaging Spectrometer (GIS) image (Fig. 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 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 or pulsations. Fluxes for spectral analysis were extracted from narrowband mosaics of all revolutions added together. A simple power law provides a good fit to the IBIS data ($\chi^2 = 6.4$, 4 degrees of freedom [dof]), a flat photon index ($\Gamma = 1.43^{+0.26}_{-0.25}$), and a 20–100 keV

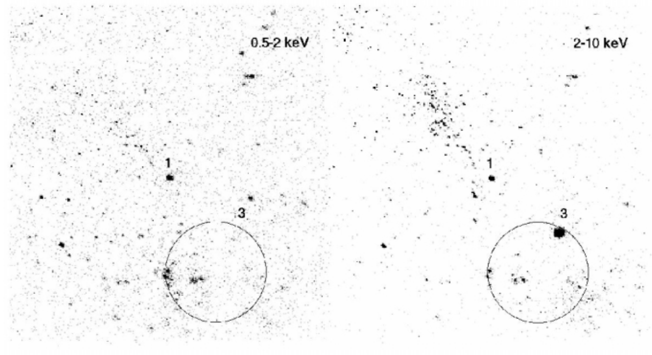

FIG. 3.—*Chandra* images in two energy bands. The circle indicates the ISGRI error box. Source 1, seen also by *Swift*, is soft and unabsorbed, while source 3 is hard and absorbed.

flux of 3×10^{-11} ergs cm^{-2} s^{-1}. Quoted errors here and in the following correspond to the 90% confidence level for one interesting parameter.

Next we analyzed 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 dof) by an absorbed power law having a photon index of $\Gamma = 1.43^{+0.05}_{-0.04}$ and a column density $N_H = (7.5 \pm 0.9) \times 10^{21}$ cm^{-2}. To account for a cross-calibration mismatch between the two instruments and any source variability between the two observing periods, we have introduced a free constant in the fit; when allowed to vary, it provides a value of 1.3 ± 0.3. 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 and Chandra Data*

In order to understand what powers the gamma rays seen from NGC 6334 by *INTEGRAL*, a Target of Opportunity observation with *Swift* (Gehrels et al. 2004) was immediately requested and granted. The observation was performed on 2005 July 12, and the source was observed for 1.5 ks with the *Swift* X-Ray Telescope in photon-counting mode (Hill et al. 2004). Data reduction was performed using the XRTDAS (ver. 2.0) standard data pipeline package. Two sources were readily detected in the region: source 1, at R.A. $= 17^h20^m31^s.88$ and decl. $= -35°51'04''.63$, and source 2, at R.A. $= 17^h20^m26^s.00$ and decl. $= -35°43'58''.80$ (J2000), with positional uncertainties of 7″ and 10″, respectively. Both sources are quite weak in X-rays, with 0.5–10 keV fluxes of 2.7×10^{-12} and 1.3×10^{-12} ergs cm^{-2} s^{-1}, respectively. The first source (also named 2E 1717.1−3548) coincides with [SHM89] FIR-III 13, a zero-age main-sequence star of type O7 that is thought to ionize the H II region NGC 6334C/core III (Straw et al. 1989); the second is coincident with the emission-line star CD −35 11482, 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, therefore suggesting weak absorption. Despite the interesting result of pinpointing X-ray emission from the star ionizing a compact H II region, the *Swift* observation was too short to be able to solve the ISGRI source enigma and to answer the question what is producing gamma rays in a molecular cloud.

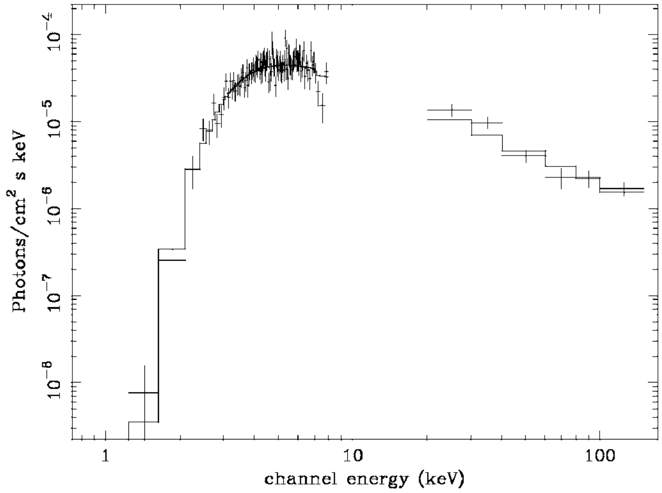

FIG. 4.—Combined *Chandra* ACIS and IBIS/ISGRI spectrum of source 3, NGC 6334B.

A search of the HEASARC archive provided two *Chandra* observations, on 2002 August 31 (OP1) and September 2 (OP2). These measurements, made with the ACIS instrument, lasted 40 ks each and were pointed at J2000 R.A. $= 17^h20^m01^s$, decl. $= -35°56'07''$ (OP1) and R.A. $= 17^h20^m54^s$, decl. $= -35°47'04''$ (OP2). Each covers 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 version 3.2. 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 and OP2 and shown in Fig. 3) and source 2 (seen in OP1 only). The *Chandra* position and location accuracy ($\lesssim 1''$) 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. $= 17^h20^m21^s.81$ and decl. $= -35°52'48''.25$ (J2000; uncertainty $\lesssim 1''$). Figure 3, which shows *Chandra* images in two different wave bands (0.5–2 keV and above 2 keV), clearly indicates that this source is very hard (heavily absorbed, spectrally flat, or both), as it is not seen below 2 keV, but it is quite bright above this energy compared with source 1, which is visible in both wave bands. In fact, spectral analysis of the *Chandra* data indicates that source 1 is very soft and only slightly absorbed [$\Gamma = 2.36 \pm 0.12$, $N_H = (7.4 \pm 0.8) \times 10^{21}$ cm^{-2}, $\chi^2 = 147$ (123 dof)], while source 3 is flat and heavily absorbed [$\Gamma = 1.6 \pm 0.4$, $N_H = (1.6 \pm 0.3) \times 10^{23}$ cm^{-2}, $\chi^2 = 97$ (101 dof)]. This was the clue to the solution of the knotty problem of NGC 6334, by identifying source 3 as that responsible for the soft gamma-ray emission. In fact, a combined analysis of the ISGRI and *Chandra* data for this source provides a good fit ($\chi^2 = 109$, 107 dof; see Fig. 4) with the following spectral parameters: $\Gamma = 1.2 \pm 0.1$, $N_H = (1.4 \pm 0.1) \times 10^{23}$ 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 ± 0.3), while the absorption remains the same. The flux corrected for absorption is 0.5×10^{-11} ergs cm^{-2} s^{-1} in the 2–10 keV band.

3.3. *Step 3: The Nature of Source 3*

Having found the source responsible for the X-ray and gamma-ray emission in NGC 6334, we next need to understand its nature. The *Chandra* position coincides with NGC 6334B (also G351.28+0.68), the only radio source possibly not associated with the molecular cloud, and likely to be a background active galaxy. This conclusion is based on a number of observations: its brightness temperature at 6 cm is far in excess of the value expected from H II regions; it is not closely associated with other sources of star formation (in fact it is not an FIR core); it has the largest scattering disk of any of the known sources (implying plasma scattering from the nearby NGC 6334A H II region); and it is time-variable at radio frequencies (Moran et al. 1990). Also, measurements of H I indicate the presence of additional absorption toward NGC 6334B with respect to the cloud and therefore a larger distance (≥6 kpc; Moran et al. 1990).

Within the *Chandra* error box, there is no optical or infrared source listed in the USNO-B1 or Two Micron All Sky Survey (2MASS) catalogs (Monet et al. 2003; Cutri et al. 2003),[8] although there is slight evidence of very faint emission (magnitude ∼15) in the 2MASS *K*-band image. Correcting for measured X-ray absorption, this corresponds to an intrinsic brightness of 7th 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 of the cloud value might be related to material located between the cloud and the galaxy. In either case, NGC 6334B 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.

[8] See http://tdc-www.harvard.edu/software/catalogs/ub1.html and http://www.ipac.caltech.edu/2mass/releases/second/doc/explsup.html, respectively.

4. CONCLUSIONS

Following a 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 NGC 6334. 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 et al. 2002). Analysis of their X-ray characteristics is beyond the scope of the present Letter, 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 NGC 6334 is dominated by three bright sources: an emission-line star (CD −35 11482), the ionizing star of the ultracompact H II region NGC 6334C ([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 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 three powerful instruments (*INTEGRAL*, *Swift*, and *Chandra*) has allowed us to finally solve the NGC 6334 enigma.

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