CONFIRMATION OF IGR J01363+6610 AS A Be X-RAY BINARY WITH VERY LOW QUIESCENT X-RAY LUMINOSITY

JOHN A. TOMSICK1, CRAIG HEINKE2, JULES HALPERN3, PHILIP KAARET4, SYLVAIN CHATY5, JEROME RODRIGUEZ5, and ARASH BODAGHEE1

1 Space Sciences Laboratory, 7 Gauss Way, University of California, Berkeley, CA 94720-7450, USA; jtomsick@ssl.berkeley.edu
2 Department of Physics, University of Alberta, Room 238 CEB, Edmonton, AB T6G 2G7, Canada
3 Columbia Astrophysics Laboratory, Columbia University, 550 West 120th Street, New York, NY 10027-6601, USA
4 Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA
5 AIM-Astrophysique Instrumentation Modélisation (UMR 7158 CEA IRFU/Service d’Astrophysique, Bât. 709, L’Orme des Merisiers, FR-91 191 Gif-sur-Yvette Cedex, France

Received 2010 September 9; accepted 2010 December 13; published 2011 January 24

ABSTRACT

The field containing the candidate High Mass X-ray Binary IGR J01363+6610 was observed by XMM-Newton on 2009 July 31 for 28 ks. A Be star was previously suggested as the possible counterpart of the INTEGRAL source, and although Chandra, during a 2007 observation, did not detect an X-ray source at the position of the Be star, we find a variable source (XMMU J013549.5+661243) with an average X-ray flux of $2 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (0.2–12 keV, unabsorbed) at this position with XMM-Newton. The spectrum of this source is consistent with a hard power law with a photon index of $\Gamma = 1.4 \pm 0.3$ and a column density of $N_H = (1.5^{+0.7}_{-0.5}) \times 10^{22}$ cm$^{-2}$ (90% confidence errors). These results, along with our optical investigation of other X-ray sources in the field, make the association with the Be star very likely, and the 2 kpc distance estimate for the Be star indicates an X-ray luminosity of 9.1 $\times$ 10$^{31}$ erg s$^{-1}$. This is lower than typical for a Be X-ray binary, and the upper limit on the luminosity was even lower ($<1.4 \times 10^{31}$ erg s$^{-1}$ assuming the same spectral model) during the Chandra observation. We discuss possible implications of the very low quiescent luminosity for the physical properties of IGR J01363+6610.

Key words: black hole physics – stars: emission-line, Be – stars: individual (IGR J01363+6610) – stars: neutron – X-rays: stars

1. INTRODUCTION

The hard X-ray imaging of the Galactic plane by the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) satellite (Winkler et al. 2003) has uncovered a large number of new or previously poorly studied “IGR” sources (Bodaghee et al. 2007; Bird et al. 2010). While INTEGRAL excels at detecting sources in the 20–50 keV band, it only localizes the sources to $1^\circ$–5’, requiring follow-up observations with other X-ray satellites to obtain secure optical or IR counterparts, allowing for a determination of the nature of the sources (Walter et al. 2006; Tomsick et al. 2008; Rodriguez et al. 2009).

As more and more of these sources have been identified, possibly the biggest surprise is the large number of High Mass X-ray Binaries (HMXBs) as well as the properties of these systems. Many of the dozens of INTEGRAL HMXBs (Bodaghee et al. 2007) have large levels of intrinsic absorption with $N_H \sim 10^{23}$–$10^{24}$ cm$^{-2}$ (e.g., Walter et al. 2006), and these are commonly called obscured HMXBs. In many cases, it appears that this is due to the compact object being embedded in a strong stellar wind (Filliatre & Chaty 2004; Moon et al. 2007; Chaty et al. 2008). Some members of the group of INTEGRAL HMXBs exhibit other extreme properties, including the high amplitude X-ray flaring of the Supergiant Fast X-ray Transients (SFXTs; in’t Zand 2005; Smith et al. 2006) or long-period pulsations from very slowly rotating neutron stars (Patel et al. 2007).

INTEGRAL observations have also led to the addition of more HMXBs in the Be X-ray binary class (Rappaport & van den Heuvel 1982). The optical flux from these systems is dominated by an early-type star with emission lines from a circumstellar disk. In most cases, transient X-ray emission demonstrates the binary nature of the system as eccentric orbits lead to periodic X-ray outbursts when the compact object approaches periastron. Of the 64 known Be X-ray binary systems, X-ray pulsations indicate the presence of a neutron star in 42 cases, and the compact object type is unknown for the remaining systems (Belczynski & Ziolkowski 2009). One of the interesting properties of this class is the observed correlation between the orbital period and the spin period of the neutron star (Corbet 1986).

IGR J01363+6610 has been tentatively classified as a Be X-ray binary. The source was discovered during INTEGRAL observations on 2004 April 19 but was not detected ~2 weeks later, indicating that the source is transient (Grebeznev et al. 2004). The peak flux observed from the source was 17 mCrab ($\sim 2.6 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$) in the 17–45 keV band and 9 mCrab ($\sim 9.1 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$) in the 8–15 keV band (Grebeznev et al. 2004). The $3\sigma$ upper limit in the 17–45 keV band two weeks later was $<11$ mCrab (Grebeznev et al. 2004), and the source has not been detected in other INTEGRAL observations even though 2.3 Ms of INTEGRAL time have been accumulated at the position of this source (Bird et al. 2010). Reports of non-detection include both detailed studies of the Cassiopeia region (den Hartog et al. 2006) and catalogs indicating that the source was only detected during the discovery outburst in 2004 (Krivonos et al. 2007; Bird et al. 2007, 2010).

Although the INTEGRAL position uncertainty of 3’7 leaves a large error region, a Be star was found within the error circle using narrow-band Hα imaging and follow-up optical spectroscopy, and it has been suggested to be the likely counterpart (Reig et al. 2004, 2005). However, a sensitive X-ray observation taken with the Chandra X-ray Observatory in 2007 failed to detect the Be star (Tomsick et al. 2008). At the 2 kpc distance estimated for the Be star (Reig et al. 2005), the non-detection
The Astrophysical Journal, 728:86 (9pp), 2011 February 20

Tomick et al.

implies an upper limit on the X-ray luminosity of \(<2 \times 10^{31} \text{ erg cm}^{-2} \text{s}^{-1}\) (Tomick et al. 2008), which is lower than quiescent luminosities for other Be X-ray binaries (Campana et al. 2002). This luminosity approaches the level that has been seen during quiescent periods from transient Low Mass X-ray Binaries (LMXBs) due to thermal emission from the neutron star surface (Brown et al. 1998; Campana et al. 1998). Although neutron stars in HMXBs might not be heated to the high levels seen for LMXBs, it is interesting that these observations probe this luminosity regime.

Currently, there are significant uncertainties about the nature of IGR J01363+6610. While we know that it is an X-ray transient, and the hard X-ray emission makes it likely that it is a binary (although its orbital period is unknown), the Chandra non-detection makes it unclear whether it is really a Be X-ray binary. Finding a Be star in the relatively large INTEGRAL error circle is not convincing because Be stars are more commonly found as single stars rather than being part of a binary system (Porter & Rivinius 2003). Furthermore, we cannot be certain that the compact object in the system is a neutron star since pulsations have not been detected.

In this paper, we report on a second sensitive X-ray observation of the IGR J01363+6610 field with XMM-Newton along with optical spectroscopy of the Be star as well as other X-ray sources with optical counterparts in the field. With XMM-Newton, we confirm that the Be star is an X-ray source. We also reanalyze the Chandra observation and discuss the 2007 results in the context of the new information from XMM-Newton.

2. OBSERVATIONS

2.1. XMM-Newton

We observed the IGR J01363+6610 field with XMM-Newton on 2009 July 31 from 14.4 h to 22.3 h UT. The observation (ObsID 0603850101) occurred during XMM-Newton revolution 1766. The EPIC pn, MOS1, and MOS2 instruments (Strüder et al. 2001; Turner et al. 2001) were all operated in Full Frame mode with a medium filter. We used the XMM-Newton Science Analysis Software (SAS-10.0.0) package to process the raw data files. We used the SAS tool edetect_chain to search for sources in the \(\sim 30'\) diameter field of view (FOV) of the MOS1 and MOS2 instruments and included photons in the 0.1–10 keV energy band. All seven of the MOS2 CCDs were operational, but, for MOS1, CCD6 was not active because it was switched off after an anomaly that occurred in 2005. While this means that some of the MOS2 FOV is not covered by MOS1, the central CCD, which includes the entire INTEGRAL error circle, is covered by both MOS units.

We found a total of 21 sources, including 14 detected by both MOS units and seven detected by MOS2 in the part of the FOV that MOS1 did not cover. We determined the number of counts for each source using 25' radius apertures and subtracted the background using circular apertures of the same size in 16 source-free regions of the detector. The mean number of background counts per aperture is 47.1 \(\pm\) 1.8 for MOS1 and 45.9 \(\pm\) 1.7 for MOS2 (in 28,180 s of exposure time). The sources range in brightness from 12 \(\pm\) 8 to 156 \(\pm\) 13 counts (both of these sources are in the region covered only by MOS2). Five of the sources are in the 3/7 INTEGRAL 90% confidence error circle for IGR J01363+6610 given in Bird et al. (2010). These five sources include the second brightest source in the field (132 \(\pm\) 9 counts) as well as sources with 74 \(\pm\) 8, 31 \(\pm\) 6, 25 \(\pm\) 6, and 19 \(\pm\) 6 counts, where these numbers of counts are averages of the two MOS detectors.

The XMM-Newton source names and positions are given in Table 1. In addition to MOS1 and MOS2, we also determined the position measured by the pn instrument for each source, and we report the average position measured by the three instruments (except for XMMU J01363.2+660924, which fell between two pn CCD chips). In averaging the positions, we weighted each measurement by its statistical uncertainty. In Table 1, we also report the overall 90% confidence position uncertainties, and, in each case, the error is dominated by the systematic pointing uncertainty of 3.4\(^6\).

Using the 2007 observation of the field by Chandra, we previously reported three sources in the INTEGRAL error circle (Tomick et al. 2008). However, in the most recent INTEGRAL source catalog (Bird et al. 2010), the best estimate of the IGR J01363+6610 position has shifted by 1.8 relative to the value used in Tomick et al. (2008), and a fourth Chandra source, CXOU J013644.5+661301, is now also consistent with the INTEGRAL position for IGR J01363+6610, and its Chandra position is R.A. (J2000) = 01\(^{1}\)36\(^{2}\)44\(^{3}\)54, decl. (J2000) =

\[\text{In the document entitled "EPIC status of calibration and data analysis" (XMM-SOC-CAL-TN-0018), Guainazzi et al. (2010) report an rms value for the systematic pointing uncertainty of 2\(^{0}\)0, and we have multiplied this by 1.7 to obtain the 90% confidence value.}\]
Table 1

| Name                  | R.A. (J2000)       | Decl. (J2000)     | Position Uncertainty | MOS Counts |
|-----------------------|-------------------|------------------|----------------------|------------|
| XMMU J013549.5+661243| 01^h 35^m 49^s 53 | +66° 12′ 43″ 1 ′ | ±3′.4                | 132 ± 9    |
| XMMU J013606.5+661304| 01^h 36^m 06^s 54 | +66° 13′ 04″ 5 ′ | ±3′.9                | 25 ± 6     |
| XMMU J013620.8+660851| 01^h 36^m 20^s 80 | +66° 08′ 51″ 0 ′ | ±3′.7                | 31 ± 6     |
| XMMU J013632.4+660924d| 01^h 36^m 32′ 48 | +66° 09′ 24″ 0 ′ | ±4′.1                | 19 ± 6     |
| XMMU J013644.2+661302| 01^h 36^m 44′ 26 | +66° 13′ 02″ 2 ′ | ±3′.5                | 74 ± 8     |

Notes.

a The position is the weighted average of the positions measured by the three XMM-Newton instruments.

b The 90% confidence uncertainty in the XMM-Newton position. This includes a systematic contribution of 3′.4 due to the absolute pointing uncertainty and a statistical contribution. We have added the two contributions in quadrature.

c The average of the 0.1–10 keV count rates measured by MOS1 and MOS2.

d This source is detected by MOS1 and MOS2, but not by the pn instrument. It falls on a gap between pn CCD chips.

Table 2

| Catalog/Source          | Separation         | Magnitudes       |
|-------------------------|--------------------|------------------|
| (1) XMMU J013549.5+661243 |                   |                  |
|                        | 2′0 ± 3′4          | B = 14.9 ± 0.3   |
|                        | 2′0 ± 3′4          | R = 12.4 ± 0.3   |
|                        | 10.04 ± 0.02       | H = 9.57 ± 0.03  |
|                        | 10.42 ± 0.02       | K_s = 9.12 ± 0.02|
| (2) XMMU J013606.5+661304 |                   |                  |
|                        | 2′3 ± 3′9          | B = 12.1 ± 0.3   |
|                        | 3′0 ± 3′9          | R = 10.7 ± 0.3   |
|                        | 10.42 ± 0.02       | H = 10.10 ± 0.03 |
|                        | 10.00 ± 0.02       | K_s = 10.00 ± 0.02|
| (3) CXOU J013609.9+661157 |                   |                  |
|                        | 0′.52 ± 0′.64      | B = 17.2 ± 0.3   |
|                        | 0′.38 ± 0′.64      | R = 13.6 ± 0.3   |
|                        | 10.42 ± 0.03       | H = 9.54 ± 0.03  |
|                        | 9.26 ± 0.02        | K_s = 9.26 ± 0.02|
| (4) XMMU J013620.8+660851 |                   |                  |
|                        | 0′.73 ± 0′.64      | B = 17.4 ± 0.3   |
|                        | 0′.73 ± 0′.64      | R = 14.4 ± 0.3   |
|                        | 12.77 ± 0.02       | H = 12.01 ± 0.03 |
|                        | 11.83 ± 0.03       | K_s = 11.83 ± 0.03|

Notes.

a The catalogs are the Two Micron All Sky Survey (2MASS) and the United States Naval Observatory (USNO-B1.0).
b The uncertainty on the separation is the addition (in quadrature) of the X-ray source position error and the 2MASS or USNO-B1.0 error.

c X-ray sources with 90% confidence uncertainty of 0′.64. Of the four Chandra sources, two are coincident with XMM-Newton sources. Thus, merging the 2007 Chandra source list with the list of 2009 XMM-Newton leaves a list of seven X-ray sources in the INTEGRAL error circle, and these sources are listed in Table 2.

3.2. Optical and IR Counterparts and Optical Spectroscopy

For the seven X-ray sources listed in order of R.A. in Table 2, we searched for optical and infrared (IR) counterparts in the United States Naval Observatory (USNO-B1.0) and Two Micron All Sky Survey (2MASS) catalogs. Four of the sources (designated as 1, 2, 5, and 7) have optical and IR counterparts, and the names of these counterparts and their magnitudes are given in Table 2. For the other three X-ray sources (3, 4, and 6), the nearest USNO and 2MASS sources are >7″ away, which indicates that these X-ray sources are not associated with any sources in the USNO or 2MASS catalogs. Figure 1 shows a red (close to R band) optical image from the Digitized Sky Survey with the revised INTEGRAL error circle and the seven X-ray sources labeled.

X-ray source 1 is the Be star that was previously identified using optical imaging and spectroscopy taken in 2004 (Reig et al. 2004, 2005). The optical spectrum of this star (USNO-B1.0 1562-0030282) is shown in Figure 2 and has the blue continuum and the Hα and Hβ emission lines indicative of a Be star. The equivalent width (EW) of Hα is −54 ± 3 Å, which is consistent
Figure 1. Red optical image from the Digitized Sky Survey. The large circle is the 3.7 INTEGRAL error circle from Bird et al. (2010). The seven X-ray sources detected by XMM-Newton and Chandra are labeled. The arrows point to the optical counterparts for four of the X-ray sources, and their optical and IR magnitudes are given in Table 2. The small circles mark the locations of the X-ray sources without known optical counterparts.

with the value measured by Reig et al. (2004), suggesting that the Be star’s circumstellar disk is stable. Interstellar absorption features in the spectrum can be used to estimate the extinction E(B − V) following the correlations in Herbig (1975). Most commonly, the 4430 Å diffuse interstellar band is used for this purpose, but it falls in a poorly exposed region of our spectrum. Instead we use the 5780 Å feature. With an EW of 1.0 Å, it corresponds to E(B − V) in the range 1.5–2.0, which is consistent with the estimate of Reig et al. (2005) based on the spectral classification and photometry, E(B − V) = 1.6.

X-ray source 2 is coincident with USNO-B1.0 1562-0030364, which is also known as the bright (V = 11.5) optical source TYC 4043-860-1. There is some confusion about whether this is an emission line star based on a catalog of stars with Hα in emission (González & González 1956). However, Hα images and optical spectra taken, respectively, 2 months and 5 months after the X-ray outburst from IGR J01363+6610 do not show evidence for Hα emission and the spectrum shows Hα in absorption (Reig et al. 2004). The XMM-Newton observation provides the first evidence that this is also an X-ray source, but the lack of an Hα emission line in 2004 makes it very unlikely to be the correct IGR J01363+6610 counterpart.

We also obtained optical spectra for the only other two X-ray sources in the INTEGRAL error circle with optical/IR counterparts. The spectra for sources 5 and 7 are shown in Figure 3, and we identify them as G-type and early M-type stars, respectively. Like Be X-ray binaries, LMXBs usually show Hα in emission during outbursts (Fender et al. 2009) and during quiescence (Orosz et al. 2002; Charles & Coe 2006). Also, symbiotic systems often show strong Hα in emission (Chakrabarty & Roche 1997). However, there are counterexamples for both LMXBs and symbiotics. In any case, as sources 5 and 7 do not have emission lines, there is no reason to consider that they might be the IGR J01363+6610 counterpart.

Thus, these observations show that the Be star that was previously considered to be the likely counterpart of IGR J01363+6610 is coincident with XMMU J013549.5+661243, which was the brightest X-ray source in the INTEGRAL error circle during the 2009 XMM-Newton observation. The fact that we have now conclusively shown that the Be star is a transient X-ray source and that none of the other fainter X-ray sources in the INTEGRAL error circle have optical properties that would be expected of a hard X-ray source strengthens the association between the Be star and IGR J01363+6610, and we focus exclusively on the X-ray properties of the Be star XMMU J013549.5+661243 in the remainder of this paper.

3.3. XMMU J013549.5+661243

3.3.1. Energy Spectrum

We used the SAS tool xmmselect to produce MOS1, MOS2, and pn energy spectra for XMMU J013549.5+661243 and considered the recommendations given in a recent EPIC (MOS and pn) calibration document7 for event filtering and energy ranges. For MOS, we used event filtering with the expression “#XMMEA_EM & & PATTERN<=12” and included events within an aperture with a 25” radius. A background spectrum was extracted from an annulus centered on the source, and the

Figure 2. Optical spectrum of the Be star XMMU J013549.5+661243 taken on 2009 August 23, which is a few weeks after the XMM-Newton observation. The optical spectrum was taken with the MDM 2.4 m telescope and shows strong Hα and Hβ lines, indicating the presence of a circumstellar disk. The lower spectrum is the upper spectrum divided by 6, allowing for all of the Hα line to be visible. This source was previously suggested as the most likely counterpart to IGR J01363+6610, and the detection of the Be star with XMM-Newton provides further confirmation of this association.

7 The document entitled “EPIC status of calibration and data analysis” by Guainazzi et al. (2010; XMM-SOC-CAL-TN-0018) is based on results obtained using SAS-10.0.0. It was released on 2010 July 16 and can be found at http://xmm2.esac.esa.int/external/xmm_sw_cal/calib/index.shtml.
source and background regions are shown in Figure 4(a). For the pn instrument, we used event filtering with the expression “FLAG=0 && PATTERN<=4” and extracted spectra from source and background regions. For all three instruments, we used the SAS tools rmfgen and arfgen to make response matrices. For the MOS detectors, we used the 0.1–10 keV bandpass, and for the pn detector, we used the 0.2–12 keV bandpass. We rebinned each spectrum, and we fitted the spectra using $\chi^2$ statistics.

We used the XSPEC version 12 software for spectral fitting, and we tried several models. The results of using an absorbed power law are shown in Table 3 and Figure 5. For absorption, we used the photoelectric absorption cross sections from Balucinska-Church & McCammon (1992) and elemental abundances from Wilms et al. (2000), which correspond to the estimated abundances for the interstellar medium. This model gives a good fit ($\chi^2/\nu = 23.1/26$), and requires a relatively hard power-law photon index of $\Gamma = 1.4 \pm 0.3$. The power-law fit gives a 0.2–12 keV unabsorbed flux of $(1.9^{+0.3}_{-0.2}) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ and a column density of $N_H = (1.5^{+0.7}_{-0.5}) \times 10^{22}$ cm$^{-2}$, which is somewhat higher than the value through the Galaxy along the line of sight, $N_H = 5.2 \times 10^{21}$ cm$^{-2}$ (Kalberla et al. 2005). Although this could indicate a small amount of absorption local to the source, it is much lower than the values near $10^{23}$ cm$^{-2}$ seen for the sources usually considered to be obscured HMXBs. Another argument
against local absorption of the X-ray source is that the value of \( E(B-V) = 1.5-2.0 \) corresponds to an \( N_H \) in the range \((1.0-1.4) \times 10^{22} \text{ cm}^{-2}\) (Ryter 1996), which is consistent with the column density determined from the X-ray spectrum.

We also fitted the energy spectrum with blackbody and thermal Bremsstrahlung models, and the parameters are given in Table 3. A fit with a 1.3 keV blackbody is similar in quality to the power law \( (\chi^2/\nu = 21.5/26) \), but the spectrum does not allow us to distinguish between thermal and non-thermal models. However, at 2 kpc, the blackbody model implies an emitting region with a radius of about \( 1.15 \times 10^3 \text{ cm} \), which is too small to be physical. The Bremsstrahlung model requires a relatively high temperature \((>11 \text{ keV})\), which makes it very similar to a power law over the XMM-Newton bandpass. Although we are not able to distinguish between models, it is important to note that the power-law fit above shows that the spectrum is hard, as expected for an IGR source and especially for an HMXB.

### 3.3.2. Long- and Short-term X-ray Variability

Comparing the two panels of Figure 4 shows the difference between fluxes in 2009 (the XMM-Newton observation) and 2007 (the Chandra observation). We did not detect the Be star during a 5 ks Chandra/ACIS observation (Tomsick et al. 2008), and 1 count is detected by ACIS within the XMM-Newton error circle. Thus, using Poisson statistics, this corresponds to a 90% confidence upper limit of <3.9 counts (Gehrels 1986).

For the power-law spectral model measured by XMM-Newton \((\Gamma = 1.4 \text{ and } N_H = 1.5 \times 10^{22} \text{ cm}^{-2})\), this corresponds to an absorbed 0.3–10 keV flux of \( \leq 1.6 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \) and an unabsorbed flux of \( \leq 2.9 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \), which is \( >0.6 \) times lower than the flux seen during the XMM-Newton observation. The original outburst detected by INTEGRAL in 2004, an 8–15 keV flux of 9 mCrab \((9.1 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1})\) was measured using the JEM-X instrument. In the 8–15 keV band, the flux measured with XMM-Newton in 2009 was \( 7.9 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\), which is a factor of 1150 lower than the outburst level. Thus, the quiescent upper limit obtained with Chandra represents a flux \( >7600 \) times lower than the level seen during outburst.

We also find evidence for shorter term variability during the XMM-Newton observation. Figure 6 shows the source and background rates combined for all three XMM-Newton detectors in the 0.2–12 keV band with 250 s time bins. The light curve shows that the 0.2–12 keV rates can change from values as low as \( -0.003 \pm 0.007 \) to \( 0.061 \pm 0.018 \). We used a \( \chi^2 \) test to determine the significance of the variability. The best fit that can be obtained with a constant rate has a \( \chi^2 = 142.5 \) for 106 degrees of freedom, which indicates that the variability is significant at the 99% confidence level.

### 4. DISCUSSION

#### 4.1. The Nature of IGR J01363+6610

Our results show that XMMU J013549.5+661243 is a hard X-ray source coincident with a Be star at a distance of \( \sim 2 \) kpc. At this distance, the inferred X-ray luminosity measured by XMM-Newton is \( 9.1 \times 10^{31} \text{ erg s}^{-1} \). While this would be a relatively high X-ray luminosity for an isolated B1 star, it is not too far above the values reported by Cohen et al. (1997) for such stars. However, in nearly all cases of isolated B-type stars, the X-ray emission is thermal with temperatures that are typically not above a few \( \times 10^6 \) K (Cohen et al. 1997; Cohen 2000), and their spectra fall very steeply above \( \sim 0.25 \) keV. The very hard X-ray spectrum that we measure for XMMU J013549.5+661243 is inconsistent with a thermal spectrum with such a low temperature, indicating that the Be star must have a compact binary companion that is emitting most of the X-ray emission.

While the X-ray luminosity and spectrum are not consistent with an isolated star, the XMM-Newton data alone are not sufficient to determine the nature of the compact binary companion. There are known Be systems with both white dwarf and neutron star companions that can produce hard spectra. For example, there are several \( \gamma \) Cas-like systems that may harbor white dwarfs and have power-law spectral components with photon
Heuvel 1982; Corbet 1986). In most systems, the orbits have indices of 1.4–1.7 (Motch et al. 2007). However, based on our study of the X-ray sources in the IGR J01363+6610 field, we argue that it is very likely that XMMU J013549.5+661243 is the quiescent counterpart to IGR J01363+6610. In this case, the outburst detected by INTEGRAL indicates that the source can produce an X-ray luminosity as high as $\sim 10^{35}$ erg s$^{-1}$ along with variations in X-ray luminosity by a factor of $> 7600$ (when the Chandra observation is considered as well). In contrast, the Cyg X-1-like systems have luminosities typically near $10^{33}$ erg s$^{-1}$, and while they show variability in flux by factors of a few, they do not have large outbursts (Motch et al. 2007). Thus, the most likely interpretation of the available information is that IGR J01363+6610 is a Be X-ray binary with a neutron star (or perhaps a black hole as discussed below) accretor. In the following, we discuss IGR J01363+6610 in this context.

4.2. Accretion Regimes and the X-ray Luminosity

Models for X-ray emission from Be X-ray binaries are based on the picture of a neutron star with a relatively strong magnetic field ($B \sim 10^{12}$ G) and a relatively slow rotation speed ($P_{\text{spin}} \sim 0.1$–1000 s) periodically accreting from the circumstellar disk around the Be star (Rappaport & van den Heuvel 1982; Corbet 1986). In most systems, the orbits have non-zero eccentricity, and “Type 1” X-ray outbursts occur when the neutron star makes its closest approach to the star so that the outburst periodicity is equal to the orbital period, $P_{\text{orb}}$.

Within this physical picture, there are two accretion regimes that are usually considered. One regime is at higher mass accretion rates when the accretion pressure overcomes the centrifugal magnetic field barrier, and matter is accreted directly onto the poles of the neutron star (Corbet 1996). The second regime is during times when the accretion is inhibited by the magnetic field. This is often called the propeller regime (Illarionov & Sunyaev 1975), and the X-ray emission is much lower in this regime because the matter being accreted only reaches the neutron star magnetosphere rather than falling onto the neutron star surface. A gap is predicted between the minimum luminosity in which the system can be in the direct accretion regime and the maximum luminosity in which the system can be in the propeller regime (Corbet 1996), and we define $\Delta$ to be equal to this luminosity ratio. For typical neutron star properties ($1.4 M_\odot$ mass, 10 km radius, $10^{12}$ G magnetic field), $\Delta = 170(P_{\text{spin}}/1 \text{s})^{2/3}$ (Campana et al. 2002), and values of $\Delta$ range from $\sim 100$ for fast rotators to $\sim 10,000$ for slow rotators (Corbet 1996).

Assuming a distance of 2 kpc and a spectral shape consistent with the power-law model measured using XMM-Newton, IGR J01363+6610 has been observed by INTEGRAL at $L_x = 1.04 \times 10^{35}$ erg s$^{-1}$ in 2004, by Chandra at $< 1.4 \times 10^{31}$ erg s$^{-1}$ in 2007, and by XMM-Newton at $9.1 \times 10^{31}$ erg s$^{-1}$ in 2009. These luminosities are unabsorbed values measured in or extrapolated into the 0.2–12 keV band. The 2004 outburst luminosity is at the lower end of typical values for normal (“type I”) Be X-ray binary outbursts, which are in the $10^{35}$ to $10^{37}$ erg s$^{-1}$ range (Stella et al. 1986; Wilson et al. 2005). Still, it is likely (but perhaps not certain if the neutron star spin or magnetic field strength have extreme values) that the source reached a high enough accretion rate to enter the direct accretion regime. Following Corbet (1996) and Campana et al. (2002), we derive an upper limit on the luminosity produced by magnetospheric emission of $L_m < 1.04 \times 10^{35} \Delta = 6.1 \times 10^{33} (P_{\text{spin}}/1 \text{s})^{-2/3}$. Thus, under the assumptions that the neutron star properties (mass, radius, and magnetic field strength) are typical and the system reached the direct accretion regime during the 2004 outburst, the luminosity measured by XMM-Newton in 2009 implies a neutron star spin period less than 17 s for IGR J01363+6610.

While the propeller regime may extend to very low luminosities, a third regime to consider is when the mass accretion rate onto the neutron star drops to zero. In this case, any X-ray emission produced could have contributions from the Be star and from the neutron star. Emission from the neutron star would be thermal in origin and would be extremely soft. Such components are seen at temperatures near 50–150 eV in LMXBs (Brown et al. 1995), assuming emission from the entire neutron star, a mass of $1.4 M_\odot$, a radius of 10 km, a distance of 2 kpc, and a magnetic field of $B = 10^{12}$ G. The upper limit on the (unredshifted) surface temperature is then 80 eV, and the unabsorbed 0.2–12 keV luminosity upper limit is $< 2.4 \times 10^{33}$ erg s$^{-1}$. Changes in the assumptions will affect this, particularly changes in the assumed $N_H$ or distance. For instance, a choice of $N_H = 2 \times 10^{22}$ cm$^{-2}$ gives $kT < 85$ eV and $L_x < 3.2 \times 10^{32}$ erg s$^{-1}$, or a distance of 3 kpc gives $kT < 88$ eV and $L_x < 3.7 \times 10^{32}$ erg s$^{-1}$. If the X-ray emission in this quiescent state is dominated by hot spots at the polar caps, their temperature may be higher, but the temperature of the rest of the neutron star surface must be even lower.
4.3. The Quiescent Luminosity and Possible Implications

The above analysis suggests that the IGR J01363+6610 luminosities can be explained within the standard picture for Be-neutron star X-ray binaries, but the luminosity upper limit that we infer from the Chandra observation is lower than has been previously reported from these systems. Campa et al. (2002) present a study that focuses on quiescent X-ray observations of three Be X-ray binaries, and their luminosities are \((1\pm3)\times10^{35}\) erg \(s^{-1}\) \((0.1\text{--}10\text{keV})\) for \(A\ 0538\text{--}66\), \((0.8\text{--}2)\times10^{33}\) erg \(s^{-1}\) \((0.5\text{--}10\text{keV})\) for \(4U\ 0115+63\), and \(5\times10^{32}\) erg \(s^{-1}\) \((0.5\text{--}10\text{keV})\) for \(V\ 0332+53\). In addition, quiescent luminosities of \((3\pm9)\times10^{33}\) erg \(s^{-1}\) and \((2.4\pm5)\times10^{33}\) erg \(s^{-1}\) have been reported for GRO J2058+42 and \(A\ 0535+26\), respectively (Wilson et al. 2005; Negueruela et al. 2000). The candidate Be X-ray binary XTE J1829-098 has been observed at a luminosity of \(3\times10^{32}\) \((d/10\text{kpc})^2\) erg \(s^{-1}\) (Halpern & Gotthelf 2007), which is low for a Be X-ray binary, but still not as low as we find for IGR J01363+6610. It should, however, be noted that, for \(A\ 0535+26\), Negueruela et al. (2000) found the source at this luminosity after it had previously been reported to have a quiescent luminosity two orders of magnitude higher (Motch et al. 1991). Thus, it is clear that even when they are not in outburst, these sources exhibit a large amount of variability, and many observations may be required for each source to define a quiescent luminosity.

While the Chandra upper limit of \(<1.4\times10^{31}\) \((d/2\text{kpc})^2\) erg \(s^{-1}\) obtained with a hard spectrum as seen in outburst is significantly lower than has been found for other Be X-ray binaries, this conclusion does depend on the validity of the distance determination. The 2 kpc distance from Reig et al. (2005) depends on the measurement of the V-band magnitude, which is given in Reig et al. (2005) to high precision \((V = 13.29 \pm 0.02, \text{based on three measurements})\), the extinction, and the spectral type. Reig et al. (2005) give a value of \(E(B-V) = 1.6\), and our determination is consistent with this suggesting that the uncertainty in the distance due to the measurement of extinction is not large. Probably the largest uncertainty is related to the spectral type. Reig et al. (2005) use a spectral type of B1IV and an absolute magnitude of \(M_V = -3.2\) for the 2 kpc estimate, but they indicate that the star could be a more luminous sub-giant (i.e., B1IV). The difference in the absolute magnitude of a main-sequence B-type star compared to a B-type sub-giant is 0.6–0.7 mag (Cox 2000), so it is unlikely that the star is more luminous than \(M_V \sim -4.0\), which corresponds to a distance upper limit near 3 kpc. This, in turn, indicates an upper limit on the quiescent X-ray luminosity of \(<3.2\times10^{31}\) erg \(s^{-1}\), which is still significantly lower than the X-ray luminosities given above for comparison.

Although it is not clear why the quiescent luminosity is so much lower for IGR J01363+6610, there are several potentially interesting possibilities. Among the more trivial is the possibility that the short (5 ks) Chandra observation occurred during an X-ray eclipse. Although eclipses are not common for Be X-ray binaries due to their typically wide orbits, we currently cannot rule out this possibility since the orbit and binary inclination for IGR J01363+6610 are unconstrained. It is also possible that Chandra did not detect the source either because the compact object was highly obscured during the Chandra observation or that Chandra happened to catch the source during a low point in its normal short-term variability. Finally, there is also the possibility that the circumstellar disk, which was strongly present in 2004 and 2009 based on the detection of the Hα emission line with an EW of \(\sim-50\) Å, had dissipated during the 2007 Chandra observation. Although dissipation and reformation of a circumstellar disk on this timescale did occur in the case of GRO J1008–57 (Coe et al. 2007), and significant disk loss was observed for IGR J06074+2205 on a timescale of \(<3\) years (Reig et al. 2010), in both of these cases, the Hα lines were significantly weaker than measured for IGR J01363+6610. There is no precedent that we are aware of for dissipation and reformation of a circumstellar disk in a system with an Hα EW as large as the one measured for IGR J01363+6610. While there are possible explanations for the luminosity upper limit measured over a short period of time by Chandra, these explanations do not apply to the XMM-Newton observation. The luminosity measured by XMM-Newton would also make it one of, if not the lowest luminosity Be X-ray binaries. Thus, it is likely that the low luminosities measured for IGR J01363+6610 require that this system has some unusual physical properties.

The Be X-ray binaries with known compact object type have neutron stars, but binary evolution models predict that between zero and two of the 64 known Be X-ray binary systems harbor a black hole instead of a neutron star (Belczynski & Ziolkowski 2009). The observational signatures for Be X-ray binaries with black holes are not as clear as neutron star signatures, such as pulsations. At high mass accretion rates, one would expect the X-ray emission from black holes to be softer and brighter due to the presence of an inner accretion disk that cannot form in systems with highly magnetized neutron stars due to the magnetosphere. At moderate to low mass accretion rates, accreting black holes typically have hard spectra (Remillard & McClintock 2006). At very low mass accretion rates, black hole systems would likely be fainter than neutron star systems because the latter exhibit magnetospheric and surface emission, which are both absent from black holes. The expected hard spectrum and the faint quiescent luminosity are both consistent with the observed properties of IGR J01363+6610.

There may, however, be a less exotic explanation if the binary orbit of IGR J01363+6610 causes a neutron star to sample an unusually low density part of the circumstellar disk. This could occur if the system has a long orbital period with relatively low eccentricity. As pointed out by Reig et al. (2005), the EW of the Hα line for IGR J01363+6610 is one of the strongest of any Be X-ray binary, suggesting the presence of a large circumstellar disk, which might favor a large and nearly circular orbit over a highly eccentric orbit. While the system may have a large circumstellar disk, Negueruela & Okazaki (2001) have shown that tidal interactions of the neutron star can lead to truncation of the circumstellar disk in low eccentricity systems. In addition to providing a possible explanation for the low quiescent luminosity of IGR J01363+6610, the fact that the disk can be truncated to a size smaller than the Be star’s Roche lobe means that the system will not show luminous outbursts (Okazaki & Negueruela 2001), which is consistent with what has been seen so far for IGR J01363+6610.

Like IGR J01363+6610, the orbital parameters for the other Be X-ray binaries with the strongest Hα emission lines, A 1118–616 (Coe et al. 1994) and IGR J01583+6713 (Kaur et al. 2008), are not known. It has been suggested that A 1118–616 has a nearly circular orbit based on its having a small number of outbursts with no clear periodicity (Coe et al. 1994). It has been argued that both of these systems have relatively long orbital periods (\(<0.6–2.2\) years) based on measured neutron star spin periods of 405.6 s and 469.2 s and the \(P_{\text{orb}}-P_{\text{spin}}\) relationship for Be X-ray binaries (Corbet 1986; Coe et al. 1994; Kaur et al. 2008).
Although some of its properties suggest that it is a fairly low quiescent luminosity. Another very interesting possibility is the suggestion that this could be a Be-black hole system. The former suggestion could be confirmed by a measurement of the orbital period (although this will be challenging since the source does not seem to produce regular outbursts), and the latter suggestion could be refuted with the detection of pulsations during another outburst from the source.

J.A.T. acknowledges partial support from NASA XMM-Newton Guest Observer award number NNX09AP91G. C.H. acknowledges support from an NSERC Discovery Grant. We thank Jia Liu for assistance with the optical observations and spectral reductions. We acknowledge helpful comments from the referee, Ignacio Negueruela. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by NASA and the National Science Foundation. This research makes use of the USNO's Image and Catalog Archive operated by the United States Naval Observatory, Flagstaff Station, and the SIMBAD database, operated at CDS, Strasbourg, France.

REFERENCES

Balucinska-Church, M., & McCammon, D. 1992, ApJ, 400, 699
Belczynski, K., & Ziolkowski, J. 2009, ApJ, 707, 870
Bird, A. J., et al. 2007, ApJS, 170, 175
Bird, A. J., et al. 2010, ApJS, 186, 1
Bosdaghe, A., et al. 2007, A&A, 467, 585
Brown, E. F., Bildsten, L., & Rutledge, R. E. 1998, ApJ, 504, L95
Campana, S., Colpi, M., Mereghetti, S., Stella, L., & Tavani, M. 1998, A&A, 398, 279
Campana, S., Stella, L., Israel, G. L., Moretti, A., Parmar, A. N., & Orlandini, M. 2002, ApJ, 580, 389
Chakrabarty, D., & Roche, P. 1997, ApJ, 489, 254
Charles, P. A., & Coe, M. J. 2006, in Compact Stellar X-ray Sources, Optical, Ultraviolet and Infrared Observations of X-ray Binaries, ed. W. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), 215
Chaty, S., Rahoui, F., Foellmi, C., Tomsick, J. A., Rodriguez, J., & Walter, R. 2008, A&A, 484, 783

Coe, M. J., et al. 1994, A&A, 289, 784
Coe, M. J., et al. 2007, MNRAS, 378, 1427
Cohen, D. H. 2000, in ASP Conf. Ser. 214, IAU Colloq. 175, The Be Phenomenon in Early-Type Stars, ed. M. A. Smith, H. F. Henriks, & J. Fabregat (San Francisco: CA: ASP), 156
Cohen, D. H., Cassinelli, J. P., & Macfarlane, J. J. 1997, ApJ, 487, 867
Corbet, R. H. D. 1986, MNRAS, 220, 1047
Corbet, R. H. D. 1996, ApJ, 457, L31
Cox, A. N. (ed.) 2000, Allen’s Astrophysical Quantities (4th ed.; New York: AIP Press)

5. SUMMARY AND CONCLUSIONS

In summary, the detection of the variable hard X-ray source XMMU J013549.5+661243 at the location of a Be star provides evidence for a smaller $P_{\text{orb}}$; however, we view the evidence for a limit on the spin period as being relatively weak.

The Astrophysical Journal, 728:86 (9pp), 2011 February 20