FURTHER STUDIES OF 1E 1740.7—2942 WITH ASCA

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ABSTRACT

We report the ASCA results of the Great Annihilator 1E 1740.7—2942 obtained with five pointing observations in a time span of 3.5 yr. The X-ray spectrum for each period is well fitted with a single power law absorbed by a high column of gas. The X-ray flux changes by a factor of 2 from period to period, but the other spectral parameters show no significant change. The photon index is flat with Γ = 0.9±1.3. The column density of hydrogen N_H is \(1.0 \times 10^{20}\) cm\(^{-2}\) and that of iron N_Fe is \(1.0 \times 10^{17}\) Fe cm\(^{-2}\). These large column densities indicate that 1E 1740.7—2942 is near the Galactic center. The column density ratio leads the iron abundance to be 2 times larger than the other elements in a unit of the solar ratio. The equivalent width of the K\(_x\) line from a neutral iron is less than 15 eV in 90% confidence. This indicates that the iron column density within several parsecs from 1E 1740.7—2942 is less than \(5 \times 10^{17}\) Fe cm\(^{-2}\). In addition, the derived hydrogen column density is about one-sixth of that of giant molecular clouds in the line of sight. All these facts support the fact that 1E 1740.7—2942 is not in a molecular cloud, but possibly in front of it; the X-rays are not powered by accretion from a molecular cloud, but from a companion star like ordinary X-ray binaries.

Subject headings: accretion, accretion disks — black hole physics — ISM: clouds — stars: individual (1E 1740.7—2942) — X-rays: stars

1. INTRODUCTION

The center of our Milky Way is one of the most complex regions in X-rays as well as the other wave bands. In fact, many X-ray point sources, including transients, have been detected with the past observations. Among these, 1E 1740.7—2942 has been found to be quite unusual. This source was discovered with the Einstein IPC in the soft X-ray band below 3.5 keV (Hertz & Grindlay 1984). Higher energy observations revealed an unusually hard spectrum (Skinner et al. 1987, 1991; Kawai et al. 1988; Cook et al. 1991; Bazzano et al. 1992; Cordier et al. 1993a, 1993b; Goldwurm et al. 1994). In fact, this is by far the brightest source within a few degrees of the Galactic center in the high-energy band above 20 keV with a power-law spectrum extending up to 100 keV or higher. It showed flux variability on timescales from a day to a few years (Bouchet et al. 1991; Sunyaev et al. 1991; Churazov et al. 1993a, 1993b; Paciesas et al. 1993; Pavlinsky, Grebenev, & Sunyaev 1994; Zhang, Harmon, & Liang 1997). Variability on timescales shorter than a day has been detected by Smith et al. (1997). The spectral shape has been almost stable in time, regardless of the flux variations. These spectra and time variabilities generally resemble those of Cygnus X-1 (e.g., Kuznetsov et al. 1997), the prototype of the galactic black hole candidate. Unlike Cygnus X-1, however, optical and IR observations have failed to find any companion stars (Prince et al. 1991; Mereghetti et al. 1992; Djorgovski et al. 1992), probably because of strong extinction in the direction of the Galactic center.

The electron-positron annihilation line at 511 keV from this source was reported with the Grenat/SIGMA observations, hence 1E 1740.7—2942 has been referred to as the “Great Annihilator” (Bouchet et al. 1991; Sunyaev et al. 1991; Churazov et al. 1993b; Cordier et al. 1993a). Jung et al. (1995), Harris, Share, & Leising (1994a, 1994b), Malet et al. (1995), Smith et al. (1996), and Cheng et al. (1998), on the other hand, reported no evidence for the annihilation line, making this issue debatable. The VLA3 radio observations revealed that 1E 1740.7—2942 has a radio counterpart with variable flux correlated to the X-ray variation (Mirabel et al. 1992, 1993). They also found nonthermal double jetlike structures emanating from the source, which resemble those of the galactic superluminal jet sources (e.g., Fender, Burnell, & Waltman 1997). Hence this source is also referred to as a “micro quasar.” These facts altogether make 1E 1740.7—2942 to be one of the best candidates of stellar-mass black holes.

The CO observations found a giant molecular cloud whose density peak is in agreement with the position of 1E 1740.7—2942 (Bally & Levenshal 1991; Mirabel et al. 1991). They proposed that 1E 1740.7—2942 is an isolated or a binary black hole, powered directly from a surrounding molecular cloud such as by Bondi-Hoyle accretion (Bondi & Hoyle 1944), although the conventional binary scenario with mass accretion from a companion star cannot be excluded.

The X-ray spectrum and time variability would be keys for the study of the nature and emission mechanisms. In particular, the equivalent width of the fluorescent iron line as a function of absorption column provides direct evidence on whether the source is really in a dense cloud or not.

3 The VLA is a telescope of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.
Churazov, Gilfanov, & Sunyaev (1996) and Sheth et al. (1996) have examined the X-ray spectra of this source with the Performance Verification (PV) and AO-2 phases of the early ASCA operations. Their derived $N_{\text{H}}$-values, and hence the conclusions, are not fully consistent with each other. This is partly due to the fact that they fitted the spectra with a different energy range. A more serious problem for the detailed spectral study of this source, particularly in the iron line, iron $K$ edge, and low-energy absorption structures, is a possible contamination of the thin thermal Galactic plasma emission which includes strong emission lines (Koyama et al. 1996). Thus, we have made further observations in AO-3 and AO-5 phases after PV and AO-2 and analyzed all the available data sets, putting particular effort into properly removing possible contamination from the plasma emission in the Galactic center region. We assume the distance of the Galactic center to be 8.5 kpc.

### 2. OBSERVATIONS

ASCA observations of 1E 1740.7—2942 were made on five occasions, which are listed in Table 1. Two sets of the Solid-State Imaging Spectrometers (SISs) were operated in parallel with the Gas Imaging Spectrometers (GISs), both located separately at foci of four identical thin-foil X-ray telescopes (XRTs). Details of this instrumentation are found in Serlemitsos et al. (1995), Burke et al. (1991, 1994), Yama-shita et al. (1997), Ohashi et al. (1996), and Makishima et al. (1996), while a general description of ASCA can be found in Tanaka, Inoue, & Holt (1994).

In the PV and AO-2 observations, 1E 1740.7—2942 was pointed near the center of the field of view, while for the other observations, 1E 1740.7—2942 was out of the SIS field of view. In addition, we have made eight sequential pointing observations near the Galactic center with 20 ks exposure for each. These series of observations covered the Galactic center region of about $1 \times 1.5$ deg$^2$, and the data were used to estimate the Galactic diffuse background (see § 3.3). Table 1 summarizes the observation log. Data reduction and cleaning were made with the standard method as described in the user guide by the NASA Goddard Space Flight Center (GSFC). The event selection and the analysis were performed on UNIX workstations with the FTOOLS and XANADU packages released by NASA GSFC.

### 3. RESULTS AND ANALYSIS

#### 3.1. X-Ray Images

The GIS mosaic images for the hard X-ray band (3–10 keV) and the soft X-ray band (0.7–1.5 keV) are given in Figures 1a and 1b, respectively. We find a strong point source at the ROSAT position of 1E 1740.7—2942 ($17^\text{h}43^\text{m}54.8^\text{s}, -29^\circ44'38'"$) in J2000 coordinates (Heindl, Prince, & Grunsfeld 1994), within the nominal ASCA error circle of about 1' radius in each image. The excess X-ray flux above the diffuse background level is higher in the hard X-ray band than that in the soft band. This immediately indicates that either the X-rays are highly absorbed or the spectrum is very hard, or probably both.

We also find a faint soft source, AX J1744.3—2940, at $17^\text{h}44^\text{m}18.8^\text{s}, -29^\circ40'1$ in J2000 coordinates with the error circle of about 1'. This position is in good coincidence with source 2 of Heindl et al. (1994) observed with ROSAT or 1WGA J1744.2—2939. It is about 7' offset from 1E 1740.7—2942, hence the photon contamination from this source for the analysis of 1E 1740.7—2942 is negligible.

#### 3.2. Light Curves

Since the X-rays from 1E 1740.7—2942 are limited to above about 2 keV (see § 3.3 or X-ray images in Fig. 1), we made light curves for each observation, accumulating 2–10 keV photons in the circular region within a 3' radius from the source. To increase statistics, we summed the data of GIS0 and GIS1 or GIS2 and GIS3 with a time bin of 256 s. As an example, we show the light curves of the AO-2

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**TABLE 1**

| PHASE   | DATE       | R.A.$^a$ | DECL.$^a$ | BIT RATE | DATA MODE | EXPOSURE$^b$ |
|---------|------------|----------|-----------|----------|-----------|--------------|
|         |            |          |           |          | GIS       | SIS          | GIS       | SIS       |
| PV ......| 1993 Sep 26| 17 43 30 | -29 50    | High     | PH        | 4CCD Faint  | 24        | 24        |
| PV$^a$  | 1993 Oct 3 | 17 45 30 | -29 14    | Medium   | PH        | 1CCD Bright | 10        | 12        |
| PV$^b$  | 1993 Oct 4 | 17 44 00 | -29 20    | High     | PH        | 4CCD Faint  | 8         | 6         |
| AO-2.....| 1994 Sep 8 | 17 43 30 | -29 50    | High     | PH        | 2CCD Faint  | 12        | 12        |
| AO-2.....| 1994 Sep 12| 17 43 30 | -29 50    | Medium   | PH        | 1CCD Faint  | 5         | 5         |
| AO-3$^c$| 1995 Mar 27| 17 44 10 | -30 03    | High     | PH        | ...         | 24        | ...       |
| AO-5$^d$| 1997 Mar 21| 17 44 59 | -29 46    | Medium   | PH        | ...         | 39        | 40        |

**Note.**—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees and arcminutes.

$^a$ Coordinate of detector center (J2000).

$^b$ In units of kiloseconds.

$^c$ These pointings do not include 1E 1740.7—2942 in their fields of view. They are used for background estimation in § 3.3.

$^d$ 1E 1740.7—2942 is out of the SIS fields of view.
Fig. 1.—GIS mosaic images near 1E 1740.7–2942. (a) In the 3–10 keV band; (b) in the 0.7–1.5 keV band. The images are taken with multiple pointings of *ASCA* in 1993–1997. The data of GIS2 and GIS3 are summed, smoothed with a Gaussian filter of $\sigma = 3$ pixels ($\sim 0.75$), and corrected for exposure, vignetting, and the detection efficiency with GIS grid, after non-X-ray background is subtracted. The dotted grids are the galactic coordinates ($l, b$). Color levels are logarithmically spaced. The stray lights by some bright sources, which are variable from epoch to epoch, make images complicated, for example, they make images discontinuous on the edges of the fields of views. A faint soft source, AX J1744.3–2940, at 17$^h$44$^m$18$^s$, −29$^\circ$40.1 in J2000 coordinates is found. The positions of Sgr A region and SNR G359.1−0.5 (Yokogawa et al. 1998) are also indicated.
first observation in Figure 2. Constant flux assumption for the light curve of each observation is rejected by $\chi^2$-tests with more than 90% confidence. Thus, the X-ray flux was found to be variable, although the variability amplitude is not large.

We also examined fast Fourier transform analysis for the GIS 2 + 3 data of high bit rate with 1/16 s time resolution, and found no periodic variation on the timescale of 1/16–1000 s from any of the five separate observations.

As for the long-term variability, we found the averaged flux in PV phase decreased to about 75% and 50% in the AO-2 and AO-3 phases, respectively, and then increased in the AO-5 phase to about the same flux as in PV phase (see Fig. 4 and § 3.3).

3.3. Spectral Analysis

The source 1E 1740.7−2942 is located near the Galactic center region, which is filled with a high-temperature plasma. The plasma emits diffuse X-rays including strong iron lines, with significant flux variations from position to position (Koyama et al. 1996). Therefore, the spectrum of 1E 1740.7−2942 may be contaminated by the diffuse X-rays, especially in the low-energy band and in the iron line feature.

To minimize a possible effect to the spectrum due to the background variation, we accumulated the source X-ray photons in a small circle of 2' radius and extracted the background taken from the annulus of 2'−4' in radius. We thus made the background-subtracted spectra with GIS2 + 3 and SIS0 + 1 for each observation phase. For the AO-3 data, we excluded the region very near the detector edge or the calibration isotope from the background region.

We fitted each spectrum with an absorbed power law, using the photoelectronic cross sections by Balucinska-Church & McCammon (1992). The abundances for the absorbing matters were fixed to the solar values (Anders & Grevesse 1989), but that of iron was allowed to vary, because the 7.1 keV edge structure carries unique information on the iron column. Examples (AO-2) of the spectra with the best-fit models are given in Figure 3, and the best-fit parameters for all the observations are listed in Table 2.

We then fitted the GIS and the SIS data for each phase simultaneously with a power-law model. The results with the best statistics are also given in Table 2. The best-fit

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**Fig. 2.** The 2−10 keV light curves with 256 s bin for the AO-2 first observation. *Left-hand panel*: GIS 2 + 3 data; *Right-hand panel*: SIS 0 + 1.

**Fig. 3.** Spectra of AO-2 with the best-fit model (solid lines). *Left-hand panel*: GIS 2 + 3; *Right-hand panel*: SIS 0 + 1.
photons cm$^{-2}$ s$^{-1}$). Since the 6.4 keV line flux is observed to be 1.0 keV, the absorbing column density is $N_{\text{H}} = 5 \times 10^{22}$ cm$^{-2}$, and the iron abundance is high and found to be about 2 solar.

Although we found no clear emission line in each spectrum, we included a 6.4 keV line for the further fitting, because the emission line from neutral iron at 6.4 keV gives direct information around the cold gas near 1E 1740.7—2942. In this fitting we fixed the line energy and the intrinsic width to be 6.4 and 0 keV, respectively. The result is that the spectral slope is rather flat. Thus, we can conclude that 1E 1740.7—2942 has been in the hard state of the galactic black hole spectrum.

Since galactic black hole candidates often have a soft component with a temperature of less than 1.0 keV (e.g., Tanaka & Lewin 1995; van Paradijs 1998), we examined whether the 1E 1740.7—2942 spectrum requires a soft component or not. We tried to fit the data with a power-law model adding a soft black body component and found no significant improvement by this procedure, hence the spectrum requires no soft component. However, it is not clear whether this is real or merely due to large absorption in the low-energy band.

![Galactic Center](image)

**Fig. 5.—Iron line distribution in the Galactic center region near 1E 1740.7—2942 estimated by a spectral analysis in a 4° radius circle of each SIS chip for the data taken in 1993 (see Table 1). The best-fit flux of the neutral iron 6.4 keV line is normalized to the value in a 2° radius region with an assumption of the uniform distribution of diffuse 6.4 keV line in the circle. These are given in the circles on the figure in units of $10^{-5}$ photons cm$^{-2}$ s$^{-1}$ (2° radius circle).**
The Galactic diffuse emission includes strong iron K-shell lines from neutral (at 6.4 keV) and highly ionized iron lines (at 6.7 and 6.97 keV) (Koyama et al. 1996; Maeda 1998). Since the K-shell line of a neutral iron (6.4 keV) plays a key role for the nature of 1E 1740.7–2942, we estimated the fluctuation of the diffuse K-shell lines (the 6.4 keV lines) in the source extraction region, using the SIS data. We made spectra from a circular region with a radius of 4' near the center of each SIS chip in the mapping observations of the Galactic center region. We then fitted each spectrum in the 4.5–10 keV band with a continuum plus three Gaussian lines fixing the center energies to be 6.4, 6.7, and 6.97 keV. The intensity ratio of the 6.7–6.97 keV lines was kept to be constant from place to place, because Maeda (1998) and Koyama et al. (1996) found no significant variation of the flux ratio. Figure 5 shows the 6.4 keV line fluxes along positions, where the flux is converted to the value in a 2' radius, the same radius of the source region. From Figure 5, we can safely conclude that the uncertainty of the iron line flux in 1E 1740.7–2942 due to the background fluctuation is less than 0.6 × 10^{-5} photons s^{-1} cm^{-2} (2' circle). This value is, at most, 15% of that from 1E 1740.7–2942 and hence can be ignored in the following discussion.

4. DISCUSSION

4.1. Absorption and Iron Abundance

The ASCA results of 1E 1740.7–2942 have been already reported by Churazov et al. (1996) and Sheth et al. (1996). Although they used essentially the same data sets, their results are not fully consistent with each other. The major difference is found in the N_H values.

With a single power-law fitting and absorption gas of solar abundance, Churazov et al. (1996) gave N_H to be 1.7 × 10^{23} H cm^{-2} of the ASCA spectrum in the range of the 4–10 keV band but found 1 × 10^{23} H cm^{-2} when the full energy range of 0.4–10 keV was used. Sheth et al. (1996) estimated N_H to be 0.8 × 10^{23} H cm^{-2} by the same model fitting but in the 0.5–12 keV range. We found that the apparent inconsistency can be solved if iron is overabundant relative to the other elements. In fact, we have shown that the spectra of 1E 1740.7–2942 are well presented with a single power model absorbed by the gas column of 1 × 10^{23} H cm^{-2}, in which iron abundance is 2 solar.

Murakami et al. (1998) analyzed the reflected X-ray by the giant molecular cloud Sgr B2, which is located in nearly the same (angular) distance but in the opposite direction from the Galactic center, and found that iron is overabundant relative to the other elements. On the other hand, Sellgren, Carr, & Balachandran (1997) and Ramirez et al. (1998), with the infrared observations of the atmosphere on the giant stars near the Galactic center, estimated that the iron abundance relative to hydrogen is consistent with the solar value. Thus, further deep observations of K-edge absorption features of X-ray sources near the Galactic center are required.

Sakano et al. (1999) analyzed many X-ray sources located near the Galactic center region and found that the N_H values can be well described by a simple function of the galactic latitude (Fig. 2 of Sakano et al. 1999). From their results, we estimate that the interstellar absorption to the 1E 1740.7–2942 direction is (1–2) × 10^{23} H cm^{-2}, in agreement with the best-fit N_H of the 1E 1740.7–2942 spectrum. No change of N_H during the ASCA long-term observations implies that the absorption region should have a size larger than a few light-years, excluding a possibility of an accretion disk or stellar corona. Thus, 1E 1740.7–2942 is very likely to be located near the Galactic center.

The radio observations of the large molecular cloud toward 1E 1740.7–2942, on the other hand, gave the total hydrogen column density to be N_H ~ 6 × 10^{23} H cm^{-2} (Bally & Leventhal 1991; Vilhu et al. 1996). One may argue, however, that the conversion factor from the CO line intensity to the hydrogen column density may have a large uncertainty. Oka et al. (1998), for example, pointed out that the usual conversion factor is not appropriate for the clouds in the Galactic center region and that the mass derived in the ordinary manner should be reduced by several factors. Taking this possible uncertainty into account, we still suspect that the molecular cloud is located behind 1E 1740.7–2942.

4.2. The 6.4 keV Iron Line

We found no significant line emission from a neutral iron (6.4 keV line). The upper limits of the equivalent width are estimated to be a few tens of electron volts, depending on the observation period and detector. The most stringent limit is found to be 15 eV in the combined (GIS and SIS) analysis of AO-2. These results of small equivalent width further confirm the result by Churazov et al. (1996) with larger data sets.

The equivalent width less than 15 eV implies that the mean iron column density around 1E 1740.7–2942 is less than N_{Fe} < 5 × 10^{17} Fe cm^{-2} (Inoue 1985; Awaki 1991). This value is smaller than 1/10 of the total column density estimated from the 7.1 keV edge depth. Hence, 1E 1740.7–2942 cannot be in a local dense cloud as suggested by Bally & Leventhal (1991) and Mirabel et al. (1991).

Bally & Leventhal (1991) estimated the required local density of the interstellar matter around 1E 1740.7–2942 for the observed luminosity of 1E 1740.7–2942 when it is powered directly by the interstellar matter in the case of Bondi-Hoyle accretion (Bondi & Hoyle 1944). The calculated luminosity is

\[ L = 2.3 \times 10^{36} \eta \left( \frac{M}{M_{\odot}} \right)^2 \left( \frac{v}{10 \text{ km s}^{-1}} \right)^{-3} \times \left( \frac{n_H}{10^4 \text{ cm}^{-3}} \right) \left( \frac{\text{ergs s}^{-1}}{10^6} \right), \]

where \( \eta \) is the fraction of the released energy with emission from the rest mass energy, \( M \) is the mass of the central compact object, \( v \) is the relative velocity of the compact object against the cloud, and \( n_H \) is the hydrogen density of the cloud. The highest luminosity of 1E 1740.7–2942 in the ASCA observations is estimated to be \( 3 \times 10^{36} \text{ ergs s}^{-1} \), from the X-ray flux of \( 2 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1} \) in the 2–10 keV band and the source distance of 8.5 kpc. Since the spectrum is extracted within a 2' radius (5 pc radius), the observed upper limit of the iron equivalent width is converted to the local density of

\[ n_H = 7 \times 10^2 (Z_{Fe})^{-1} (\text{H cm}^{-3}), \]

where \( Z_{Fe} \) is iron abundance relative to solar.

Then, assuming \( \eta = 0.1 \), we can set possible ranges of \( M \) and \( v \) for the Bondi-Hoyle accretion scenario as is given in Figure 6 with solid lines, while the dashed line shows the most probable case of \( Z_{Fe} = 2 \) in equation (2). Thus, we find...
that the velocity of 1E 1740.7−2942 must be less than 10 km s\(^{-1}\) even in the case of the large mass of 20 \(M_\odot\) under the Bondi-Hoyle accretion scenario.

The velocity of black holes would be larger than that of normal stars because of additional kick velocity by supernova explosions. Since no data of the velocity dispersion of black holes are found, the best alternative way to estimate the velocity of 1E 1740.7−2942 is to use the velocity dispersion of neutron stars, which are also produced by supernova explosions. Thus, we refer to the velocity dispersion of the radio pulsars (neutron stars) (Lorimer, Bailes, & Harrison 1997; Hansen & Phinney 1997) and find that the velocity of 1E 1740.7−2942 would be larger than 10 km s\(^{-1}\) with more than 99% probability. We therefore conclude that the Bondi-Hoyle scenario that 1E 1740.7−2942 is powered directly from a molecular cloud is unlikely.

4.3. Long-Term Variability

Pavlinsky et al. (1994) reported the long-term variability of 1E 1740.7−2942 measured with ART-P on board Granat. According to their results, 1E 1740.7−2942 was usually in a medium or high state since 1990 with occasional exceptions of low state. Since the spectral shape during the ASCA observations showed no significant change except for the variability of the total flux, we safely assume that the spectra in the Granat observations have the same photon index (\(\Gamma \sim 1.2\)) as those of the ASCA spectra. Then we found that the ASCA fluxes of \((1−2) \times 10^{-10}\) ergs cm\(^{-2}\) s\(^{-1}\) in the 2−10 keV band correspond to \((2.5−5) \times 10^{-10}\) ergs cm\(^{-2}\) s\(^{-1}\) in the 8−20 keV band, the middle- to high-state fluxes of Granat. The ASCA flux is also in agreement with the BATSE light curve for the same period (Zhang et al. 1997). The similarity between the ASCA and BATSE light curves is another indication of the spectral invariance over a larger energy range.

5. SUMMARY

Using all the ASCA data of 1E 1740.7−2942 available at the time of this writing, we conclude as follows:

1. We found that 1E 1740.7−2942 was in the middle to high flux state, showing long-term variation of a factor of 2 in a span of 3.5 yr, while the photon index and column density have been nearly constant.

2. The wide-band spectrum in the 1−10 keV band is well fitted with an absorbed power law, where the iron abundance is twice the others in units of solar value. The power-law slope is particularly flat with \(\Gamma = 0.9−1.3\), which implies that 1E 1740.7−2942 was in the hard state. The large hydrogen column density of \(N_H \sim 1 \times 10^{23}\) cm\(^{-2}\) supports the location of 1E 1740.7−2942 being near the Galactic center.

3. From the iron-edge structure we estimated the iron column density to be \(N_{Fe} \sim 1 \times 10^{19}\) Fe cm\(^{-2}\).

4. The iron equivalent width is very small, with an upper limit of 15 eV. This indicates that the iron column near around 1E 1740.7−2942 is less than \(N_{Fe} < 5 \times 10^{17}\) Fe cm\(^{-2}\).

5. Our results favor the geometry that 1E 1740.7−2942 is not in the radio molecular cloud. The cloud would be, by chance, in the line of sight to, or possibly behind, 1E 1740.7−2942. This indicates that the X-ray emission does not originate by direct accretion from the molecular cloud. 1E 1740.7−2942 is probably a normal black hole binary.

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