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Position and Variability of 2A 1704+241

W. A. MORGAN, JR.
Department of Physics and Astronomy, Dickinson College, P.O. Box 1773, Carlisle, PA 17013; morgan@dickinson.edu
AND
M. R. GARCIA
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; mgarcia@head-cfa.harvard.edu
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ABSTRACT. We present results of analyses of observations of the X-ray source 2A 1704+241 with the *ROSAT* Position Sensitive Proportional Counter (PSPC) and the High Resolution Imager (HRI). The source 2A 1704+241 was first associated with the M giant star HD 154791 based on observations with the *HEAO 1* scanning modulation collimator and the *Einstein* IPC and analysis of a spectrum of HD 154791 obtained with the *International Ultraviolet Explorer*. This identification was unusual because there are few bright X-ray binaries associated with an M giant star. We observed 2A 1704+241 with the PSPC and the HRI in order to determine more accurately the position of the X-ray source and in order to study the previously seen 900 s variability in the *Einstein* data. Based on the previous identification and determination of the position of MS 1703.7+2417, an active galactic nucleus in the field, and the position of three previously unreported X-ray sources that we have associated with stars in the USNO-A2.0 catalog, we have greatly reduced the X-ray positional error of 2A 1704+241. HD 154791 remains the prime candidate as the optical counterpart of the X-ray source. While the 50% modulation in the X-ray flux seen by the *Einstein* IPC is apparent in the *ROSAT* data, it appears to be at a slightly different frequency.

1. INTRODUCTION

The X-ray source 2A 1704+241 was first detected by the *Ariel* observatory (Cooke et al. 1978) and was associated with the $V = 7.3$ M giant star HD 154791 (Garcia et al. 1983) based on a positional coincidence of *Einstein* IPC and *HEAO* A-3 X-ray positions and ultraviolet observations of HD 154791 with the *International Ultraviolet Explorer* (*IUE*).

This identification of an X-ray binary with an M giant star was unusual. There are only a few other bright X-ray binaries with M giant secondaries, e.g., a few symbiotic stars (Kenyon 1986) and GX 1+4. At the distance of HD 154791, the X-ray luminosity of 2A 1704+241 is $L_X = 1.6 \times 10^{33}$ ergs s^{-1} (Garcia et al. 1983), which is well within the very wide range of luminosities seen in symbiotic stars (T Coma Berenices has $L_X = 4.2 \times 10^{30}$ ergs s^{-1} [Kenyon 1986], and AG Draconis has $L_X = 9.5 \times 10^{36}$ ergs s^{-1} [Greiner et al. 1997]). The X-ray luminosity of GX 1+4 is 10^{37} ergs s^{-1} (Chakrabarty & Roche 1997).

The *Einstein* IPC had a relatively low spatial resolution of 1′.5 (Pye et al. 1981), while the *ROSAT* Position Sensitive Proportional Counter (PSPC) had a spatial resolution of 30″ (Bocchino, Maggio, & Sciortino 1994). The *IUE* had a spectrograph slot of size 10″ × 20″ (Newmark et al. 1992). In order to test more accurately the spatial coincidence of HD 154791 and 2A 1704+241, we carried out *ROSAT* High Resolution Imager (HRI) observations of the field.

Another unusual characteristic of 2A 1704+241 is its strong X-ray variability: the IPC observations revealed a 50% variability of the source on a scale of about 900 s. In addition, Gaudenzi & Polcaro (1999) noted that the optical and X-ray spectra of HD 154791 show significant variability on approximately yearlong timescales. Garcia et al. (1983) determined that any changes in the radial velocity imparted by any companion to HD 154791 were no more than 3 km s^{-1}. To explain the observed variations in the optical and X-ray spectra, Gaudenzi & Polcaro (1999) proposed a model of a neutron star in a wide orbit about HD 154791 and accreting from the stellar wind from the M giant. Given that M giant winds are often inhomogeneous, the variations in accretion rate caused when the neutron star traverses these regions could produce the observed variations in the optical and X-ray spectra.

2. OBSERVATIONS

We obtained from NASA's High Energy Astrophysics Science Archive Research Center both the *Einstein* IPC and *ROSAT* PSPC data sets. The dates of the observations were as follows: IPC: 1980 March 7 and September 26; PSPC: 1992 March 22–24; HRI: 1997 September 8–22. The total PSPC and HRI exposure times were 7689 and 10,620 s, respectively. The exposures were often interrupted by Earth block and/or radiation zone passage, so the longest contiguous observations were

TABLE 1
PSPC SOURCE POSITIONS

Source	R.A. (J2000.0)	Decl. (J2000.0)	Error (2 σ) (arcsec)	Signal-to-Noise Ratio	Candidates
1	17 06 25.6	23 50 01.8	17.0	3.8	…
2	17 07 17.2	23 52 12.3	13.5	3.5	…
3	17 07 31.0	23 53 25.4	13.5	3.2	…
4	17 06 34.8	23 58 17.4	1.1	59.7	Star, HD 154791
5	17 06 51.8	24 04 13.7	7.7	4.7	Star, USNO-A2.0 1125-08012053
6	17 05 19.6	24 04 15.6	14.0	4.9	HRI 3
7	17 06 15.1	24 05 41.7	10.7	4.1	Star, USNO-A2.0 1125-08005309
8	17 06 22.3	24 06 34.6	13.9	4.4	Star, USNO-A2.0 1125-08006697
9	17 07 09.1	24 08 30.1	14.6	3.3	…
10	17 05 48.5	24 13 04.2	5.7	9.3	AGN, MS 1703.7+2417

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

~1000 s; there were four such PSPC observations and eight such HRI observations.

3. DATA ANALYSIS

Except where noted, all data were analyzed using the Image Reduction Analysis Facility's Post-Reduction Off-line Software (IRAF/PROS).

3.1. Position

Our first goal was to determine the best position of 2A 1704+241 by registering X-ray positions of PSPC and HRI objects with their optical counterparts. We ran the IRAF/PROS LDETECT task on the HRI field with the parameters of a 24″ cell size and a broad energy band. On the PSPC field, we ran LDETECT with the parameters of a 60″ cell size and broad energy band.

Ten sources with signal-to-noise ratio greater than 3 were found in the PSPC field; they are listed in Table 1 along with their possible counterparts. The 2 σ errors on the position are also listed. For reference, the position of HD 154791 in the *Hipparcos* catalog is (J2000.0) R.A. = $17^h06^m34^s.52$, decl. = $+23°58'18''.6$ (Perryman et al. 1997).

PSPC source 10 is positionally coincident with a galaxy first detected by *Einstein* (Stocke et al. 1991) and listed in the *Einstein* Extended Medium-Sensitivity Survey. It has a redshift of 0.113.

PSPC source 5 is positionally coincident with USNO-A2.0 1125-08012053 ($B = 19.5$, $R = 18.9$), while PSPC sources 7 and 8 are positionally coincident with USNO-A2.0 1125-08005309 ($B = 19.0$, $R = 18.4$) and USNO-A2.0 1125-08006697 ($B = 19.0$, $R = 16.4$), respectively. This latter source may be a dMe star, based on color ($B-R = 3.6$, which is comparable with other dMe stars; Bopp & Espenak 1977).

The six sources with signal-to-noise ratio greater than 3 that were found in the HRI field are listed in Table 2 along with possible counterparts.

In order to register the PSPC images to the USNO coordinate frame, we performed a weighted least-squares fit to the positions of PSPC sources 5, 7, 8, and 10. The fit indicated an offset between optical and X-ray positions of the four PSPC sources of $-0^s.2$ of time in right ascension and $-0''.09$ in declination. The position of 2A 1704+241 determined from the registered PSPC image is (J2000.0) R.A. = $17^h06^m34^s.6$, decl. = $+23°58'17''.3$ with a 2 σ error radius of $4''.2$, where this error includes both the registration error and the error in the X-ray position. The PSPC position is $1''.7$ from the *Hipparcos* position of HD 154791.

Because the active galactic nucleus (AGN) is the only source

TABLE 2
HRI SOURCE POSITIONS

Source	R.A. (J2000.0)	Decl. (J2000.0)	Error (2 σ) (arcsec)	Signal-to-Noise Ratio	Candidates
1	17 06 34.4	23 58 29.1	0.5	83.3	Star, HD 154791
2	17 04 58.5	24 00 11.2	10.6	3.1	…
3	17 05 18.4	24 04 12.1	1.6	8.7	PSPC 6
4	17 06 14.9	24 05 52.6	1.3	3.8	…
5	17 05 53.2	24 07 00.0	2.7	3.2	…
6	17 05 47.8	24 13 19.3	1.1	13.2	AGN, MS 1703.7+2417

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

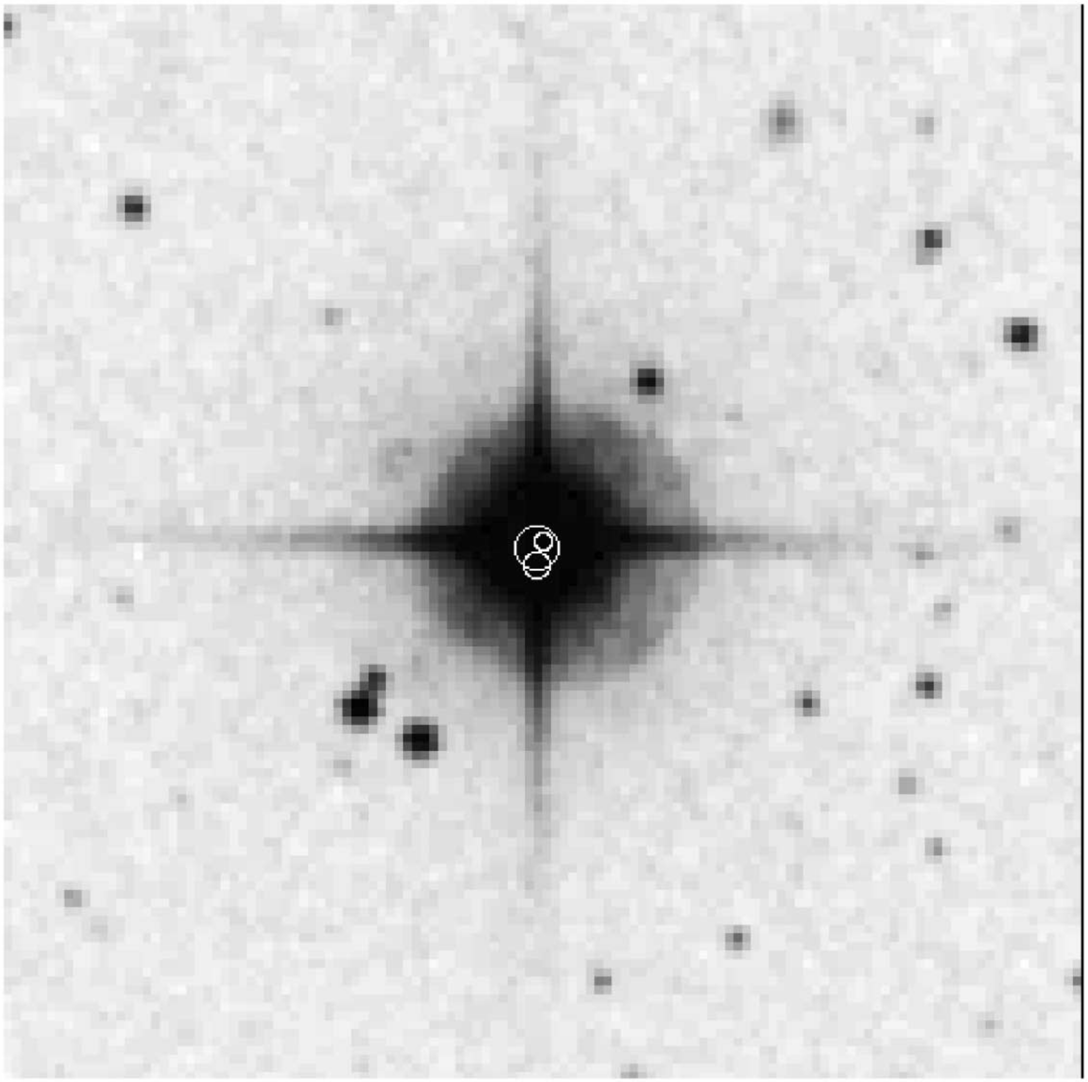


FIG. 1.—HD 154791 and PSPC and HRI X-ray positions, superposed on the Digitized Sky Survey image (red filter). The smallest (northern) circle indicates the *Hipparcos* position of HD 154791 (size of circle only for ease of locating); the small (southern) circle indicates our determined HRI position of 2A 1704+241 (size of circle indicates 2 σ error); the largest circle indicates our determined PSPC position of 2A 1704+241 (size of circle indicates 2 σ error). North is at the top, and east is at the left.

in the HRI image that has an optical identification, we simply registered the HRI image with the USNO coordinate frame by using MS 1703.7+2417. To accurately determine the optical position of the AGN, we calculated a plate solution of the Digital Sky Survey field using 16 USNO-A2.0 stars. The optical position of the AGN of the nucleus was R.A. $= 17^{\rm h}05^{\rm m}48\overset{\rm s}{.}0$, decl. $= +24°13'04\overset{''}{.}3$, with a $0\overset{''}{.}4$ rms error. The HRI position of the AGN required a shift of $+0\overset{\rm s}{.}2$ of time in right ascension and $-14\overset{''}{.}9$ in declination in order to coincide with this. By shifting the HRI position of 2A 1704+241 by the same amounts, we find that the position of 2A 1704+241 is (J2000.0) R.A. $= 17^{\rm h}06^{\rm m}34\overset{\rm s}{.}6$, decl. $= +23°58'14\overset{''}{.}0$ with a 1 σ error radius of $1\overset{''}{.}3$, where this error includes the errors on the HRI positions of both MS 1703.7+2417 and 2A 1704+241 and the optical error on the position of MS 1703.7+2417. The HRI position of 2A 1704+241 differs $1\overset{''}{.}5$ in right ascension and $4\overset{''}{.}6$ in declination from the *Hipparcos* position of HD 154791 (Perryman et al. 1997).

In right ascension, there is a 1.2 σ difference in position; in declination there is a 3.5 σ difference. We investigated three possible causes for the difference in the optical and HRI positions: (1) error in the *Hipparcos* HD 154791 position, (2) proper motion of HD 154791, and (3) correction to the HRI scale factor of $0\overset{''}{.}5$ pixel^{-1}. We quickly discounted the first two possibilities. The *Hipparcos* position errors are 0.7–0.9 mas

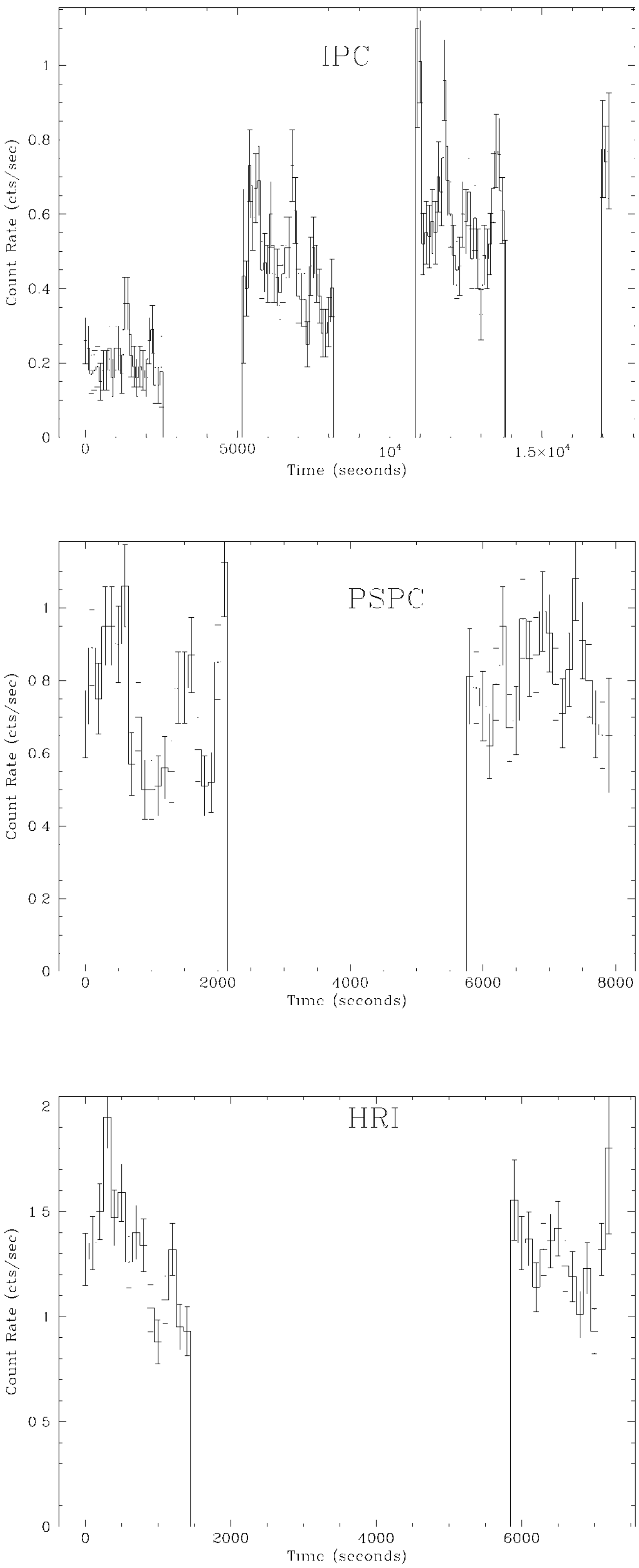


FIG. 2.—IPC, PSPC, and HRI light curves. The light curves include the sections that were analyzed for this work, binned in 100 s increments. The time shown is the duration of the observation; 1 σ error bars are depicted.

for stars brighter than 9 mag, while the proper motion of HD 154791 is less than 8 mas yr^{-1} (Perryman et al. 1997). However, the scale factor of the HRI is 99.72% of what was originally reported (Hasinger et al. 1998). If we take into account this scale factor correction, then the difference between optical and HRI positions for HD 154791 and 2A 1704+241 in right ascension would be 1.″0, a 0.8 σ deviation, and in declination 2.″1, or a 1.6 σ deviation. The total offset is 2.″3.

Figure 1 shows the PSPC and HRI positions of 2A 1704+241 as determined above. The 1.6 σ offset indicates that there is a 10% probability of the identification of HD 154791 as the optical counterpart of 2A 1704+241. There are 105 sources in the 2A catalog (Cooke et al. 1978) and 48,000 stars as bright as or brighter than HD 154791 in the Henry Draper catalog. The random chance of any star as bright or brighter than HD 154791 falling within 2.″3 of any one of the 105 2A sources is 2×10^{-4}. While low, this is not sufficient to totally discount the possibility of a random coincidence. For example, Aql X-1 (Callahan, Filippenko, & Garcia 1999) and GX 17+2 (Deutsch et al. 1999) have shown that random coincidences of X-ray sources with unrelated stars do occur.

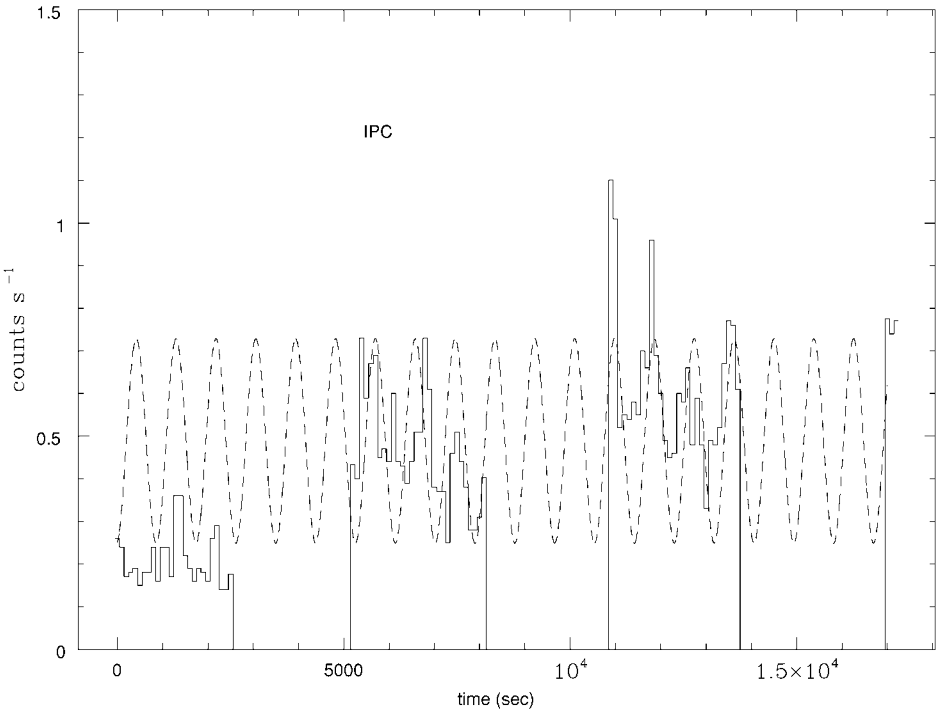
The surface density of stars visible on the Digital Sky Survey image indicates that there is a 5×10^{-3} probability of an interloper brighter than 20th magnitude being within 2.″3 of 2A 1704+241.

The ultraviolet, X-ray, and optical properties of 2A 1704+241 might be fully explained if a cataclysmic variable (CV) were interloping within 2.″3 of 2A 1704+241: such an object would be lost in the glare from HD 154791. This probability can be calculated from the surface density of CVs, but this number is rather uncertain. A lower limit can be taken from the list of known CVs (e.g., Table 9.4 in Warner 1995), which indicates the probability of a CV interloper within 2.″3 of any 2A source is $\sim 2 \times 10^{-6}$. An upper limit might be taken from Shara et al. (1993), who found 13 CV candidates within a 2 deg^2 field, which would indicate the probability of such an interloper to be $\sim 9 \times 10^{-4}$. While these numbers are low, they do not allow us to totally discount the possibility of an interloping CV.

3.2. Variability

During earlier observations with the *Einstein* IPC, and during the observations discussed here, 2A 1704+241 displays ~50% variability on a timescale of ~900 s. This variability is reminiscent of that seen in some magnetic CVs (e.g., Warner 1995, Table 6.7; Mason 1984). For example, 2A 0311−27 shows a quasi-periodic oscillation with low coherence and a ~6 minute period (Patterson, Williams, & Hiltner 1981); and E2003+225 shows apparently even lower coherence oscillations with a period between 4 and 11 minutes (Osborne et al. 1987).

Figure 2 shows the light curves that we analyze for each of the three instruments. These are binned in 100 s intervals and include 1 σ error bars. The 50% variability is clearly seen. For



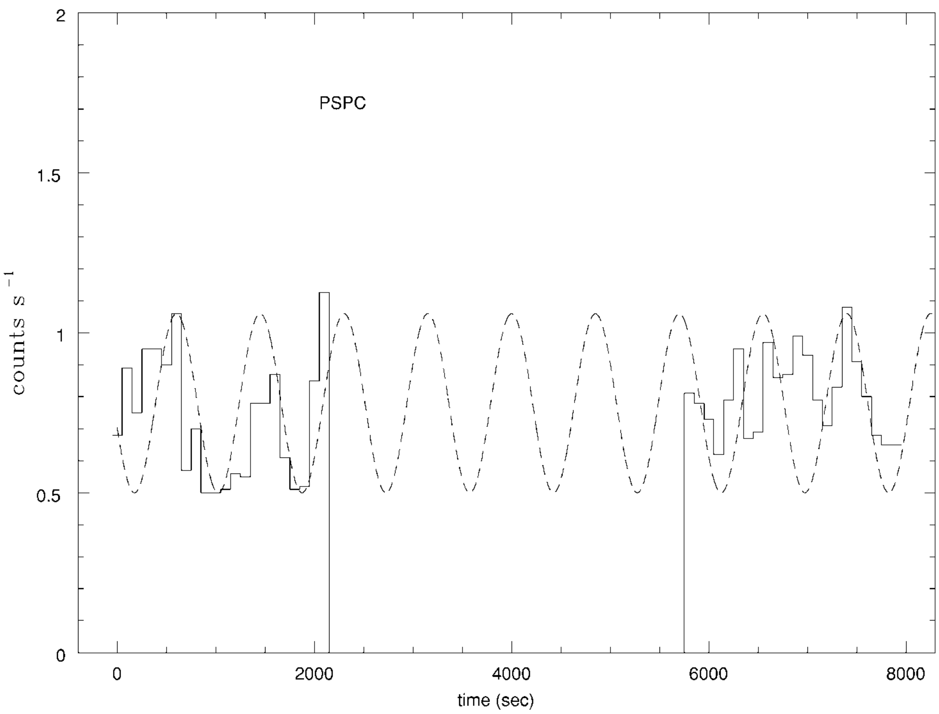


FIG. 3.—IPC and PSPC light curves with sine waves superposed on them to determine Q. The light curves are binned in 100 s increments. The best-fit period for the IPC is 880 s and for the PSPC is 850 s.

example, during the first ∼2000 s interval of PSPC data, there are three clear peaks; during the first ∼1500 s HRI observation, there are two clear peaks.

In order to study the variability, we first barycenter-corrected the data from the *Einstein* IPC, *ROSAT* HRI, and *ROSAT* PSPC. The data were then binned in units of 1 s each, and the power spectra were determined for each of the data sets. We searched for periods between 200 and about 8500 s because we were primarily interested in long-period variability. While the PSPC and HRI power spectra did not show peaks at 900 s, we caution that the length of contiguous data intervals (particularly for the HRI) limits our sensitivity at 900 s. The highest peaks in the PSPC power spectra are at ∼1440 and ∼790 s. This former period is sufficiently close to the length of the contiguous data streams that we do not consider it in what follows.

To further characterize the variability, we attempted to determine the phase coherence of the flux modulation by counting the number of cycles ($=N$) elapsed until the modulation is 180° out of phase. We then define $Q = 2N$.

We estimated Q by matching a sine waves of 700, 710, 720, etc., up to 1000 s periods to the first modulation in the data and then determining a later point at which the sine wave and the light curve first were 180° out of phase. The results that gave the highest Q were for a period of 880 s for the IPC data ($Q > 28$) and 850 s ($Q > 16$) for the PSPC data. The data with these best-fitting sine waves overlaid are shown in Figure 3. We estimate that these periods are accurate to ∼10 s, because sine waves deviating from the best fit by this amount are significantly out of phase by the end of the data segments. It is also clear that the best-fitting periods are significantly different, in that attempting to fit an 880 s period to the PSPC data indicates a $Q < 8$, and an 850 s period applied to the IPC data yields a $Q < 6$. The results from the IPC and PSPC data show that the modulation, while strong and clearly present, may have rather low coherence. This technique proved ineffective for the HRI data due to our inability to determine the modulation phase in the second interval of HRI data.

4. CONCLUSIONS

We have greatly reduced the positional error of 2A 1704+241 to 2″.3 (1 σ), resulting in a 200 times decrease in the size of the error region. While HD 154791 remains a viable candidate, a random coincidence with a field star and/or an interloping CV cannot be totally discounted. The improved position is based on aligning the *ROSAT* HRI and PSPC and *Einstein* IPC X-ray positions of the AGN MS 1703.7+2417 and three other objects with their respective optical positions.

The 50% modulation previously seen in *Einstein* data is still visible in the *ROSAT* PSPC and HRI data, but the period of the modulation appears to be slightly different. The brevity of the individual data sets allows us to set only modest limits to the coherence of the modulation of $Q > 16$ (PSPC data) or $Q > 28$ (IPC data).

The association of HD 154791 with 2A 1704+241 remains unusual in that there are very few bright X-ray sources associated with M giants. These are a rather diverse group of objects, including the X-ray pulsar GX 1+4 and such symbiotic stars as T Coma Berenices and AG Draconis. While the former contains a neutron star accretor, the latter two contain white dwarf or main-sequence accretors. The optical spectra of all three of these objects also display marked differences from a normal M giant, while these differences are much less clear in HD 154791. Indeed, Garcia et al. (1983) remarked that the optical spectrum was entirely normal, but subsequent observations by Bocchino et al. (1994) showed that there are significant abnormalities in the optical spectrum. The binary model as presented by Garcia et al. (1983) and Bocchino et al. (1994) argues against an accreting white dwarf and for an accreting neutron star. The main reason for this is that if the stellar wind is typical of other M giants, only a neutron star has a potential well deep enough to generate the observed X-ray flux while at the same time generating the less than 3 km s^{-1} reflex motion seen in the M giant (Garcia et al. 1983). In conclusion, we note that the improved positional capability of *Chandra* could reduce the X-ray error region by another factor of greater than 10, therefore providing a more stringent test of this unusual association.

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REFERENCES

Bocchino, F., Maggio, A., & Sciortino, S. 1994, ApJ, 437, 209
Bopp, B. W., & Espenak, F. 1977, AJ, 82, 916
Callahan, P. J., Filippenko, A. V., & Garcia, M. R. 1999, IAU Circ. 7086
Chakrabarty, D., & Roche, P. 1997, ApJ, 489, 254
Cooke, B. A., et al. 1978, MNRAS, 182, 489
Deutsch, E. W., et al. 1999, ApJ, 524, 406
Garcia, M., et al. 1983, ApJ, 267, 291
Gaudenzi, S., & Polcaro, V. F. 1999, A&A, 347, 473
Greiner, J., et al. 1997, A&A, 322, 576
Hasinger, G., Burg, R., Giacconi, R., Schmidt, M., Trümper, J., & Zamorani, G. 1998, A&A, 329, 482

Kenyon, S. J. 1986, The Symbiotic Stars (Cambridge: Cambridge Univ. Press)
Mason, K. O. 1984, Space Sci. Rev., 40, 99
Newmark, J. S., et al. 1992, NASA *IUE* Newsl., 47, 1
Osborne, J. P., Beuermann, K., Charles, P., Maraschi, L., Mukai, K., & Treves, A. 1987, ApJ, 315, L123
Patterson, J., Williams, G., & Hiltner, W. A. 1981, ApJ, 245, 618
Perryman, M. A. C., et al. 1997, A&A, 323, L49
Pye, J. P., Pounds, K. A., Rolf, D. P., Seward, F. D., Smith, A., & Willingale, R. 1981, MNRAS, 194, 569
Shara, M., Moffat, A., Potter, M., Bode, M., & Stephenson, F. R. 1993, in Cataclysmic Variables and Related Physics, ed. O. Regev & G. Shaviv (Bristol: IPP), 84
Stocke, J. T., et al. 1991, ApJS, 76, 813
Warner, B. 1995, Cataclysmic Variable Stars (Cambridge: Cambridge Univ. Press)