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IDENTIFICATION OF TWO HARD X-RAY EMITTING Be STARS USING THE *HEAO 1* SCANNING MODULATION COLLIMATOR

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ABSTRACT

Using precise positions from the *HEAO 1* Scanning Modulation Collimator experiment, we identify two hard X-ray sources, 4U 0728−25 = 3A 0726−260 and 4U 2206+54 = 3A 2206+543, with early-type stars. In both cases broad (10 Å FWHM) Hα emission is detected. The *UBV* colors suggest that the optical counterparts are main-sequence B0–B2 stars at 2–6 kpc, implying a mean X-ray luminosity of order 10^{35} ergs cm^{-2} s^{-1} (2–10 keV). The X-ray emission in both cases is highly variable, and we suggest that they belong to the class of X-ray emitting Be stars, containing a neutron star in a widely separated binary system.

Subject headings: stars: Be — X-rays: binaries — X-rays: sources

I. INTRODUCTION

We report the identification of two bright (10^{-10} ergs cm^{-2} s^{-1}, 2–10 keV) X-ray sources with Be star systems. We detect persistent X-ray emission at the level of 10^{34}–10^{35} ergs s^{-1}, with flarelike increases by a factor of 10 over the minimum emission. These two X-ray sources, 0726−260 and 2206+542, were first reported in the fourth and second *Uhuru* catalogs (Forman *et al.* 1978; Giacconi *et al.* 1972), respectively. The X-ray source locations were refined by the *Ariel V* Sky Survey Instrument (SSI) (Villa *et al.* 1976; "3A" low-latitude catalog, Warwick *et al.* 1981), which also measured the X-ray light curves reported here. The identifications are based on precise (few arcmin^2) X-ray locations measured with the Scanning Modulation Collimator (MC) experiment (Gursky *et al.* 1978; Schwartz *et al.* 1978) on the first *High Energy Astronomy Observatory* (*HEAO 1*) mission. In each case only one of the multiple diamond-shaped areas allowed by the MC was within the 3A location, with one or two other diamonds just outside the 3A box. As well as being within the MC and 3A joint location, both candidates are within lines of position which we derive using the NRL Large Area Sky Survey data from *HEAO 1*. Five-color photometry shows that the optical candidates have early B spectral type, and broad Hα emission is seen in spectra of both stars.

The canonical picture of these systems (cf. Rappaport and van den Heuvel 1982) is that of a neutron star in a widely separated, often eccentric orbit, accreting mass from the Be star. Five of the 12 previously known systems are persistent, although variable, X-ray sources of luminosity $10^{33.5}$–$10^{35.5}$ ergs s^{-1}. The mass transfer in these cases may be via a quasi-steady stellar wind (cf. White *et al.* 1982). Seven of those 12 systems are known only as X-ray transients, with peak luminosities between 10^{36} and 8×10^{38} ergs s^{-1}, and in two cases (4U 0115+63 and A0538−66) at least 10^4 times the quiescent luminosity. Such large accretion rates may be associated with episodic mass losses from the Be star (cf. Kriss *et al.* 1983) and/or intermittent Roche-lobe overflow, perhaps from a disk or ring surrounding the B star, due to the eccentricity of the orbit (cf. Maraschi, Treves, and van den Heuvel 1976). The large orbital separations (periods greater than 10 days, when known), implies that the persistent X-ray emission affords a unique opportunity to study the mass loss from the primary and the accretion onto the compact star as independent processes, free from interactions such as Roche lobe overflow or X-ray stimulation of the wind (cf. Avni and Goldman 1981).

II. 4U 0728−25 = 3A 0726−260

Figure 1 shows the optical counterpart. Our astrometry gives the following coordinates (1950): $\alpha = 7^h26^m50^s.0$, $\delta = -26°0'13''.3$, with an rms error of 0''.6. This is the brightest star in either of the two MC diamonds, each of area 1.2 arcmin^2, within or nearest the 3A location (Warwick *et al.* 1981). We have also taken spectra of the three next brightest objects (40'' NNE, 35'' SW, and 55'' S of the counterpart in Fig. 1) and find them to be normal stars. The approximate galactic coordinates are $l = 240°.3$, $b = -4°.1$.

The optical counterpart was observed with the SIT vidicon on the Cassegrain spectrograph of the 4 m telescope at CTIO. The spectrum showed broad (13 Å FWHM) Hα emission, which did not show any structure at the resolution of 5 Å. Hβ was observed in absorption. Interstellar absorption lines were also evident. From the 13% central depth of the 6284 Å feature we can estimate a reddening, $E(B-V)$, of about 0.4, according to the calibration of Bromage and Nandy (1973).

A follow-up spectrum was obtained with the photon counting Reticon on the 1.5 m telescope at the Whipple Observatory (FLWO) (Fig. 2). The increased resolution of 3.5 Å indicates structure within the line, with a full-width at zero intensity of 10 Å. There is no evidence for a P Cyg profile; therefore, the star is not likely to have an optically thick, spherical wind. The emission presumably originates in a disk or shell around either the star or the compact, accreting object.

We measured *UBVRI* magnitudes with the 91 cm telescope

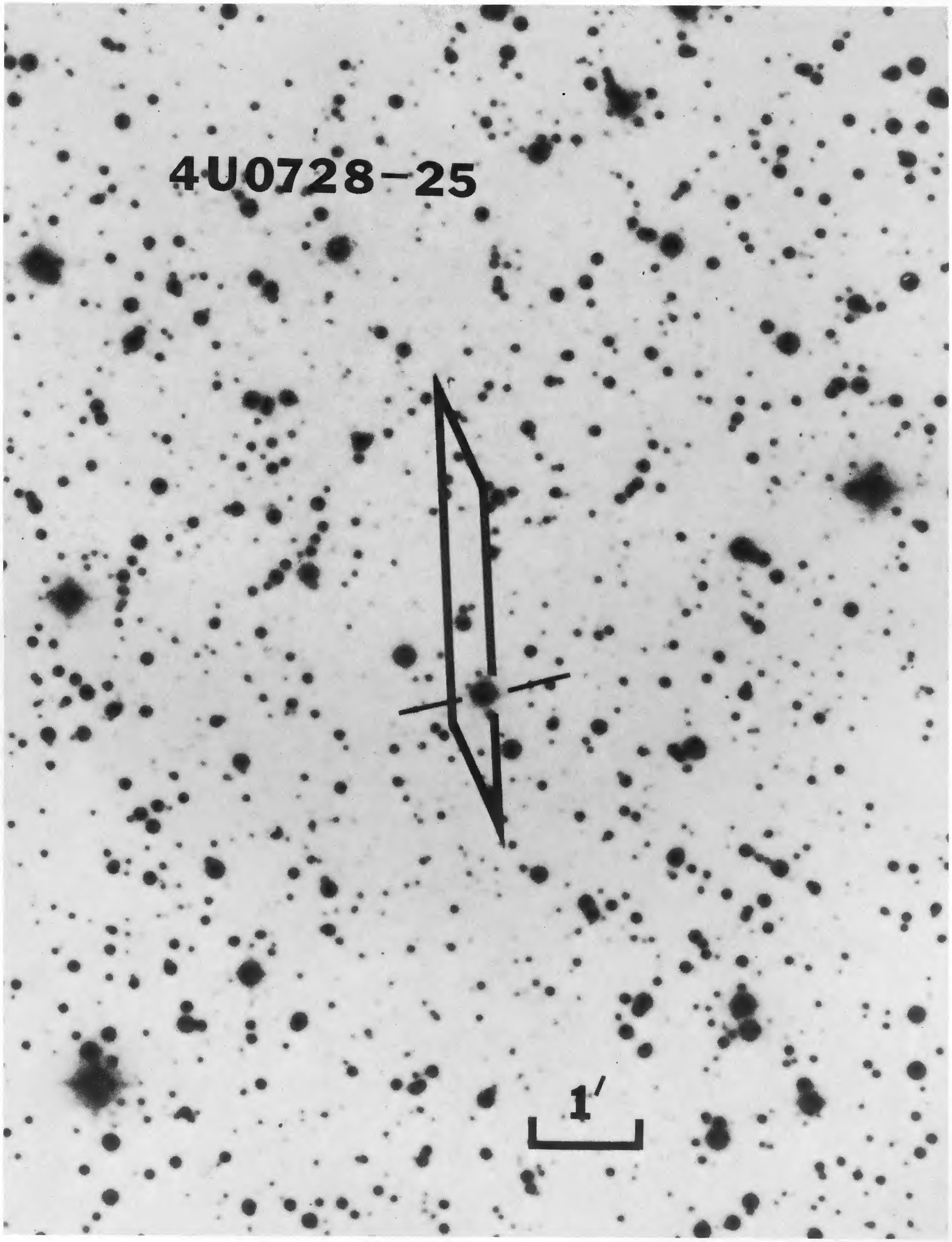

FIG. 1.—An enlargement (20 ×) of the POSS E print showing the optical counterpart of 0726 − 260, the brightest star in the MC location diamond

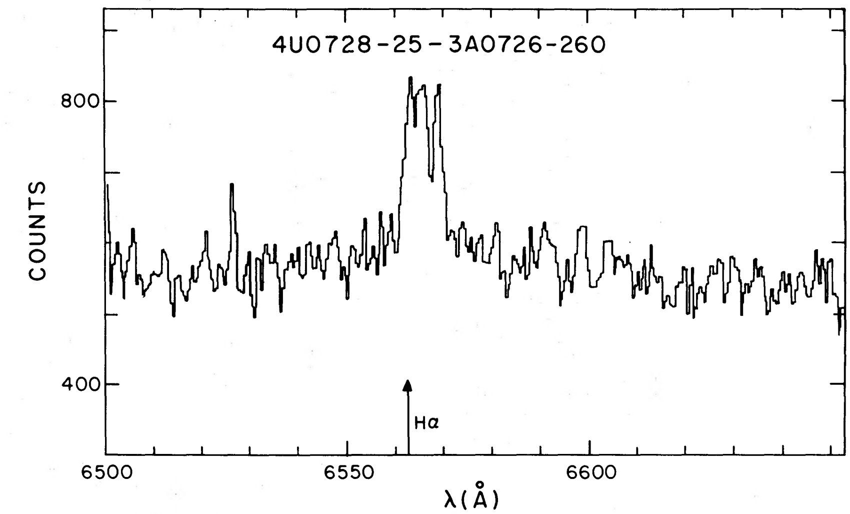

FIG. 2.—A portion of the optical spectrum taken at 3.5 Å resolution with the photon counting Reticon at the FLWO. (The relative detector response has been removed, but the observations are not photometric.)

TABLE 1
PHOTOMETRY

Color	0726−260	2206+542
V	11.56	9.85
$U-B$	−0.60	−0.60
$B-V$............	0.31	0.20
$V-R$	0.42	0.24
$R-I$	0.41	0.20

at Kitt Peak National Observatory (Table 1) on 1981 October 4. The colors in Table 1 are accurate to ± 0.04 mag and correct the preliminary values quoted in Schwartz *et al.* (1981). From the $U-B$ versus $B-V$ diagram (cf. Deutschman, Davis, and Schild 1976) we can infer a spectral type B0–B1 with a reddening $E(B-V)$ of 0.6. Using $A_v = 3.1E(B-V)$ and an absolute magnitude for a giant to dwarf in the range $M_v = -5.0$ to -3.6 (Deutschman, Davis, and Schild 1976) we derive the distance range 6.0–4.6 kpc, assuming luminosity class V. We favor a smaller distance in view of the concentration of Be stars to the galactic plane (cf. Egret 1982) and will adopt 5.0 kpc for numerical estimates of the X-ray luminosity.

The X-ray light curve derived from the *Ariel V* SSI is shown in Figure 3. The observations were obtained between 1974 November and 1977 April and are averaged over 1–2 day intervals. The weighted mean flux, excluding the flare on MJD 42661 (1975 September 6), is 7.6×10^{-11} ergs cm^{-2} s^{-1}, 2–10 keV. This corresponds to a mean X-ray luminosity of 2.2×10^{35} ergs s^{-1}, within a factor of 2 uncertainty depending on the distance. The probability is only 4% that the source was constant, exclusive of the flare.

The insert in Figure 3 shows the flare observation resolved into individual satellite orbits, about 1.6 hours. The rise time of the flare is clearly resolved and is 1 day. Unfortunately *Ariel V* did not scan this region again for 123 days, so we have no information on the duration of the event.

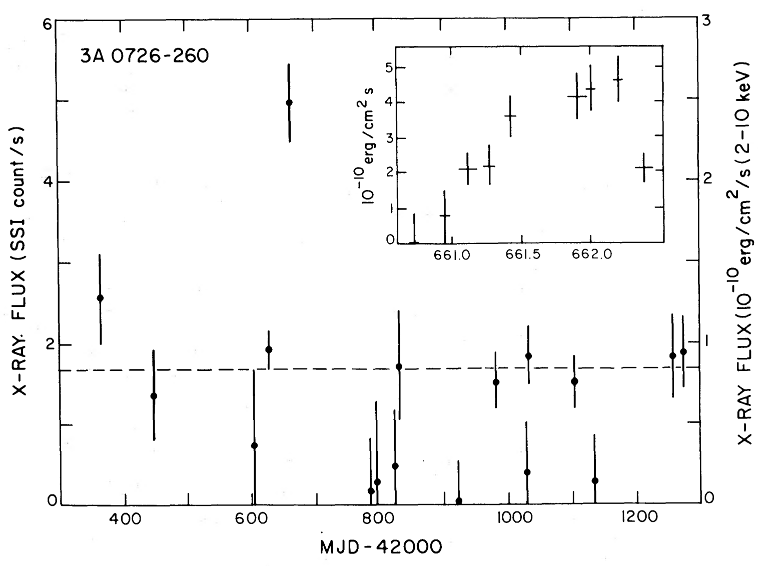

FIG. 3.—X-ray light curve of 0726−260, obtained by the SSI on *Ariel V*. Each data point is the average over 1 or 2 days during which the satellite spin axis was fixed. The insert shows the flare on MJD 42661 (1975 September 6) resolved into individual satellite orbits of about 1.5 hr duration.

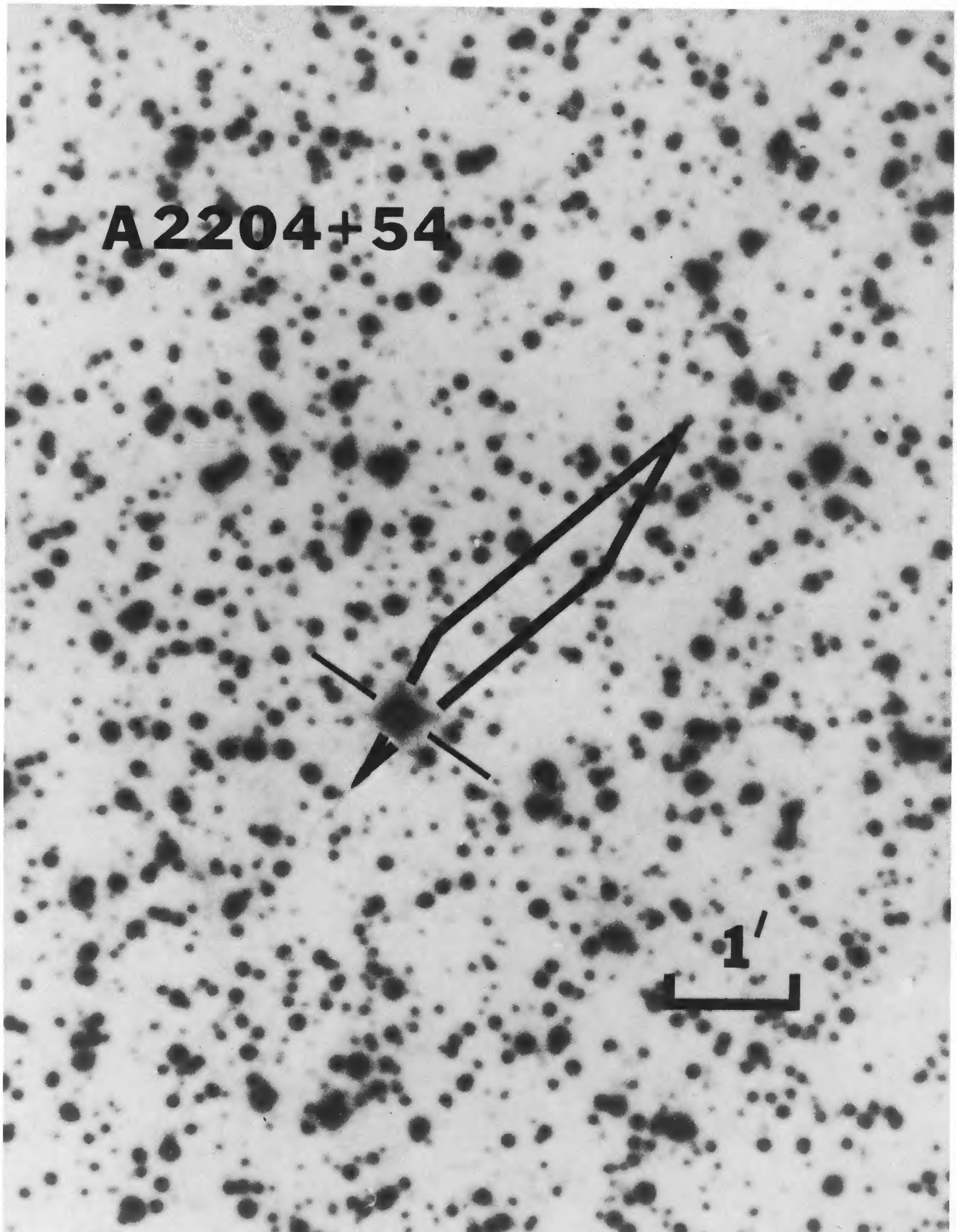

FIG. 4.—An enlargement (20 ×) of the POSS E print showing the optical counterpart of 2206 + 542 as the brightest star in the MC location diamond

The mean flux observed in Figure 3 is about twice that cataloged by *Uhuru* (Forman *et al.* 1978) using the "point summation technique" but agrees very closely with the flux 3.7 *Uhuru* counts $s^{-1} = 8.8 \pm 0.5 \times 10^{-11}$ ergs cm^{-2} s^{-1} (2–10 keV) which is obtained by averaging only the positive detections by *Uhuru*. The flux measured by the *HEAO 1* MC experiment corresponds to $9 \pm 1.5 \times 10^{-11}$ ergs cm^{-2} s^{-1}, averaged over 1977 October 19–23. From the independent MC detections at 5.8 σ in the 1.2–2.5 keV channel and 2.4 σ in the 5.5–13.5 keV channel of the 30″ FWHM collimator, we can derive very crude spectral constraints following the method described by Bradt *et al.* (1979). For an assumed power-law shape, the energy spectral index must be flatter than 1.5, and the absorption N_H less than 2×10^{22} H atoms cm^{-2}. A thermal spectrum must have $kT > 3$ keV and $N_H < 10^{22}$ H atoms cm^{-2}.

The *Einstein X-Ray Observatory* pointed the High Resolution Imager (HRI) (Giacconi *et al.* 1979) at a portion of the 3A location error box on 1980 April 27. An extremely weak source, 0.006 ± 0.0024 counts s^{-1}, was found 1″.5 E and 2″.5 S of the optical counterpart; i.e., well within the 5″ uncertainty in HRI location. The simultaneous monitor proportional counter (MPC) data indicate a net rate 0.18 ± 0.05 counts s^{-1}, 2–6 keV. We will treat this as an upper limit equivalent to 0.3 *Uhuru* counts s^{-1}. A source of this 2–6 keV flux with a power-law spectrum of energy index 1.5 and low-energy absorption $E_a = 2$ keV ($N_H \sim 3 \times 10^{22}$ cm^{-2}) would give the HRI counting rate, which basically samples the 0.25–1 keV range. Therefore either a steeper spectral index or less low-energy absorption would reconcile HRI and MPC count rates, with the latter option being consistent with the crude *HEAO 1* spectral inference.

Another *Einstein* HRI observation which pointed at a portion of the *Uhuru* location 22′ away from the optical counterpart gave no detectable signal in either the HRI or MPC.

III. 4U 2206+54 = 3A 2206+543

Figure 4 shows the optical counterpart. Our astrometry gives the coordinates (1950): $\alpha = 22^h6^m7^s.4$, $\delta = 54°16'23''.2$, with an rms error of 1″.6. The diamond-shaped MC location has 1.5 $arcmin^2$ area. Spectra of the nine next brightest stars, in this and the MC location diamond north of the *Ariel V* position, show normal stellar features. The approximate galactic coordinates are $l = 100°.6$, $b = -1°.08$.

The brightest star in the MC diamond is about 9.8 mag. A spectrum obtained with the photon counting Reticon on the 1.5 m telescope at the Whipple Observatory showed Hα in emission. Figure 5 shows the spectrum obtained with 3.5 Å resolution. Two components of Hα are clearly separated, with a velocity difference corresponding to about 460 km s^{-1}. Such profiles are commonly seen in Be stars and are thought to originate in a disk or shell seen edge-on ($i \gtrsim 45°$) around a rapidly rotating star. A spectrum obtained with 15 Å resolution at the McGraw-Hill Observatory on 1981 September 9 does not resolve the components but confirms the Hα emission feature.

Table 1 gives *UBVRI* magnitudes measured with the 91 cm telescope at KPNO on 1981 October 5. From the *UBV* colors we estimate a spectral type of B1 ± 1 with a reddening $E(B-V)$ of 0.48. For a dwarf, the expected absolute magnitude $M_v = -4.2$ to -2.5 (Deutschman, Davis, and Schild 1976) gives a distance estimate of 3.3 to 1.5 kpc. We will adopt 2.5 kpc for numerical estimate of the X-ray luminosity.

Figure 6 shows the SSI X-ray observations between 1974 November and 1977 March, plus a final data point in 1978 June. The mean 2–10 keV flux is 1.0×10^{-10} ergs cm^{-2} s^{-1}, corresponding to a mean luminosity 7.0×10^{34} ergs s^{-1} at the adopted distance. Overall variability by a factor of 10 appears to be present. The relatively large statistical errors on the 1 day averages, and the sparse and irregular data coverage prohibit identification of individual "events." The χ^2 value for these 28 data points is 213 for 27 degrees of freedom, so the probability is negligible that all the data are consistent with the mean value.

The MC flux measurements (2–10 keV) are $(4.0 \pm 1.5) \times 10^{-11}$ ergs cm^{-2} s^{-1} averaged over 1977 December 27–31, and $(7.5 \pm 1.7) \times 10^{-11}$ ergs cm^{-2} s^{-1} averaged over 1978 June 23–27. We detect the source just at 3 σ in each energy channel and can only estimate that a power law energy index would be flatter than 2.5, or $kT > 2$ keV, and that $N_H < 10^{23}$ H atoms cm^{-2}.

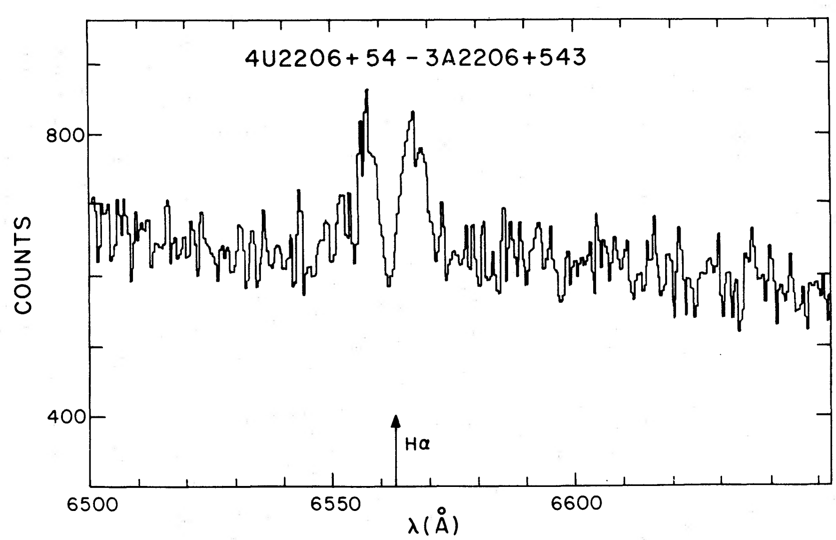

FIG. 5.—A portion of the optical spectrum of 2206+542, corrected for the relative detector response, taken with the 1.5 m telescope at the FLWO. Two components of Hα are resolved.

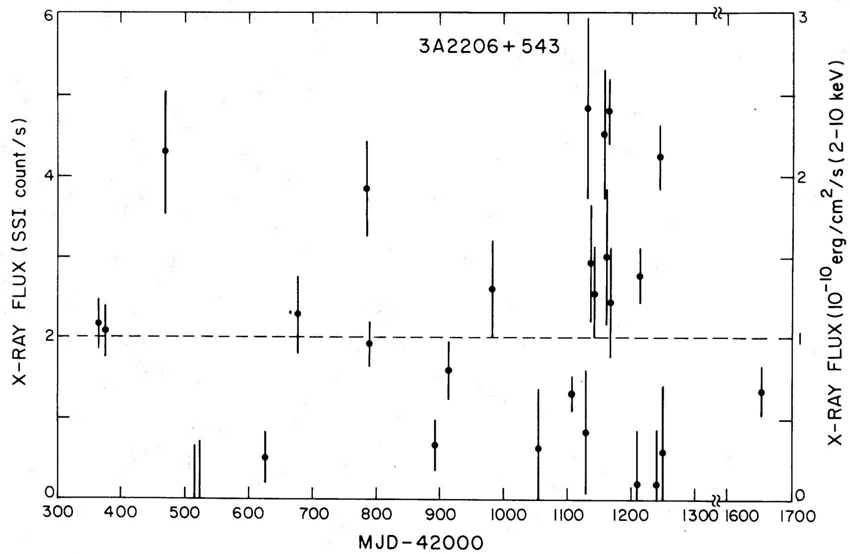

FIG. 6.—X-ray light curve of 2206+542, obtained by the SSI. The statistics do not allow identification of any individual events; however, the source is clearly variable by a factor of 5 to 10.

IV. DISCUSSION

We interpret the quasi-steady X-ray emission as accretion from a stellar wind onto a neutron star. Following White *et al.* (1982) we can estimate a mass loss rate from the Be star of $\dot{M} = 6 \times 10^{-9} L_{35} V_3{}^4 P^{4/3}\ M_\odot\ \mathrm{yr}^{-1}$ for a neutron star of 1.4 $M_\odot$ and 10 km radius with orbital period P days about a 5 $M_\odot$ primary. If the wind velocity $V_3 = (v/10^3)$ km s^{-1} is less than 1, then for periods of order 100 days reasonable mass loss rates $\lesssim 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$ are required. However, because of our ignorance of the period and of the primary mass, a rate as high as the $10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ inferred by White *et al.* (1982) for γ Cas, is also possible. With the sensitive dependence of X-ray luminosity on the relative velocity of the stellar wind, it is perhaps surprising (cf. Avni and Goldman 1981) that stronger X-ray variability has not yet been observed in these two cases if they are in elliptical orbits, and especially if the binary orbit is inclined to the equatorial plane of the Be star.

Further X-ray monitoring is clearly necessary, especially to detect the expected transient episodes. Optical monitoring may be able to predict such an occurrence (cf. Kriss *et al.* 1982). A search should also be made for X-ray pulsations and orbital modulations, although we do not expect eclipses to be found because of the wide separation expected for the orbit.

If 10^{34} ergs s^{-1} is a typical value for the quasi-steady minimum luminosity of these systems, then we expect many more will be discovered among the unidentified *Uhuru* and *Ariel V* galactic plane sources. In particular, the SSI low galactic latitude catalog (Warwick *et al.* 1981) lists 12 unidentified sources at $|b| < 4°$ which are variable by a factor greater than 5. This may be consistent with rough estimates of 50–100 by Rappaport and van den Heuvel (1982) for the numbers of systems within 2.5 kpc emitting more than 10^{33} ergs s^{-1}. Finally, if the mean luminosity, of order 10^{35} ergs s^{-1}, of these two systems is not extremely unusual, then Be/neutron star systems must contribute to the unidentified X-ray sources found by Long, Helfand, and Grabelsky (1981) in the Large Magellanic Cloud, and therefore such sources are *not* a previously unrecognized population.

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