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OPTICAL IDENTIFICATION OF 2S 1417–62

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ABSTRACT

The 17 s X-ray pulsar 2S 1417–62 has been identified with a $V \sim 16.9$ mag OB star on the basis of an X-ray position obtained with the *Einstein X-Ray Observatory* and spectrophotometry with the 4 m telescope at Cerro Tololo Inter-American Observatory. Strong Hα emission is observed as well as significant changes in X-ray luminosity. The optical counterpart may be either a Be or a B I star, but the Hα emission strength and galactic position suggest that a Be star is more likely. A Be star identification also further supports the $\gtrsim 15$ day limit on the system binary period obtained by Kelley *et al.* from pulse timing studies.

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

I. INTRODUCTION

The 17 s X-ray pulsar (Kelley *et al.* 1981) is interesting since it is among the few with pulsation periods intermediate between the short-period (e.g., Her X-1 at 1.24 s) and long-period (e.g., 4U 0900–40 at 283 s) X-ray pulsars. It is also unusual in that the X-ray pulsations show a very large rate of change in period with $\dot{P}/P \approx -0.02$ yr^{-1} (Kelley *et al.*), which is among the largest known for binary X-ray pulsars.

The program of *Einstein* studies of galactic X-ray sources included an observation of 2S 1417–62 with the high-resolution imager (HRI) on the *Einstein X-ray Observatory* (Giacconi *et al.* 1979). Our primary objective was to obtain a more precise position that would enable optical identification of the source. A preliminary HRI position for 2S 1417–62 was obtained in 1981 April and used by one of us (J. E. G.) to search for the optical counterpart. Observations of the 2S 1417–62 field were conducted with the Cerro-Tololo Inter-American Observatory (CTIO) 4 m telescope and Ritchey-Chretién spectrograph in 1981 May. A candidate optical counterpart was identified (Grindlay 1981) on the basis of strong Hα emission in the spectrum of a $V \sim 16.9$ mag star in the HRI error box. Follow-up spectra with higher resolution were obtained with the CTIO 4 m (by L. D. P. and J. E. M.) in 1981 June. We report here our combined results, as well as earlier work, which elucidate the nature of this X-ray pulsar.

II. OPTICAL IDENTIFICATION

X-ray observations of 2S 1417–62 were carried out on 1979 August 24, with the HRI detector on the *Einstein X-ray Observatory*. Due to an error in the guide-star selection program, the bright visual binary system α Cen A/B was chosen as a guide star for one of the two stars required for *Einstein* observations. The overly bright magnitude ($m_v \sim 0.3$) and 19″ separation between the binary components of α Cen combined to give an ambiguity of ~8″ for the derived X-ray position. This is considerably less precise than the 3″.2 (90% confidence radius) HRI positions now generally available (Grindlay *et al.* 1984). The HRI position (epoch 1950.0) for 2S 1417–62 is then

$$\alpha(1950) = 14^h17^m25^s.7\ , \quad \delta(1950) = -62°28'16''\ ,$$

with a 10″ uncertainty (90% confidence radius) which includes uncertainties in aspect, centroiding, and absolute position.

The *Einstein* position is consistent with either of two stars visible on the European Southern Observatory (ESO) Quick Blue Survey print of the field. These are stars 7 and 8 as labeled by Apparao *et al.* (1980). Several other fainter, and redder, stars are also consistent with the HRI error box as was evident on both the 4 m TV guider and in (subsequent) comparison with the ESO/Science Research Council (SRC) Deep Blue Survey print of the field. The HRI location is plotted, and stars 7 and 8 are identified on this print in Figure 1 (Plate 6). Spectra were obtained of star 7 on 1981 May 6 and 7, with the 4 m telescope and Ritchey-Chrétien spectrograph with the "blue" SIT vidicon detector. We also obtained a spectrum of the fainter star approximately 8″ NW of star 7; it is a reddened late-type star of spectral class G or K. Star 7 shows strong Hα emission and is the probable optical counterpart of 2S 1417–62. This star (star 7) was misidentified as star 8 in the initial report by Grindlay (1981).

III. OPTICAL SPECTRUM AND COLORS

In Figure 2 we show the spectra of star 7 recorded on the nights of 1981 May 6–7. The dominant feature in the spectra is the Hα emission. The Hα equivalent width is approximately 12 Å on May 6 and approximatedly 7 Å on May 7. The uncertainties in equivalent width are estimated to be 2 Å, so there is marginal evidence for Hα variability. Both spectra have approximately 15 Å resolution, which is sufficient to show that the Hα emission on May 6 is significantly broadened with FWHM ≈ 1400 ± 200 km s^{-1}, whereas on May 7 the Hα profile is unresolved. The broadened Hα profile observed on

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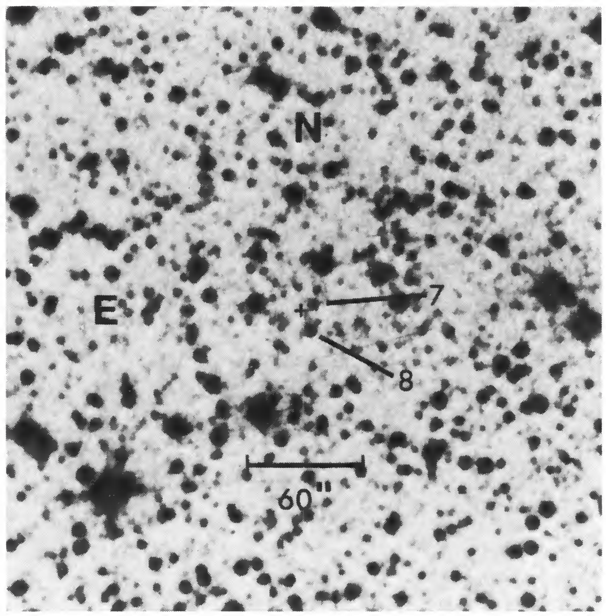

FIG. 1.—Finding chart for the 17 s X-ray pulsar 2S 1417−62. The suggested optical counterpart, star 7, is within the 10″ (90% confidence radius) error circle (center marked by a plus sign) derived from the detection of the source with the HRI on the *Einstein Observatory*.

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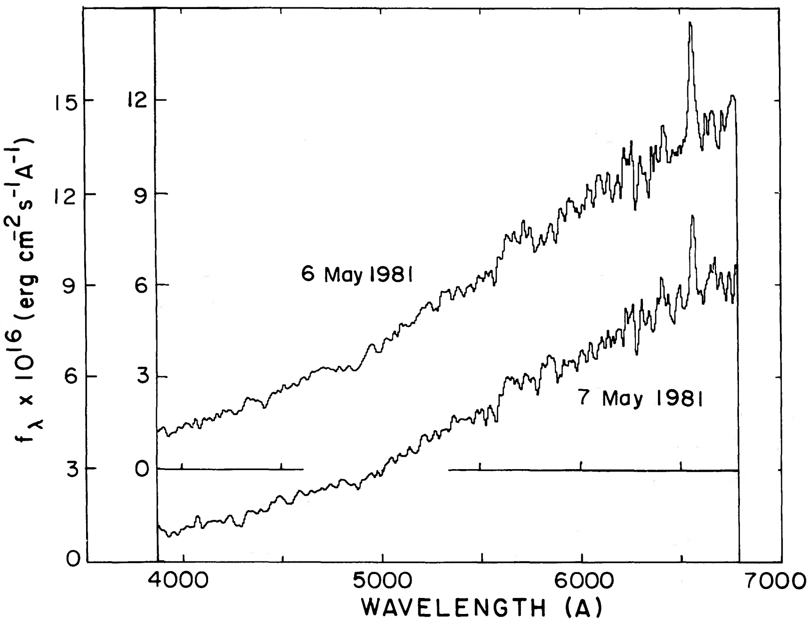

FIG. 2.—SIT vidicon spectra (~15 Å resolution) of the 2S 1417−62 optical counterpart recorded with the 4 m telescope at CTIO on 1981 May 6 and 7. The Hα emission is both broadened and more intense on May 6 than on May 7.

May 6 indicates velocities considerably in excess of the largest values (500–900 km s^{-1}) observed by Kriss *et al.* (1983) for the X-ray/Be system 4U 0115+63.

A follow-up spectrum of star 7 was obtained at CTIO on June 8 with the 4 m telescope and Ritchey-Chrétien spectrograph/blue SIT combination as before, but at higher resolution (~7 Å FWHM). This spectrum is plotted in Figure 3 and shows the blue absorption spectrum in much more detail than in Figure 2. No emission is apparent in the wavelength range 3900–5400 Å, which is consistent with the spectrum observed a month earlier (Fig. 2). Comparison of Figures 2 and 3 shows them to be very similar both in continuum flux and color.

A precise MK spectral type of the candidate cannot be determined given the limited signal-to-noise ratio of the spectrum shown in Figure 3. Such a classification is dependent upon the strengths of weak He I, He II, and metal lines which are approximately equal to the noise of our spectrum. An approximate spectral type may be determined based upon the following considerations. The hydrogen lines are present, but weak, suggesting an O/B or F/G spectral type. The latter range is ruled out by the absence of both strong Ca II K and the G-band. The earlier range of spectral types is supported by the presence of He I λ4471 and λ4387. The large strength of He I λ4471 relative to Hγ suggests a type near B1, with an estimated uncertainty of two subclasses. Refinement of this estimate and determination of the luminosity class is precluded by the signal-to-noise ratio of the lines used for classification. For example, the presence of features near Si III λ4553 and

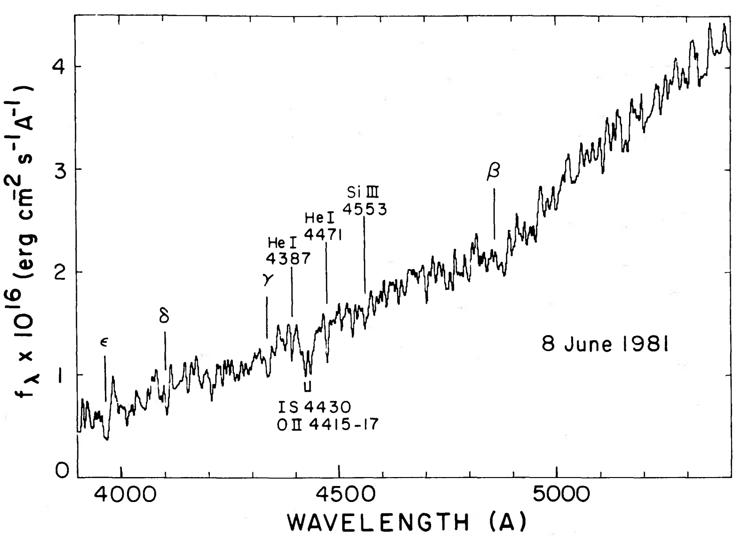

FIG. 3.—As in Fig. 2, but with higher (~7 Å) spectral resolution. The absorption-line spectrum shows that the optical counterpart is most probably a B1 V star.

O II $\lambda\lambda$4415–4417 suggest that the star may be a giant or supergiant, but the absence of O II $\lambda\lambda$4070–4076 and O II $\lambda\lambda$4346–4351 argues against this.

The presence of Hα emission suggests that the star is either a Be star or a B supergiant star, but the strength ($|w| = 7$–12 Å) of the Hα emission suggests that the Be identification is correct. A survey of Hα equivalent width in Be stars by Schild (1978) shows the typical equivalent width to be in the range 0–40 Å, but a survey of OB supergiants by Rosendahl (1973) revealed that none of the 30 stars have an Hα equivalent width as great as that observed here. However, one of the 33 supergiants (HD 152236, B1 Ia+) had an equivalent width nearly ($|w| = 5.25$) as great as that observed here. A similar situation exists for the OB X-ray binaries. The observed Hα equivalent width is typical of the Be/X-ray binary systems (Rappaport and van den Heuvel 1982), but is at the high end of the range of values found for the O BI/X-ray systems. Some reported values for X-ray OB I systems are: Cyg X-1, 4–6 Å (Hutchings *et al.* 1974); SMC X-1, 2.2 Å (Hutchings *et al.* 1977); X0900−40, 3.3 Å (Wickramasinghe *et al.* 1974); and 4U 1223−62, 8.3 Å (Hammerschlag-Hensberge *et al.* 1979). Better spectra of the 2S 1417−62 counterpart are needed to settle the issue, although these considerations suggest to us that the Be identification is more likely than the B I.

Photometry on the Johnson *UBV* system of the candidate was obtained by us during prediscovery observations with the CTIO 1.5 m telescope in 1979 May and 1980 May. The magnitudes and colors are given in Table 1. Although it appears that the star is variable, both in magnitude and color, *UBV* photometry of star 8 in 1979 and 1980 shows similar (~0.5 mag) "variations" in V suggesting that there may be a zero-point shift in the photometry for the 2 years. The difficulties of aperture photometry of faint stars in crowded fields may also contribute to the magnitude differences. For the observed range, $B-V = 1.72$–2.38 of color and $m_v \approx 16.92$–17.26, and adopting the unreddened colors of O9–B3 V–Ia stars (Johnson 1966) we infer that $E_{B-V} = 1.9$–2.7, $A_V = 6.1$–8.9 (or $N_H \approx 1.4$–2.0×10^{22} cm^{-2}, using the N_H versus A_v relation from Gorenstein 1975). For the luminosity class range V–III (Be stars), the allowed range of distances is $d = 1.4$–11.1 kpc. The corresponding range of heights above the galactic plane is $z = 40$–300 pc, and the range of X-ray luminosity allowed (adopting $F_x = 10$ *Uhuru* flux units [UFU] $= 1.7 \times 10^{-10}$ ergs cm^{-2} s^{-1}) is $L_x = 4 \times 10^{34}$ to 3×10^{36} ergs s^{-1}. Similarly, for luminosity classes Ia and Ib, the allowed ranges are $d = 6.6$–36.0 kpc, $z = 300$–1000 pc, and $L_x = 9 \times 10^{35}$ to 3×10^{37}. These considerations do not decisely distinguish the Be and supergiant possibilities, but a conventional galactic plane distance would again favor a Be star interpretation.

IV. X-RAY SPECTRUM

The X-ray spectrum is best fitted by a power law with energy index $\alpha \approx 0.4 \pm 0.2$ and an absorption column density of $1.4^{+7}_{-1.4} \times 10^{21}$ cm^{-2} (yielding $\chi^2 = 0.2$ for 4 degrees of freedom) or a thermal spectrum with $kT \approx 12^{+8}_{-4}$ keV (with $\chi^2 = 1.0$) and an absorption column density of $N_H = 0.3^{+8}_{-0.3} \times 10^{21}$ cm^{-2}. These spectral parameters were derived from the *Einstein* MPC data from the 1979 August 24 observation. (Analysis of the *Einstein* MPC data for the 17 s pulsations revealed no evidence for pulsations with a pulsed fraction upper limit of 30% [Naranan 1983]). In a second MPC observation on 1981 January 16, the flux was 2.80 UFU, and the best fit spectrum was a power law with energy index $\alpha = 0.10 \pm 0.2$ and $N_H = 3.1^{+1.0}_{-1.8} \times 10^{22}$ cm^{-2} (with $\chi^2 = 1.9$). The 90% confidence level for the allowed α versus N_H values for the two MPC spectra do not overlap, indicating that X-ray spectral variations occur. We note that the estimate of $N_H \approx 1.7 \times 10^{22}$ from the optical photometry of the candidate is marginally consistent with the value derived from the X-ray spectra.

TABLE 1

UBV PHOTOMETRY OF 2S 1417−62

Date	V	$B-V$	$U-B$
1979 May 24	17.26(±0.05)	2.38(±0.10)	...
1980 May 17	16.92(±0.03)	1.72(±0.06)	0.69(±0.25)

V. DISCUSSION AND CONCLUSIONS

The 2S 1417−62 system is very similar to the seven X-ray pulsars previously identified with Be systems (Rappaport and van den Heuvel 1982) as well as the two Be star X-ray sources recently identified with *HEAO 1* (Steiner *et al.* 1983). The possibly variable Hα emission may be due to variable mass loss from the primary star as expected for a Be star. Strongly variable Hα emission is also observed for the Be star counterpart of 4U 0115+63 (Kriss *et al.* 1983). Large variations in the X-ray luminosity of 2S 1417−62 of at least an order of magnitude are also observed since the approximately 1.0 UFU flux detected in the *Einstein* observations in 1979 August is a factor of approximately 30 lower than that detected in 1978 July by *SAS 3* as reported by Apparao *et al.* (1980). Thus the source resembles the recurrent hard X-ray transient sources such as A0535+26 and 4U 0115+63 which are also pulsars identified with Be star companions (Rappaport and van den Heuvel 1982).

We conclude 2S 1417−62 is most likely a rotating neutron star in orbit about a Be star. A Be star, with a radius of (typically) approximately 7 $R_\odot$ (Allen 1973) constrains the orbital separation to be $\gtrsim 5 \times 10^{11}$ cm and thus the orbital period to be $\gtrsim 0.6$ days. In fact, the X-ray pulse-timing studies of Kelley *et al.* (1981) constrain the orbital period to be much longer. The mass function inferred from our observations is $f(M) = m_c \sin^3 i/(1+q)^2 \geq 1\ M_\odot \sin^3 i$ for a Be star mass $m_c \approx 15\ M_\odot$ (see Rappaport and van den Heuvel 1982) and for $q \approx 0.1$, which corresponds to a likely neutron star mass of approximately 1.4 $M_\odot$ (Rappaport and Joss 1981). The variations in pulse period are most likely due to binary orbital motion (i.e., $\dot{P}_{\text{accretion}} \approx 0$) because the observed value of $\dot{P}$ is much greater than expected from accretion torques given the modest X-ray luminosity. Using the constraints derived from X-ray timing studies (see Fig. 5 in Kelley *et al.*) with $f(M) \geq 1$ (e.g., for $i \gtrsim 24°$) and $\dot{P}_{\text{accretion}} = 0$, we find $P_{\text{orb}} \gtrsim 25$ days. This is consistent with the orbital periods for Be star/X-ray binaries such as 4U 0115+63, which has a period of 24.3 days.

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