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THE HIGH ENERGY X-RAY SPECTRUM OF 4U 1700−37 OBSERVED FROM *OSO 8*

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ABSTRACT

The most intense hard X-ray source in the confused region in Scorpius has been identified as 4U 1700−37 (= HD 153919). Observations extending over three binary periods in 1978 September were carried out with the high-energy X-ray spectrometer on *OSO 8*. The 3.4 day modulation is seen above 20 keV with the intensity during eclipse being consistent with zero flux. The photon-number spectrum from 20 to 150 keV is well represented by a single power law with a photon-number spectral index of -2.77 ± 0.35 or by a thermal bremsstrahlung spectrum with $kT = 27$ $(+15, -7)$ keV. The counting rate above 20 keV outside of eclipse shows no evidence for the 96.8 minute X-ray modulation previously reported at lower energies. Despite the difficulties that exist in reconciling both the lack of periodic modulation in the emitted X-radiation and the orbital dynamics of the system with our currently accepted theories of the evolution and physical properties of neutron stars, the observed properties of 4U 1700−37 are all consistent with the source being a spherically accreting neutron star rather than a black hole.

Subject headings: stars: neutron — X-rays: binaries — X-rays: spectra

I. INTRODUCTION

The region around the X-ray source 4U 1700−37 (Giacconi *et al.* 1972; Forman *et al.* 1978) includes the prominent sources Sco XR-2 (Bowyer *et al.* 1965) = GX 349+2 = 4U 1702−36, Sco X-2 (Clark *et al.* 1965) = 4U 1702−42, and OAO 1653−40 (Polidan *et al.* 1978). The region was observed with the High Energy X-ray Spectrometer on *OSO 8* (Dennis *et al.* 1977) during 1978 September. The most intense X-ray source above 20 keV in this region was found to be 4U 1700−37, the secondary in the eclipsing binary system whose primary is HD 153919. Bessell *et al.* (1974) have suggested that 4U 1700−37 is a black hole based on the mass estimated for the secondary in this system but 4U 1700−37 is now generally accepted to be a neutron star rather than a black hole based on more recent theoretical work. The model of the secondary as a neutron star leads to several difficulties in reconciling the orbital dynamics of the system with theoretical studies of the evolution of binary systems containing a neutron star secondary. We present here the high-energy X-ray spectrum of this source, its X-ray light curve from 21 to 84 keV, and the results of a search of its uneclipsed X-ray emission for modulation with periods of 96.80 minutes (Matilsky, La Sala, and Jessen 1978) and near 24 minutes (Branduardi, Mason, and Sanford 1978). Theoretical studies applicable to models of the source as a neutron star, black hole, and white dwarf are then reviewed, leading us to conclude that the secondary is probably a spherically accreting neutron star.

II. OBSERVATIONS

The source 4U 1700−37 was observed during the period 1978 September 1.40 UT to September 11.97 UT. The position of the strong source seen in this region is consistent with that of 4U 1700−37. The intensity of X-radiation received from the source was variable, with a temporal behavior that suggested the existence of an eclipse every 3.4 days (Fig. 1). JD 2,442,231.13, the epoch of "X-ray mid-eclipse" derived from 3.5 to 10.5 keV observations (Mason, Branduardi, and Sanford 1976), was adopted as zero phase and the 21 to 84 keV observations were folded modulo the 3.4111 day spectroscopic period (Hammerschlag-Hensberge 1978) of HD 153919. The resulting X-ray light curve (Fig. 2) confirms the identity of the source as 4U 1700−37. The intensity of the source at minimum is consistent with zero flux. The two standard deviation upper limit on the minimum flux observed is less than 0.37 of the weighted mean flux observed outside eclipse. This behavior of the high-energy X-ray flux indicates that the system exhibits a true geometric eclipse.

The duration of the eclipse as measured at low energies seems to be variable, although always longer than the duration we observe. Mason, Branduardi, and Sanford (1976) give the eclipse duration in the 3.5–10.5 keV range as 0.88 ± 0.06 days or a duration of 0.25 ± 0.02 in phase. Jones *et al.* (1973) observed a duration of 1.10 ± 0.07 days in 2–6 keV X-rays, or a duration of 0.32 ± 0.02 in phase. Branduardi, Mason,

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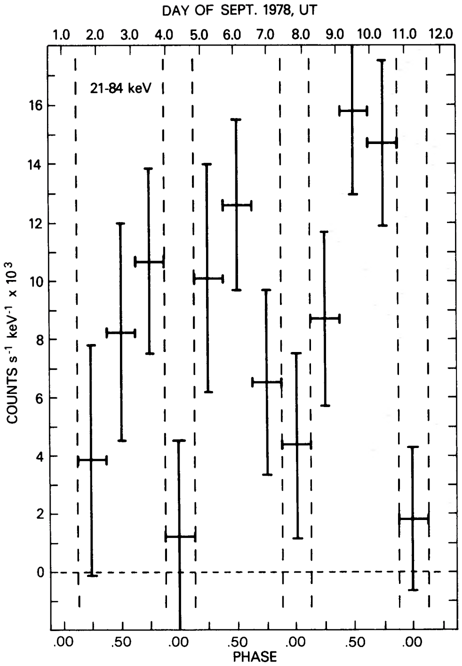

FIG. 1.—The 21 to 84 keV counting rate observed from 4U 1700 −37, 1978 September 1 to 11. Orbital phase is calculated from the ephemeris given in the text. Eclipses occur in low-energy X-rays between phases 0.875 and 0.125; these intervals are demarcated by the vertical dashed lines. The error bars represent ± one standard deviation uncertainties derived from the statistics alone.

and Sanford (1978) observed a duration in 2.8–8.7 keV X-rays of 0.75 ± 0.07 days (0.22 ± 0.02 in phase) in 1976 and of 0.61 ± 0.07 days (0.18 ± 0.02 in phase) in 1975. Mason *et al.* point out that the ingress into eclipse is more gradual than the egress from eclipse at low energies, and ascribe this asymmetry in the light curve to absorption in a high-density accretion wake trailing the secondary. There is independent evidence for the existence of this accretion wake in the spectroscopic observations of the system in the visual (Fahlman, Carlberg, and Walker 1977; Moffat and Dachs 1977; van Genderen and Uiterwaal 1976). Branduardi, Mason, and Sanford (1978) also observed a similar asymmetry, and showed that the amount of absorbing matter along the line of sight derived from low-energy X-ray spectral observations increased toward ingress into eclipse. The eclipse we see at higher energies (Fig. 2) appears to be centered at a slightly later phase than that given in the epoch of Mason, Branduardi, and Sanford (1976). The results are consistent with the ingress into eclipse at low energies being influenced by absorption in material in the system. Our observations are less affected by absorption in this material mimicking a geometric eclipse, since the photoelectric absorption cross section for X-rays at 25 keV is only 1.8×10^{-3} that at 5 keV as calculated for non-ionized material with normal abundances (Bell and Kingston 1967).

The eclipse we observe must be closer in duration to that of the true geometric eclipse than the duration

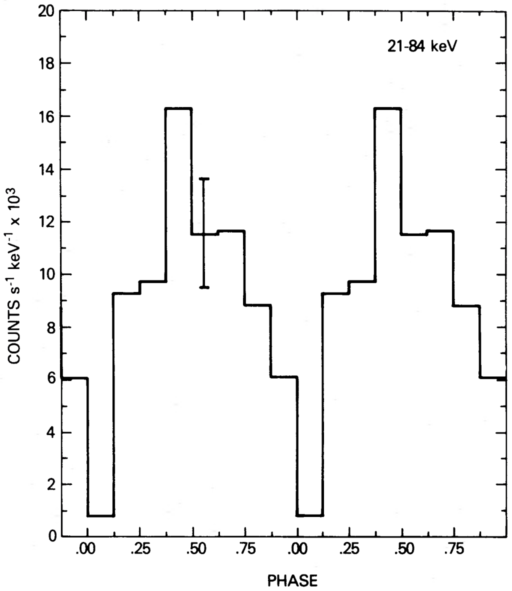

FIG. 2.—The data included in Fig. 1, folded modulo the orbital period of 4U 1700 − 37. Eclipses in low energy X-rays occur centered on phase 0.0. All phase bins have ± one standard deviation uncertainties derived from the statistics alone similar to the error bar shown. The same data points are repeated twice for clarity.

observed at lower energies. The light curve (Fig. 2) allows us to conclude that the eclipse duration must be significantly less than that given in Mason, Branduardi, and Sanford (1976). The discrepancy between the time of X-ray mid-eclipse (Mason, Branduardi, and Sanford 1976) and epoch of superior conjunction of the secondary, which occurs at phase 0.06 in the X-ray light curve of Figure 2 according to the orbital solution of Hammerschlag-Hensberge (1978), is then resolved. This is consistent with the analysis of van Paradijs, Hammerschlag-Hensberge, and Zuiderwijk (1978), who calculated the true duration of eclipse as twice the interval between the time of mid-eclipse obtained from spectroscopic data and the observed exit from X-ray eclipse. The eclipse duration they derived was 0.47 ± 0.11 days, or a duration of 0.14 ± 0.03 in phase.

The photon-number spectrum of 4U 1700−37 obtained during the time of our observations when the source was uneclipsed is shown in Figure 3. The spectrum was derived by the matrix inversion technique described by Dolan *et al.* (1977). The photon-number spectrum we observe is well represented between 16 and 180 keV by a single power law,

$$\frac{dN}{dE} = (1.42 \pm 0.22) \times 10^{-3}\left[\frac{E}{32.4}\right]^{-2.77 \pm 0.35} \text{photons cm}^{-2}\,\text{s}^{-1}\,\text{keV}^{-1}. \quad (1)$$

The uncertainties represent the 68% confidence interval ($\chi^2_{\min} + 2.3$) calculated according to the method of Lampton, Margon, and Bowyer (1976), and may be taken to represent the one standard deviation uncertainties. The normalization energy was chosen to

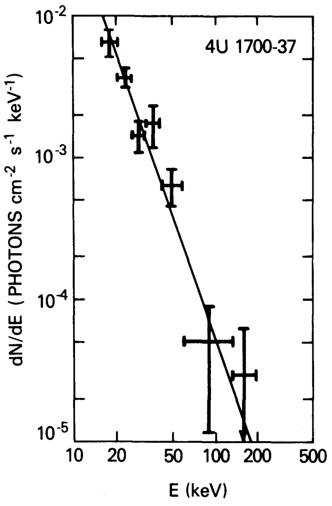

FIG. 3.—The photon-number spectrum of 4U 1700 − 37 observed 1978 September 1 to 11 outside of eclipse. The straight line is the power law given in eq. (1) in the text which acceptably represents the data. The error bars represent ± one standard deviation uncertainties derived from the statistics alone.

circularize the contours of equal χ^2 in parameter space, indicating the independence of the two parameters in that space. The spectrum may also be acceptably represented by a thermal bremsstrahlung spectrum,

$$\frac{dN}{dE} = (0.274 \pm 0.043)E^{-1.4} \exp\left[-(E-25)/kT\right] \text{ photons cm}^{-2}\,\text{s}^{-1}\,\text{keV}^{-1}, \quad (2)$$

where $kT = 26.7$ $(+15, -6.7)$ keV. No attempt was made to find other simple spectral forms which may also represent the data.

The X-ray flux between 21 and 84 keV was searched for evidence of a 96.80 minute modulation reported by Matilsky, La Sala, and Jessen (1978) to exist in their observations of the 1–10 keV flux in 1977 March with a pulsed fraction of 0.60 ± 0.15. The data taken outside eclipse were folded modulo this period using the epoch of zero phase, JD 2,442,500.0, given by Matilsky, La Sala, and Jessen (1978). Zero phase corresponds roughly to maximum intensity in the quasi-sinusoidally shaped light curve they observed. The resulting X-ray light curve is poorly represented by the hypothesis of a constant intensity source at its weighted mean intensity (Table 1). Neither is the light curve acceptably represented by a sinusoidal modulation of amplitude a_1 plus a constant intensity, a_0, of the form

$$S(i) = a_0 + a_1 \cos\left[2\pi(\phi(i) - \delta)\right] \text{ counts s}^{-1}\,\text{keV}^{-1}, \quad (3)$$

where $S(i)$ is the count rate in the bin whose central phase is $\phi(i)$, and δ is the phase of the sinusoid where it attains a maximum.

TABLE 1

FITS TO LIGHT CURVES

Parameter	Constant Intensity[a]	Sinusoid[b] (equation [3])
χ^2 (96.80 min period)	26.50	18.96
Probability of fit	0.002	0.008
χ^2 (23.73 min period)	26.56	16.72
Probability of fit	0.002	0.019

[a] 9 degrees of freedom.

[b] 7 degrees of freedom.

Branduardi *et al.* (1979) also searched for significant modulation in the 3.1–9.4 keV flux from 4U 1700 − 37 in 1978 July with a null result. They set an upper limit on the pulsed fraction with periods between 90 and 100 minutes of approximately 20% in this energy range at that time. Hammerschlag-Hensberge, Henrichs, and Shaham (1979) have suggested that the 96.8 minute modulation observed by Matilsky *et al.* is not intrinsic to 4U 1700 − 37, but is caused by gaps in the data at the similar, but flanking, periods of the satellite's orbit and its passage through the South Atlantic Anomaly. Although Matilsky *et al.* present observational evidence that the 96.8 minute modulation is not an artifact of their satellite's orbital period, Hammerschlag-Hensberge *et al.* are able to duplicate most of these observations synthetically by assuming certain specific, ad hoc distributions of data gaps and data transmission windows. The erratic light curve we observe from 4U 1700 − 37 for a 96.80 minute period may likewise be an artifact of the orbital period of *OSO 8*. The synodic periods between Earth occultations of the source, passages through the South Atlantic Anomaly, and data transmission gaps would be different from those on the satellite from which Matilsky *et al.* observed, possibly leading to the difference in observed light curves.

Because of the irregular spacing of the data and the low signal-to-noise ratio inherent in our high-energy X-ray observations, no power-spectrum analysis was performed on the data. Following the method of Lampton, Margon, and Bowyer (1976), a two standard deviation upper limit may be placed on the pulsed fraction, $p_f = (a_1/a_0)$, of any sinusoidal modulation in our data as that value of p_f given by the values of a_0 and a_1 (eq. [3]) for which χ^2 increases from that of the best sinusoidal fit by 6.18 (two free parameters). The upper limit we derive for the pulsed fraction of any sinusoidal modulation in our data between 21 and 84 keV is $p_f \leq 0.41$.

Branduardi, Mason, and Sanford (1978) report the existence of a modulation in the 3–10 keV radiation from 4U 1700 − 37 with period 23.91 minutes in 1974 July and 23.64 minutes in 1976 August. Pulsed fractions of 0.075 and 0.15 were observed at the two times, respectively. Branduardi *et al.* note that the difference in period "is consistent with the spin-up expected for a neutron star over this interval of time." Linearly extrapolating the change in period to the 1978 September epoch of our observations gives a period of 23.37 minutes. Our 21–84 keV observations outside eclipse were folded modulo this period with the same epoch of phase zero used in searching for a 96.80

minute modulation. Once again, the resulting X-ray light curve is poorly represented by the hypothesis of either a constant intensity source or a sinusoidal modulation (cf. Table 1). The upper limit we are able to put on the existence of any 23.37 minute modulation in the source is $p_f \leq 0.46$, similar to that obtained for a 96.80 minute modulation. Branduardi *et al.* (1979) also observed no modulation in the 3–10 keV radiation from 4U 1700−37 with periods in the range between 20 and 30 minutes in 1978 July. They quote upper limits on the pulsed fraction of typically 0.19.

III. DISCUSSION

a) Spectrum

The intensity of 4U 1700−37 at lower energies varies by a factor of 2 on time scales ranging from seconds (Jones *et al.* 1973) to hours (Mason, Branduardi, and Sanford 1976; Branduardi, Mason, and Sanford 1978) to years (Lambert and Tomkin 1979). Such variations over a time scale of days are also visible in the 21–84 keV counting rates we observe (Fig. 1). Hence, it is difficult to compare the spectrum we derive with any observations taken nonsimultaneously at lower energies. The 4U catalog (Forman *et al.* 1978) gives the average intensity of 4U 1700−37 in the early 1970s between 2 and 6 keV as $\sim 7 \times 10^{-2}$ photons $\mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}$. This value lies a factor of 5 below the value of the flux we derive from the power-law spectrum represented by equation (1) extrapolated to 4 keV, but is close to the value obtained at 4 keV from the thermal bremsstrahlung spectrum represented by equation (2). The discrepancy between the extrapolation of the power law and the reported 4 keV flux, however, could be explained by circumbinary absorbing material from the primary's stellar wind always being present in the line of sight (see Weedman and Hall 1972). Hence we are unable to distinguish between the two spectral forms at the source on the basis of our data combined with other published spectra.

Pringle and Rees (1972) and Davidson and Ostriker (1973) point out that a thermal spectrum is characteristic of an X-ray source powered by accretion onto a magnetized, rotating neutron star via an accretion disk. Accretion onto the surface of the star would take place along the field lines and the X-rays would be emitted thermally from regions near the magnetic poles. Even if the star had a negligible magnetic field, the spectrum would be expected to be thermal, with equal amounts of X-ray power coming from the star and the disk. Only in the case of a black hole, where the observed radiation comes almost entirely from the disk, did Pringle and Rees find a power-law X-ray spectrum. In the case of spherical accretion of gas onto the surface of a neutron star, Zel'dovich and Shakura (1969) and Shapiro and Salpeter (1975) found an emitted X-ray spectrum similar to a blackbody spectrum at low energies with a quasi–power law extension at energies greater than 10 keV. It is apparent that such a compound spectrum could be parametrically adjusted to fit both our high-energy spectrum and the average 4 keV flux reported in the 4U catalog. Because no observed spectrum of 4U 1700−37 below 20 keV has been published, however, we have not attempted to find the best values of these parameters. The hard X-ray spectrum observed from 4U 1700−37 is consistent with the source being either a neutron star or a black hole.

The X-ray flux we observe at high energies apparently rules out a white dwarf as the secondary. Kylafis and Lamb (1979) calculate a spectrum above 20 keV for accretion onto a white dwarf which lies below that which we observe by a factor of 10^3, even for accretion at the Eddington limit for a white dwarf of maximum allowable mass. A distance of 1.7 kpc was assumed for the HD 153919 system (Jones *et al.* 1972; Bolton and Herbst 1976). Kylafis and Lamb also predict a power-law X-ray photon spectrum above 10 keV with spectral index −4.6, which is not in agreement with our observed spectrum of 4U 1700−37.

b) Modulation

The lack of any periodic modulation observed in the X-ray flux received from 4U 1700−37 is most naturally explained by invoking the mechanism of quasi-spherical accretion via a stellar wind rather than by incipient Roche lobe overflow via an accretion disk. Pringle and Rees (1972) explained the pulsed X-radiation received from several X-ray sources as being caused by the rotation of a neutron star secondary whose rotational and magnetic axes were not aligned. Rappaport and Joss (1977) catalog nine X-ray pulsars with periods between 0.715 s and 13.7 minutes, all believed to be rotating neutron stars. If we accept 4U 1700−37 as having no evidence for modulation existing in its X-radiation in a similar range of periods (cf. Branduardi *et al.* 1979), then this indicates a difference between 4U 1700−37 and binary pulsars of the Cen XR-3 class. De Freitas Pacheco (1974) suggested that in 4U 1700−37 the accreted matter is transferred from the primary via a stellar wind rather than by incipient Roche lobe overflow to an accretion disk. If the secondary in 4U 1700−37 is a neutron star, then either it is rotating very slowly (with a rotational period similar to its orbital period, 3.41 d); or it has a negligible magnetic field; or its magnetic axis is closely aligned with its rotation axis; or the geometry of quasi-spherical accretion enables the source to avoid emitting most of its X-ray energy from regions near its magnetic poles. We believe this last possibility is the most plausible explanation. A black hole would exhibit no periodic modulation of the X-ray emission, with the possible exception of repetitive bursts of radiation in the millisecond range emitted at irregular intervals by material in one of the closest stable orbits about the hole. Blumenthal *et al.* (1972) and Vauclair (1972) have proposed that the accretion of matter onto the surface of a white dwarf would produce X-radiation by causing surface pulsation of the white dwarf to heat its atmosphere by shock waves. The resulting X-radiation would then exhibit modulation with a period in the range of seconds to minutes. This mechanism has been reanalyzed by Katz and Salpeter (1974), who find it unable to produce the observed luminosity at X-ray energies. In any case, the lack of observed modulation in the X-ray flux of 4U 1700 − 37 would rule out a white dwarf radiating by this mechanism as the secondary in the system.

c) Orbital Dynamics

Observations of the absorption lines associated with the O6f primary show it to be rotating at approximately one-half the orbital velocity of the secondary (Conti and Cowley 1975; Wolff and Morrison 1974; Dachs 1976). Hutchings (1974) has criticized this method of obtaining the rotational velocity of HD 153919, and used the emission lines in the system to measure a rotational velocity essentially synchronous with the orbital velocity of the secondary. The eccentricity of the secondary's orbit is also a matter of disagreement. Hutchings (1978) proposes an eccentricity $e = 0.05 \pm 0.01$ from fitting theoretical models to the observed photometric light curve. The same author derives $e = 0.20 \pm 0.11$ (Hutchings 1974) from an analysis of the spectroscopic radial velocity curves, but questions whether this is the real value of the eccentricity. Hammerschlag-Hensberge (1978) ascribes the value of the eccentricity derived from the radial velocity observations as being "partly due to the nonsphericity of the stellar wind" and derives $e \sim 0.06$ by correcting for this effect.

It appears likely that the orbit of 4U 1700−37 is nearly circular ($e \sim 0.05$), but the rotation of HD 153919, the primary, is not synchronous. If this is indeed the case, then there appear to be difficulties with our current understanding of the evolution of the system. Neutron stars are believed to be formed as the result of a supernova explosion of a progenitor star. If the remnant is to be left in a close binary system after the explosion, it must have been in such a binary system before the explosion. If the supernova explosion does not disrupt the binary, it results in an extremely eccentric orbit ($e \gtrsim 0.5$). For this model to be applicable to the 4U 1700−37/HD 153919 system, the time scale for circularization must be shorter than the time scale for synchronization. Turbulent viscosity in the convective envelope of the primary, if it has one, appears to be the most efficient mechanism for circularizing the orbit by transferring angular momentum from the secondary to the primary (Zahn 1977). On the other hand, the torque exerted by the secondary on the tidal bulge formed on the primary produces synchronization (Lecar, Wheeler, and McKee 1976). Based on these results, the time scale for circularization of the orbit is much longer than the time scale for synchronization of the orbit (Zahn 1977; Chevalier 1975; Alexander 1973), in contradistinction to what appears to be the case in the 4U 1700−37/HD 153919 system. Other mechanisms for circularizing the orbit on a shorter time scale have been suggested. Mass loss by the primary is ineffective by itself in circularizing the orbit (Chevalier 1975; Alexander, Chau, and Henriksen 1976). Alexander *et al.* suggest mass loss and atmospheric drag from the stellar wind as important processes in the orbital dynamics of 4U 1700−37. Chevalier (1975) suggests that a combination of mass loss and mass transfer is the circularization mechanism of the orbit, although he remarks that "a delicate balance between the two is required." Zahn (1977) mentions that the mass ratio of X-ray binaries can be so small as to render the circularization time shorter than the synchronization time. In any case, given our current ideas about the evolution of close binaries containing a neutron star, 4U 1700−37 presents a distinct problem to our understanding of orbital dynamics.

If 4U 1700−37 were a black hole formed without a supernova explosion, the orbital parameters of the system would require less explanation. The mass derived for the compact secondary, however, does not seem to be large enough to allow us to consider it to be a black hole. Hammerschlag-Hensberge (1978) derived a mass function,

$$f(m) = m_x{}^3 \sin^3 i/(m_p + m_x)^2 \,,$$

of 0.0023 (±0.0005) from the optical spectroscopy observations of HD 153919. Because of the duration of the eclipse, the system is believed to have an inclination close to 90°. If we adopt m_p, the mass of the primary derived from its spectral type and luminosity class, as lying between 30 and 62 $M_\odot$, then $f(m)$ gives m_x as lying between 1.3 and 2.1 $M_\odot$. Hutchings (1974) likewise derives a mass for the secondary in this range from spectroscopic data. Hutchings (1978) also derives a mass ratio of secondary mass to primary mass of 0.048 (±0.007) based on model light curves which approximate the observed photometric light curve. He puts an upper limit of 70 $M_\odot$ on the mass of the primary, giving a maximum mass to the secondary of 3.3 $M_\odot$. Van Paradijs, Hammerschlag-Hensberge, and Zuiderwijk (1978) were unable to reproduce the observed photometric light curve of HD 153919 from model light curves produced by a tidally distorted (and corotating) primary. They attribute their lack of success to the dynamical effects on the atmosphere of the primary caused by its strong stellar wind. The value of secondary mass which came closest to representing the data lay between 0.56 and 2.8 $M_\odot$ for primary masses between 8 and 70 $M_\odot$, respectively. Bessell *et al.* (1974) derived a mass for the secondary of 2.7 $M_\odot$ by using a less accurate value of the mass function and adopting a mass of 65 $M_\odot$ for the primary. This value led them to make the original suggestion that 4U 1700 −37 was in fact a black hole. It now seems that the mass of the secondary required by the spectroscopic mass function is less than the upper mass limit, $\sim 3\ M_\odot$ (Rhoades and Ruffini 1974; Chitre and Hartle 1976; but see Hegyi 1977), of stable, rotating neutron stars. This would rule out a black hole as the secondary in the system, since stars are thought not to evolve into black holes if any other stable configuration exists for them to adopt. Of course, if the progenitor star to 4U 1700−37 could find an evolutionary track on which it did not adopt such a configuration but evolved directly into a black hole, the fact that its mass lies below the highest stable mass for a rotating neutron star would be no theoretical objection to its existence as a black hole. Such tracks are not known to exist, however.

IV. CONCLUSIONS

The observational properties of the 4U 1700−37/HD 153919 system suggest that the mass transfer mechanism to the secondary is via the primary's stellar wind rather than via incipient Roche lobe overflow. The lack of periodic modulation in the emitted X-radiation and the orbital dynamics of the system are difficult to reconcile with our currently accepted theories of the evolution and physical properties of neutron stars. Neither of these problems is so inexplicable, however, as to prevent us from concluding that the secondary may be a spherically accreting neutron star, particularly because the mass of the secondary appears to be below that either requiring or allowing it to be a black hole. The source 4U 1700−37 may prove to be a valuable observational resource for honing our theories of the evolution of neutron stars.

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Note added in proof.—Trümper *et al.* (*Ap. J.*, in press) and Ricker *et al.* (*Ap. J.*, **207**, 333 [1976]) also present spectra of 4U 1700−37 above 20 keV taken at epochs different from ours. Both authors fit a thermal bremsstrahlung spectrum to their data in agreement with that derived in this paper.

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