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HIGH-ENERGY X-RAY SPECTRA OF CYGNUS XR-1 OBSERVED FROM *OSO 8*

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ABSTRACT

X-ray spectra of Cygnus XR-1 were measured with the scintillation spectrometer on board the *OSO 8* satellite during a period of $1\frac{1}{2}$ to 3 weeks in each of the years from 1975 to 1977. Observations were made when the source was both in a high state and in a low state. Typical spectra of the source between 15 and 250 keV are presented. The spectra are well represented by a single power-law expression whose photon number spectral index α is different for the two intensity states: a typical spectrum observed during the low state has $\alpha = 1.83 \pm 0.06$ ($\chi^2_{\rm min} + 1$), while a typical spectrum observed during the high state has $\alpha = 2.21 \pm 0.18$. The observed pivoting effect is consistent with two-temperature accretion disk models of the X-ray emitting region. No significant break in the spectrum occurs at energies up to 150 keV. The high state as defined in the 3–6 keV bandwidth is found to be the higher-luminosity state of the X-ray source. One transition from a low to a high state occurred during our observations. The time of occurrence of this and other transitions is consistent with the hypothesis that all intensity transitions occur near periastron of the binary system, and that such transitions are caused by changes in the mass-transfer rate between the primary and the accretion disk around the secondary.

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

I. INTRODUCTION

Cygnus XR-1 has been an object of continuing interest since its discovery by Bowyer *et al.* (1965). It is one of the strongest celestial X-ray sources observed at the Earth, has a hard X-ray spectrum, and is variable at all X-ray energies. Further, the source is identified with the secondary in the binary system whose primary is HDE 226868 (Webster and Murdin 1972; Tananbaum *et al.* 1972), and spectroscopic studies in the optical have led to models in which the secondary can be only a black hole (cf. Bolton 1975). Observations of this source above 20 keV would help to resolve the question of whether the shape and temporal behavior of its spectrum are consistent with that expected from models of the system which attribute the X-radiation to an accretion disk surrounding a black hole secondary (cf. Shapiro, Lightman, and Eardley 1976; Eardley and Lightman 1976). Knowledge of the source's variability at higher energies would also increase our ability to determine the cause of the long-term variability present in its X-ray luminosity. For all of these reasons, Cyg XR-1 was considered worthy of extended study whenever accessible to observation with the high-energy scintillation spectrometer on board the *OSO 8* satellite.

A complete description of the instrument and its operating environment is given by Dennis *et al.* (1977). The spectrometer is located in the rotating wheel section of the satellite. The CsI(Na) scintillation spectrometer has a sensitive area of 27.5 cm^2 and is actively collimated with additional CsI shielding, which provides a circular field of view of 5°.1 full width at half-maximum (FWHM). An associated 256-channel pulse-height analyzer on the spacecraft, together with a choice of electronic gains available on command from the ground, allows the analysis of incident spectra between photon energies of 10 keV and 3 MeV. The instrument is mounted with the axis of its field of view offset by 5° from the (negative) spin axis of the rotating wheel. Once every 10 s, the period of rotation of the wheel, a source positioned 5° from the spin axis will pass through the center of the field of view. The measured energy resolution (FWHM/E) of the detector is 21% at 662 keV and 43% at 59.6 keV.

Because of the pointing requirements of the spacecraft, the spin axis is constrained to precess around the sky once every year. The resultant geometry allows the spacecraft to view the position of Cyg XR-1 for a maximum duration of approximately 3 weeks each year. The observations described here were made during the periods listed in Table 1.

TABLE 1
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Year	Times and Binary Phases (Φ)
1975..........	Nov 11, 0230 UT–Nov 19, 0800 UT ($\Phi = 0.33$) ($\Phi = 0.80$)
1976..........	Oct 27, 2000 UT– Oct 31, 2245 UT ($\Phi = 0.15$) ($\Phi = 0.88$) Nov 8, 0745 UT–Nov 16, 0030 UT ($\Phi = 0.20$) ($\Phi = 0.57$)
1977..........	Oct 21, 1145 UT– Oct 31, 0015 UT ($\Phi = 0.20$) ($\Phi = 0.90$) Nov 11, 0500 UT–Nov 17, 0900 UT ($\Phi = 0.90$) ($\Phi = 0.00$)

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II. OBSERVATIONS

The raw counting rates from the source were determined in the manner described by Dolan *et al.* (1977*a*). These pulse-height spectra were then reduced to the photon spectra incident at the detector by the matrix inversion technique described by Dolan (1972). The effect of the finite energy resolution of the detector is removed by apodization; then the effects of fluorescent escape photons, detector quantum efficiency, and absorption in overlying material are removed by using the measured properties of the detector obtained during laboratory calibration. The data are analyzed in energy bins of bandwidth approximately 1 standard deviation (0.424 FWHM) of the energy resolution of the detector. The effects of instrumental gain changes on the resultant spectra (Dennis *et al.* 1978) are not significant for sources as strong as Cyg XR-1. During the observations described in this paper, bins 10 keV wide were used between 13 and 123 keV, and bins 30 keV wide above 123 keV. After the completion of this reduction procedure, the resultant incident fluxes derived for adjacent bins may be combined to produce an average intensity in a wider energy bandwidth which is statistically more significant. The incident spectrum so derived is then compared directly with the intensity predicted by any assumed source mechanism in order to determine whether any simple set of spectral parameters is consistent with the data.

The raw counting rates observed in the bandwidth 23–153 keV during the times listed in Table 1 are shown in Figure 1. Data are grouped in intervals of 0.55995 days, or a phase interval of 1/10 the period of the HDE 226868 binary system (Bolton 1975). As can be seen by inspection, the apparent brightness of the source in this energy band was significantly lower in 1975 than in 1976 or 1977. Comparison with lower energy proportional counter data taken simultaneously by Holt *et al.* (1976), Holt (1978), and Serlemitsos *et al.* (quoted in Dolan *et al.* 1976) reveals that Cyg XR-1 was in a low state as defined at 3–6 keV during all of our observations in 1976 and 1977. In using the terms "high state" and "low state", we shall always refer to the intensity state as observed at lower energies, 3–6 keV. A transition from a low to a high state occurred on 1975 November 16, simultaneous with the drop in our 23–153 keV counting rate (Dolan *et al.* 1977*b*). After that time, the source was in a high state during our observations in 1975. Hence we have observed Cyg XR-1 in both its high-intensity state and low-intensity state, and have also observed it during one transition between states.

Typical spectra taken during the low-intensity state are shown in Figure 2. The observed spectra are well represented by a single power law of the form

$$dN/dE = C(E/E_0)^{-\alpha} \text{ photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1}\,. \quad (1)$$

Contours of equal χ^2 in (C, α) parameter space are elliptical, with axes approximately parallel to the C and α axes when the energy is expressed in units of E_0, the weighted mean energy of our total bandwidth. This implies that the uncertainties in C and α are independent. Values of C, α, and E_0 for each spectrum are given in Table 2. The statistical uncertainties quoted in Table 2 for each spectral representation are 68% ($\chi^2_{\min} + 2.30$) confidence intervals derived from the contours of equal χ^2 in the two-dimensional parameter space (Lampton, Margon, and Bowyer 1976). Real variability is seen in the half-day averages of the 23–153 keV flux when the source is in a low state (cf. Fig. 1), but these short-term fluctuations do not correlate with any systematic variations in the spectral index α of the power-law spectrum representing the observations.

TABLE 2

POWER-LAW REPRESENTATIONS OF OBSERVED SPECTRA
[$dN/dE = C(E/E_0)^{-\alpha}$ photons cm^{-2} s^{-1} keV^{-1}]

Figure	α	C (10^{-3} photons cm^{-2} s^{-1} keV^{-1})	E_0 (keV)
2*a*.......	1.83 ± 0.09	8.69 ± 0.57	32.5
2*b*.......	1.89 ± 0.13	7.67 ± 0.72	34.3
2*c*.......	1.88 ± 0.15	8.40 ± 0.73	29.6
2*d*.......	1.85 ± 0.15	6.86 ± 0.58	34.2
2*e*.......	1.87 ± 0.17	6.99 ± 0.53	25.8
3........	2.21 ± 0.27	6.80 ± 0.97	23.8

A typical spectrum taken when Cyg XR-1 was in a high state is shown in Figure 3. The line representing the power law which best represents the low-state spectrum shown in Figure 2*d* is also plotted in this figure. It is apparent that a high state corresponds to a lower intensity above 20 keV than does a low state. Further, the change in intensity above 20 keV is accompanied by a change in spectral index α in the sense that the low state corresponds to a harder spectrum. The change in intensity in the two different bandwidths is consistent with a spectrum whose shape is always a single power law but which seems to pivot about a point between the two energy ranges (cf. also Tananbaum *et al.* 1972; Coe, Engel, and Quenby 1976; Matteson *et al.* 1976). From the observations of Coe, Engel, and Quenby (1976), this pivot point occurs at approximately 7 keV.

If the spectrum in Figure 3 is taken as typical of the high state and if the spectrum extends unchanged to 0.1 keV (Shapiro, Lightman, and Eardley 1976; Eardley and Lightman 1976), then the luminosity of the source between 0.1 and 150 keV is

$$\begin{aligned} L_X &= 4\pi R^2 \int_{0.1}^{150} E(dN/dE)\,dE \\ &= 4R^2 C E_0^{\alpha} \int_{0.1}^{150} E^{(1-\alpha)}\,dE\,, \qquad (2) \end{aligned}$$

where R is the distance to the source. If we adopt 2.5 kpc as the value of R (Margon, Bowyer, and Stone 1973), $L_X = 5.5 \times 10^{37}$ ergs s^{-1} in the high state. If the spectrum of the source immediately before the transition (Fig. 2*e*) is taken as typical of the low state and if it likewise extends unchanged to lower energies,

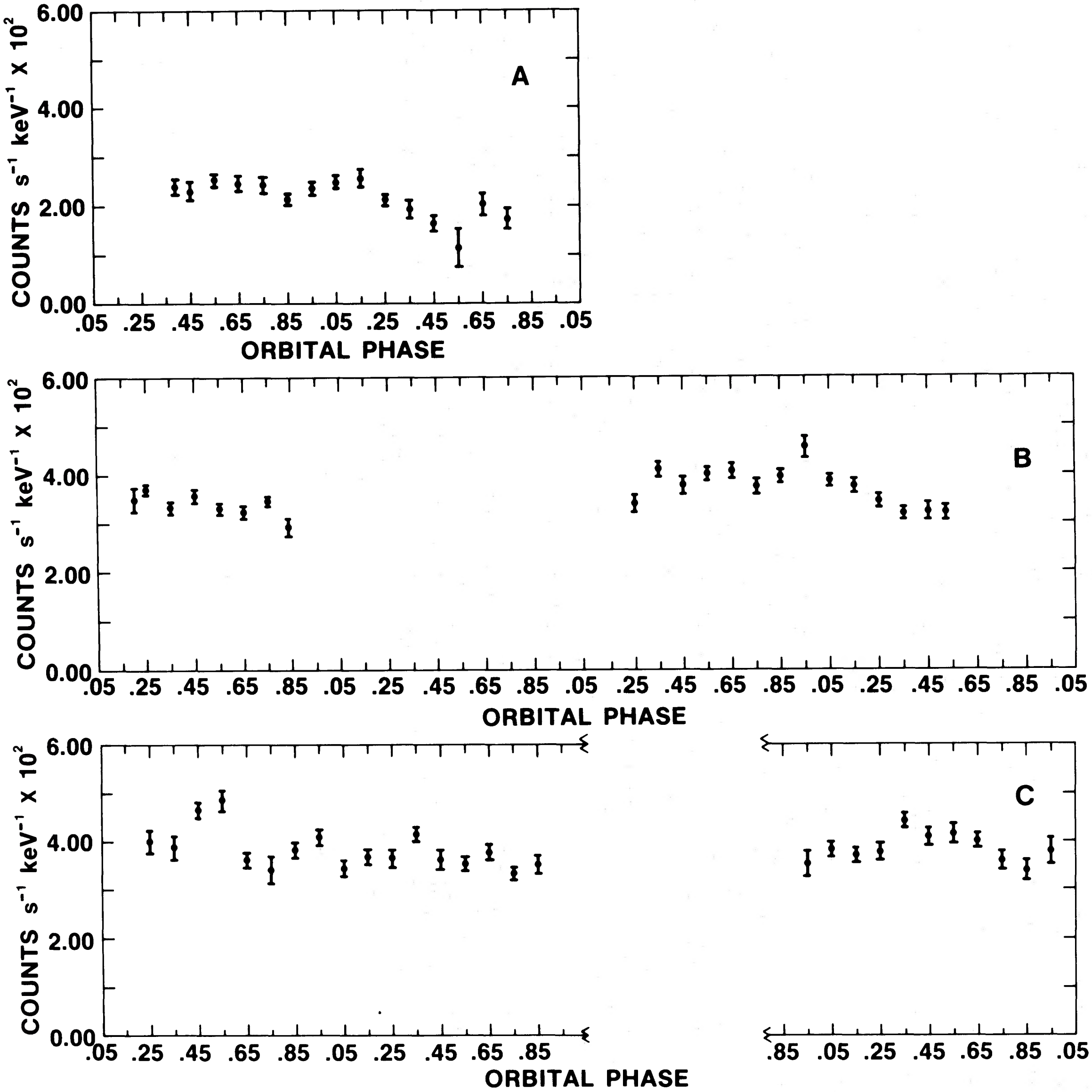

FIG. 1.—Raw counting rate, in counts s^{-1} keV^{-1}, observed from Cyg XR-1 in the bandwidth 23–153 keV. (*a*) Data taken in 1975. (*b*) Data taken in 1976. The two data sets are separated by a gap of 8 days (slightly over 1 binary period) during which time the spacecraft axis was pointed at Cyg XR-1. (*c*) Data taken in 1977. Note that the two data sets are separated by a gap of 12 days (2 binary periods) during which time spacecraft pointing precluded observations with our instrument.

then $L_X = 3.3 \times 10^{37}$ ergs s^{-1} in the low state of the system. The high state is then properly named: it is the higher-luminosity state of the system. The existence of any additional soft component of the spectrum below 7 keV with a very steep spectral index, sometimes seen during the high state by others (Tananbaum *et al.* 1972), would only strengthen this conclusion.

The intensity of each individual spectrum we observed, measured over durations of 0.1 in the binary phase of the system, could be well represented by a simple power law (eq. [1]) in the energy range between 20 and 200 keV. The intensity of some of the spectra we observed could also be well represented by a double power-law spectrum, with an increase in spectral index at higher energies of 0.5 or larger. The break point between the two power laws typically occurred between 40 and 125 keV for different spectra. Since only about one-third of our spectra could be represented by a double power law with a break in α this large while all of our spectra could be represented by a single power law, we believe that our data provide no independent evidence for the existence of a break point in the spectrum of Cyg XR-1 below an energy of approximately 150 keV.

The transition we observed occurred on 1975 November 16 (cf. Fig. 1*a*). The 23–153 keV counting rate decreased by approximately 50%, with the source remaining at a significantly lower counting rate after

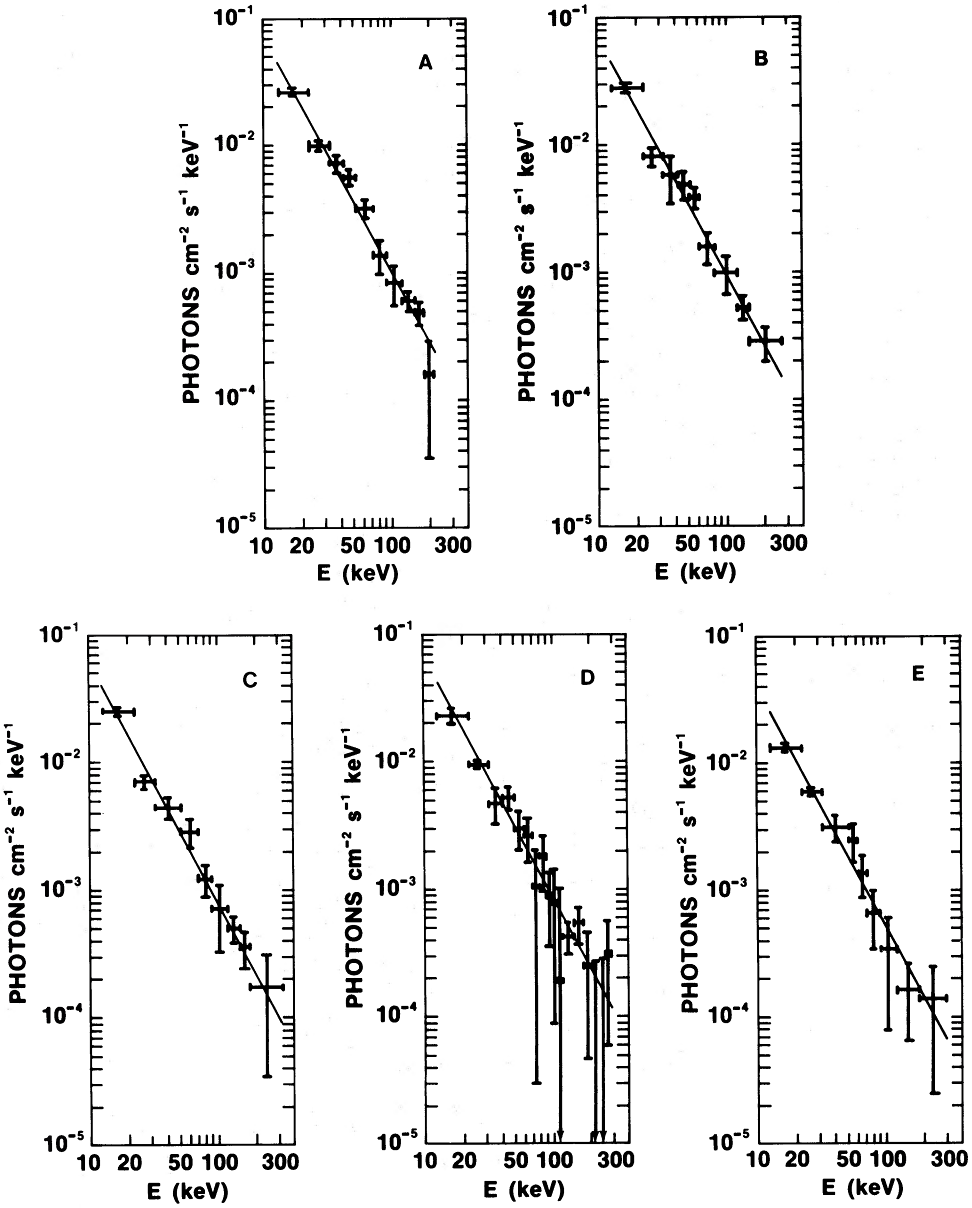

FIG. 2.—Typical spectra of Cyg XR-1 observed by *OSO 8* when the source was in a low state as defined at lower energies. The straight line in each spectrum is the single power-law expression which gives an acceptable minimum χ^2 distribution about the observed intensities. The resultant values of α, C, and E_0 for each spectrum, as defined in eq. (1), are given in Table 2. (*a*) Spectrum observed 1977 November 13, 1050 UT–November 14, 0015 UT (Φ = 0.30–0.40). (*b*) Spectrum observed 1977 October 22, 0115 UT–1445 UT (Φ = 0.30–0.40). (*c*) Spectrum observed 1976, November 11, 1630 UT–November 12, 0600 UT (Φ = 0.80–0.90). (*d*) Spectrum observed 1976 November 10, 0000 UT–1330 UT (Φ = 0.50–0.60). (*e*) Spectrum observed 1975 November 14, 2000 UT–November 15, 0930 UT (Φ = 0.00–0.10).

the transition than before it. Boldt (1976) distinguishes between "transitions" and "transient events." In transient events, the 3–6 keV intensity fluctuates by a large amount from its previous value but returns to its original level within a few binary periods; in transitions, the flux remains at its new level for many binary periods. Because of the restriction on the pointing requirements of the spacecraft, we cannot distinguish between these two possibilities for the event of 1975 November 16 with our data alone. The continuing observations of Holt *et al.* (1976), however, clearly reveal the event to have been a true transition.

III. DISCUSSION

The pivoting of the spectrum which we observe around transitions in Cyg XR-1 is consistent with models of the system in which the X-ray emission is

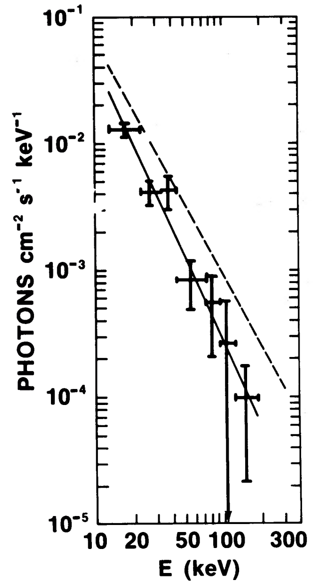

FIG. 3.—Spectrum of Cyg XR-1 observed 1975 November 17, 0200 UT–1530 UT (Φ = 0.40–0.50), when the source was in a high state. The values of α, C, and E_0 of the power law which best represents the data are given in Table 2; the power law is shown in the figure as the solid line. The dashed line is the power law which best represents the low-state spectrum shown in Fig. 2*d*.

produced in a two-temperature accretion disk surrounding the secondary component of the binary system (Shapiro, Lightman, and Eardley 1976; Eardley and Lightman 1976). In these models, the inner part of the accretion disk, ballooned up by gas pressure, is geometrically thick but optically thin to higher-energy X-rays. The high-energy radiation, predicted to have a power-law spectrum, is produced from the lower-energy X-ray or ultraviolet photons by inverse Compton scattering off the relativistic electrons in the inner region of the disk. The lower-energy photons being scattered originate in the cooler, outer portions of the disk. Basically, an increase in the lower-energy photon flux arriving at the inner region of the disk "cools off" the electrons by causing them to undergo more inverse Compton collisions. This results in a lower mean energy gained by the photons per scattering and hence a lower flux of high-energy photons. The anticorrelation between the fluxes in the two energy ranges would then be observed as the same type of pivoting of the spectrum which we observe in Cyg XR-1.

According to these two-temperature accretion disk models, the emergent X-ray spectrum is a simple power law in form, dependent upon several reasonable assumptions about the incident "soft" spectrum (Eardley and Lightman 1976). For energies greater than approximately (2–3)kT_e, where T_e is the electron temperature in the scattering region of the inner disk, the emergent spectrum falls below the extrapolated power law, approximating a decreasing exponential in form (Pozdnyakov, Sobol', and Syunyaev 1977). The hard X-ray spectra we observe from Cyg XR-1 are well represented by the power-law form predicted by this model. Our observations indicate no decrease in the observed fluxes below that predicted by a single power law which best represents the data up to an energy of approximately 150 keV in either state. Such a change to an exponentially decreasing spectrum at 150 keV (cf. Haymes *et al.* 1968; Coe, Engel, and Quenby 1976; Coe 1976) would be consistent with our highest-energy data points, however. Observations with a detector providing spectral data at energies of 200 keV and above having better statistical accuracy are required to determine where this transition between spectral forms occurs. Our observations by themselves reveal nothing about the origin or the nature of the source of lower-energy photons required by the models.

Transitions in Cyg XR-1 are observed to occur at irregular intervals but seem to occupy much the same duration, about 1 day, regardless of the direction of the transition or the interval since the last transition (cf. the references cited in Table 3). A list of all observed transitions between intensity states in the source is given in Table 3. We note that not only the transition we observed but also seven of the nine other reported transitions commenced near periastron, which occurs at phase 0.18 (Bolton 1975). The two reported events which did not commence near periastron (cf. Table 3) are probably not true transitions as defined at the end of § II.

It is reasonable to assume that transitions in the luminosity of Cyg XR-1 are linked to variations in the mass-transfer rate from the primary to the accretion disk surrounding the secondary. Alme and Wilson (1976) have proposed a model of the system in which matter is transferred primarily by radiation-driven density waves generated in the atmosphere of the primary, which fills only about 85% of the volume of its Roche lobe. In such a model having the orbital eccentricity (e = 0.06) (Bolton 1975) and period of the HDE 226868 system, nearly all the mass is transferred in an interval approximately 1 day long near periastron. As pointed out by Alme and Wilson, the period between mass-transfer "pulses" is not critically phase locked and the period between pulses is small compared with the characteristic disk transfer time. Hence variations in the X-ray emission at this period would be difficult to detect if approximately the same amount of mass were transferred every pulse. If the primary suddenly and drastically changed the amount of matter it transferred per pulse, however, the disk might then be expected to show a changed luminosity commencing near periastron. A large increase in mass transferred per pulse would increase the low-energy photon flux in the outer regions of the disk. The high-energy flux would then follow in an anticorrelated fashion, as discussed above. The difference between transitions and transient events would then be related to whether the mass that was transferred in succeeding pulses was maintained at its new value or returned to its previous level.

A sudden change in the amount of matter trans-

TABLE 3

TRANSITIONS IN CYGNUS XR-1

Date	Transition	Binary Phase at Start	Reference
1971 Mar 30...........	High to low	$0.7 < \phi < 1.6$	Tananbaum *et al.* 1972
1975 Apr 22...........	Low to high	$0.10 < \phi < 0.28$	Holt *et al.* 1975
1975 May 3*...........	Low to high	$0.9 < \phi < 1.2$	Gursky *et al.* 1975
1975 May 9...........	High to low	$0.1 < \phi < 0.3$	Sanford *et al.* 1975
1975 Jun 2†...........	Low to high	0.67	Sheffer *et al.* 1977
1975 Sep 6–7‡..........	Low to high	$0.4 < \phi < 0.6$	Holt *et al.* 1976
1975 Oct 29–30§........	Low to high	$0.08 < \phi < 0.17$	Walker *et al.* 1976
1975 Nov 4–5§.........	Low to high	$0.15 < \phi < 0.28$	Grindlay and Schreier 1975; Holt *et al.* 1976
1975 Nov 16...........	Low to high	$0.1 < \phi < 0.2$	Dolan *et al.* 1976; Holt *et al.* 1976
1976 Feb 19...........	High to low	$0.12 < \phi < 0.22$	Kaluzienski *et al.* 1976; Holt *et al.* 1976

* May be a transient event rather than a transition (cf. Holt *et al.* 1975).

† Probably not a transition: referred to in Sheffer *et al.* 1977 as an emersion from a short intensity dip caused by absorption in a gas stream crossing the line of sight (cf. also Holt *et al.* 1976).

‡ Probably not a transition but a temporary increase in the 3–6 keV intensity of the low state (cf. Holt *et al.* 1976).

§ May be a connected series of transient events (cf. Holt *et al.* 1976).

ferred per pulse may be related to the fundamental rotation properties of the free modes of oscillation of the primary. A particular example of this type of phenomenon as applied to X-ray sources is given by Wolff and Kondo (1978). According to the theory outlined by Wolff (1974), the nondegenerate star is pulsating in a broad array of *g* modes, global in scale and lacking spherical symmetry. Under slow rotation and sufficient nonlinear coupling, the *g* modes can combine to form a much smaller set of nonlinear modes grossly departing from azimuthal symmetry. As the main antinodes of the nonlinear modes rotate past each other, the oscillatory power density at these locations is temporarily enhanced. An increased amount of mass may be transferred whenever the main antinodes are effectively aligned with the subsecondary point on the surface of the primary. On the Sun, effective alignments of *g* modes typically last about $\frac{1}{2}$ year (Wolff 1976); for HDE 226868, the time scale of effective alignments may be shorter because of its more rapid rotation. Because of the large number of *g* modes excited in the primary star, many different periods between successive effective alignments of different sets of *g* modes are possible, some operating over a time scale of years. Hence, if this mechanism were the cause of luminosity variations in Cyg XR-1 by means of occasionally enhancing the mass-transfer rate in the system, the periodicity in such enhancements would be difficult to detect over an observational duration as short as 5 years, especially since the mechanism requires the occurrence of the aligned antinodes at specific location on the stellar surface, the subsecondary point. Instead, transitions would appear to occur at random intervals, as they do in Table 3. If the effective alignment of certain main antinodes were to last only 1 binary period or less at the subsecondary point on the primary, the increased mass transfer would exist for only 1 pulse at periastron and produce a transient event rather than a transition.

Observations of Cyg XR-1 should be continued in order to see whether the correlation of commencement time with phase near periastron is borne out in future transitions and whether any pattern appears in the times of occurrence of transitions and transient events.

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