THE ASTROPHYSICAL JOURNAL, 235:L153–L157, 1980 February 1

EVIDENCE FOR THE DEGENERATE DWARF NATURE OF CYGNUS X-2

G. BRANDUARDI,[1] N. D. KYLAFIS,[2] D. Q. LAMB,[2,3] AND K. O. MASON[4]
Received 1979 September 4; accepted 1979 October 25

ABSTRACT

Observations of Cygnus X-2 using the *Copernicus* satellite have revealed a novel relationship between the spectral hardness and the intensity of this source in the 3–8 keV band. This behavior is very similar to that predicted for a spherically accreting nonmagnetic degenerate dwarf. The data, interpreted in terms of this model, yield a mass $0.35 \pm 0.05\ M_{\odot}$, a luminosity $7 \pm 2 \times 10^{34}$ ergs s^{-1}, and a distance 250 ± 50 pc for Cyg X-2. These parameters are at variance with the values derived from optical observations of the system. We examine the implications of this discrepancy for our understanding of the source.

Subject headings: stars: white dwarfs — X-rays: binaries — X-rays: sources

I. INTRODUCTION

Cygnus X-2 is one of the three bright X-ray sources in Cygnus, and as such has been observed since the earliest days of X-ray astronomy. Despite the large amount of data available, no clear understanding of the object has yet emerged. The source is identified with a ~15 mag star (Giacconi *et al.* 1967). Various authors have searched for periodic phenomena in both the X-ray and optical emission of the star, but again no consensus has emerged and periods between 0.25 and ~14 days have been suggested. In particular, the most recent optical work indicates an orbital period of 9.843 days (Cowley, Crampton, and Hutchings 1979). There have been reports of a modulation in the X-ray flux corroborating this period (Marshall and Watson 1979; Ilovaisky *et al.* 1979). However, the highest-quality X-ray data, which have been taken with the *Ariel 5* All Sky Monitor over an interval of 4 years, show no evidence of a modulation at 9.84 days but instead suggest a period of ~11.2 days (Holt *et al.* 1979).

We observed Cyg X-2 on several occasions using the 3–8 keV X-ray detector on board the *Copernicus* satellite. In this *Letter* we report on a novel type of spectral and intensity variability which appears to be a characteristic of this source. The data are compared with a model of spherical accretion onto nonmagnetic degenerate dwarfs (Kylafis and Lamb 1979, hereafter KL).

II. THE X-RAY OBSERVATIONS

Table 1 lists the times of the *Copernicus* X-ray observations, which were of two types. In one mode, data were taken continuously with a sampling period of 62.9 s (apart from times of Earth occultation and passages in the South Atlantic Anomaly). In the second mode, the source was observed for of the order of 40 minutes every 12 or 24 hours to monitor long-term variability. The gain of the detector decreased monotonically with time after launch, and so the effective energy range in which each observation was made is also listed in Table 1.

In this *Letter* we concentrate on two observations which showed the most pronounced spectral variability. They were made during 1975 June and 1976 October 20–21. These data are plotted in Figure 1. For the 1975 June data each point represents a single orbit observation (~40 min). For the 1976 October observation each bin covers ~2^{h} of data. In the lower panel we show the count-rate as a function of time and in the upper panel the spectral hardness ratio, which is the ratio of the counts above and below 5.8 keV with the *Copernicus* X-ray detector response folded in. The 1975 June data have been corrected to the same gain as in 1976 October in order to facilitate comparison. It is clear that both the intensity and the hardness ratio are variable but that there is not a 1:1 relation between the two quantities.

In Figure 2 we have plotted the hardness ratio versus the count rate. In this diagram the two sets of measurements lie on a similar locus which can be divided into two parts: one at relatively high values of hardness ratio, where the intensity varies independently of the spectrum, and the second at lower values, where the hardness of the spectrum is correlated with the observed count rate. The first 11 bins of the 1976 October observation are labeled chronologically. They show that during the first day the source moved smoothly around the locus. Subsequently, the count rate varied but the value of the hardness ratio remained within the horizontal portion of the distribution (see also Fig. 1). The observations during 1975 June are spaced ~1^{d} apart and do not show any orderly progression. This suggests that when excursions around the locus occur, they do so on a time scale of ~1^{d}. The values of the hardness ratio in the horizontal part of the distribution correspond to a temperature of ~5 keV for a thermal bremsstrahlung fit to the data. The values in the lowest part correspond to a temperature of ~3 keV. These results are in agreement with the range of temperatures

[1] Harvard-Smithsonian Center for Astrophysics.

[2] Department of Physics, University of Illinois at Urbana-Champaign.

[3] Department of Physics, Massachusetts Institute of Technology.

[4] Astronomy Department and Space Sciences Laboratory, University of California, Berkeley.

TABLE 1

JOURNAL OF OBSERVATIONS

Time of Observation	Remarks	Energy Range (keV)
1973 Jul 20–21	28^h continuously	2.5–7.5
1974 Sep 17–22	$\sim 12^h$ continuously for 3 times	2.6–8.0
1974 Oct 28–Nov 2, Nov 22–25, Nov 30–Dec 2	3–5 one-orbit (~40 min) observations, one or two a day	2.6–8.0
1975 Jun 5–17	13 one-orbit observations (one a day)	2.7–8.3
1975 Oct 23–Nov 3	16 one-orbit observations (one or two a day)	2.8–8.4
1976 Oct 15–19	5 one-orbit observations (one a day)	2.9–8.7
1976 Oct 20–21	40^h continuously	2.9–8.7
1976 Nov 28–Dec 1	56^h continuously, except for 2 half-day intervals	2.9–8.7
1977 Aug 16–18	$\sim 2^d$ continuously, except for an 18^h interval	3.0–9.0

reported by previous observers (Bleach *et al.* 1972; Burginyon *et al.* 1973; Ulmer *et al.* 1974).

Correlations between luminosity and spectral slope have been observed in other galactic X-ray sources, particularly the so-called "bulge" sources (Mason *et al.* 1976; White *et al.* 1978; Swank 1977; Worrall *et al.* 1978). However, the data on Cyg X-2 are unique in displaying a horizontal extension when the spectrum is hardest.

III. DISCUSSION

It is difficult to account for the relationship between spectral hardness and X-ray flux observed in Cyg X-2 in terms of existing models of nonmagnetic or magnetic neutron stars without introducing many ad hoc features. Further, the pulsating X-ray sources, which we know to be magnetic neutron stars, do not behave in this way. On the other hand, calculations of X-ray emission from nonmagnetic and weakly magnetic degenerate dwarfs predict a correlation like that seen in Cyg X-2 (see KL, Fig. 5). This correlation comes about because of variations in the rate of mass accretion onto the star. At high accretion rates the X-ray spectrum emitted at the stellar surface is degraded by Compton scattering as it passes through the accreting matter. This modifies the shape of the emergent spectrum in such a way that in the 3–8 keV band the observed slope steepens and the luminosity decreases as the accretion rate goes up (see KL, Fig. 4). The lower part of the locus in Figure 2 may be produced in this way. At low accretion rates the accreting matter is optically thin and the spectrum emitted at the stellar surface is observed directly. In this case the emergent spectrum is independent of the accretion rate and therefore of the luminosity. This accounts for the horizontal portion of the distribution in Figure 2.

We have used the model spectra calculated by KL to predict the behavior of a degenerate dwarf X-ray source as it would be observed by the *Copernicus* X-ray detector. Figure 3 shows curves of the predicted correlation for stellar masses of 0.2, 0.3, and 0.4 $M_\odot$. Superposed are the data from Figure 2. In the case of Cyg X-2 the observed value of the hardness ratio in the horizontal part of the distribution lies between the values predicted for stars of 0.3 and 0.4 $M_\odot$. This fixes the mass of the degenerate dwarf at $M = 0.35 \pm 0.05\ M_\odot$. The observed count rate and the luminosity calculated from the model then uniquely determine the distance of the source to be 250 ± 50 pc. The peak 3–8 keV X-ray luminosity is then $7 \pm 2 \times 10^{34}$ ergs s^{-1}.

While the general shape of the observed and theoretical distributions are similar, we note that the predicted amplitude of the variation in hardness ratio is larger than that actually observed. The lower part of the curve, where the optical depth is high, is most subject to the effects of absorption, line emission, and departures of the accretion flow from spherical symmetry, which have not been included in the model. These effects are expected to be particularly important for low-mass ($M \lesssim 0.5\ M_\odot$) degenerate dwarfs. If included, they would act in the direction of reducing the amplitude of the predicted hardness ratio variation. We note that it is also just in this lower part of the curve that the two data sets, which were taken ~16 months apart, differ. On the horizontal part of the curve, however, the 1975 and 1976 data are in very good agreement. Within the framework of the model this must necessarily be so, since along the horizontal part of the curve the accreting matter is optically thin and cannot alter the observed spectrum from that produced near the stellar surface. Agreement along the horizontal portion of the hardness ratio distribution therefore constitutes one crucial future test of this model for Cyg X-2.

The above picture conflicts with the interpretation of the optical data presented by Cowley, Crampton, and Hutchings (1979). These authors observe variations in the radial velocity of certain spectral lines from which they infer binary motion with a period $P = 9^d.843$ and a velocity amplitude $K = 87 \pm 3$ km s^{-1}. These values require the mass of the X-ray emitting star to be greater than 0.7 $M_\odot$. Further, if the companion star fills its Roche lobe, it must be evolved. The high luminosity thus implied yields a distance to the Cyg X-2 system of ~8 kpc and an X-ray luminosity of $\sim 10^{38}$ ergs s^{-1}.

Given that the degenerate dwarf model elegantly describes the X-ray data, let us review each link in the chain of arguments leading to the optical result and examine the implications for the degenerate dwarf model of Cyg X-2. First, the existence of an orbital period as long as 9 days does not by itself rule out a degenerate dwarf interpretation of the source. However, the large value measured for the orbital velocity necessarily implies a larger mass for the X-ray emitting star than can be accommodated within the degenerate

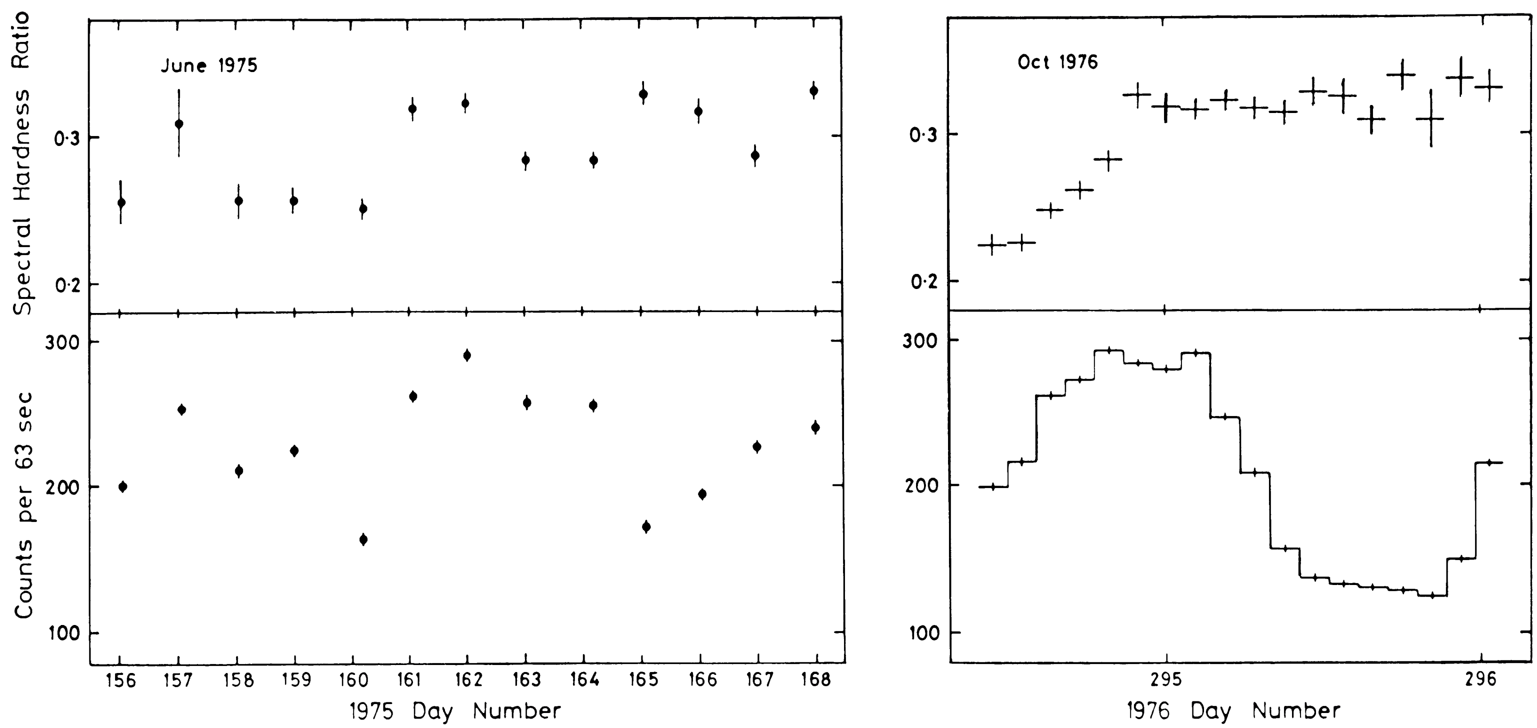

FIG. 1.—1975 June and 1976 October *Copernicus* X-ray observations of Cyg X-2. At the bottom is the count rate, at the top the spectral hardness ratio (the ratio of the counts above and below 5.8 keV, with the *Copernicus* X-ray detector response folded in). For the 1975 June data each point represents a single-orbit observation (~40 min). For the 1976 October observation each bin covers ~2^h of data. The vertical bars are the $\pm 1\,\sigma$ errors. The 1975 June data are corrected to the same gain as in 1976 October.

dwarf hypothesis. (We note, however, that a reduction of $\sim$20% in the orbital velocity would bring the lower limit on the mass of the X-ray emitting star down to $\sim$0.4 $M_{\odot}$). The assumption that the optical star fills its Roche lobe produces the most serious problem because of the distance and luminosity which it implies. If this distance and luminosity are borne out, the calculations of KL allow us to rule out unequivocally a degenerate dwarf model for Cyg X-2. This follows from the fact that in such a model the spectral variations necessarily arise from degradation of the spectrum by the accreting matter. KL find a firm maximum luminosity of 4×10^{36} ergs s^{-1} for spherical accretion onto degenerate dwarfs. The maximum luminosity can be increased by relaxing the assumption of spherical symmetry, but then a hard spectrum and no spectral variations are expected.

If Cyg X-2 is not an accreting degenerate dwarf, can we find an alternative explanation for its X-ray behavior? Based on our current understanding, it is difficult to account for the X-ray observations of Cyg X-2 in terms of accretion onto a neutron star. No spectral variations are expected from spherically accreting, nonmagnetic neutron stars until the luminosity approaches the Eddington limit ($\sim 1.4 \times 10^{38}$ ergs s^{-1} for a 1 $M_{\odot}$ star). The spectral temperature is then expected initially to *increase* (Kylafis *et al.* 1979), rather than decrease as observed in Cyg X-2. The interesting, but difficult, case of disk accretion onto nonmagnetic neutron stars has so far received little attention. The behavior observed for Cyg X-2 is different from that observed for accreting magnetic neutron stars, and an explanation in terms of current theoretical models of such stars requires additional ad hoc assumptions.

IV. CONCLUSION

We have reported observations of Cyg X-2 which show a novel relationship between X-ray spectral

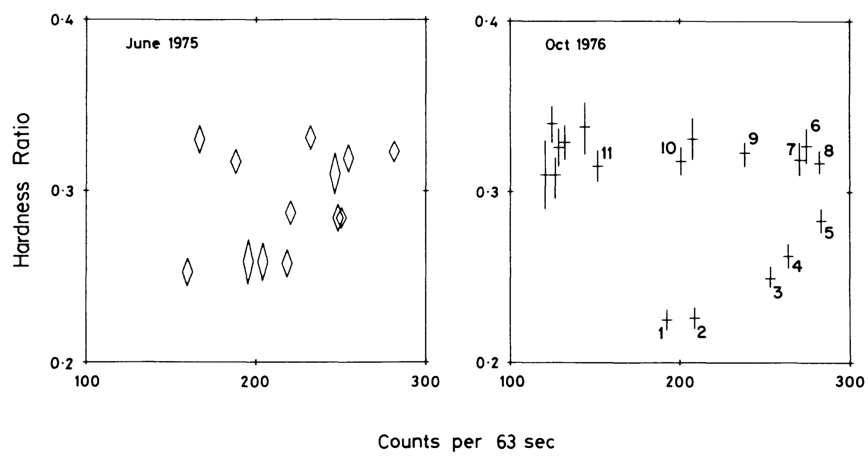

FIG. 2.—Hardness ratio plotted versus the count rate for the 1975 June and the 1976 October data of Cyg X-2. The first 11 bins of the 1976 October observation are labeled chronologically.

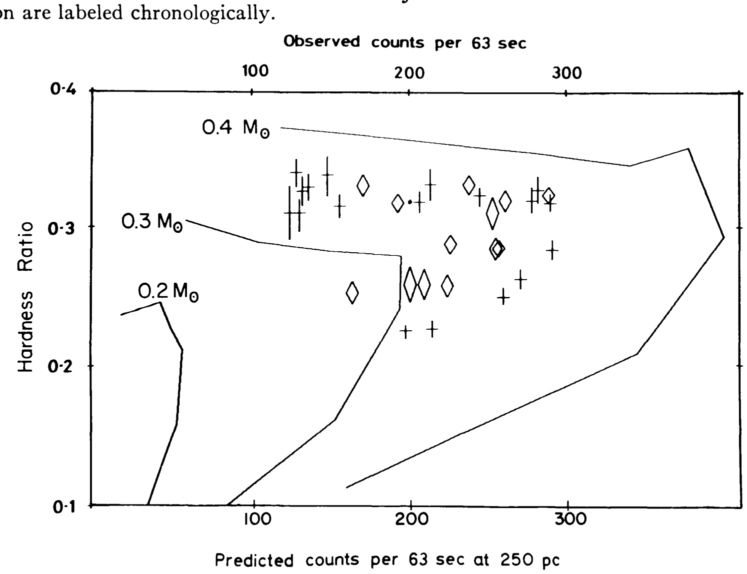

FIG. 3.—Data from Fig. 2 superposed on curves of the predicted correlation between hardness ratio and count rate for different values of mass of the X-ray star.

hardness and intensity. The observed behavior is in general agreement with that predicted by theoretical calculations of X-ray production by spherically accreting, nonmagnetic degenerate dwarfs. Assuming the validity of this model we are able to determine uniquely a mass of $0.35 \pm 0.05\ M_{\odot}$, a luminosity of $7 \pm 2 \times 10^{34}$ ergs s^{-1}, and a distance of 250 ± 50 pc for the X-ray source Cyg X-2. These parameters are at variance with those deduced from the optical data by Cowley *et al.* (1979). The two results cannot be reconciled without either modifying the assumptions which enter into the (standard) analysis of the optical data, or improving our understanding of X-ray emission by compact objects. It is important to resolve this question in view of the exciting possibility that we are able to uniquely identify the nature of the X-ray emitting object in Cyg X-2, and measure its mass, luminosity, and distance, simply by knowing the temporal behavior of its X-ray spectrum.

We are grateful to Fred Lamb for extensive discussions of the physics of compact X-ray sources, and to Anne Cowley, David Crampton, and John Hutchings for valuable discussions of their optical observations. We also thank Peter Sanford, who is Project Scientist for the *Copernicus* X-ray instrumentation. D.Q.L. gratefully acknowledges financial support from the John Simon Guggenheim Memorial Foundation and K.O.M. from the Miller Institute for Basic Research. This research was supported in part by NSF grant PHY78-04404 and NASA contract NAS5-11450.

REFERENCES

Bleach, R. D., Boldt, E. A., Holt, S. S., Schwartz, D. A., and Serlemitsos, P. J. 1972, *Ap. J.*, **171**, 51.

Burginyon, G,. Hill, R., Palmieri, T., Scudder, J., Seward, F., Stoering, J., and Toor, A. 1973, *Ap. J.*, **179**, 615.

Cowley, A. P., Crampton, D., and Hutchings, J. B. 1979, *Ap. J.*, **231**, 539.

Giacconi, R., Gorenstein, P., Gursky, H., Usher, P. D., Waters, J. R., Sandage, A., Osmer, P., and Peach, J. V. 1967, *Ap. J.* (*Letters*), **148**, L129.

Holt, S. S., Kaluzienski, L. J., Boldt, E. A., and Serlemitsos, P. J. 1979, *Ap. J.*, **233**, 344.

Ilovaisky, S. A., Chevalier, C., Motch, C., and Janot-Pacheco, E. 1979, *IAU Circ.*, No. 3325.

Kylafis, N. D., and Lamb, D. Q. 1979, *Ap. J.* (*Letters*), **228**, L105 (KL).

Kylafis, N. D., Lamb, D. Q., Masters, A. R., and Weast, G. J. 1979, *Proc. 9th Texas Symposium on Relativistic Astrophysics* (*Ann. N.Y. Acad. Sci.*), in press.

Marshall, N., and Watson, M. G. 1979, *IAU Circ.*, No. 3318.

Mason, K. O., Charles, P. A., White, N. E., Culhane, J. L., Sanford, P. W., and Strong, K. T. 1976, *M.N.R.A.S.*, **177**, 513.

Swank, J. H. 1977, *Bull. APS*, **22**, 588.

Ulmer, M. P., Sammuli, A., Baity, W. A., Wheaton, W. A., and Peterson, L. E. 1974, *Ap. J.*, **189**, 339.

Worrall, D. M., Swank, J. H., Boldt, E. A., Holt, S. S., and Serlemitsos, P. J. 1978, *Bull. AAS*, **10**, 515.

White, N. E., Mason, K. O., Sanford, P. W., Johnson, H. M., and Catura, R. C. 1978, *Ap. J.*, **220**, 600.

G. Branduardi: Mullard Space Science Laboratory, Holmbury St. Mary, Dorking, Surrey, England

N. D. Kylafis: Theoretical Astrophysics, California Institute of Technology 130-33, Pasadena, CA 91125

D. Q. Lamb: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

K. O. Mason: Astronomy Department and Space Sciences Laboratory, University of California, Berkeley, CA 94720