THE ASTROPHYSICAL JOURNAL, 241:L161–L164, 1980 November 1

SPECTROSCOPIC OBSERVATIONS OF THE OPTICAL COUNTERPART OF CENTAURUS X-4[1,2]

J. VAN PARADIJS
Astronomical Institute, University of Amsterdam; and Center for Space Research, Massachusetts Institute of Technology

F. VERBUNT AND T. VAN DER LINDEN
Astronomical Institute, University of Amsterdam

AND

H. PEDERSEN AND W. WAMSTEKER
European Southern Observatory
Received 1980 June 24; accepted 1980 July 30

ABSTRACT

We have observed the optical spectrum of the transient X-ray burst source Centaurus X-4 about 5 weeks after the source reached its maximum. The brightness of the optical counterpart had decreased to $V = 18.2$, and the star had become appreciably redder ($B - V = 0.7$) compared to its color at maximum. The spectrum of Centaurus X-4 is similar to that of cataclysmic variables, showing strong emission lines of H I and weaker lines of He I and He II. The N III λ4640 line is not visible. The continuum energy distribution of Centaurus X-4 shows the presence of a main-sequence star in the system, with spectral type between K3 and K7. This is consistent with the orbital period of 8.2 hr proposed by Kaluzienski *et al.*, if the main-sequence star is close to filling its Roche lobe. Thus Centaurus X-4 is the first X-ray burst source for which the binary character has been established observationally. We discuss the very slow decay rate of the emission-line fluxes as compared to the X-ray and optical continuum fluxes.
Subject headings: X-rays: binaries — X-rays: bursts — X-rays: sources

I. INTRODUCTION

Cen X-4, which reappeared in 1979 May after a period of invisibility lasting ~10 yr (Kaluzienski, Holt, and Swank 1980; Matsuoka *et al.* 1980) is a clear example of a soft X-ray transient. (For a discussion of the classification of X-ray transients see Kaluzienski *et al.* 1977; Cominsky *et al.* 1978). The source brightened between 1979 May 10 and 16, reached a maximum flux of $\sim 1.6 \times 10^{-7}$ ergs cm^{-2} s^{-1} between May 16 and 24, and from May 24 on declined rapidly with an *e*-folding time of about 3 days. Kaluzienski, Holt, and Swank (1980) found evidence for a regular small-amplitude (~10%) modulation of the X-ray flux with a period 8.2 ± 0.2 hr. Matsuoka *et al.* (1980) reported the discovery of a type I X-ray burst (Hoffman, Marshall, and Lewin 1978) from Cen X-4 during the decline phase, which reached a maximum flux ~25 times the Crab.

The optical counterpart of Cen X-4 (Canizares, McClintock, and Grindlay 1979, 1980) brightened from $B \gtrsim 19$ to $B \approx 12.8$ near May 20, and subsequently declined at an average rate of 0.12 mag per day, reaching $B \approx 18.5$ at the end of 1979 June. Near maximum the star was quite blue ($B - V \approx 0.0$), but during the decay it reddened appreciably. The optical spectrum near maximum was similar to that of other X-ray burst sources, showing weak emission lines of H I, He II, and N III, which indicate the importance of X-ray reprocessing in the system (McClintock, Canizares, and Tarter 1975). Near maximum the brightness of Cen X-4 showed significant flickering, which suggests that a nonnegligible fraction of the optical light comes from an accretion disk.

In this *Letter* we present the results of spectroscopic observations of this object made 5 weeks after the source reached its maximum.

II. OBSERVATIONS

Spectroscopic observations were made on 1979 June 24, 25, 26, and 27 using the image-dissector scanner attached to the Boller & Chivens spectrograph on the ESO 3.6 m telescope. The spectra cover the wavelength interval from 4000 to 6800 Å with a dispersion of 170 Å mm^{-1} and have a resolution of ~10 Å. A flux calibration of the spectra was made through observations of the white-dwarf standard star LDS 749B (Oke 1974), except on the night of June 26, when the observations had to be prematurely terminated because of instrumental problems. The data were reduced using the ESO Image Reduction Facility in Geneva.

III. RESULTS

The spectra obtained during the nights when also standard stars were observed are shown in Figure 1. The most prominent features in the spectrum are the strong Balmer emission lines and the weaker emission lines of He I (λλ4471, 4921, 5016, 5876, and 6678) and

[1] Based on observations carried out at the European Southern Observatory.

[2] Supported in part by the National Aeronautics and Space Administration under contract NAS5-24441.

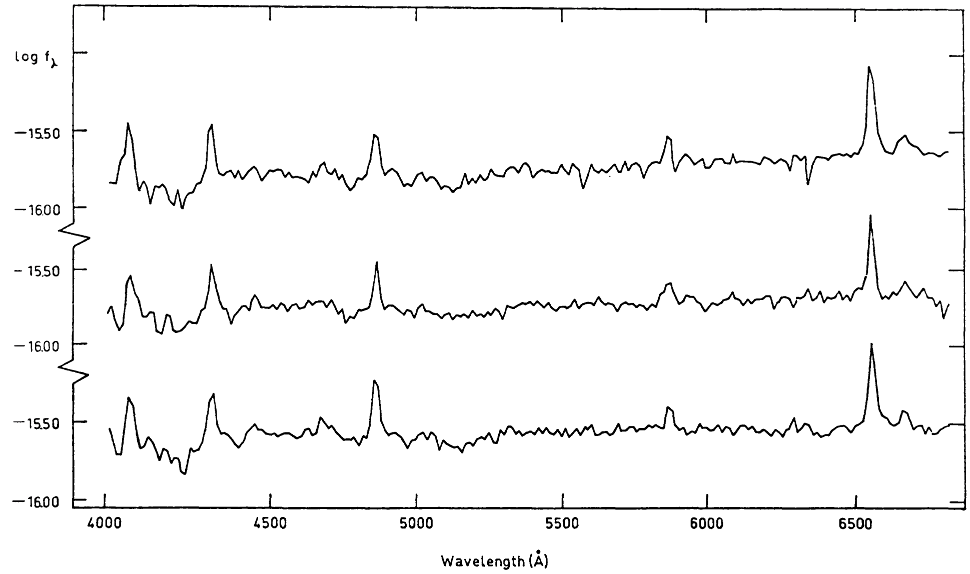

FIG. 1.—Spectra of the optical counterpart of Cen X-4 as obtained on three different nights. Log F_λ (ergs cm^{-2} s^{-1} Å) is plotted vs. λ (Å).

He II (λ4686). The λ4640 blend of N III, which was prominent in the spectra discussed by Canizares, McClintock, and Grindlay (1980) is not visible in the present spectra.

Perhaps the star was somewhat brighter during the last night (by ~0.4 mag). However, in view of the rather large uncertainty in the absolute photometry we do not consider this an established fact. Using the calibration of the *UBV* system of Johnson (1966), we derive an average $V = 18.2$ and $B - V = 0.7$. Thus, at the end of June the optical counterpart of Cen X-4 had approximately reached its preoutburst magnitude of $B \approx 19$ (Canizares, McClintock, and Grindlay 1980).

The equivalent widths of the emission lines were substantially constant during the observing period, and we present their average values only (see Table 1). For the conversion of the equivalent widths to integrated line fluxes we used the average values of the continuum fluxes. The errors in the equivalent widths are the standard deviations of the distributions of the individual values for the different nights. Especially for the weaker lines in the blue spectral region, possible errors due to the uncertainty in the continuum level may be more important. The errors given for the integrated fluxes contain an additional estimated 20% error in the average continuum fluxes.

TABLE 1

EMISSION-LINE STRENGTHS

Line	Equivalent Width (Å)	Flux (10^{-15} ergs cm^{-2} s^{-1})
Hδ......	36.6±7.5	5.1±1.5
Hγ......	45.5±1.5	6.6±1.3
4471.....	6.3±1.8	1.0±0.4
4686.....	9.4±0.8	1.5±0.4
Hβ......	36.7±5.3	6.8±1.7
5016.....	8.3±2.7	1.5±0.6
5876.....	12.9±2.3	2.6±0.7
Hα......	59.0±5.4	14.2±3.1

A comparison with the line fluxes given by Canizares, McClintock, and Grindlay (1980) shows that between about May 28 and about June 25 the Balmer lines had become weaker by a factor of 2.5, the He II λ4686 line by a factor of ~6, and the N III λ4640 line by more than a factor of 40.

Wyckoff's (1979) observation of Cen X-4 on 1979 July 15, shows that Hγ had by then slowly decreased by another factor of 1.5. The continuum flux near 4400 Å is in good agreement with our results. As opposed to Wyckoff, we do not find evidence for a strong [O III] line at 4363 Å (see Fig. 1).

Over a large wavelength range the continuum flux varies smoothly, except from ~4800 to ~5200 Å, where a depression relative to a straight-line interpolation appears to be present. Also below ~4400 Å the continuum is lower than expected from a smooth extrapolation from larger wavelengths. We have determined the shape of the continuous energy distribution using those parts where no obvious contribution from emission lines is present. The results, normalized to 100 at 5500 Å, are shown in Figure 2.

IV. DISCUSSION

a) The Continuous Energy Distribution

The energy distribution of Cen X-4 clearly indicates a significant contribution from a cool stellar companion, whose spectral type was determined by a comparison with energy distributions of undisturbed stars (Straizys and Sviderskiene 1972). The data can be satisfactorily represented by the sum of a K3 to K7 main-sequence star and a smooth blue continuum. The companion cannot have a spectral type earlier than K3, because the dip near 5100 Å (due to MgH and the Mg *b* triplet)

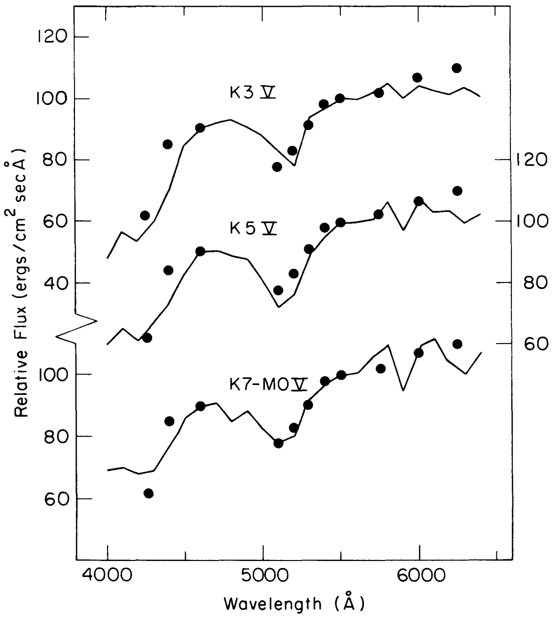

FIG. 2.—The observed continuous energy distribution (*filled circles*) in regions where emission lines do not disturb are compared with theoretical energy distributions expected from a main-sequence star (spectral type indicated) to which a smooth blue continuum has been added. The wavelength dependence of this continuum has been represented by λ^{-1}, but either a $\lambda^{-0.5}$ or a λ^{-2} dependence does not produce a significantly different result. The relative contribution of this blue continuum at 5500 Å equals 0% for a K3 companion, between 17% and 35% at K5, and between 27% and 50% at K7/M0.

is too weak in those stars. Similarly, a spectral type later than K7–M0 can be excluded, since the TiO bands near 6200 Å, which strongly increase in those spectra, are not visible in the spectrum of Cen X-4. (We can exclude a giant star because of the implausible distance of ~50 kpc implied by the faint apparent magnitude.)

The relative amount of continuum light to be added to the stellar continuum to fit the observed energy distribution of Cen X-4 depends on the spectral type of the companion. It is not possible to put strong limits on the wavelength dependence of this additional light. If we assume it is smooth, simple power-law representations $F(\lambda) = K\lambda^{-n}$ will fit for n in the range 0.5–2. Near 5500 Å the contribution from the companion star lies between ~100% (for a K3 V star) and ~60% (for a K7 V star).

With the luminosity calibration of Blaauw (1963) the distance to Cen X-4 then turns out to lie between 1 and 2.5 kpc. This is consistent with the value of 1.5 kpc derived by Matsuoka *et al.* (1980) from the assumption that the peak luminosity of the X-ray burst from Cen X-4 equals the Eddington limit of a 1 $M_\odot$ object (cf. van Paradijs 1978, 1980).

The period of 8.2 hr found by Kaluzienski, Holt, and Swank (1980) allows an estimate of the companion star mass if we make the following assumptions (Faulkner, Flannery, and Warner, 1972; Warner 1976):

a) The 8.2 hr correspond to the orbital period.

b) The companion star is a Roche-lobe–filling main-sequence star.

c) The mass-radius relation for main-sequence stars is given. We then find (see Warner 1976) that the mass of the companion star equals 0.94 $M_\odot$.

The masses of main-sequence stars with spectral types between K3 and M0 lie between 0.5 and 0.75 $M_\odot$ (Allen 1973). These slightly lower values may indicate that the companion underfills its Roche lobe by a small amount or that the assumed mass-radius relation is not entirely applicable (e.g., the star may have evolved a bit off the main sequence).

We conclude that the combined X-ray and optical data consistently show that Cen X-4 is a binary system, in which a neutron star is accompanied by a star near the main sequence, with a mass between 0.5 and 0.9 $M_\odot$. Thus Cen X-4 is the first case of an X-ray burst source for which direct observational evidence has been obtained supporting the long-held hypothesis that these systems are accreting neutron stars in low-mass binary systems (see Lewin and Clark 1980).

The properties of the low-mass companion of Cen X-4 are strikingly similar to those of the other soft X-ray transients for which the companion star has been discovered: A0620 − 00 and Aql X-1, which have K7 V and K0 V companion stars, respectively (Oke 1977; Thorstensen, Charles, and Bowyer 1978). The masses suggested by these spectral types (just a bit below 1 $M_\odot$) are appreciably larger than the values that have been suggested for the steady, soft galactic X-ray sources, based in particular on eclipse considerations (Joss and Rappaport 1979). Perhaps this rather high mass is somehow connected to their transient character.

b) *The Emission Lines*

If the decay rate of the X-ray intensity observed in the *Hakucho* and *Ariel 5* data (Matsuoka *et al.* 1980; Kaluzienski, Holt, and Swank 1980) between 1979 May 24 and June 11 persisted until the end of June, the decrease in the X-ray flux between the times of Canizares, McClintock, and Grindlay's (1980) observations and the present observations is approximately a factor of 10^4. During this period the optical brightness in the B and V bands dropped by 5.5 and 4.8 mag, respectively. Since, furthermore, a significant, and possibly a major, fraction of optical brightness at the end of June is due to the photospheric flux of a companion star (see the discussion above), the corresponding decrease of the optical flux related to the X-ray emission is at least a factor of 100 (and could be as high as ~10^3).

The decay of the emission-line fluxes (by a factor of 2.5 and 6 for H I and He II, respectively) has been extremely slow compared with that of the X-ray and optical fluxes. This very large difference in the decay rates suggests that mechanisms other than X-ray reprocessing play a role in the formation of the emission lines. A similar slow decay of the emission lines was found for A0620 − 00 (Whelan *et al.* 1977; Oke 1977).

The line spectrum of Cen X-4 is quite similar to those of cataclysmic variables (Warner 1976; Robinson

1976), in which the emission of the Balmer lines and He II λ4686 is determined primarily by the disk as a whole. The luminosity in the Hγ line of Cen X-4 during our observation ($\sim 2 \times 10^{30}$ ergs s^{-1}) is about an order of magnitude larger than the typical value given by Warner (1976) for dwarf novae. If the line emission from Cen X-4 is also determined by the accretion disk as a whole, it is unlikely that the mass transfer rate in Cen X-4 could have been much less than the typical value for dwarf novae ($\sim 10^{-9}\, M_\odot$ yr^{-1} according to Warner 1976). The absence of X-ray emission (the *Hakucho* data imply an upper limit to the accretion rate of $\sim 10^{-11}\, M_\odot$ yr^{-1}) makes a cataclysmic variable type of model for the line emission of Cen X-4 rather unattractive.

The later appearance of the [O III] λ4363 line in the spectrum of Cen X-4 (Wyckoff 1979) suggests that part of the line emission may originate in a low-density environment. This raises the possibility that during the process underlying the X-ray transient phenomenon some matter is expelled from the system. (Evidence for large mass loss in the case of the dwarf nova Z Cam has been presented by Robinson 1973). On the other hand, the relative intensities of the Balmer lines (Hα/Hβ = 2.1; Hγ/Hβ = 1.0; Hδ/Hβ = 0.75) suggest that a major fraction of their energy is emitted from a region of quite high density. The presence of the He II λ4686 line suggests electron temperatures of $\sim 2 \times 10^4$ K. According to the calculations by Drake and Ulrich (1980), the observed Balmer decrement indicates an electron density between 10^{12} and 10^{13} cm^{-3}. From their tables of Hβ emissivities we then derive that the size of the emitting region is of the order of a few times 10^{10} cm, which is appreciably smaller than the distance between the two components of Cen X-4 ($\sim 1.5 \times 10^{11}$ cm). This suggests that most of the Balmer emission originates from a region well contained within the binary system.

A possible source of radiation to keep this matter ionized might be the neutron star heated by the energy generated during the high state of the transient source. In calculations of the spectrum due to accretion onto white dwarfs, it is assumed that half of the energy liberated by accretion is radiated away and the other half is heating the accreting object (Kylafis and Lamb 1979). Even with a much smaller fraction ($\sim$10%) of the energy going into the neutron star there would be in principle sufficient energy available to, for example, maintain blackbody radiation at a temperature of 3×10^6 K for 2 yr (for an assumed neutron star radius of 10 km). In view of the expected blackbody-like character of this radiation, only a minor fraction of this radiation would appear at energies above 1.5 keV, and the source would be below the detection limit of the *Hakucho* instruments. On the other hand, this emission would be sufficient to power the observed line emission.

If such a hot neutron star were present in Cen X-4, another mechanism that might contribute to the line emission is the formation of a large chromospheric temperature rise in the outer layers of the K-type companion, as a result of X-ray heating (Milgrom 1976*a*, *b*; *c*, *d*).

We thank Drs. J. McClintock and J. Krolik for stimulating discussions. F. V. is supported by the Netherlands Foundation for Pure Research Z. W. O.

REFERENCES

Allen, C. W. 1973, *Astrophysical Quantities* (London: Athlone).
Blaauw, A. 1963, in *Basic Astronomical Data*, ed. K. Strand (Chicago: University of Chicago Press), p. 383.
Canizares, C. R., McClintock, J. E., and Grindlay, J. E. 1979, *IAU Circ.*, No. 3362.
———. 1980, *Ap. J.* (*Letters*), **236**, L55.
Cominsky, L., Jones, C., Forman, W., and Tananbaum, H. 1978, *Ap. J.*, **224**, 46.
Drake, S. A., and Ulrich, R. K. 1980, *Ap. J. Suppl.*, **42**, 351.
Faulkner, J., Flannery, B. P., and Warner, B. 1972, *Ap. J.* (*Letters*), **175**, L79.
Hoffman, J. A., Marshall, H. L., and Lewin, W. H. G. 1978, *Nature*, **271**, 630.
Johnson, H. L. 1966, *Ann. Rev. Astr. Ap.*, **4**, 191.
Joss, P. C., and Rappaport, S. A. 1979, *Astr. Ap.*, **71**, 217.
Kaluzienski, L. J., Holt, S. S., Boldt, E. A., and Serlemitsos, P. J. 1977, *Ap. J.*, **212**, 203.
Kaluzienski, L. J., Holt, S. S., and Swank, J. H. 1980, *Ap. J.*, submitted.
Kylafis, N., and Lamb, D. Q. 1979, *Ap. J.* (*Letters*), **228**, L105.
Lewin, W. H. G., and Clark, G. W. 1980, Proc. NATO Advanced Study Institute, Cape Sounion, Greece, June 1979, in press.
Matsuoka, M., *et al.* 1980, *Ap. J.*, submitted.
McClintock, J. E., Canizares, C. R., and Tarter, B. 1975, *Ap. J.*, **198**, 641.
Milgrom, M. 1976*a*, *Ap. J.*, **205**, 545.
———. 1976*b*, *Ap. J.*, **207**, 902.
———. 1976*c*, *Ap. J.*, **208**, 191.
———. 1976*d*, *Astr. Ap.*, **50**, 273.
Oke, J. B. 1974, *Ap. J. Suppl.*, **27**, 21.
———. 1977, *Ap. J.*, **217**, 181.
Robinson, E. L. 1973, *Ap. J.*, **186**, 347.
———. 1976, *Ann. Rev. Astr. Ap.*, **14**, 119.
Straizys, V., and Sviderskeine, Z. 1972, *Bull. Vilnius Astr. Obs.*, No. 35.
Thorstensen, J., Charles, P., and Bowyer, S. 1978, *Ap. J.* (*Letters*), **220**, L131.
van Paradijs, J. 1978, *Nature*, **274**, 650.
van Paradijs, J. 1980, *Nature*, submitted.
Warner, B. 1976, in *IAU Symposium 73, Structure and Evolution of Close Binary Systems*, ed. P. Eggleton, S. Mitton, and J. Whelan (Dordrecht: Reidel), p. 85.
Whelan, J. A. J., *et al.* 1977, *M.N.R.A.S.*, **180**, 657.
Wyckoff, S. 1979, *IAU Circular*, No. 3386.

H. Pedersen and W. Wamsteker: European Southern Observatory, Casillia 16317, Correo 9, Santiago, Chile (285006)

T. van der Linden, J. van Paradijs, and F. Verbunt: Astronomical Institute, University of Amsterdam, Roetersstraat 15, 1018 WB Amsterdam, The Netherlands