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δ Cap – The Secondary Revealed

D Wonnacott B J Kellett L Matthews C A Clayton G E Bromage C Lloyd T J Sumner and S D Sidher

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δ Cap — The Secondary Revealed

D. Wonnacott [1], B. J. Kellett [1], L. Matthews [2], C. A. Clayton [3], G. E. Bromage [1], C. Lloyd [1], T. J. Sumner [2], S. D. Sidher [2]
[1] *Astrophysics Division, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon., OX11 0QX*
[2] *Blackett Laboratory, Imperial College of Science, Technology and Medicine, Prince Consort Road, London, SW7 2BZ*
[3] *Planetary and Astrophysical Data Division, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon., OX11 0QX*

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SUMMARY
The recent detection of the eclipsing metallic-lined binary δ Cap in the extreme ultraviolet as part of the *Wide Field Camera All-Sky Survey* has prompted a re-examination of the available data in order to attempt to locate the source of the emission. It can be shown that a white dwarf is unable to account for the emission, and the possibility of coronal emission on one of the four other faint objects within the *WFC* error circle and the Am star can be rejected. The available data are consistent with the visually unseen secondary being weakly active.

1 INTRODUCTION

The southern star δ Cap (HR 8322, HD 207098 or ADS 15314 A) has been known to be a (radial velocity) variable star since Slipher (1906) detected radial velocity variations which he cited as evidence for duplicity. This was shown to be the case when Luyten (1936)—and subsequently Stewart (1958) and Batten (1961a)—obtained the orbital parameters for this bright ($V = 2.^{m}87$) single-lined binary with a period of just over one day ($P = 1.^{d}022$).

Slettebak (1949) has classified δ Cap as A6 from the Ca II K line, as F2 from the hydrogen lines, and as F5 IV using the metal lines, and Abt & Bidelman (1969) gave the system the metallic-lined A star (Am) designation.

The eclipses of δ Cap were first noted by Eggen (1956). More recently, Ohmori (1981) has shown that the depth of the primary minimum is variable by a few hundredths of a magnitude. The light curve itself exhibits a scatter of about this amplitude and can also show epoch-dependent variations as large as $\Delta V = 0.^{m}06$. Cowley *et al.* (1969) denoted δ Cap as a δ Del star, a class of sometimes-pulsating, (marginally) metallic-lined A stars that has since been shown to be both spectroscopically and photometrically inhomogeneous (Gray & Garrison 1989) in that it seems to be a collection of large-amplitude δ Scuti stars, normal A stars *and* Am stars. The latter authors recommend that this class be dropped. This system has also received a δ Scuti classification (Levato 1972) which marks it as a low-amplitude pulsator, possibly in an attempt to account for the photometric scatter. However, this classification does not appear to be pre-dated by any published analysis of the 'pulsation', perhaps indicating a confusion between the δ Del and δ Scuti groups. Lloyd & Wonnacott (1992) have recently performed such an analysis of some of the available photometry and find no evidence of *coherent* pulsational activity.

There exist two sets of wide-band polarization measurements: the first by Tinbergen (1979) claims that δ Cap has zero polarization quoting the Stokes' parameters (Q/I, U/I) as $(-4 \pm 3, -4 \pm 3) \times 10^{-3}$ % between 4000–7000 Å, whereas Luna (1981) measured (Q/I, U/I)= $(9 \pm 4, 5 \pm 4) \times 10^{-2}$ % with unfiltered observations and denotes δ Cap as "possibly variable", but makes no mention of any contribution due to instrumental polarization. If the polarization is variable at this level then it seems likely that there is some circumstellar material present, a result in accord with the Hα-index photometry of Dorren *et al.* (1980) who find an excess of absorption between phases $\phi = 0.5$–0.93. Although this is consistent with either a large spot on the A star or an Algol-type stream, the former would almost certainly have been detected in the aforementioned period analysis of the system and the latter would probably show up in the Mg II ($\lambda\lambda$2795, 2803) and Fe II (λ2599) lines as in the case of U Cep (Kondo, McCluskey Jr. & Stencel 1979): neither set of lines shows any significant asymmetry.

Several aspects make the EUV detection reported here interesting. Firstly, there is simply the question of whether or not any of the neighbouring objects on the sky are EUV sources—are they nearby and weak or distant yet strong? Secondly, there is the intriguing possibility that pulsations (or whatever is causing the photometric scatter) in δ Cap A are generating a corona-like structure detectable in the EUV, and thirdly, the faint secondary is a substantially unknown object—is the EUV a window onto it?

2 THE EXTREME ULTRAVIOLET

The British *Wide-Field Camera*, launched as part of the *ROSAT* mission, has recently completed the first survey of the entire sky at extreme ultraviolet wavelengths (67–200 Å in two bandpasses), detecting many hundreds of new sources as well as casting new light (literally) on more familiar ones. (For a more comprehensive summary see Pounds *et al.* 1991).

The *Wide-Field Camera* detects signals from two main types of source; thermal emission from white dwarfs and emission from the hot (10^6–10^7 K) plasma surrounding coronally active stars. Both possibilities must be examined in the context of δ Capricorni, as distant white dwarfs close to the line-of-sight to δ Cap could just as easily be responsible for the detection as could a nearby active star.

2.1 EUV radiation from a white dwarf?

The Aitkin Double Star catalogue lists four stars at or near the position of δ Capricorni, namely the binary components of δ Cap, ADS 15314 B ($V = 15.^{m}8$), and ADS 15314 C ($V = 12.^{m}7$): no other information has been published on these two dim objects. It is therefore appropriate to consider the possibility that a nearby white dwarf is responsible for the *WFC* detections, given that one of the faint stars may be such an object or that the system may be similar to the well-known Sirius system (A1 Vm + DA).

The white dwarf models are the pure hydrogen (LTE and hydrogen line-blanketed) model atmospheres of Wesemael *et al.* (1980), extended into the EUV and X-ray region, with $\log g = 8.0$ and with corrections for trace helium due to Petre, Shipman & Canizares (1986). This gives a total of sixteen models which have been interpolated with tension splines onto a helium abundance versus temperature grid consisting of 18×15 models. The model white dwarfs have $R_{WD} = 0.01\,R_{\odot}$ and are assumed to lie at the distance of δ Cap (11.5 pc, taken from Hoffleit 1982). In Paresce (1984), the columns to the stars nearest to δ Cap ($l = 37.^{\circ}6, b = -46.^{\circ}0$) are $10^{18}\,\mathrm{cm}^{-2}$ (ε Ind; $l = 336^{\circ}, b = -48^{\circ}$, D = 3.5 pc) and $7 \times 10^{18}\,\mathrm{cm}^{-2}$ (α Gru; $l = 350^{\circ}, b = -52^{\circ}$, D = 23.9 pc). The mean of these values, scaled to the distance of δ Cap, is $3.6 \times 10^{18}\,\mathrm{cm}^{-2}$ and will be used as the column to δ Cap in subsequent calculations.

A convolution of these models with the *WFC* instrument efficiencies and survey filter passbands produces a grid of count-rate predictions as a function of both temperature and helium abundance. The δ Cap detections are given in table 1 and the predicted count-rates in table 2.

The solution space is given by the region where count-rate contours with the above values cross in the (T_{WD}, n_{He}/n_{H}) plane. Nominally, the S1a and S2a fluxes agree over the range $(2.7 \pm 0.2) \times 10^4$ K and for helium abundances in the range $(1.5 \pm 0.5) \times 10^{-4}$ (see figure 1).

As well as EUV emission, hot DA white dwarfs are strong sources of UV radiation. With the grid of models generated above, it is possible to calculate the expected flux in the *IUE* range (specifically, at as short a wavelength as possible to maximize the detection of the hypothetical white dwarf whilst avoiding Ly α). These fluxes are also given in table 2. Only fluxes for pure hydrogen models are quoted as the helium abundance does not significantly affect a white dwarf's spectrum longwards of 912 Å.

The *IUE* archive contains one high-resolution spectrum of δ Cap in each wavelength region (SWP31084 and LWP10895). Extraction was performed using the STARLINK packages IUEDR (Rees 1987) and DIPSO (Howarth & Murray 1987). The wavelength scale was set to the laboratory rest-wavelengths of the lines (both wavelength and velocity shifts were removed) and the fluxes were calibrated using the latest inverse sensitivities (Rees 1991). The fluxes are in excellent agreement with those measured in the S2/68 ultraviolet sky survey on the TD-1 satellite (Jamar *et al.* 1976). At $\sim$ 1300 Å, the integrated *IUE* flux is limited by the noise due to the short exposure of 450 s, but integrated over a 50 Å region around 1325 Å (which avoids Ly α) is $6.5 \times 10^{-11}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$. Comparison of this value with table 2 shows that the computed model band-fluxes are substantially larger, making it impossible to obtain a solution which is simultaneously consistent with the *WFC* and *IUE* observations of this system. This rules out the possibility that the *WFC* detections are due to a white dwarf at the same distance as the δ Cap system.

The possibility of a white dwarf *between* the Earth and δ Cap can be excluded because lowering the column to the EUV source does not change the EUV fluxes in any significant way, but moving the source closer rapidly increases the *IUE* flux, strengthening the disagreement between prediction and observation. A more distant white dwarf must be further than $\sim$ 50 pc to be consistent with both the EUV and UV observations.

2.2 Photometry in the *WFC* error circle

As the *IUE* large aperture used for the observations of δ Cap is $10'' \times 20''$ (Boggess *et al.* 1978), the above arguments exclude white dwarfs along the line-of-sight, but cannot be used to exclude faint objects which lie outside the *IUE* aperture but inside the $66''$ *WFC* 99 % error circle centred on $\alpha_{2000} = 21^{h}\,47^{m}\,1.^{s}6, \delta_{2000} = -16^{\circ}\,7'\,7''$

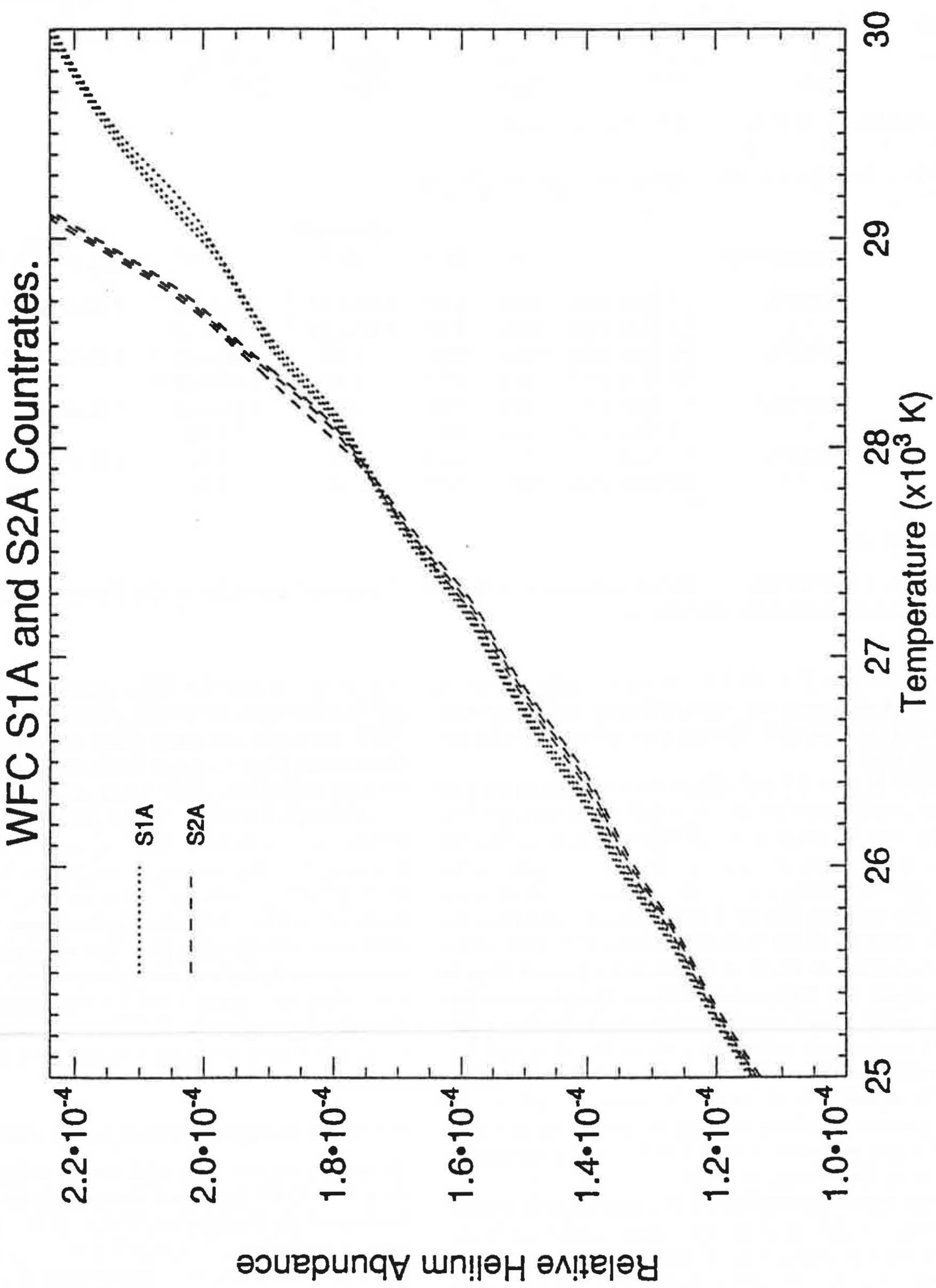

Figure 1. *Contours of constant count-rate in the temperature versus helium abundance plane for model DA white dwarfs assuming a negligible column. Both S1a and S2a count-rates are shown bracketed by one-standard-deviation error-contours*

Filter	Effective wavelength (Å)[a]	Bandwidth (Å)[a]	Total exposure time (sec)	Count-rate (counts/sec)	Significance (σ)
S1a	100.0	70.8	1246	0.0520 ± 0.009	8.9
S2a	137.9	88.3	1663	0.0504 ± 0.009	11.0

[a]Data taken from the *ROSAT/WFC* AO-2 document

Table 1. *Data for the WFC survey observations of δ Cap*

Temperature		n(He)/n(H) 0	10^{-5}	10^{-4}	10^{-3}	$f_{1325\,\text{Å}}$ (erg s^{-1} cm^{-2})
25000 K	S1 Flux (c/s)	2.01	1.37	8.40×10^{-2}	5.65×10^{-7}	3.88×10^{-10}
	S2 Flux (c/s)	3.87	2.39	8.07×10^{-2}	1.65×10^{-5}	
30000 K	S1 Flux (c/s)	27.4	20.3	2.15	1.39×10^{-4}	8.58×10^{-10}
	S2 Flux (c/s)	49.2	32.3	1.54	3.79×10^{-2}	
40000 K[a]	S1 Flux (c/s)	288	236	53.1	1.03×10^{-2}	1.21×10^{-9}
	S2 Flux (c/s)	491	367	42.2	1.50	
50000 K	S1 Flux (c/s)	1670	1510	661	4.47	1.70×10^{-9}
	S2 Flux (c/s)	2810	2380	658	6.67	

[a]Interpolated

Table 2. *Predicted S1a and S2a count-rates and the UV 'continuum' fluxes for model DA white dwarfs of various temperatures and helium abundances*

(*not* on δ Cap). For this reason, imaging photometry of the δ Cap sky region was undertaken at the SAAO with the RCA SID 53612 CCD chip on the 1-metre telescope in July 1991.

Both *B* and *I* band filters were employed to give colours, and the images show a total of eight objects (excluding the binary system), of which two are within the *WFC* error circle (see figure 2). It is not possible to unambiguously identify any of the objects as ADS 15314 B or C. However, the observed magnitudes are such that the latter, having a visual magnitude above 13[th], must either lie beyond the the edges of the CCD images and thus be well outside the *WFC* error circle, or the proper motion of δ Cap has moved the two into sufficiently close alignment to hide the former in the glare of the latter; this last possibility, unfortunately, cannot be entirely ruled out.

The *B* and *I*-magnitudes are listed in table 3. All the objects, are too red to be white dwarfs. In fact, they are *strongly* reddened making a *WFC* detection unlikely because of the column involved.

This leaves the possibility that a (distant) white dwarf lies within $\sim 29''$ of δ Cap (the region of the CCD saturated by the bright star in figure 2) and also within the error circle, yet outside the region covered by the *IUE* aperture. Although there are approximately 1300 white dwarfs known (McCook & Sion 1987), the *WFC* preferentially detects the hottest of these (DA1–2-types) amounting to $\sim$ 50 known prior to the survey and $\sim$ 50 new discoveries. This is out of a total of 1000–1500 EUV sources detected by the *WFC* implying that the probability that this small (currently unobserved) area contains a *WFC-detectable* and *single* white dwarf is less than 10 %. Interacting binary systems harbouring white dwarfs can be more stringently ruled out as shown below.

Although several (new and previously known) Cataclysmic Variables have also been seen in the survey and typically have a visual magnitude fainter than $V \sim 15$, all these detections (bar one on the noise limit) are between four and six times brighter than the fluxes measured here and, more significantly, they are *strongly* modulated in a characteristic fashion which is certainly not present in these data (see figure 4 for the time-series). Based on the experience from the *WFC* survey, therefore, this detection is almost certainly *not* due to a CV or AM Her system.

2.3 EUV radiation from an active star?

To date, no active stars with visual magnitudes greater than $V \sim 13.^{m}5$ have been detected in the *WFC* survey because of the limiting sensitivity of the *WFC*. On this basis, it is highly unlikely that the two objects seen within the *WFC* error circle are active enough to account for the observed EUV signal. Star four is, however, sufficiently red to warrant suspicion. Using the Image Tube Spectrograph and the Reticon Photon Counting System on the 1.9-metre at the SAAO also in July 1991, a spectrum of star four was acquired in the Ca II H&K region (3500–4200 Å) at a resolution of ~ 1 Å as part of a larger and

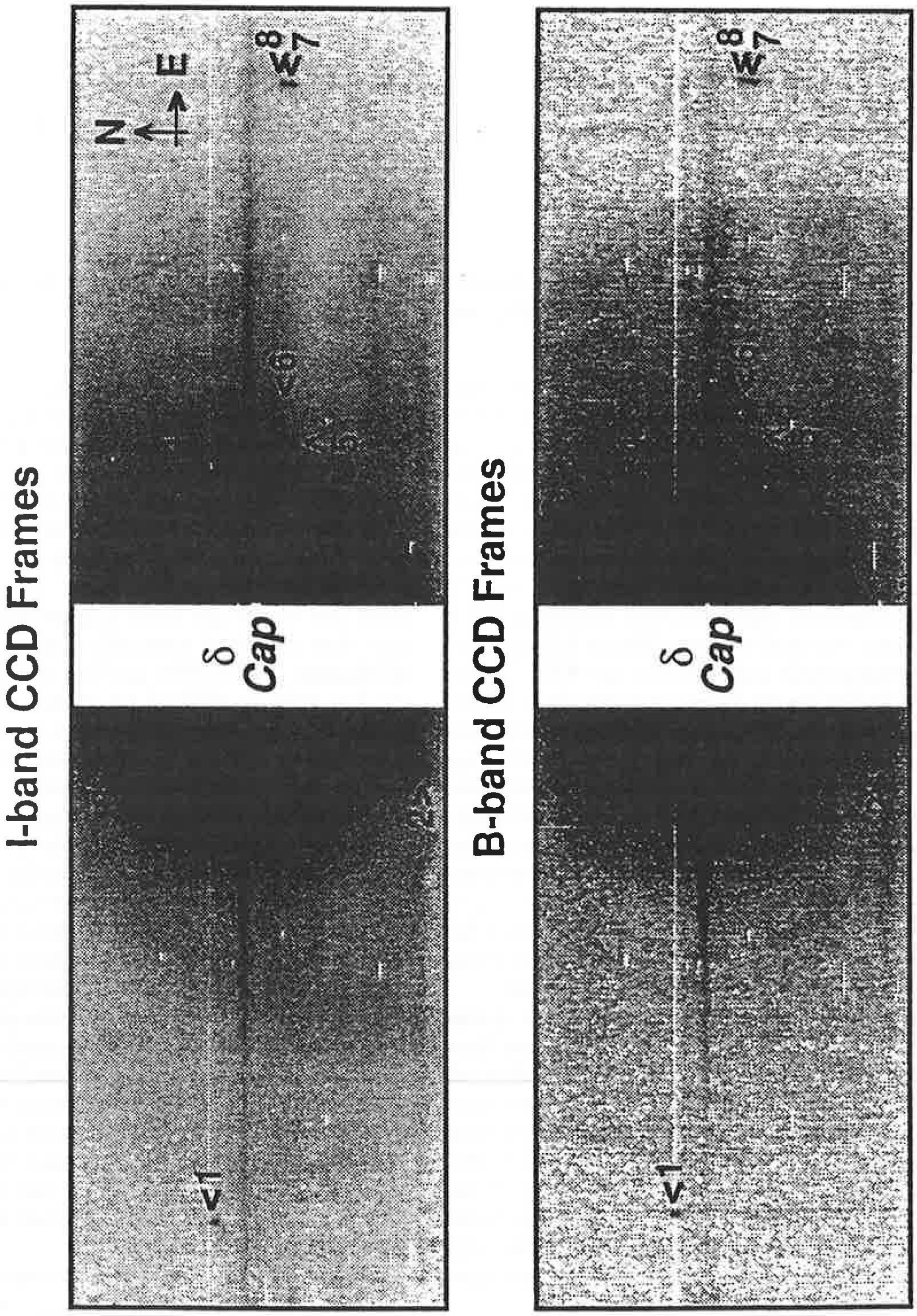

Figure 2. *B and I-band images of the field around δ Cap. The objects are labelled as listed in table 3*

Object	*WFC* offset / ″	*B*	*I*	
1	196	17.5	15.9	
2	91	17.3	14.8	
3	47	> 17.8	17.2	
4	43	15.7	14.1	(ADS 15314 B?)
5	69	> 17.8	16.2	
6	80	> 17.8	17.4	
7	181	> 17.8	16.1	
8	181	> 17.8	16.3	

Table 3. *SAAO photometry of the sky region around δ Cap. The WFC 99 % error circle is 66″ in radius, and the offsets are (EUV source position − optical position) and are accurate to 20 %*

ongoing project to identify and study *WFC* active stars. Figure 3 shows the sky-subtracted, flat-fielded and wavelength calibrated spectrum. Also shown for comparison is the spectrum of an active star of similar spectral type taken on the same run, and although the exposure times differ by a factor two, it is plain that to within the noise there is *no* Ca II emission indicative of coronal activity.

The primary of δ Cap is a late-A dwarf or early-F sub-dwarf. This spectral type is the very earliest in which coronal activity is expected to occur (Simon & Landsman 1991) and is consequently unlikely to be the *WFC* source.

The *Wide-Field Camera Survey* was examined for detections of, or limits on, the count-rates from a selection of nearby stars spanning the spectral type range of δ Cap (A6 V–F5 IV). Nearby objects were selected as they provide the tightest limits and are less likely to exhibit differences between the filters due to any interstellar column. One object at the extreme of the allowed range was detected, the others were not; all are presented in table 4. Also given are the percentage contributions (f_1 and f_2) such limits would give to the observed signals from δ Cap if it were at the same distance as the sampled stars.

It is readily apparent from table 4 that the A star primary of the δ Cap system can contribute *no more* than 40 % of the observed flux in the extreme case, and, in all probability, is responsible for a totally negligible amount.

In Holmesian fashion, this leaves the dim secondary of δ Cap as the source of the EUV radiation. To date, practically nothing is known about the secondary of the δ Cap system. Batten (1961b) states that it must be three visual magnitudes fainter than the primary, and the only attempt to fit a light curve (Malasan *et al.* 1989) assumes a temperature of 4000 K for the secondary.

The *WFC* light-curve is shown in figure 4. Owing to the low level of activity observed in this system, the photons have been folded on the orbital period prior to binning in order to minimize the photon noise. The error bars are derived from the Poisson statistics of the photon arrivals. Both filters are shown; note that the absence of data in the ϕ = 0.2–0.3 region is due to the detector switch-off when crossing the South Atlantic Anomaly which would otherwise saturate the detector.

The intriguing feature of these data is that, although δ Cap is an eclipsing binary with a one-day period, there is no obvious eclipse to be seen; the light curve is statistically indistinguishable from constancy (χ_ν^2 = 0.48 and 0.86 for the S1a and S2a filters respectively, although these low values are more a reflection on the large errors than a lack of detectable variability). The model of Malasan *et al.* (1989) predicts that the faint companion has 45 % or 27 % of its surface still visible during secondary eclipse depending upon whether the primary is evolved or still on the Main Sequence. Neither case is ruled out by the EUV observations and the metallic-lined condition of the primary makes an accurate spectral classification very difficult. However, a larger visible area would be preferred. Conversely, the LEIT instrument on board *EXOSAT* overlaps both the S1a and S2a filter bands, and this failed to detect soft X-ray eclipses in Algol (White *et al.* 1986) where the visible eclipses are almost total, and this was interpreted as implying that extended coronal features were present. The EUV data presented here do not permit such a conclusion to be drawn *or* excluded, as the low number statistics inhibit a clear identification of an EUV eclipse at any phase.

The count rates and the hardness ratio can be used as before but with an RS plasma model (Raymond & Smith 1977) to deduce the temperature and (isothermal) emission measure for the secondary (assuming $\log_{10} N_H = 3.6 \times 10^{18}\,\mathrm{cm}^{-2}$).

There are four permitted solutions:

$$\mathrm{T} = 8.0 \times 10^5\,\mathrm{K} \text{ and}$$
$$\mathrm{EM} = 0.7 \times 10^{50}\,\mathrm{cm}^{-3},$$

$$\mathrm{T} = 2.0 \times 10^6\,\mathrm{K} \text{ and}$$
$$\mathrm{EM} = 2.6 \times 10^{50}\,\mathrm{cm}^{-3},$$

$$\mathrm{T} = 1.0 \times 10^7\,\mathrm{K} \text{ and}$$

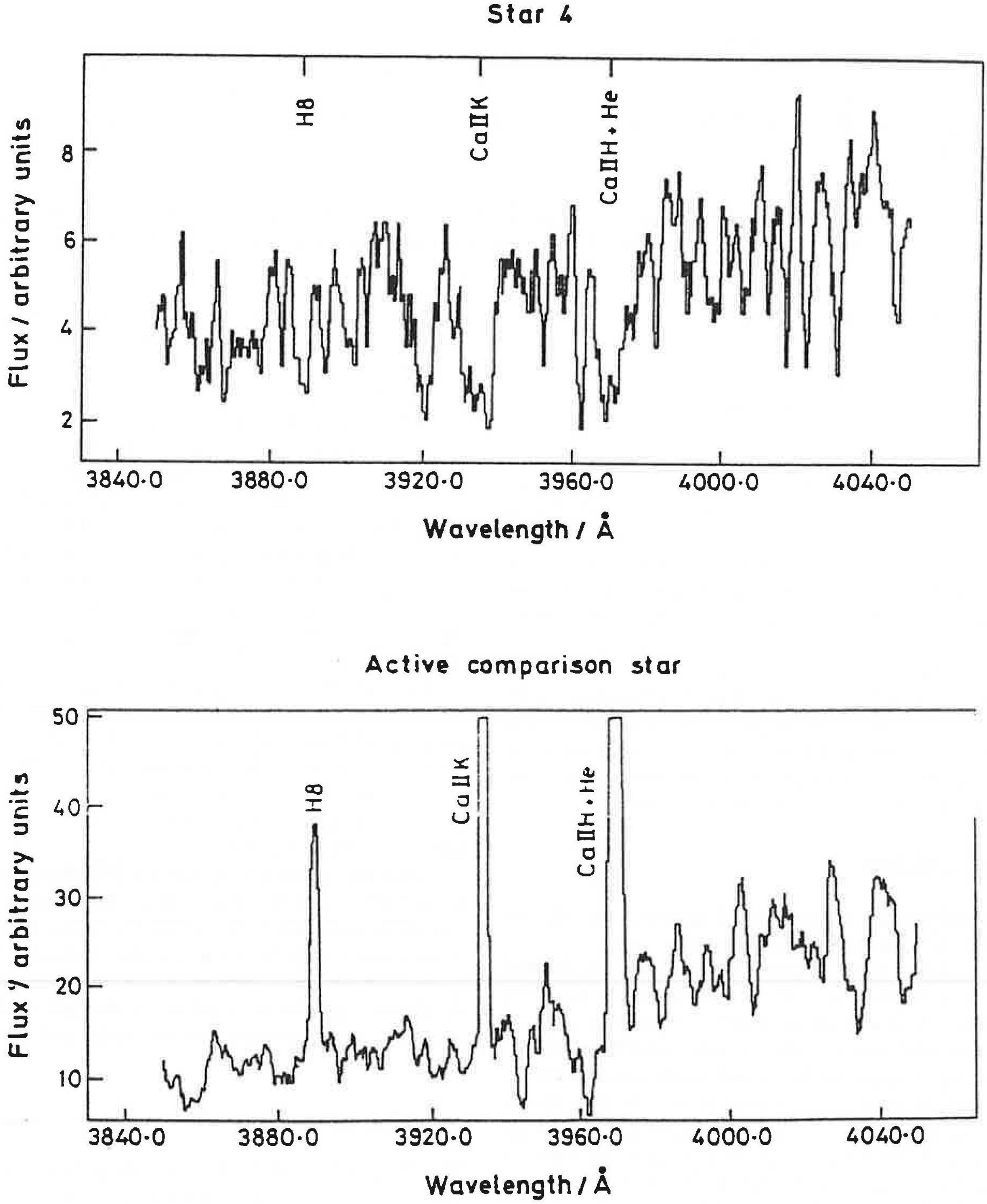

Figure 3. *A spectrum of star number 4 showing the calcium H & K region, and, for comparison, a spectrum of an known active star of the same magnitude and spectral type scaled to approximately the same 'arbitary units'. The lack of Ca II emission is self-evident*

Object	Sp. T.	D / pc	S1a / c/s	S2a / c/s	f_1 / %	f_2 / %
α Aql	A7 V	4.95	$< 2.66 \times 10^{-2}$	$< 1.71 \times 10^{-2}$	9.5	6.3
α Hyi	F0 V	20.8	$< 2.14 \times 10^{-3}$	$< 2.07 \times 10^{-3}$	13.5	13.5
HR 4102	F2 IV	11.7	$< 4.18 \times 10^{-3}$	$< 2.87 \times 10^{-3}$	8.3	5.9
α CMi	F5 IV–V	3.47	0.112	0.216	19.6	39.0

Table 4. *WFC Survey data for stars similar to δ Cap A. The limits and detections quoted, when compared with the observed rates for δ Cap, demonstrate that the A star primary is most unlikely to be responsible for the EUV signal*

$$\mathrm{EM} = 3.3 \times 10^{50}\,\mathrm{cm}^{-3},$$

and

$$\mathrm{T} = 3.0 \times 10^{7}\,\mathrm{K} \text{ and}$$
$$\mathrm{EM} = 14 \times 10^{50}\,\mathrm{cm}^{-3}.$$

Unfortunately, there is no way of distinguishing between the various temperatures—all are equally valid without further information.

Comparison of the emission measures given above with the others derived from X-ray data for RS CVns (Schmitt *et al.* 1990) or the late-type components of Algols (e.g., White *et al.* 1986)—both of which are *tentative* identifications for the δ Cap system (Srivastava 1988a; Srivastava 1988b)— which are typically of the order of 10^{52}–10^{53} cm^{-3}: the implication is, therefore, that δ Cap B is only *mildly* active in the sense that either or both of the emitting volume and the electron density are smaller than in more common active systems.

3 DISCUSSION

The optical and EUV data unambiguously identify the secondary of δ Cap as an active late-type star.

If, as seems likely (Zahn 1966; Tassoul & Tassoul 1990), the secondary is rotating synchronously, then the active region(s) would remain fixed in phase and any material suspended in the magnetic loops would give rise to emission, particularly in Hα, which could account for the phased variations seen by Dorren *et al.* (1980) in the α-index. The spot need not be exactly synchronous as the spot migration time for active stars is typically between a year and a decade (see *Individual Notes* in Strassmeier *et al.* 1988) and the α-index observations were taken over a period of just over a year. The spot(s) would have to be located on the trailing hemisphere of the secondary to be consistent with the observed decrease in the strength of Hα between phases $\phi = 0.93$–0.5.

There have been two sets of radio observations of δ Cap, both around 8.5 GHz. Slee *et al.* (1987) observed the system nine times and detected it only once, yielding a flux of 2.6±0.8 mJy and Stewart *et al.* (1989) obtained detections twice out of twelve attempts, finding a maximum flux of 6.2±1.5 mJy, the median of the observations being 4.4 mJy.

The interpretation that the detections are due to gyrosynchrotron radiation from electrons trapped in the magnetic field structures can be used to derive a local magnetic field induction and the calculations of Stewart *et al.* give a value B $\sim$ 150 G. This figure appears to be larger than the field strengths seen in RS CVns in quiescence, e.g., Kuijpers & van der Hulst (1985) estimate the field strength for σ^2 CrB to be 27–35 G between the stars, but smaller than the fields deduced during flares on Algol (White *et al.* 1986; B > 200 G) and HR 1099 (Barstow 1985; B $\sim$ 360 G).

The detection limit for the Parkes observation is about 1–2 mJy which implies a minimum detectable field strength of $\mathrm{B}_{\mathrm{min}} \sim$ 24–48 G, i.e., δ Cap in quiescence is probably just below detection, and when it was observed (on average once in about 8 times) the field strengths were similar to, but slightly weaker than, those seen in flares on other active stars.

A further possibility is that the 2 % photometric scatter in *UBV* could be caused either by emission from the material contained in the magnetic loops or even from circumstellar material from coronal mass ejections, the latter being most applicable if the loops extend outside the Roche lobe of the secondary. A detailed analysis must await a more accurately defined stellar and loop geometry.

4 CONCLUSION

The observations of the binary system δ Cap in the EUV and in the radio clearly demonstrate that the secondary is a mildly active star. It is deduced that as the secondary is likely to be synchronously rotating with the binary system, an active spot (or spots) has remained fixed on the trailing hemisphere of the *faint* star and material suspended in magnetic loops caused the excess Hα absorption seen by Dorren *et al.* (1980). It is also possible that mass-ejections during flares gives rise to sufficient

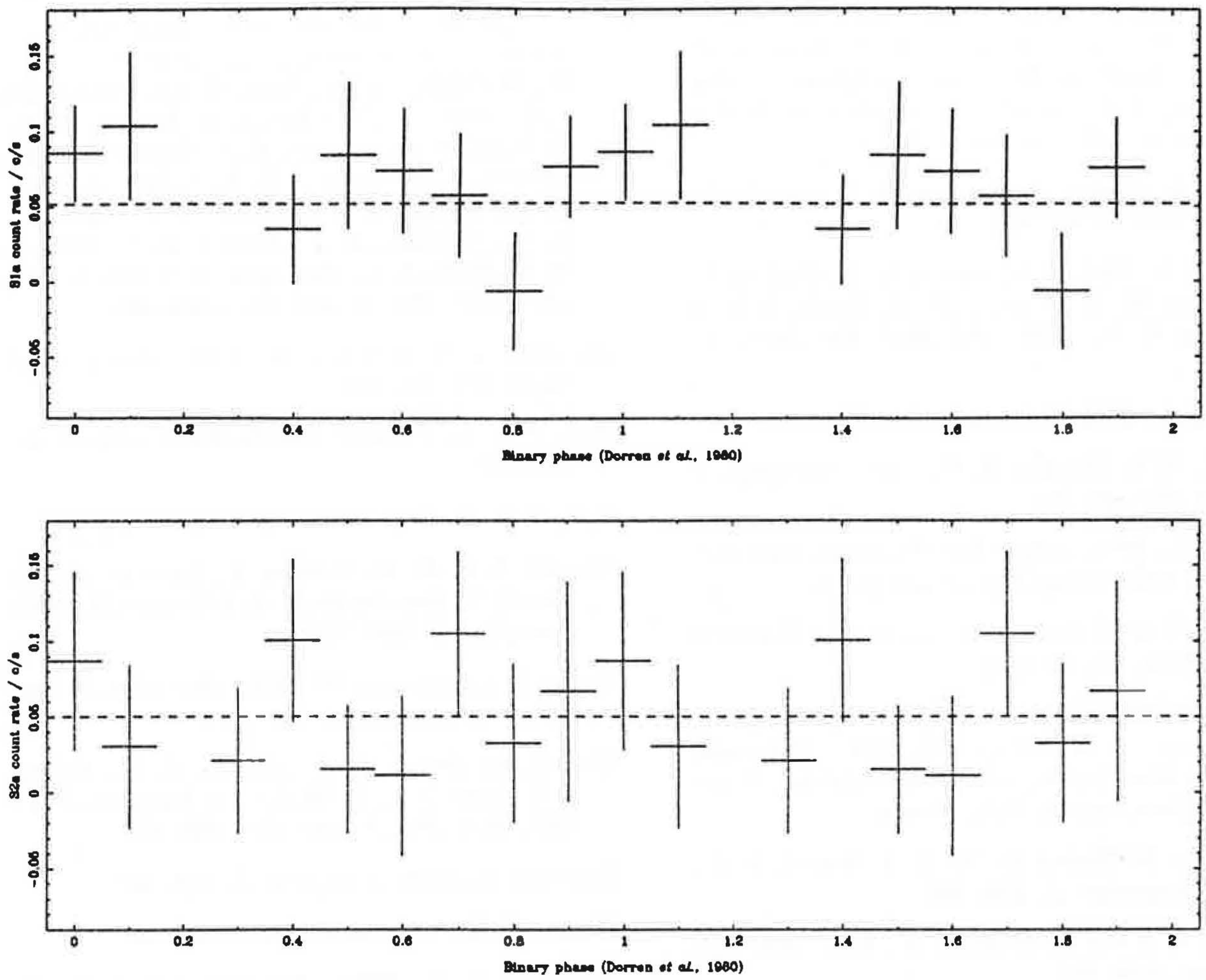

Figure 4. *Wide-Field Camera light curve of δ Cap. The counts have been phased up prior to binning to increase the signal-to-noise and the light-curve is repeated over two cycles for clarity*

circumstellar material to account for the scatter in the *UBV* photometry.

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