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THE WINDS IN CATACLYSMIC VARIABLE STARS

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Abstract

Ultraviolet spectrophotometry of two dwarf novae, CN Ori and RX And, at various phases of their outburst cycles confirms that the far UV flux increases dramatically about 1 - 2 days after the optical outburst begins. At this time the UV spectral line profiles indicate the presence of a high velocity wind. The detectability of the wind depends more on the steepness of the spectrum, and thus on the flux in the extreme ultraviolet, than on the absolute value of the far UV luminosity. The UV continuum during outburst consists of (at least) two components, the most luminous of which is located behind the wind and is completely absorbed by the wind at the line frequencies. Several pieces of evidence suggest that the UV emission lines that are observed in many cataclysmic variables during quiescence have a different location in the binary than the wind, and are affected very little by the outburst.

I. INTRODUCTION

Ultraviolet spectroscopy has shown that high velocity winds emanate from many cataclysmic variable (CV) stars (cf. references in Cordova and Mason 1984; hereafter, CM84). These stars are binary systems in which a low-mass red star overflows its Roche lobe and transfers material via an accretion disk onto a degenerate dwarf. The winds are seen only in CVs with high luminosity such as the dwarf novae during outburst and the novalike stars. In systems in which the disk is viewed face-on, broad, shortward-shifted absorption lines with terminal velocities of 3000 - 5000 km s^{-1} are observed. The terminal velocity is similar to the escape velocity from the surface of a white dwarf, suggesting that the wind emanates from near this star. In many CVs some of the line profiles also have emission components, hence the common appellation "P Cygni profile" after the well-observed mass-losing O star that has coarsely similar line profiles. When the disk is seen edge-on, as in the eclipsing novalike systems UX UMa (Holm, Panek and Schiffer 1982; King et al. 1983) and RW Tri (Cordova and Mason 1985), the line radiation from the wind is observed entirely in emission. The line profiles in RW Tri and UX UMa are asymmetric, peaking at wavelengths longer than the rest wavelength of the line. This may result from partial absorption on the blueward side of the line. An interpretation of these profiles is that they are formed in an accelerating flow that is not projected against a UV continuum source. The UV emission lines are not eclipsed to the same degree as the continuum; therefore the emission line forming region is large compared to the UV continuum emitting region. These properties are consistent with a wind which is accelerated from the inner disk/white dwarf region and which extends substantially above the disk.

The only estimates for the mass-loss rate due to the wind are in the range 10^{-11} to 10^{-10} $M_{\odot}$ yr^{-1}, or about 10^{-3} to 10^{-2} of the mass accretion rate that is deduced by fitting disk models to the continuum (cf. refs. in CM84). The only viable mechanism yet proposed for accelerating the winds in CV to the high velocities observed is radiation pressure in the lines, analogous to the driving mechanism of winds in OB stars. This view is supported by the fact that the momentum rate of the radiation from the disk, $L_{tot}/c = 10^{24}$ g cm s^{-2}, is of the same order as the momentum rate of the wind (Cordova and Mason 1982). It is difficult, however, to determine either quantity to within at least a factor of ten: the spectrum, and hence the radiant energy, in the EUV is as yet unknown, and the mass loss rate is extremely uncertain because of lack of knowledge of the ionization structure of the wind and the wind's geometry and homogeneity. The material in the wind is thought to be photoionized rather than collisionally ionized (King et al. 1983; Cordova and Mason 1985), although the origin and shape of the photoionizing spectrum is unclear (cf. Kallman 1983). The detection of mass outflow during a brief flare of the slow magnetic CV rotator TV Col (Szkody and Mateo 1984) suggests that the origin of the wind may be mechanical rather than a radiative in some cases.

Because cataclysmic variables as a class undergo dramatic changes in brightness, they offer an unique opportunity to study the effects on the wind of changes in the radiation field. This is particularly true of the dwarf novae, which have dramatic outbursts of a few magnitudes amplitude lasting several days and recurring on timescales of a few weeks. The outburst in a dwarf nova is believed to be caused by an increase in the rate of mass accretion through the disk.

We and other groups have been engaged in programs to measure the ultraviolet spectra of many dwarf novae at various stages of their outbursts. All the observations presented here have been made using a low resolution (~6 Å) spectrometer with a wide (10" x 20") aperture on the International Ultraviolet Explorer (IUE) satellite. The UV data were either taken by ourselves or are from the IUE archives. In this paper we present some new, preliminary results of the investigation into the behavior of the line spectrum in two CVs as a function of outburst epoch. A more complete analysis, including studies of several additional CV systems, is in preparation by the authors.

II. THE IUE SPECTRA: Observations, Deductions

1. Spectral Lines

A comparison of the spectra of dwarf novae in quiescence reveals that they fall into two types: those having emission lines of considerable equivalent width (EW as high as 80 Å), and those having weak or no detectable emission lines (EW <8 Å). The bottom panels of Figures 1a and 1b show examples of both types of spectrum. Here the spectra of the dwarf novae CN Ori and RX And are plotted in the wavelength range 1200 Å - 1600 Å. The ultraviolet spectrum of RX And in quiescence exhibits a number of emission lines, the most prominent being C IV 1550 Å, Si IV 1400 Å, and N V 1240 Å. The quiescent-state spectrum of CN Ori exhibits no lines.

The remaining panels in Figure 1 show these stars at various stages in their outburst cycles (Q denotes the quiescent phase; R, the rise to outburst; P, the peak of the outburst; and D, the decline from outburst). The optical state of the star at the epoch of each spectrum is illustrated in Figure 2, where we have marked the time of each IUE spectrum on a plot of the visual light curve of the star composed from data of the American Association of Variable Star Observers (AAVSO). Figure 1 illustrates that in the brighter states both stars develop broad absorption lines which are shifted shortward of the rest wavelength. RX And's C IV line profile has a distinctive emission component, but none of CN Ori's lines have such a feature.

Various parameters of the spectral lines are listed in Table 1[1]. These include the equivalent width (EW) of the emission and absorption components, the (interpolated) continuum level at the rest wavelength of the spectral line, the "blue" edge velocity (v_B) of the absorption component when it is present, and the "red" edge velocity (v_R) of the emission component; v_B represents an approximate estimate of the terminal velocity under the assumption that a wind is present.

Table 1, in combination with the information about the outburst state from Figure 2, reveals how the flux and EW of the line components vary as a function of outburst phase and UV and optical continuum brightnesss levels. The flux and EW of the absorption components correlate positively with the continuum brightness level; however, the flux in the absorption component grows faster than the continuum. The flux in the emission component of RX And's lines does not change by more than a factor of three during any phase in the outburst

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[1] The errors on the quantities given in Table 1 are roughly 10% for the Equivalent widths, Line fluxes, and Continuum fluxes; 30% for v_b for the outburst spectra and 50% for v_b for the quiescent spectra; and 50% for all measurements of v_r. A full discussion of the error analysis is given in a paper in preparation.

cycle; but, on average, this flux is somewhat higher when the continuum is higher. The EW of the emission component inversely correlates with UV continuum brightness.

Inspection of Figure 1b shows that the flux level at the bottom of the absorption component stays about the same during the outburst. This suggests that there may be two sources of continuum flux during the outburst: a [illegible]nt that dominates during quiescent phases and may increase somewhat during the outburst, and an additional, steeper component that arises during the outburst and contributes most of the far UV outburst light. The wind must be in front of the latter component in order to absorb all the continuum of this component at the wavelengths of the UV resonance lines.

The following evidence suggests that the emission and absorption components originate in different places:

(a) The ratios of the line fluxes and equivalent widths of different elements are not the same for the emission and absorption components, suggesting that they are formed in regions of different physical conditions.

(b) Theoretical mass-loss models don't fit the absorption and emission components simultaneously. This could be due to a non-spherical geometry for the wind, and/or to the superposition of an added emission component arising elsewhere than in the wind.

(c) The data presented here together with similar published data on other dwarf novae (e.g. Hassall et al. 1983) reveal that the stars that show prominent emission lines during quiescence also display emission line components during outburst, while those stars having no emission lines during quiescence exhibit no emission line components during outburst. Yet the velocity-shifted absorption components seen in CN Ori behave like those in

RX And, AB Dra and other stars which have emission components. Thus it appears that the wind produces the absorption, and the emission is extra.

Emission lines appear to be absent in those stars that have steep (α >2.0) spectra in quiescence. Such a steep spectrum could indicate a relatively small disk, i.e. little contribution by lower temperature emission from the outer disk to the near UV spectrum. Then stars showing emission lines and having flatter spectra in quiescence (e.g. RX And) could be expected to have larger disks than stars with no emission lines and steeper spectra (CN Ori). The maximum size of the disk is set by the orbital period and the mass ratio, so that if our hypothesis were correct, we might expect a correlation between the presence of the emission lines and these parameters. However, the dwarf novae VW Hydri and WX Hydri have very similar mass ratios and orbital periods (see references in Ritter 1984), yet the latter has strong UV emission lines, whereas the former does not (Hassall et al. 1983). An additional consideration is the mass accretion rate: it will affect both the size of the disk (cf. Frank and King 1981) and the temperature of the white dwarf. If CN Ori and VW Hyi have much lower accretion rates than RX And and WX Hyi, they may not only have smaller disks, but the spectrum of the white dwarf in these systems may be too cool to photoionize the UV resonance lines.

2. Continuum Slope

To determine the continuum slope of the UV spectra, we have integrated the data in bins between 25 Å and 100 Å wide, avoiding spectral lines. We have fit each spectrum with a power law (i.e., $F_\lambda \propto \lambda^{-\alpha}$) modified by reddening (E(B-V) = 0.0 and 0.02 for CN Ori and RX And, respectively). The results of these fits, together with the value of the continuum at C IV and the V mag and outburst state of the star, appear in Table 2. Some examples of the continuum spectral fits are shown in Figure 3.

For RX And the spectral slope becomes systematically steeper as the luminosity increases. The power-law slope, α , varies from 1.0 in quiescence to 1.9 near the peak of an outburst. In the case of CN Ori the slope of the continuum during quiescence is indistinguishable from that at the peak of the outburst, in both cases being about 2.0. A spectrum of CN Ori taken during the rising phase of the outburst, however, has a much flatter distribution, with a slope of 1.0. The flattening of the spectrum during the optical rise to outburst has been reported for another dwarf nova, VW Hyi, by Hassall et al. 1983, and is interpreted as an initial brightening of the outer (i.e. cooler parts of the) accretion disk.

III. TRIGGERING THE WIND

The shortward-shifted absorption lines appear only during the outbursts of the dwarf novae, indicating that the onset of the wind is a function of the star's luminosity. The presence of C IV, N V and Si IV ions requires a substantial flux of ionizing EUV radiation, so we would expect these lines to correlate with the amount of EUV flux emitted by the star. The data on CN Ori and RX And presented here support this view.

The visual magnitude of the star does not, in general, provide a reliable estimate of the luminosity at higher energies. For example, the maximum UV flux we have detected from CN Ori occured on 1982 Jan 4, when the star was undergoing an optical outburst and had a V mag of 12.6. Two weeks later, CN Ori was detected at a somewhat brighter V mag of 12.4 on the rise to its next outburst. The far UV flux at this time however was only one-half the level during the Jan 4 observation. A second illustration of this is provided by RX And. The visual magnitude during the 1980 Feb. 28 observation (on the rise to outburst) was two magnitudes higher than during the 1982 Aug. 9 observation (quiescence), yet the far UV fluxes are nearly the same. In fact, most of the discrepancies in comparing the UV and visual light curves occur on the rise to outburst. The inference from the data presented here is that dwarf novae brighten at optical wavelengths before they brighten in the far UV , and this is supported by the observed change in the slope of the spectrum during the rise to outburst (e.g. CN Ori's 1982 Jan. 16 spectrum). Sometime after the spectrum flattens, the far UV flux increases dramatically by at least an order of magnitude. A delay of 1 - 2 days is indicated from the available data (Hassall et al. 1983; this paper). The spectrum at this time can be much steeper than during quiescence (e.g. RX And) or the same as during quiescence (CN Ori). During the decline both UV and V fall together (cf. Table 2).

Two things argue that it is the EUV flux that is important in determining whether the wind is present: (a) the development of the wind-like profiles in the spectral lines is associated with the steepening of the spectrum after the initial flattening, and (b) the presence of the wind (i.e. shortward-shifted absorption) is not a smooth function of the local continuum flux. For instance, spectra of RX And taken on 1980 Dec. 10 and 1982 Aug. 5, both far down on the decline from maximum outburst light, have far UV continuum levels that differ by less than a factor of two, yet the former spectrum shows marked shortward-shifted absorption, whereas the latter spectrum exhibits no evidence for any absorption. The slope of the UV continuum, however, is very different, $\alpha = 1.4$ for the former spectrum, and $\alpha = 1.2$ for the latter. In fact, the wind is only observed in RX And when $\alpha > 1.4$.

In the previous Section we suggested that there might be two separate contributors to the far UV flux. One is observed during quiescence and changes very little during the outburst. The second contributor is responsible for most of the increase in the far UV luminosity during the outburst. The spectral lines demonstrate that the wind is apparently in front of the latter UV source; when the source turns on near the peak of the optical outburst, the wind is ionized and absorbs all of the source's continuum flux at the resonant line frequencies. When this far UV source diminishes, there is nothing for the wind to absorb (the remainder of the UV radiation, i.e. that which we see during quiescence, coming from a different location), and we are unable to detect the presence of the wind.

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Table 1a: Spectral Line Data for CN Orionis

Line: NV (1240 Å)

U.T. Date of SWP Observations	Emission+		Absorption+		Continuum Flux++ at Line Center	v_{blue}	v_{red}
	EW	Flux	EW	Flux		(km s^{-1})	
1979 Dec 13.38	--	--	3.9	8.3	2.1	5000	--
1982 Jan 4.36	--	--	3.5	20	5.6	2500	--
Jan 6.40	--	--	2.5	7.4	3.0	3600	--
1982 Jan 15.18	--	--	--	--	0.35	--	--
Jan 16.18	--	--	--	--	0.39	--	--
Jan 18.22	--	--	4.8	17	3.4	4300	--

Line: Si IV (1400 Å)

U.T. Date of SWP Observations	Emission+		Absorption+		Continuum Flux++ at Line Center	v_{blue}	v_{red}
	EW	Flux	EW	Flux		(km s^{-1})	
1979 Dec 13.38	--	--	4.5	7.6	1.7	4600	--
1982 Jan 4.36	--	--	4.1	19	4.6	2800	--
Jan 6.40	--	--	6.1	15	2.5	4200	--
1982 Jan 15.18	--	--	--	--	0.27	--	--
Jan 16.18	--	--	6.7	2.0	0.30	2700	--
Jan 18.22	--	--	3.9	11	2.8	3000	--

Line: C IV (1550 Å)

U.T. Date of SWP Observations	Emission+		Absorption+		Continuum Flux++ at Line Center	v_{blue}	v_{red}
	EW	Flux	EW	Flux		(km s^{-1})	
1979 Dec 13.38	--	--	4.4	6.6	1.5	4400	--
1982 Jan 4.36	--	--	4.2	6.0	3.6	2500	--
Jan 6.40	--	--	3.6	6.8	1.9	4100	--
1982 Jan 15.18	--	--	--	--	0.17	--	--
Jan 16.18	--	--	--	--	0.32	--	--
Jan 18.22	--	--	4.6	11	2.3	2900	--

+Equivalent width (EW) in Angstroms; spectral line flux in units of 10^{-13} erg cm^{-2} s^{-1}.

++Continuum flux in units of 10^{-13} erg cm^{-2} s^{-1} Å^{-1}.

Table 1b: Spectral Line Data for RX Andromedae

Line: NV (1240 Å)

U.T. Date of SWP Observations	Emission^{+}		Absorption^{+}		Continuum Flux^{++} at Line Center	v_{blue} (km s^{-1})	v_{red}
	EW	Flux	EW	Flux			
1980 Feb 28.16	9.1	17	--	--	1.8	--	1700
1980 Dec 8.33	0.4	4.2	11	130	12	4700	3500
Dec 9.40	2.7	14	5.7	30	5.3	4100	3300
Dec 10.31	2.2	7	1.3	3.7	3.0	4100	3400
1982 Aug 5.38	9.2	18	--	--	2.0	--	2800
1982 Aug 9.69	7.7	10	--	--	1.4	--	3700
Aug 13.04	--	--	11	180	17	4000	--
Aug 13.96	--	--	11	240	22	3300	--
Aug 14.78	--	--	12	240	20	4600	--
Aug 16.04	--	--	6.6	63	9.6	3800	--
Aug 16.82	--	--	10	105	10	5000	--

Line: Si IV (1400 Å)

U.T. Date of SWP Observations	Emission^{+}		Absorption^{+}		Continuum Flux^{++} at Line Center	v_{blue} (km s^{-1})	v_{red}
	EW	Flux	EW	Flux			
1980 Feb 28.16	9.8	1.3	--	--	1.4	--	1200
1980 Dec 8.33	0.5	4.2	8.9	76	8.8	5400	2100
Dec 9.40	1.3	6.2	7.1	34	4.8	5300	2100
Dec 10.31	1.1	2.9	5.0	13	2.7	3900	2400
1982 Aug 5.38	3.4	6.7	--	--	1.9	--	1600
1982 Aug 9.69	6.7	7.2	--	--	1.1	--	1400
Aug 13.04	--	--	9.3	110	12	4700	--
Aug 13.96	--	--	8.1	120	15	4600	--
Aug 14.78	--	--	10	140	14	4800	--
Aug 16.04	--	--	9.6	98	10	4600	--
Aug 16.82	0.7	5.6	8.4	66	7.7	4700	--

Line: C IV (1550 Å)

U.T. Date of SWP Observations	Emission⁺		Absorption⁺		Continuum Flux⁺⁺ at Line Center	v_{blue} (km s^{-1})	v_{red}
	EW	Flux	EW	Flux			
1980 Feb 28.16	43	45	--	--	1.0	--	2600
1980 Dec 8.33	8.6	58	8.8	63	6.7	5400	2100
Dec 9.40	12	62	7.7	35	4.3	5100	2000
Dec 10.31	6.8	17	3.2	7.8	2.5	2600	3200
1982 Aug 5.38	19	29	--	--	1.5	--	2600
1982 Aug 9.69	24	22	--	--	0.9	--	2600
Aug 13.04	4.8	49	6.9	95	10	5000	1800
Aug 13.96	3.4	42	11	150	13	4300	2400
Aug 14.78	4.0	45	12	140	12	5400	1700
Aug 16.04	3.2	26	10	90	8.4	4500	2300
Aug 16.82	9.1	57	8.5	55	6.3	4700	3100

Table 2: Spectral Slope Compared with Other Parameters

RX Andromedae

U.T. Date	Power law Slope, α ($F\lambda \propto \lambda^{-\alpha}$)	Continuum Flux at 1550 Å erg cm^{-2} s^{-1} $Å^{-1}$	V mag	Outburst State	Wind?
1980 Feb 28.16	1.1	1.0	11.5	K	no
1980 Dec 8.33	1.8	6.7	11.4	D	yes
Dec 9.40	1.8	4.3	11.9	D	yes
Dec 10.31	1.4	2.5	12.6	D	yes
1982 Aug 5.38	1.2	1.5	12.6	D	no
1982 Aug 9.69	1.0	0.9	13.3	Q	no
Aug 13.04	1.6	10.0	11.4	R	yes
Aug 13.96	1.9	13.0	10.9	P	yes
Aug 14.78	1.8	12.0	11.1	D	yes
Aug 16.04	1.7	8.4	11.3	D	yes
Aug 16.82	1.7	6.3	11.5	D	yes

CN Orionis

U.T. Date	Power law Slope, α ($F\lambda \propto \lambda^{-\alpha}$)	Continuum Flux at 1550 Å erg cm^{-2} s^{-1} $Å^{-1}$	V mag	Outburst State	Wind?
1979 Dec 13.38	2.0	1.5	13.25	D	yes
1982 Jan 4.36	2.1	3.6	12.6	P	yes
Jan 6.40	2.0	1.9	12.85	D	yes
1982 Jan 15.18	2.1	0.2	14.0	Q	no
Jan 16.18	1.2	0.3	13.65	R	no
Jan 18.22	1.8	2.3	12.35	R	yes

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FIGURE CAPTIONS

Fig. 1 The ultraviolet line spectra in various outburst states from 1200 Å to 1600 Å: (a) CN Ori, (b) RX And. The legends indicate the dates of the IUE observations. The letters in parentheses following the dates indicate the visual outburst state: quiescence (Q), rise (R), decline (D), and peak (P).

Fig. 2 Visual light curves from AAVSO data. Circled crosses indicate times of IUE observations: (a) CN Ori, (b) RX And.

Fig. 3 The ultraviolet continuum spectra in various outburst states with model power law fits: (a) CN Ori, (b) RX And. The legends are ordered in descending flux level. The spectral slopes are given in Table 2. Other legend designations are same as in Fig. 1.

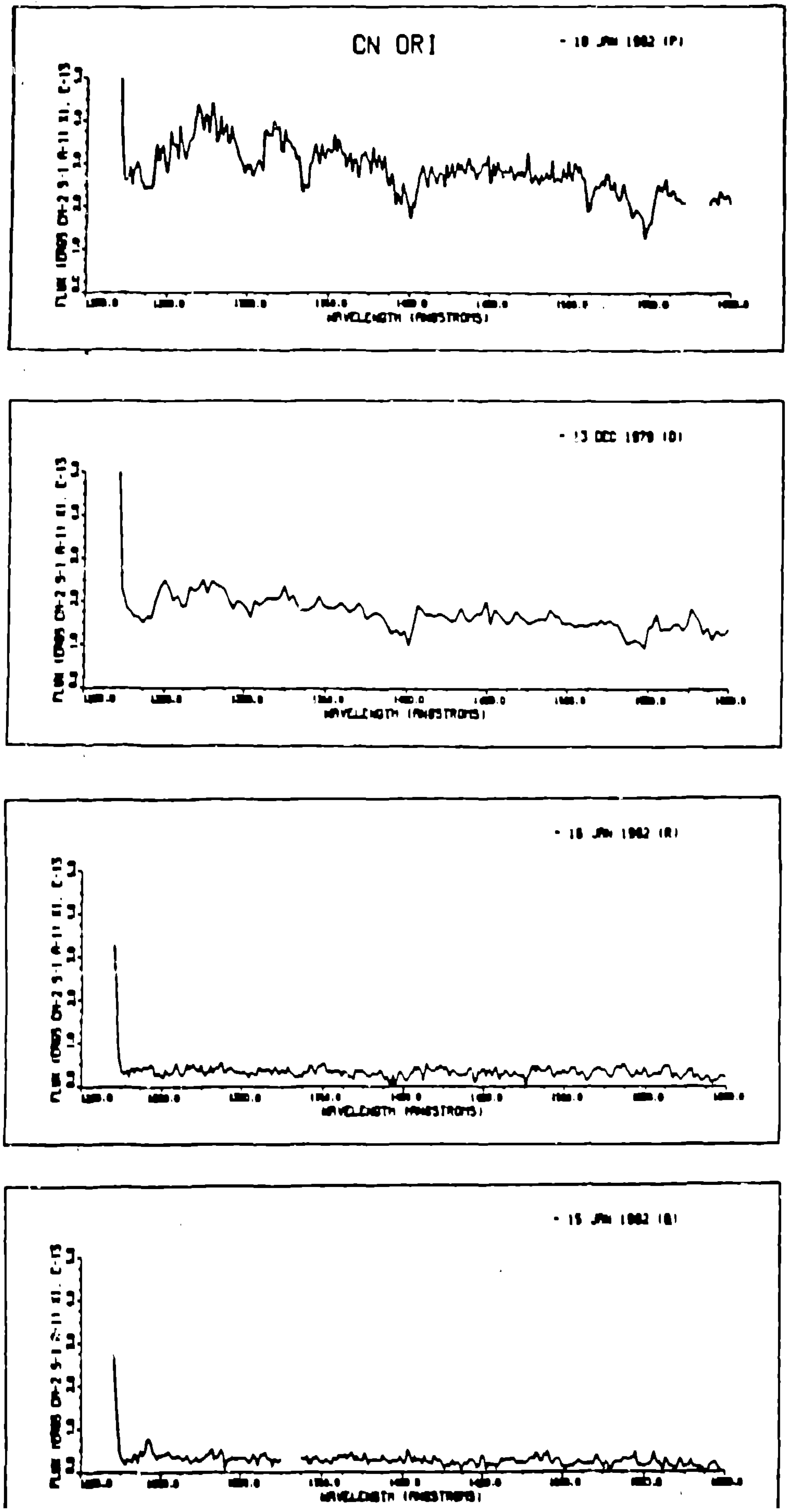
CN ORI
- 10 JAN 1982 (P)
FLUX (ERGS CM-2 S-1 A-1) X1. E-13
WAVELENGTH (ANGSTROMS)
- 13 DEC 1979 (D)
FLUX (ERGS CM-2 S-1 A-1) X1. E-13
WAVELENGTH (ANGSTROMS)
- 16 JAN 1982 (R)
FLUX (ERGS CM-2 S-1 A-1) X1. E-13
WAVELENGTH (ANGSTROMS)
- 15 JAN 1982 (B)
FLUX (ERGS CM-2 S-1 A-1) X1. E-13
WAVELENGTH (ANGSTROMS)

Figure 1a

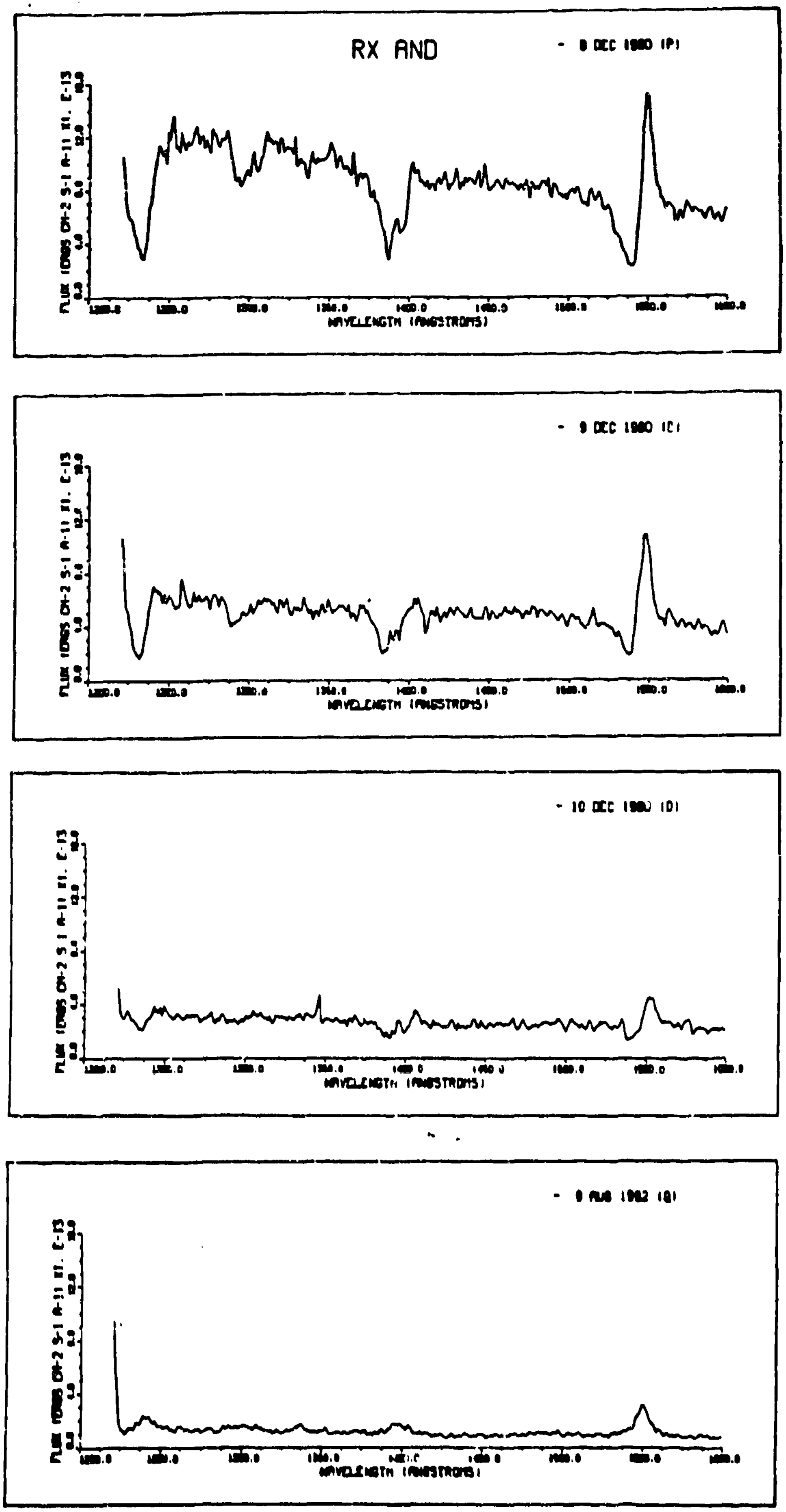
RX AND
- 8 DEC 1980 (P)
- 9 DEC 1980 (C)
- 10 DEC 1980 (D)
- 8 AUG 1982 (Q)
FLUX (ERGS CM-2 S-1 A-1) X1. E-13
0.0
4.0
8.0
12.0
16.0
1200.0
1250.0
1300.0
1350.0
1400.0
1450.0
1500.0
1550.0
1600.0
WAVELENGTH (ANGSTROMS)

Figure 1b

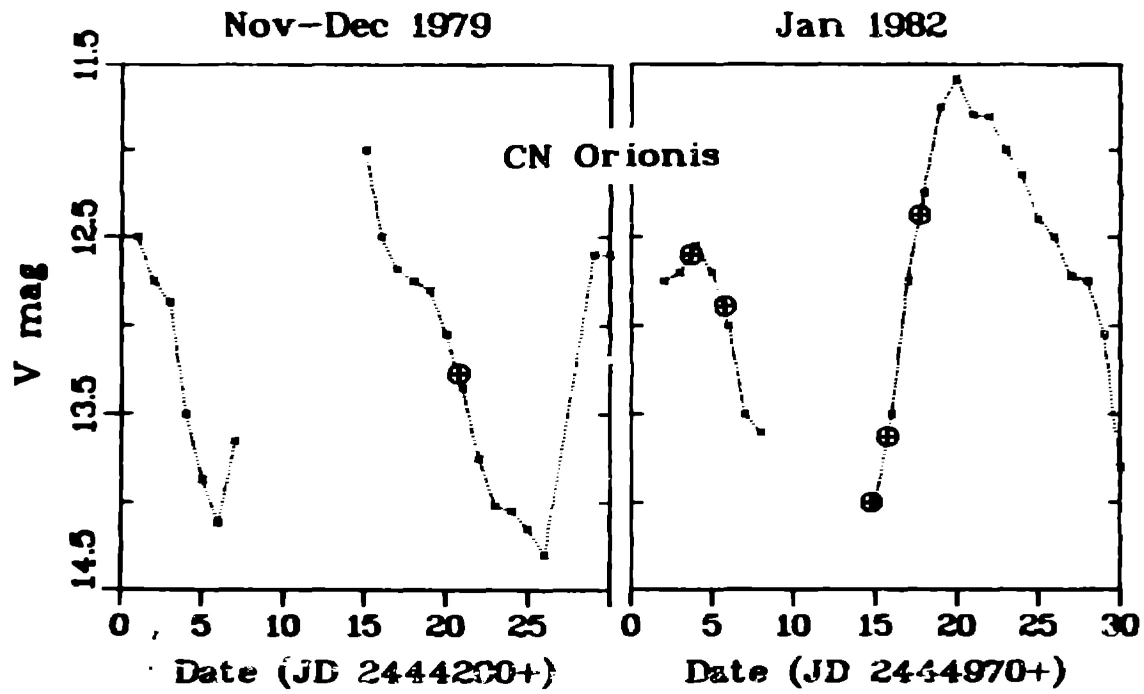
Nov-Dec 1979
Jan 1982
CN Orionis
V mag
11.5
12.5
13.5
14.5
0
5
10
15
20
25
30
Date (JD 2444200+)
Date (JD 2444970+)

Fig. 2a

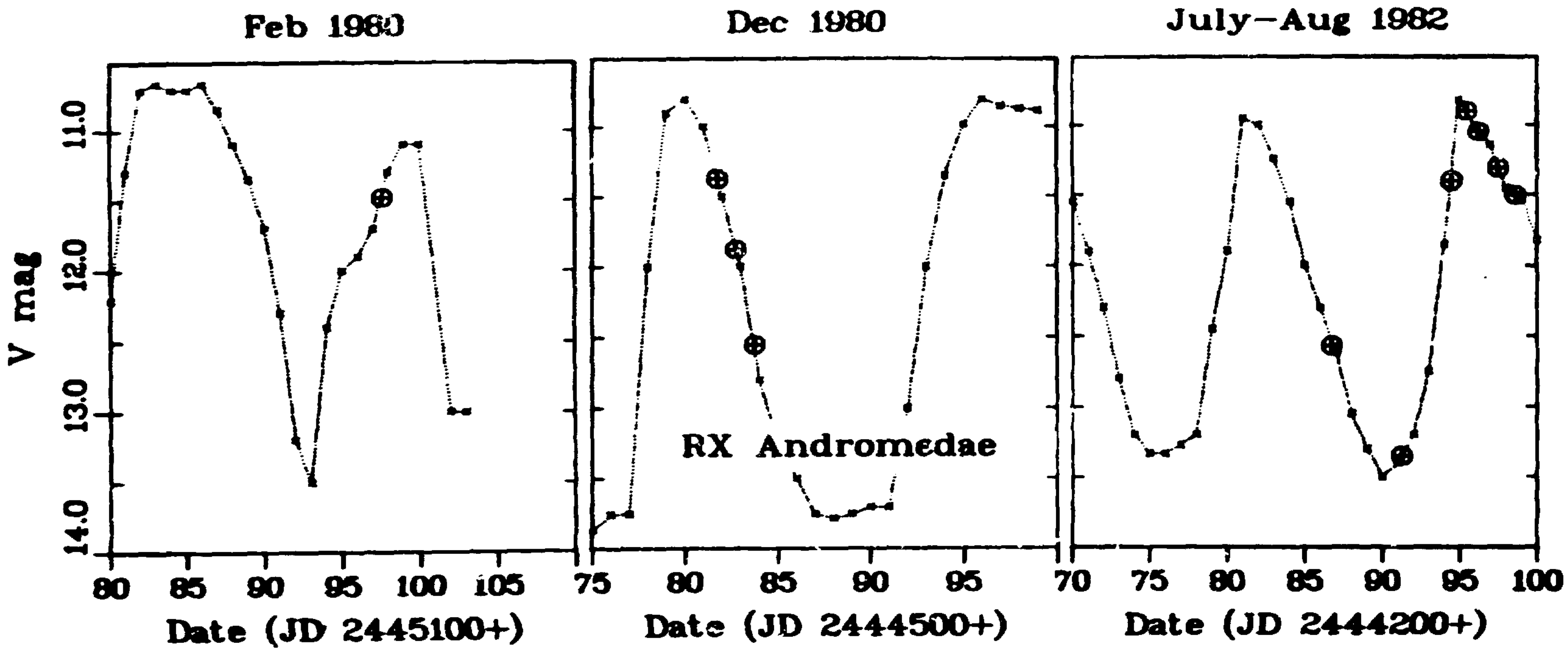
Feb 1980
Dec 1980
July–Aug 1982
V mag
11.0
12.0
13.0
14.0
RX Andromedae
80
85
90
95
100
105
Date (JD 2445100+)
75
80
85
90
95
Date (JD 2444500+)
70
75
80
85
90
95
100
Date (JD 2444200+)

Fig. 2b

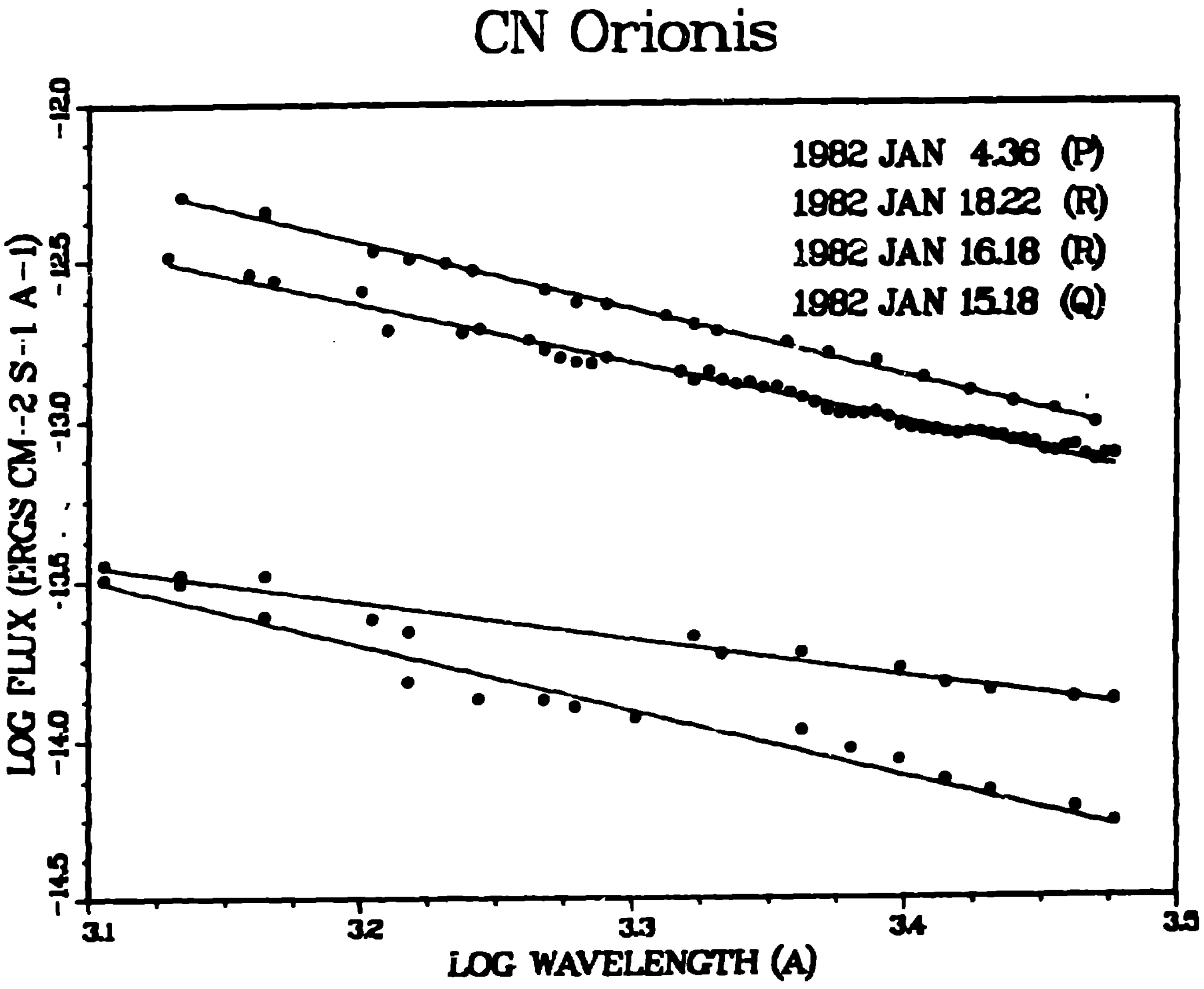
CN Orionis
1982 JAN 4.36 (P)
1982 JAN 18.22 (R)
1982 JAN 16.18 (R)
1982 JAN 15.18 (Q)
LOG FLUX (ERGS CM-2 S-1 A-1)
-12.0
-12.5
-13.0
-13.5
-14.0
-14.5
3.1
3.2
3.3
3.4
3.5
LOG WAVELENGTH (A)

Fig. 3a

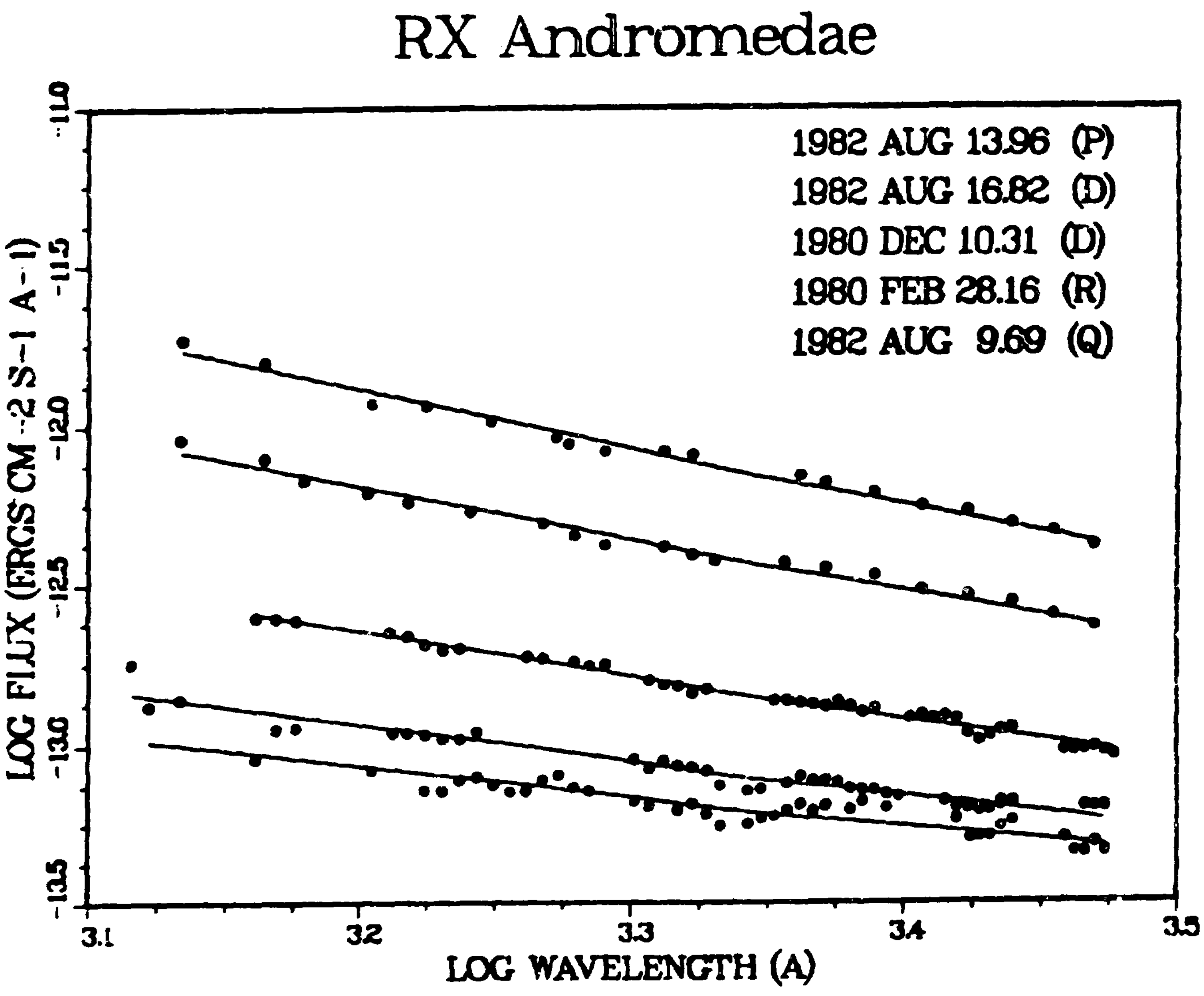
RX Andromedae
1982 AUG 13.96 (P)
1982 AUG 16.82 (D)
1980 DEC 10.31 (D)
1980 FEB 28.16 (R)
1982 AUG 9.69 (Q)
LOG FLUX (ERGS CM -2 S-1 A-1)
-11.0
-11.5
-12.0
-12.5
-13.0
-13.5
3.1
3.2
3.3
3.4
3.5
LOG WAVELENGTH (A)

Fig. 3b