Astron. Astrophys. 322, 183–192 (1997)

ASTRONOMY AND ASTROPHYSICS

The Be/X-ray binary LS I +61° 235/RX J0146.9+6121: physical parameters and V/R variability

P. Reig[1], J. Fabregat[2], M.J. Coe[1], P. Roche[3], D. Chakrabarty[4,5], I. Negueruela[1], and I. Steele[6]

[1] Physics and Astronomy Department, Southampton University, Southampton. SO17 1BJ, UK
[2] Departament d'Astronomia i Astrofísica, Universitat de Valencia, E-46100 Burjassot-Valencia, Spain
[3] Astronomy Centre, CPES, University of Sussex, Falmer, Brighton, BN1 9QH, UK
[4] Palomar Observatory and Space Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125, USA
[5] Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[6] John Moores University, Liverpool, UK

Received 3 September 1996 / Accepted 2 December 1996

Abstract. We present the results of spectroscopic and photometric observations of LS I +61° 235. Blue 4100-4900 Å spectra of the system are used to assign a spectral type of B1V to the optical companion while detailed $uvby\beta$ photometric data permit us to derive its astrophysical parameters. The monitoring of this high mass X-ray binary since its discovery in 1991 has resulted in the detection of considerable variability in the Hα line profile. The observations cover a complete V/R cycle with a period of approximately three years. We discuss models which may explain the origin of the variation and conclude that these variations are due to intrinsic changes of the circumstellar envelope rather than being caused by the neutron star. The model which best fits the observational data is the global one-armed oscillation model.

Key words: stars: individual: LS I +61° 235 – binaries: close – X-rays: stars – stars: fundamental parameters

1. Introduction

Be/X-ray binaries consist of a compact star, presumably a neutron star, orbiting around a Be star. Be stars are defined to be early-type stars of spectral type B and luminosity class III-V showing at times Balmer line emission. Another observational property of Be stars is the marked infrared excess in the form of continuum free-free emission. These two phenomena are attributed to the presence of circumstellar material, with a disk-like geometry which surrounds the Be star equator. The X-ray emission is believed to be caused by accretion of circumstellar material onto the neutron star. The exact form of the accretion mechanism, whether a strong stellar wind, enhanced mass ejection or disruption of the envelope as the neutron star passes through it, it is not yet clear.

The source LSI +61° 235 (RX J0146.9+6121) was identified by Motch et al (1991) from the ROSAT sky survey as a Be/X-ray system. The first X-ray spectrum of RX J0146.9 +6121 taken by ROSAT appeared extremely hard, with most photons detected above 1 keV. The fact that the X-ray spectrum fitted well to a power law with photon index in the range 1-2 and with a low energy absorption of $N_H \approx 10^{22}$ cm^{-2} suggests that the source is a Be/X-ray binary. The X-ray luminosity in the 0.1-2.4 keV is of the order of $L_x \sim 10^{34} - 10^{35}$ erg s^{-1}, while in the range 1-20 keV reaches 10^{36} erg s^{-1}.

Motch et al. (1991) also made optical spectroscopic observations and reported prominent Hα emission with an equivalent width of ≈ -10 Å and pronounced interstellar absorption lines. Two years later Coe et al. (1993) carried out infrared and optical observations and confirmed that the optical companion showed characteristics typical of a Be star, such as the presence of an infrared excess and the development of a "shell-type" emission spectrum. They concluded that the system LS I +61° 235 was at a low level of activity, with little material around the Be star.

White et al. (1987) discovered a periodicity of 25 minutes in the X-ray flux while pointing at 4U 0142 +614 with EXOSAT. Since the Medium Energy (ME) experiment did not image, they could not be certain whether this originated from 4U 0142 +614, a probable low-mass X-ray pulsar, or from another possible transient source. After the discovery of RX J0146.9+6121 by Motch et al. (1991) and the identification of its optical counterpart LS I +61° 235, Mereghetti et al. (1993) proposed that this source was the origin of the 25-minute pulsation. At the same time, Israel et al. (1993) re-analyzed EXOSAT data and discovered an X-ray periodicity at $\sim$ 8.7 seconds which they attributed to 4U 0142+614. Hellier (1994) undertook new ROSAT observations to secure the origin of the 25 minute and 8.7 second pulsations.

Send offprint requests to: pablo@astro.soton.ac.uk

Table 1. Optical photometric results

Date	MJD	y	$(b-y)$	m_1	c_1	β
17/11/91	48577.6	11.454 ± 0.034	0.571 ± 0.005	-0.243 ± 0.012	0.127 ± 0.033	-
19/12/91	48610.4	11.524 ± 0.038	0.566 ± 0.021	-0.259 ± 0.041	0.154 ± 0.021	2.471 ± 0.024
20/12/91	48611.4	11.512 ± 0.038	0.571 ± 0.021	-0.247 ± 0.041	0.132 ± 0.021	2.475 ± 0.024
05/12/92	48962.4	11.433 ± 0.011	0.579 ± 0.006	-0.177 ± 0.009	0.073 ± 0.018	2.558 ± 0.008
23/09/93	49253.7	11.331 ± 0.008	0.600 ± 0.007	-0.229 ± 0.010	0.118 ± 0.009	2.496 ± 0.008
		U	B	V	R_c	I_c
19/01/95	49738	11.99 ± 0.20	12.13 ± 0.05	11.49 ± 0.02	10.96 ± 0.02	10.37 ± 0.05

Table 2. Infrared measurements

MJD	Date	J	J err	H	H err	K	K err
48492	23/08/91	10.04	0.04	9.80	0.03	9.63	0.03
48493	24/08/91	10.02	0.09	9.82	0.05	9.66	0.05
48494	25/08/91	9.96	0.04	9.72	0.03	9.55	0.04
48496	27/08/91	9.92	0.03	9.69	0.03	9.54	0.03
48497	28/08/91	9.94	0.03	9.71	0.02	9.58	0.04
48590	29/11/91	9.9	0.1	9.7	0.1	9.5	0.1
48592	01/12/91	9.95	0.05	9.76	0.06	9.66	0.06
48665	12/02/92	9.92	0.03	9.66	0.02	9.54	0.03
48856	21/08/92	9.74	0.06	9.58	0.05	9.23	0.05
48857	22/08/92	9.80	0.08	9.58	0.05	9.32	0.04
48858	23/08/92	9.72	0.08	9.57	0.06	9.30	0.08
48999	11/01/93	9.96	0.02	9.76	0.02	9.64	0.05
49232	01/09/93	9.69	0.18	9.53	0.09	9.38	0.17
49341	19/12/93	9.82	0.05	9.65	0.05	9.42	0.07
49513	09/06/94	9.83	0.08	9.62	0.05	9.43	0.04
49514	10/06/94	9.81	0.08	9.72	0.03	9.42	0.07
49661	04/11/94	9.95	0.09	9.66	0.03	9.48	0.05
49664	07/11/94	9.92	0.03	9.69	0.03	9.50	0.04
49665	08/11/94	9.93	0.06	9.67	0.06	9.48	0.07
49720	02/01/95	9.89	0.08	9.65	0.05	9.47	0.04
49721	03/01/95	9.88	0.11	9.65	0.06	9.45	0.05
49928	29/07/95	9.97	0.06	9.70	0.07	9.45	0.05
49932	02/08/95	9.88	0.08	9.68	0.04	9.50	0.05
50002	11/10/95	10.20	0.10	9.84	0.08	9.89	0.09
50005	14/10/95	10.08	0.03	9.88	0.04	9.60	0.04

He confirmed that the 8.7 second period corresponded to 4U 0142+614 and the longer period, to RX J0146.9+6121. This makes RX J0146.9 +6121 the most slowly rotating neutron star in a Be/X-ray system known so far.

2. Observations

2.1. Photometry

A total of five sets of Strömgren and Crawford Hβ photometry were obtained. Three of them were carried out in two runs, November and December 1991, with the 1.23m telescope of the Spanish-German Astronomical Center located in Calar Alto (CA) (Almería, Spain), using the GEC10 CCD detector equipment with the $uvby$ and Hβ narrow and wide filters and have already been published in Coe et al (1993). The data from the other two sets represent new observations. They were obtained using the 1.0m Jacobus Kapteyn Telescope (JKT) located on La Palma island (Spain) on the December 5th 1992 and September 23rd 1993. It was equipped with the People's photometer, attached to the Cassegrain focus of the telescope. We used the photometer in a single-channel mode, measuring sequentially the star and the sky background through the four Strömgren $uvby$ and the narrow and wide Hβ filters. A sufficient number of standard stars were observed for each run in order to compute the atmospheric extinction coefficients and the transformation to the standard system. Table 1 shows the resulting magnitudes and colours.

UBVRI photometry was obtained from the JKT on January 19th 1995 using the TEK#4 CCD.

The infrared observations were made at the Teide Observatory (Tenerife, Spain), using the 1.5m Carlos Sánchez Telescope (TCS), equipped with the continuously variable filter (CVF) photometer and are summarized in Table 2.

2.2. Spectroscopy

Table 3 presents the journal of the optical spectroscopic observations. They cover the visual, blue and red part of the optical spectrum, i.e. 3600-9000 Å. The data were obtained from the 2.5m Isaac Newton Telescope (INT) and the 1.0m Jacobus Kapteyn Telescope (JKT), both located at the Roque de los Muchachos observatory in La Palma (Canary Islands, Spain), the 1.5m at Palomar Mountain (PAL) and the 2.2m telescope at Calar Alto, owned by the Max Planck Institute. The INT was used with the Intermediate Dispersion Spectrograph + 235mm camera + 1200B grating + TEK CCD, giving a nominal dispersion of 0.7 Å/pixel with $\sim$ 1024 pixels available. The JKT observations were carried out using the Richardson Brealey Spectrograph with the 1200 grating, the red optics and the EEV7 CCD chip, giving a dispersion of 1.2 Å/pixel. Additional observations were taken from the 1.5m telescope at Palomar Mountain (PAL) in the USA using the f/8.75 Cassegrain echelle spectrograph in regular grating mode at 0.8 Å/pixel dispersion. One more observing

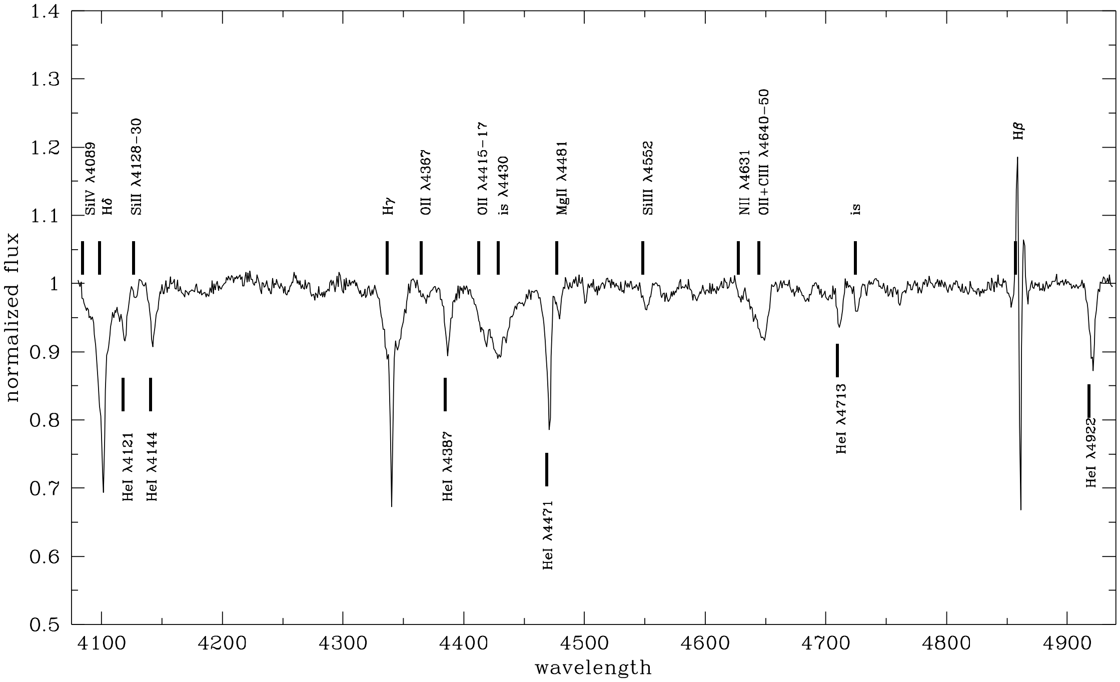

Fig. 1. Blue spectrum of LS I +61° 235. Notice the strong OII+CIII λ4540-50 blend and the absence of HeII lines indicating a B1 star. The weak silicon triplet SiIII λ4552-68-75 points towards a luminosity class V

run was carried out with the Cassegrain spectrograph attached to the 2.2m Max Planck Institute telescope at Calar Alto observatory in August 1993. The instrumentation used was the GEC15 CCD and the f/1.5 camera which provided a dispersion of 1.36 Å/pixel and a resolution of about 2.7 Å at 6000 Å.

The spectra were reduced using the *Starlink* FIGARO soft package (Shortridge 1991) while the analysis of the spectroscopic lines was done with the *Starlink* DIPSO package (Howarth & Murray 1991) always normalizing the continuum to unity.

The shape of the line profile is indicated in the last column of Table 3. Four different shapes have been identified: double peak, either blue- or red-dominated, shell and single peak emission. The data cover a complete V/R cycle (quasiperiod $\sim$ 3 years) starting with V $>$ R. Hα always appears in emission as well as Hβ. Hγ, however is always in absorption. Hβ also shows shell characteristics.

3. Spectral type and luminosity class

Classification of Be stars is a difficult task since the surrounding envelope distorts the characteristic photospheric spectrum. So far the spectral classification of LS I +61° 235 had been carried out using photometric data. Slettebak (1985) suggested a B5III star. Coe et al. (1993) however, making allowance for the contributions to the colours from the circumstellar disk, proposed an O9-B0 star. Our blue spectra provide, for the first time, the opportunity of deriving the spectral type using spectroscopic data. Fig. 1 is the result of averaging five spectra in the classification region taken from the INT in 1995 July.

In this figure we can see the following features.

i) HeII λ4686 if present, is extremely weak. No other HeII lines are seen. Thus the star must be later than B0. This is confirmed by the weak SiIV λ4089.
ii) However, strong HeI lines indicate an early-type spectrum. MgII λ4481 and SiII λ4128-30, although present are not very strong . Since the strength of these lines increases in prominence from B2 towards later types (Walborn & Fitzpatrick 1990) the star can not have a spectral type later than that.
iii) The ratios SiIII λ4552/SiIV λ4089 and SiII λ4128-30/SiIII λ4552 are very close to those of the B1V standard given by Walborn & Fitzpatrick (1990) in their spectral classification atlas of OB stars.
iv) SiIII λ4552 is the only appreciable line of the silicon triplet. The main luminosity criteria for a B1 star are the ratios SiIII λ4552/HeI λ4387 and SiIV λ4089/HeI λ4026-4121-44 (visible in the August 1993 spectrum) which show a smooth increasing progression from main sequence towards supergiant stars. These ratios are $\ll$ 1 for LS I +61° 235 indicating a luminosity class V.
v) The OII+CIII λ4640-50 blend is quite strong. For main-sequence stars the strength of this blend begins to decrease quickly for stars later than B1.5.

Thus we conclude that LS I +61° 235 is a B1 main-sequence star. This spectral classification is supported by the colour index $(B-V)_0$ and the Q parameter, defined as Q=$(U-B)-0.72(B-V)$, independent of reddening. According to Deutschman et al. (1976) a B1V star should have $(B-V)_0 = -0.280$, which is

Table 3. Journal of spectroscopic observations

Local date	MJD	Telescope	Wavelength coverage (Å)	Profile shape of the Balmer lines
28/08/91	48497	INT	6400-6700	Hα: V/R>1
13/12/91	48604	INT	6300-6800	Hα: V/R>1
18/05/92	48761	PAL	6300-6900	Hα: shell
19/05/92	48762	PAL	6500-6700	Hα: shell
16/08/92	48851	PAL	6300-6900	Hα: V/R<1
17/08/92	48852	PAL	6300-6900	Hα: V/R<1
18/08/92	48853	PAL	6300-6900	Hα: V/R<1
13/11/92	48940	PAL	6300-6900	Hα: V/R<1
08/03/93	49055	PAL	6300-6900	Hα: single peak
10/03/93	49057	PAL	6300-6900	Hα: single peak
11/08/93	49211	CA	6000-7200	Hα: single peak
13/08/93	49213	CA	3600-4900	Hβ: single peak
23/09/93	49254	PAL	6300-6900	Hα: single peak
24/09/93	49255	PAL	4000-6600	Hα,Hβ: single peak
05/12/93	49327	PAL	6300-6900	Hα: single peak
06/12/93	49328	PAL	4300-5000	Hβ: V/R<1
07/12/93	49329	PAL	6300-6900	Hα: single peak
25/06/94	49509	JKT	4200-5200	Hβ: in-filled
26/06/94	49510	JKT	6100-7000	Hα: V/R>1
27/06/94	49511	JKT	4200-5200	Hβ: in-filled
16/09/94	49612	JKT	5700-6700	Hα: V/R>1
17/09/94	49613	JKT	8000-8900	Paschen lines in absorption
12/02/95	49761	JKT	6200-7200	Hα: V/R>1
11/07/95	49910	INT	4100-4900	Hβ: shell
13/07/95	49912	INT	4100-4900	Hβ: shell
14/07/95	49913	INT	4100-4900	Hβ: shell
15/07/95	49914	INT	4100-4900	Hβ: shell
16/07/95	49915	INT	4100-4900	Hβ: shell
04/08/95	49934	JKT	6400-7300	Hα: shell
04/08/95	49934	JKT	8100-9000	Paschen lines in absorption
05/08/95	49935	JKT	4100-5000	Hβ: shell
06/08/95	49936	JKT	6400-6700	Hα: shell
28/02/96	50142	JKT	6400-6700	Hα: V/R>1

almost exactly what we obtain if we use a colour excess E(B-V)=0.93 (see below). The value of the Q-parameter that was obtained, -0.850, lies within the range (-0.796 to -0.896) given by Halbedel (1993) for B1V stars. Also the visual brightness parameter F_V = 4.152 derived for LS I +61° 235 agrees very well with that of a B1 main-sequence star (Popper 1980). With regard to the $uvby\beta$ photometry, c_0 is the primary temperature parameter whereas the β index is the primary measure of luminosity. The computed c_0 and β indices for LS I +61° 235 corresponds to a B1V type star as can be checked in Crawford (1978), Moon (1985) or Cameron & Beatty (1995).

4. Astrophysical parameters

In this section we make use of the optical photometric data to derive the astrophysical parameters of the underlying B star. The results, summarized in Table 4, were obtained by taking the mean of the five observations. Prior to their use in the photometric calibrations the colours were corrected for circumstellar emission using the equations of Fabregat & Reglero (1990).

4.1. Extinction, absolute magnitude and distance

Following the Crawford (1978) procedure we found a mean colour excess index $E(b-y)$ = 0.667 ± 0.009 or $E^{is}(B-V)$ = 0.90 ± 0.01 if we use $E(B-V) = 1.35E(b-y)$ (Crawford & Mandwewala 1976). The error is the standard deviation calculated from the five photometric measurements. To this value which represents the interstellar extinction we must add the reddening caused by the material surrounding the equator of the Be primary. Evidently, this circumstellar reddening is variable, depending on the envelope size. From the equations of Fabregat & Reglero (1990) we estimated $E^{cs}(B-V) \leq 0.04$. The highest value corresponds to an Hα emission of $\sim$ -18 Å. Thus we estimate the total extinction to be $E(B-V) = 0.93 \pm 0.02$ magnitudes.

Balona & Shobbrook(1984) used data from 421 stars in 13 open clusters to calibrate the Strömgren β index as a luminosity indicator for early-type stars. With their calibration we obtained M_V = -3.1 ± 0.5, where the error has been computed using $\sigma_{M_V} = 3.3\sigma_\beta/(\beta - 2.515)$, as indicated by the authors, since it is greater than the standard deviation of the mean. The colour excess obtained above gives an extinction in the V band of A_V=2.88. We use the distance-modulus relation to obtain a distance of 2.3 $\pm$ 0.5 kpc. The error has been calculated taking into account the error in $E(B-V)$ and M_V and assuming an error for the observed V magnitude of 0.02.

Fabregat et al. (1996) suggested that LS I +61° 235 is a member of the open cluster NGC 663 on the basis of its position in the cluster photometric diagrams. This fact provides an excellent opportunity to check the extinction, absolute magnitude and distance just derived.

According to Phelps & Janes (1994), the colour excess to NGC663 is $E(B-V)$ = 0.80 and the true distance-modulus $(V-M_V)_0$=12.25, or a distance of 2.8 kpc. Assuming a mean V magnitude of 11.45 one obtains $M_V = -3.3$. The values of the distance and absolute magnitude agree well with those reported above, within the error limits. The difference in $E(B-V)$ can be ascribed to the circumstellar disc surrounding the Be star but above all to the variable reddening observed in different regions of the cluster (Tapia et al. 1991).

4.2. Effective temperature

Since there are no published empirical calibrations for the temperature based on $uvby$ photometry, we carried out our own temperature calibration using the data from Napiwotzki et al. (1993), Cayrel de Strobel et al (1992), Moon & Dworetsky (1985) and Malagnini et al. (1986). The photometric data, if not provided by these references, were taken from the Hauck-Mermilliod (1990) catalogue. This photometry was dereddened using the Crawford (1978) procedure. We tried polynomial fits using $(b-y)_0$ and c_0 indices as the independent variable since both are well related to the effective temperature for early-type stars. The fit with the highest correlation index (r = 0.99) was $\log T_{eff} = 0.186c_0^2 - 0.580c_0 + 4.402$. The standard deviation is 0.025 in $\log T_{eff}$.

By substituting each colour index c_0 into this equation and taking the mean we obtained T_{eff}=24000$\pm$1500 K. This value compares to the mean effective temperature of 25500 K for a B1II-V star given by Remie & Lamers (1982). It also agrees with the 23000 K derived from Balona's (1994) calibration, which gives T_{eff} in terms of c_0 and β indices.

Another way to estimate the effective temperature is by fitting the photometric data to a Kurucz model (Kurucz 1979). We have compiled data from both Johnson and Strömgren photometric systems. A plot of the fit can be seen in Fig. 2. The model was normalized to the B band. Before the fit was performed, the data were dereddened using $E(B-V)$ = 0.93. The best fit Kurucz model had an effective temperature of T_{eff}=25000 K and a surface gravity of log g=4.0 corresponding to a B1V star. The fact that no IR excess is observed is proof of the validity of the Fabregat & Reglero (1990) calibration.

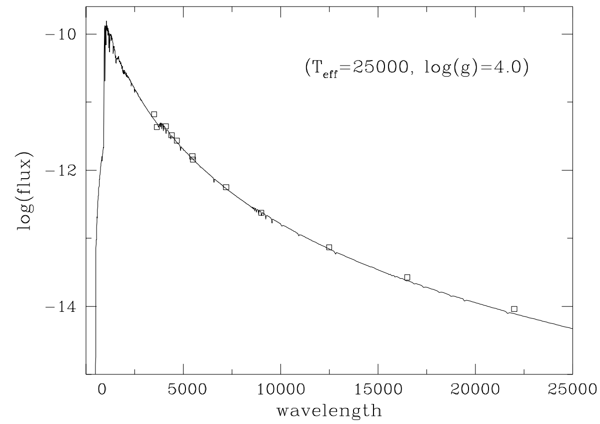

Fig. 2. The combined dereddened optical ($uvby$, UBVRI) and infrared (JHK) photometric data presented in comparison to a typical Kurucz model atmosphere for a star with T_{eff}=25000 and log g=4.0

Table 4. Astrophysical parameters of LS I +61 235, the optical counterpart to RX J0146.9+6121

Spectral type	B1V
E(B-V)	0.93$\pm$0.02
T_{eff}	24000$\pm$1500 K
Radius	7$\pm$1 $R_\odot$
Mass	11$\pm$2 $M_\odot$
M_V	-3.1$\pm$0.5
Distance	2.3$\pm$0.5 kpc
BC	-2.4$\pm$0.2
M_{bol}	-5.5$\pm$0.5
$\log g$	3.9$\pm$0.2 cm^2 s^{-1}
v sin i	200$\pm$30 km s^{-1}

4.3. Radius

The radius was determined by using $M_{bol} = 42.36 - 5\log(R/R_\odot) - 10\log(T_{eff})$. The zero point corresponds to $T_{eff,\odot}$ = 5770 K and $M_{bol,\odot}$ = +4.74 (Zombeck 1990). In order to derive the bolometric magnitude, the bolometric correction BC was calculated first by means of Balona's (1994) calibration, valid for O-F stars. We obtained $BC = -2.40$. Therefore $M_{bol} = -5.5 \pm 0.5$. Now, substituting into the previous equation we derived R = 7$\pm$1 $R_\odot$ (log($R/R_\odot$)=0.845$\pm$0.143). This value compares well to the average radii in terms of MK spectral types calculated by Moon (1985), who gave log($R/R_\odot$)=0.802 for a B1V star.

4.4. Mass and gravity

With the previous values of temperature ($\log T_{eff}$ = 4.380) and bolometric luminosity (1.2 $\times 10^4$ $L_\odot$), we can estimate the mass from evolutionary models. We have used the interpolation formula given by Balona (1994) for the Claret & Giménez (1992)

Table 5. Equivalent widths of the Balmer lines Hα, Hβ and Hγ. Data marked with 1 is from Motch et al. (1991) and 2 from Mereghetti et al. (1993)

Julian Date (2,400,000+)	EW (Å)	Julian Date (2,400,000+)	EW (Å)
Hα line (emission)			
48204	≈ 10[1]	49057	12.4
48283	≈ 10[1]	49211	17.2
48497	8.1	49254	18.1
48604	8.2	49255	17.5
48761	7.7	49327	14.5
48762	7.6	49329	15.4
48851	6.5	49510	8.8
48852	6.6	49612	8.5
48853	6.8	49761	10.5
48940	7.9	49934	9.0
48997	8.5[2]	49935	8.9
49055	12.0	50142	9.5
Hβ line (emission)			
49213	1.6	49509	0.5
49255	1.3	49910	0.2
49328	1.2	49935	0.1
Hγ line (absorption)			
49213	1.8	49509	2.2
49255	1.7	49910	2.0
49328	1.6	49935	2.0

models and found M = 11 $\pm$ 2 $M_\odot$. Once we know the mass and radius of the star we can calculate its gravity by means of the formula

$$\log g = 4.44 + \log M - 2 \log R \quad (1)$$

where M and R must be given in solar units. The result is $\log g$=3.9 $\pm$ 0.2 cm s^{-1}, consistent with the value of $\approx$ 4.0 determined from the Kurucz model fitting.

4.5. Rotational velocity

We have obtained the projected rotational velocity $v \sin i$ using the approximation of Buscombe (1969)

$$\frac{v \sin i}{c} = \frac{FWHM}{2\lambda_0 (\ln 2)^{1/2}} \quad (2)$$

where λ_0 is the rest wavelength of the line and $FWHM$ represents the full width at half maximum corrected for instrumental resolution. We have used the HeI λ4471 and HeI λ4922 lines to obtain $v \sin i$ = 200 $\pm$ 30 km s^{-1}.

5. V/R variations

Asymmetric double-peak emission lines are usually described by their V/R ratio, defined as the ratio of violet-side to red-side peak intensities above continuum in units of continuum intensity. Long-term variations in the ratio of the intensity of the violet and red hydrogen emission peaks is not a rare phenomenon in the spectra of Be stars (Mennickent & Vogt 1991). In Be/X-ray systems, the optical appearance is dominated by the intrinsic light of the early type companion. The ratio of X-ray to optical luminosity (L_x/L_{opt}) is in the range 10^{-5} to 10. Consequently, the optical effects due to the X-ray source are usually small and, therefore, it is not surprising to find V/R variability as occurs in isolated B stars. Other Be/X-ray binaries which show such behaviour are 4U 1258 -61 (Corbet et al. 1986), γ Cas (Telting & Kaper 1994) and A0535 +26 (Clark et al. 1996).

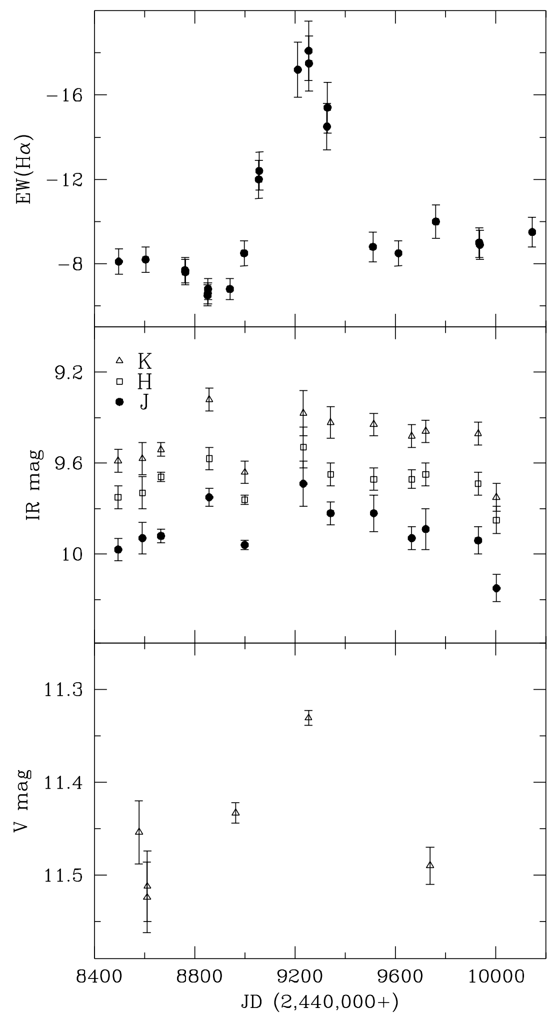

Fig. 3. The star went through a maximum strength in the Hα line and V magnitudes in 1993 September

The Hα profiles of LS I +61° 235 show large changes in the line strength and shape over the time-span covered by our observations. Our spectroscopic data reveal the presence of a period of enhanced Hα emission where the star increased its equivalent width from about –7 to –18 Å. This Hα outburst is accompanied by a brightening of the optical magnitudes and colours. Fig. 3 shows the infrared and optical lightcurves covering the period 1991-1996, together with the variation of the Hα equivalent width. The optical maximum occurred in September-October 1993 with an increment with respect to the initial values for the V band of 0.2 magnitudes and an increase for the equiv-

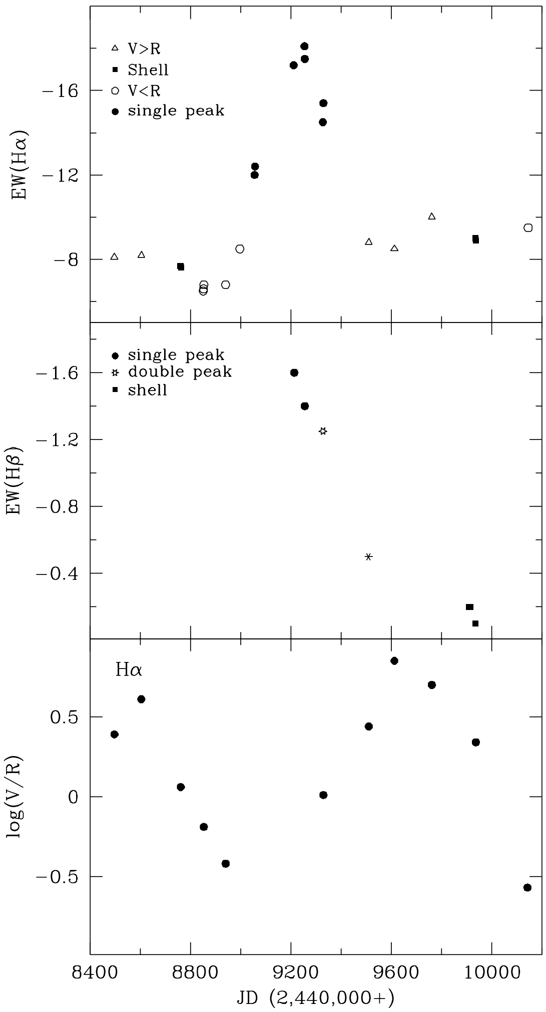

Fig. 4. Hα outburst and the relationship with the Hβ line and the V/R variations. The data indicate a quasiperiod of $\sim$ 3 years

alent width of ≈ –10 Å. The rise and the decay of the optical "flare" are remarkably symmetric, lasting about 270 days each. Notice, however, the small amplitude of variation in the infrared colours.

In Fig. 4 the relationship between the Hα outburst and the V/R variations is shown. The evolution with time of the profile of the Hα line is shown in Fig. 5 and 6, where four different structures can be seen: double peak (both blue and red dominated), single peak and shell-like profiles. We will leave to the next section the discussion of the different models which have been proposed to explain these variations. Now we summarize the observational facts that can be extracted from the data.

i) The data, which are spread over five years (1991-1996), cover a complete cycle showing a period for the V/R variations of ≈ 3 years.
ii) During the transition from V $>$ R to V $<$ R a shell-like profile with a central absorption reaching the continuum level is observed, whereas during the transition from V $<$ R to V $>$ R the shell spectrum is replaced by a single peak profile. Starting from the V $>$ R profile the evolution of the asymmetric double peak emission lines is V $>$ R $\longrightarrow$ shell $\longrightarrow$ V $<$ R $\longrightarrow$ single peak $\longrightarrow$ V $>$ R.
iii) The V<R phase is shorter than the V>R phase. The shell $\longrightarrow$ V<R $\longrightarrow$ single peak process took place in a *maximum* of 10 months whereas the single peak $\longrightarrow$ V>R $\longrightarrow$ shell process lasted a *minimum* of 14 months.
iv) Single peak profiles are associated with maximum values of the Hα equivalent width.
v) The duration of the Hα "flare" is shorter (more than a factor of two) than the V/R cycle, but the red-dominated phase coincides with the onset of the optical outburst and the blue-dominated phase coincides with the end of its decay.
vi) During the Hα increase the infrared colours hardly experienced any variation (see Fig. 3).

6. Discussion

The spectral and luminosity classification as a B1V star is in accordance with those of other Be/X-ray binaries, which are restricted to the intervals O9-B2 and III-V, respectively. However, two characteristics make this system different: it is the only Be/X-ray system which belongs to an open cluster and has the most slowly rotating neutron star known so far.

The models that have been put forward to explain similar V/R behaviour in Be stars are very numerous but we can split them into two general groups:

1. Models which predict a modulation with the orbital period, that is, which explain the V/R period as a consequence of the orbital motion of both components. Examples of this group are: the tidal distortion model (Cowley & Gugula 1973), which assumes that the V/R variability is due to the gravitational asymmetry of the envelope caused by the presence of a binary companion, the X-ray ionization model (Corbet et al. 1986) for which the V/R modulation is explained by a non-uniformed ionization of the disk by X-rays, and the model by Apparao & Tarafdar (1986) which attributes it to the relative position of the Strömgren spheres of the Be star and the neutron star.
2. Models which attribute the V/R variability to intrinsic changes in the circumstellar envelope of the Be star: such as the precession of an elliptical emission ring (Huang 1973), the global one-armed oscillation model (Kato 1983; Okazaki 1991) and the rotation-pulsation model (McLaughlin 1961)

Unfortunately, one important parameter of many of the models, the orbital period of LS I +61° 235 is not known. Nevertheless, we can reach some important conclusions by considering the general properties of Be/X-ray systems.

Corbet (1986) discovered a correlation between the pulse period and the orbital period in Be/X-ray binaries. The pulse period of RX J0146.9 +6121 is 1413 s (Hellier 1994), From the P_{spin}-P_{orb} diagram we obtain $P_{orb} \approx 400$ days. Our spectroscopic data show that the V/R variations cover a complete cycle in ≈ 1000 days making any possible orbital modulation unlikely.

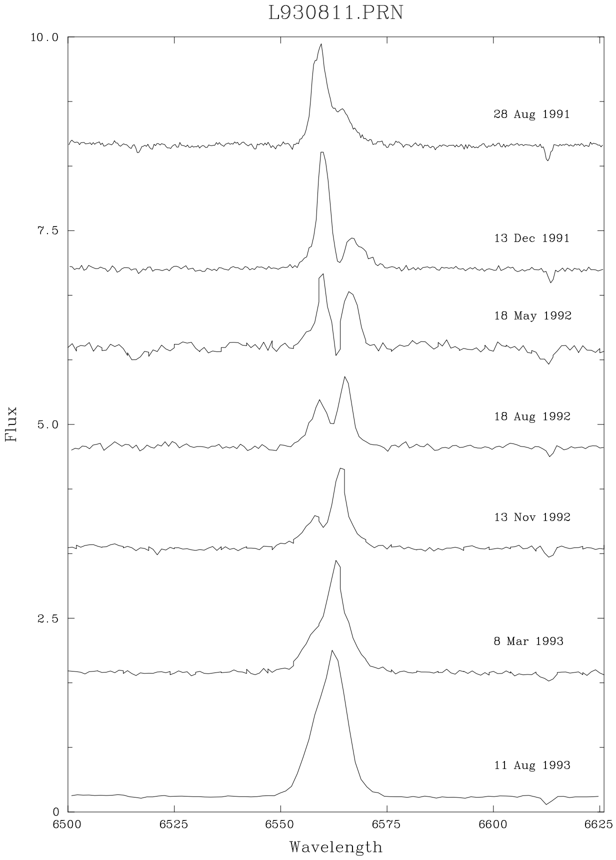

Fig. 5. Evolution of the Hα profile observed in LS I +61° 235. The y-axis represents arbitrary flux. All the spectra have had the continuum level normalised to unity and are offset vertically to allow direct comparison.

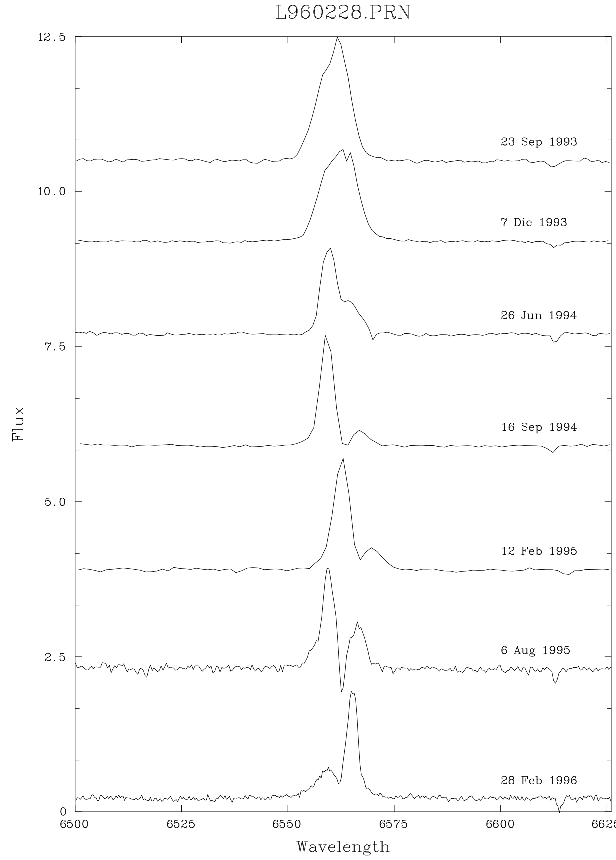

Fig. 6. Evolution of the Hα profile observed in LS I +61° 235 (cont.)

Even if we permit an orbital period of $\approx$ 1000 days then the binary separation between the compact object and the Be star, assuming (see Section 4) a mass of 11 $M_{\odot}$, a radius of 7 $R_{\odot}$ and a neutron star mass of 1.4 $M_{\odot}$, would be $a \sim 10^3$ $R_{\odot} \approx 200$ R_*. With such a long distance, it is very unlikely that there would be appreciable tidal or ionization effects. The Apparao & Tarafdar (1986) model would not be applicable either because this model assumes that the neutron star is immersed in the gas envelope, that is, the envelope radius would be of the same order as the binary separation, which is clearly not true. In fact, according to Thomson (1984) the radius of the Strömgren sphere for a B1V star is $s_0 \sim 20$ R_*. Thus, for LS I +61° 235, s_0 would be $\sim$ 140 $R_{\odot}$, i.e. one order of magnitude lower than the binary separation. We conclude therefore that the V/R variability is not linked to the orbital motion but to the dynamics of the envelope itself.

The main flaw of the elliptical ring model is the stability of the elliptical orbits since one should expect that orbits differentially precess, intersect and circularize preventing such a disk from being stable on the timescales of the V/R variations. Moreover, it does not reproduce the shape of the central reversal observed in most double emission line profiles and predicts periods of precession 30 times greater than the observed ones (Mennickent & Vogt 1991).

In the rotation-pulsation model the star ejects matter into space in an irregular way. This matter returns to the star's surface when this flux temporarily decreases or stops. The V<R phase would correspond to the expansion of the envelope (material moving outwards), whereas the V>R phase would correspond to the contraction of the envelope (material in-falling). Evidence against this model would be: *i)* it is not clear why the V/R asymmetry only appears at the beginning and at the end of the expansion and contraction phases and not *during* these phases, *ii)* (inverse) P Cygni lines should be seen as a proof of (inflow) outflow fluxes of matter, *ii)* according to Hubert et al. (1987) the phase with V>R should be shorter than the phase with V<R; the opposite is observed. Also, since circumstellar envelopes of Be stars are thought to be fuel for the accretion processes onto the surface of neutron stars in Be/X-ray systems, we would expect that the expansion of the disk would imply an increase in the X-ray emission. To the authors' knowledge there has been no increase in the X-ray luminosity of this source during or after the optical outburst. However, the X-ray coverage is very sparse and any significant X-ray variability may well have been missed.

The global oscillation model explains V/R variability in terms of a non-axisymmetrical equatorial disk in which a one-armed perturbation (a zone in the disk with higher density) propagates (Okazaki 1991). In this model the one-armed perturbation precesses as a result of preasure forces in the disk in the direction counter to the semi-Keplerian motion. Papaloizou et al. (1992) included the gravitational effect of the rotational flattening of the Be star by which the disturbance region is naturally confined within a few stellar radii from the stellar surface (Savonije & Heemskerk 1993). When the disk is cool enough for preasure effects to be small the quadrupole term of the oblate Be star's gravitational potential gives rise to prograde precession of the one-armed disturbance. When the high-density part of the disk perturbation is located on the side of the disk where the rotational motion is directed away from us we see enhanced red emission (V $<$ R), while the blue-dominated profile (V $>$ R) occurs when the perturbation is on the other side of the disk.

The similarity between the shape of the Hα lines in LS I +61° 235 and those predicted by the global one armed oscillation theory is remarkable as long as a prograde mode is considered (Telting et al. 1994). The only difference is that LS I +61° 235 shows a single peak structure instead of a double peak with a weak central absorption during the transition from V $<$ R to V $>$ R and that the shell spectrum is not so marked. This difference, however may be explained by assuming a smaller inclination angle of the orbit to the line of sight. Support for this model is found in the absence of variability of the infrared magnitudes and colours. In the global one-armed oscillation model no changes in the slope of the infrared continuum are expected because the V/R variations are not the result of changes in the radial density gradient of the circumstellar gas (Telting et al. 1993).

The time resolution of our observations is not enough to determine if the optical enhancement and increase of the Hα equivalent width represents a phase in the V/R cycle or, on the contrary, it is caused by external changes in the disk structure. The optical enhancement occurs during the transition from red-dominated phase to blue-dominated phase, that is, when the high-density zone is behind the star. If $i < 90°$, the star does not completely hide the high-density part of the envelope where most of the Balmer emission is formed. This emission is in addition to the normal emission from the rest of the envelope. Alternatively, it may occur that the optical "outburst" is due to an increase in the size and/or density of the emitting region as a consequence of the disk being fed by new material ejected from the underlying B star. The asymmetry in the duration of the two phases (V/R $<$ 1 and $>$ 1) may also be caused by this enhanced mass loss episode. More observations are required to decide on these issues.

7. Conclusion

Detailed spectroscopic and photometric measurements of LS I +61° 235, the optical counterpart of the massive Be/X-ray binary RX J0146.5+6121, have permitted us to classify it as a B1V star and to derive its astrophysical parameters. These are summarized in Table 4. The monitoring of this source for the last five years has shown long-term V/R variations with a quasiperiod of $\sim$ three years. We have discussed possible models to account for the V/R Hα variability and concluded that the only model which can explain the observational data is one which attributes this variability to the prograde precession of a one-armed mode confined in the equatorial disk.

New observations of this source may reveal a possible cyclic nature of the optical "outburst" and V/R variability. The source seems to be beginning a new outburst as indicated by the last spectrum taken on the 28th February 1996, in which the corresponding Hα equivalent width was – 9.5 Å, larger than the preceeding values. The shape of the line is again red-dominated, perhaps also marking the beginning of a new V/R cycle. More observations would also show if this optical "outburst" occurs during the same phase of the V/R cycle, implying that it is caused by intrinsic changes in the disk, since mass loss events from the B star are expected to be sporadic.

Acknowledgements. We wish to thank the referee, Dr G.L. Savonije, for his helpful comments, which improved the discussion on the one-armed oscillation model. The authors acknowledge the support, both software and data analysis facilities, provided by Starlink, which is funded by the UK PPARC. The TCS is operated on the island of Tenerife by the Instituto de Astrofísica de Canarias in the Spanish Observatorio del Teide. The JKT and INT are operated on the island of La Palma by the Instituto de Astrofísica de Canarias in the Spanish Observatorio del Roque de Los Muchachos. The 1.23m and 2.2m telescopes are owned by the Max Planck Institut für astronomie in the Spanish-German Astronomical Center in Calar Alto (Almería-Spain). The 1.5m telescope at Mount Palomar is jointly owned by the California Institute of Technology and the Carnegie Institute of Washington. PR thanks the Nuffied Foundation for support from a grant to new science lectures. DC is supported by a NASA Compton Postdoctoral Fellowship. IN acknowledges receipt of a University of Southampton studentship.

References

Apparao K.M.V. and Tarafdar S.P. 1986, A&A 161, 271.
Balona L., Shobbrook R., 1984, MNRAS 211, 375.
Balona L., 1994, MNRAS 268, 119.
Buscombe W., 1969, MNRAS 144, 1.
Cameron Reed B. and Beatty A.E. 1995, AJ 109, 2252.
Cayrel de Strobel G., Bentolila C., Hauck B. and Duquennoy A., 1985, A&AS 59, 145.
Claret A. and Giménez A., 1992, A&AS 96, 255.
Clark S., Tarasov A., Steele I.A. et al 1996, MNRAS (submitted).
Coe M.J., Everall C., Norton A.J. et al. 1993, MNRAS 261, 599.
Corbet R.H.D. 1986, MNRAS 220. 1047.
Corbet R.H.D., Smale A.P., Menzies J.W. et al 1986, MNRAS 221, 961.
Cowley A.P. & Cugula E. 1973, A&A 22, 203.
Crawford D.L., 1978, AJ 83, 48.
Crawford D.L. and Mandwewala N., 1976, PASP 88, 917.
Deutschman W.A., 1976 ApJ Suppl. Ser. 30, 97.
Fabregat J. and Reglero V, 1990, MNRAS 247, 407.
Fabregat J., Torrejón J.M., Reig P. et al. 1996, A&AS 119,271.
Halbedel E.M., 1993, PASP 105, 465.
Hauck B. and Mermilliod, 1990, A&AS 86, 107.
Hellier C., 1994, MNRAS 271, L21.
Howarth I.D. and Murray J., 1991, Starlink User Note 50.13, R.A.L.
Huang S., 1973, ApJ 183, 541.
Hubert A.M., Floquet M. and Chambon M.T., 1987, A&A 186, 213.
Israel G.L., Mereghetti S. and Stella L., 1994, ApJ 433, L25.

Kato S. 1983, PASJ 35, 249.
Kurucz R.L., 1979, ApJS 40,1.
Malagnini M.L., Morossi C., Rossi L. and Kurucz R.L., 1986 A&A 162, 140.
Mennickent R.E. and Vogt N. 1991, A&A 241, 159.
Mereghetti S., Stella L. and De Nile F., 1993, A&A 278, L23.
McLaughlin D.B., 1961, J.R. Astron. Soc. Canada 55,73.
Moon T., 1985, Astroph. Sp. Sci. 117, 261.
Moon T and Dworetsky M., 1985, MNRAS 217, 305.
Motch C., Belloni T., Buckley D. et al. 1991, A&A 246, L24.
Napiwotzki R., Schönberner D. and Wenske V., 1993, A&A 268, 653.
Okazaki A.T. 1991, PASJ 43, 75.
Phelps R.L. and Janes K.A., 1994 ApJ Suppl. Ser. 90, 31.
Popper D.M., 1980, ARA&A 18, 115.
Remie H. and Lamers H.J.G.L.M. 1982, A&A 105, 85.
Savonije G.J. and Heemskerk M.H.M. 1993, A&A 276, 409.
Shortridge K., 1991, Starlink Miscellaneous User Document, 13, R.A.L.
Slettebak A., 1985, ApJS, 59, 769.
Tapia M., Costero R., Echevarría J. and Roth M., 1991, MNRAS 253, 649.
Telting J.H., Waters LBFM, Persi P. and Dunlop S.R. 1993, A&A 270, 355.
Telting J.H. and Kaper L., 1994, A&A 284, 515.
Telting J.H., Heemskerk M.H.M. Henrichs H.F. and Savonije G.J. 1994, A&A 288, 558.
Thomson R., 1984, ApJ 283, 165.
Walborn N. and Fitzpatrick E., 1990, PASP 102, 379
White N.E., Mason K.O., Giommi P., et al. 1987, MNRAS 226, 645.
Zombeck M.V., 1990, in *Handbook of Space Astronomy and Astrophysics*". Cambridge University Press.

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