The FUOR characteristics of the PMS star BN Orionis inferred from new spectroscopic and photometric observations*

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Received 4 June; accepted 7 October, 1996

Abstract. BN Ori is a young emission-line star with a peculiar light curve. During the first half of this century the star showed strong irregular brightness-variations, similar to those of Herbig Ae stars. In the current half of the century the light curve resembles that of a FU Ori-object (FUOR, after Ambartsumian 1971). It can be characterised by an initial large-scale rise in brightness followed by a gradual decay over a period of about 15 years. From various photometric patrol programmes we concluded that the star remained at the same brightness level for the last 30 years. Between 1991 and 1995 the spectrum of BN Ori was intensively observed and was found to exhibit some unique peculiarities. We have analysed the visual spectra obtained with the 6 m BTA telescope of the SAO, the 60 cm and 48 cm telescopes at Mt. Maidanak, the 1.4 m CAT and the 1.5 m telescope of ESO and the UV-spectra obtained with the IUE in 1984 and 1986. The spectra show certain similarities with those of classical FUORs, such as a large-scale thermal stratification, with Balmer lines showing A6 – A7 spectral type wings, while other lines are typical for late F-type stars. However, in contrast to classical FUORs, BN Ori is not of high luminosity-class.

On the other hand the spectrum also shows similarities with those of Herbig A7e stars, although these stars have much stronger absorption lines in the UV from their outer shell and their circumstellar dust excesses are much larger than for BN Ori. Also, the rotation rate $v \sin i$ of BN Ori is between 180 and 220 km s⁻¹, which is typical for A-type stars of 2 – 5 $M_{\odot}$. This may indicate that BN Ori is a

fast rotating FUOR with an intermediate-mass precursor on which the outburst had a different effect than in the case of the classical FUORs (which are rotating slower and have a low-mass T Tauri star as precursor). In the BN Ori outburst most of the massive gas- and dust shell, characteristic for Herbig Ae stars, seems to have been removed, except for the H α - and Mg II-emission region close to the photosphere. The disappearance of the circumstellar dust shell may explain the drastic variability-change in the light curve of BN Ori. The mass-accretion rates of BN Ori and several Herbig A7e stars (derived from the analysis of their UV-spectra in terms of disc-accretion) suggest that the FUOR outburst in BN Ori was due to a thermal runaway (Bell 1994) in its inner accretion-disc which was triggered by a modest increase in the accretion rate.

Key words: circumstellar matter — stars: emission-line — stars: BN Ori — stars: pre-main-sequence

1. Introduction

BN Ori (HD 245465, BD+06°971) is an emission-line star about 3° South-East to the λ Ori cluster and probably connected to the star-formation region RSF1 in the Orion B complex by a dark lane of dust. A detailed review of the star’s properties and the observational history up to 1989 has been given by Shevchenko (1989). Because red-sensitive photographic plates for astronomical use did not become widely available until the fifties, the (H α) emission character of BN Ori during the first half of the century cannot be ascertained at present. Nevertheless, before 1947 the star had several characteristics of the class which is presently known as the Herbig Ae stars: spectral type A7 (Cannon 1931) and, similar to T Ori (Beyer 1937), strong and irregular variations in brightness and colour, characteristic for the variability of circumstellar dust extinction. Around 1947 its variability character changed (Fig. 1): the amplitude of the large brightness-variations

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* Based on observations collected at/with:

- Mt. Maidanak Observatory, Samarkand, Uzbekistan,
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- European Southern Observatory, La Silla, Chile,
- Kitt Peak National Observatory, Tucson AZ, U.S.A.,
- Dutch Astronomical Station Ausserbinn, Switzerland,
- International Ultraviolet Explorer.

decreased and, after a large-scale rise of $\sim 0^m.5$ during the next 6 months, the brightness slowly decreased until it settled down at $V^J \approx 9^m.6$ around 1965. Since then the brightness remained at this level, apart from a small and short variation in 1991. The photometric history and the photometric observations made during the last decade are summarised in Sect. 2.

Table 1. Log of photometric observations of BN Ori, NN denotes the number of nights

Photometric system	Observatory + Telescope	Dates	NN	Observers
Walraven <i>WULBV</i> (Table 2)	ESO	Feb'85	2	JK, ED
	Dutch - 0.9 m	Dec'85	8	YN
		– Jan'86		
		Nov'86	1	JP
Strömgren <i>uvby</i>	ESO	Jan'85	62	LTPV
	SAT - 0.5 m	– Jan'90		-group
Johnson/ Cousins <i>UBV(RI)_C</i> (Table 3)	DASA - 0.4 m	Nov'84	5	ABl, YN, HC
	ESO - 0.5 m	Nov'86	1	GC, PL
	DASA - 0.4 m	Nov'86	11	HG, FI
	KPNO- 0.9 m	Nov'86	6	ABr, CA
	DASA - 0.4 m	Nov'89	1	TM, CK
	DASA - 0.4 m	Nov'92	1	FM
	ESO - 0.5 m	Jan'94	1	FM
Johnson <i>UBVR</i> (Table 12)	Mt. Maidanak	Dec'76	155	ROTOR
	0.5 m, 0.6 m	– Sep'95		-group
ESO <i>JHK_L</i> (Table 4)	ESO - 1 m	Feb'86	2	HC
Observers are:				
ABl	- A. Blom	GC	-	G. Carrasco
ABr	- A. Brown	HC	-	H. Cuyppers
CA	- C. Ambruster	HG	-	H. Grootjen
CK	- C. Koulis	JK	-	J.P.M. Koninx
ED	- E.M.F. Damen	JP	-	J.W. Prein
FI	- F. Inklaar	PL	-	P. Loyola
FM	- F.J. Molster	TM	-	T. Meinen
		YN	-	Y.K. Ng

Shevchenko (1989) was the first to discuss the possibility to interpret the light curve of BN Ori after 1945 in terms of a process related to the large-scale light-variations of classical FUORs. The phenomenon of FUOR (Herbig 1977), although a prominent eruptive event of great intensity and duration, cannot be predicted nor explained by the present evolution models (e.g. Palla & Stahler 1992, 1993) of pre-main-sequence stars. At the same time, more and more young non-stationary stars exhibiting high-amplitude eruptions can be considered as related to FUORs. Herbig (1977) selected a group of stars (EX Lup, UZ Tau and VY Tau) showing recurrent brightening with great intensity and duration and later labelled them “EXORs” by the name of its brightest member EX Lup. In the early sixties, DR Tau, the most active classical T Tauri star (CTTS), exhibited a progressive brightening lasting for more than 15 years (Götz 1980). Some eruption related with those of FUORs were found from the light curves and the spectra of Z CMA

(Hartmann et al. 1989), V1331 Cyg and other stars which differ widely from classical FUORs.

The large-scale light curve of BN Ori as well as several spectral peculiarities indicate a certain similarity of the BN Ori properties with those of the FUORs. In this paper we first discuss the large-scale historical light curve of BN Ori (Sect. 2).

During the last decade we have obtained several high- and low-resolution spectra of BN Ori in the visual and in the UV. A description of these spectra and a discussion of the peculiar spectral features is given in Sects. 4.2, 4.3 and 5. The analysis of the optical spectra reveals a noticeable thermal stratification of the envelope of BN Ori, which is similar to what has been deduced from the analysis of the spectra of classical FUORs on the descending branch of their light curves. In BN Ori the stratification is reflected by the different values for the full-width at half maximum (FW hereafter) for lines from different temperature regions in the envelope. This can be interpreted by differential rotation in a rotationally flattened envelope or disc. Another similarity with classical FUORs is the high wind-velocity measured from the fast variable (on time-scale of 1 day or less) P-Cygni type H α and Mg II h&k profiles of BN Ori. This type of outflow can probably only be driven by strong magnetic fields, e.g. produced in the neighbourhood of an accretion-disc boundary layer. Nevertheless, there are also differences between the spectrum of BN Ori and those of classical FUORs. Such differences may not be surprising in view of the fact that BN Ori is more massive ($\sim 2 M_{\odot}$) and is rotating much faster than the classical FUORs.

We suggest that BN Ori in its present phase is the result of FUOR type outburst in a strongly variable Herbig A6 – 7e star. A similar transition was observed in 1983 for the Herbig A7e star V351 Ori (HD 38238), which changed from a strongly variable phase into a non-variable A7e phase (van den Ancker et al. 1996), demonstrating that such phenomena are not exceptional for Herbig Ae stars. If this also happened with BN Ori, it becomes of interest to compare its spectral features with those of a Herbig A6 – 7e star as such a star might be similar to BN Ori before the FUOR outburst. We made a detailed comparison with the spectrum of HR 5999 (V856 Sco), a bright and strongly variable Herbig A5 – 7e star, which has been intensively studied during the last two decades (Bessell & Eggen 1972; Tjin A Djie et al. 1989; Baade & Stahl 1989). BN Ori has most lines in common with HR 5999, although the line-widths are partly different. However, it appears that the lines from the cool outer parts of the envelope (shell) are much fainter in BN Ori than in HR 5999, as is indicated by the smaller values of the equivalent widths (EW hereafter) listed in Table 8. This is consistent with the remarkable absence of circumstellar components of the Na I D lines in the high-resolution spectra of BN Ori and the negligible near-infrared excess (NIRE) and colour-excess in the

spectral energy distribution (SED) of BN Ori. This comparison suggests that the FUOR outburst in BN Ori has removed its outer envelope almost completely, except for an optically-thin inner part where $H\alpha$ is formed.

In Sect. 6 we summarise the similarities between the spectral features of BN Ori and those of the classical FUORs and the Herbig Ae stars. We also suggest a cause for the outburst in BN Ori, based on the mass-accretion rates of BN Ori, HR 5999 and BF Ori (A7e), which have been derived from the analysis of their low-resolution UV-spectra taken with IUE (Blondel & Tjin A Djie 1994, 1996).

2. Photometry

2.1. History

The variable character of BN Ori was detected by Cannon (1919) and since then the star has been monitored extensively both visually and photographically. Tsevech made nearly 4000 m_{pg} estimates of BN Ori from sky patrol photographic plate collections of the Harvard, Odessa, Sonneberg and Dushanbe observatories and constructed a light curve of m_{pg} over the period 1898 – 1964 (Dragomiretskaya 1965; Tsevech & Dragomiretskaya 1973).

Fig. 1. Lightcurve of m_{pg} for BN Ori over the period 1898 – 1964, constructed by Tsevech & Dragomiretskaya (1973), and extended up to 1995

This light curve of BN Ori shows quiet periods with maximum brightness $m_{pg} \sim 9^m.7$, during which the brightness frequently decreases by at most $0^m.5$, separated by episodes of roughly 12.5 years, during which the mean brightness dropped with 1^m or 2^m over 100 – 200 days or with 3^m over 20 – 50 days. Superposed on this long-term variability are rapid fluctuations with amplitude of $1^m.5$ during about 10 days. It was already noted by Beyer (1937) and confirmed by Hoffmeister (1949) and Payne-Gaposhkina (1952) that the behaviour of BN Ori is reminiscent of that of the RW Aur variables T Ori and XY Per

Table 2. Photometric Data of BN Ori on the Walraven (WULBV) system

RJD#	V	V – B	B – U	U – W	B – L	V ^J
111.576	–1.117	0.197	0.402	0.200	0.228	9.66
122.591	–1.105	0.207	0.399	0.201	0.230	9.63
428.642	–1.111	0.205	0.411	0.200	0.233	9.64
430.630	–1.119	0.199	0.402	0.199	0.222	9.66
436.617	–1.111	0.198	0.405	0.195	0.228	9.65
442.621	–1.125	0.194	0.408	0.199	0.230	9.68
443.627	–1.119	0.198	0.403	0.193	0.221	9.67
450.665	–1.108	0.201	0.408	0.195	0.228	9.64
451.631	–1.107	0.202	0.406	0.194	0.224	9.64
452.680	–1.116	0.202	0.405	0.203	0.233	9.66
745.763	–1.124	0.201	0.401	0.195	0.226	9.67*
error:	0.006	0.003	0.005	0.006	0.005	0.02
#JD–2446000	* simultaneous with IUE.					

Table 3. Photometric Data of BN Ori on the Johnson/Cousins $UBV(RI)_C$ system. The last column (N, O) gives the number of observations per night and the observatory: DASA(D), ESO(E) or Kitt Peak(K)

RJD#	V	B – V	U – B	V – R _C	V – I _C	N, O
6001.549	9.69	0.44	0.17	0.32	0.58	4,D
6002.525	9.65	0.48	0.20	0.29	0.59	4,D
6005.575	9.67	0.47	0.19	0.30	0.58	5,D
6006.546	9.64	0.49	0.17	0.29	0.57	5,D
6007.584	9.86	0.41	0.18	0.24	0.54	4,D
6731.596	9.70	0.46	—	0.29	0.58	3,D
6739.917	9.66	0.45	0.14	0.29	0.59	1,K
6742.994	9.66	0.47	0.14	0.29	0.59	1,K
6743.823	9.62	0.46	0.13	0.30	0.60	1,K
6743.947	9.64	0.46	0.14	0.29	0.57	1,K
6745.427	9.67	0.44	—	0.31	0.58	3,D*
6747.494	9.64	0.46	—	0.27	0.56	3,D*
6747.801	9.68	0.47	0.16	0.29	0.57	1,E*
6748.836	9.65	0.45	0.14	0.29	0.60	1,K
6748.912	9.70	0.45	0.12	0.30	0.61	1,K
6754.766	9.66	0.47	0.14	0.28	0.59	1,K
6754.951	9.64	0.45	0.16	0.30	0.59	1,K
6759.433	9.76	0.42	—	0.31	0.59	3,D
6760.433	9.61	0.47	—	0.25	0.58	3,D
6762.490	9.68	0.45	—	0.29	0.58	3,D
6763.528	9.56	0.47	—	0.28	0.56	3,D
6764.445	9.69	0.43	—	0.29	0.58	3,D
6765.424	9.71	0.44	—	0.30	0.55	3,D
6766.463	9.66	0.45	—	0.29	0.59	3,D
6767.444	9.65	0.46	—	0.28	0.57	3,D
7854.516	9.66	0.49	—	0.25	0.52	3,D
8936.646	9.69	0.47	—	0.31	0.43	1,D
9371.616	9.62	0.52	0.09	0.30	0.58	1,E
error:	0.01	0.01	0.02	0.01	0.02	E,K
	0.04	0.02	0.02	0.02	0.02	D
#JD–2440000	* simultaneous with IUE.					

and we can extend the similarity now to other Herbig Ae stars with Algol-type minima such as BF Ori, UX Ori, WW Vul and HR 5999. In a discussion of the photometric variability of BN Ori, Dragomiretskaya (1965) concluded that the large amplitude-variations cannot be due to temperature differences on the stellar surface, since a dimming

Table 4. NIR photometric data of BN Ori

JD	<i>J</i>	<i>H</i>	<i>K</i>	<i>L</i>
2446486.5	8.74	8.41	8.33	>8.0
2446488.5	8.68	8.36	8.25	>8.0
error:	0.08	0.08	0.06	—

by 1^m5 would already require a full coverage by cool spots of the stellar surface. Dragomiretskaya also used the visual photometry by Esch (1925), Beyer (1937) and Martinov (1951), to derive the colour indices for a number of dates and the resulting colour-magnitude diagram shows that the strong variations of BN Ori follow a reddening-line similar to those followed by many Herbig Ae stars. Such a type of variation is usually ascribed to obscuration by variable amounts of circumstellar dust (Wenzel 1968; Wenzel et al. 1971). For BN Ori the slope of the reddening-line was about 3, which is close to that of interstellar dust. Tsesevich & Lange observed that BN Ori showed Algol-like variations with a period of 27 days (Martinov 1951). From an analysis of quasi-periodic features during high-activity episodes in the light curve of BN Ori, Ishchenko (1982) detected a quasi-cyclic 18 – 22 day periodicity superimposed on a stochastic behaviour and attributed this periodicity to the rotation of obscuring circumstellar dust clouds.

Figure 1 shows that the large-scale structure of the light curve changed around 1940: the amplitude of the strong variations decreased and the brightness maximum increased to $m_{pg} \approx 9^m2$ in Dec'46. Since then the variations were gradually quenched from an amplitude of 0^m4 to about 0^m1 in 1966, while the maximum of the brightness-variations slowly decreased to $m_{pg} \sim 10^m1$. In Sect. 6 we shall compare this behaviour with those of classical FUORs. After 1965 all observations have been made photoelectrically. Between 1965 and 1975 Zajtseva (1968, 1970), Kolotilov & Zajtseva (1976) and Kolotilov et al. (1977) have made several observations of BN Ori on the *UBV* and *JHKL* photometric systems, but they did not detect a pronounced variation.

2.2. Photometry since 1976

The star has been observed regularly by various observers on several photometric systems (see Table 1).

1. Between 1976 and 1995 *UBVR* observations were obtained at the Mt. Maidanak observatory near Samarkand (Table 12). This was done in the course of the ROTOR (*Research of Traces of Rotation*) photometric program with a single-channel photometer mounted on the 60 cm Zeiss reflector and the 48 cm AZT¹14 reflector (Kilyachkov & Shevchenko 1977).

¹ Astronomicheskii Zerkalnyi Teleskop.

The data of JD 2448582 are simultaneous with the high-resolution spectroscopy at SAO (Sect. 4.3)

2. From 1985 to 1990 BN Ori was observed on the Strömgren *ubvy* system by the LTPV-group (*Long Term Photometry of Variables*) of ESO observers, with the Strömgren Automatic Telescope (SAT; formerly known as the Danish 50 cm telescope) at La Silla. This telescope is equipped with a simultaneous multi-colour photometer. Any systematic effects due to non-simultaneous measurements at the different passbands are therefore avoided. Since these observations have already been published (Sterken et al. 1993, 1995), they are not listed in this paper.
3. Photometric data on the Walraven *WULBV* system were obtained during 3 observing runs in 1985 and 1986 with the Dutch Light Collector at ESO, La Silla. Measuring and reduction procedures have been explained by Lub & Pel (1977). During these observations the Walraven *WULBV* – $\log_{10}$ intensity values were measured simultaneously in the different passbands. The results of these measurements are listed in Table 2, where the last column gives the corresponding magnitude on the Johnson system calculated with the formula suggested by Brand & Wouterloot (1988).
4. Optical photometry of BN Ori, on the Johnson/Cousins *UBV(RI)_C* system, has been obtained in 1986 and 1994 with the ESO 50 cm telescope at La Silla, in Nov'86 with the KPNO 90 cm telescope at Kitt Peak and on several occasions between 1984 and 1992 with the 40 cm telescope at the Dutch Astronomical Station at Ausserbinn (DASA), Switzerland. The results of these measurements are collected in Table 3 and the data of JD 2446747 were obtained simultaneously with the high-resolution IUE observation of BN Ori.
5. Since 1984 BN Ori has also been observed on the *UBV(RI)_C* system by W. Herbst and collaborators in the course of a monitoring program at the “Van Vleck” observatory (private communication).
6. NIR photometric data on the ESO *JHKL* system (Bouchet et al. 1989, 1991), of BN Ori were obtained in Feb'86 with the ESO 1 m telescope at La Silla. During these observations, the telescope was equipped with an InSb detector with a 15'' diaphragm. Sky subtraction was achieved by chopping with a frequency of 8 Hz in the east-west direction with a throw of 30'' amplitude. The results are given in Table 4.

After transformation of the data on the various systems to the Johnson magnitude V^J and colour $(B - V)^J$ we can hardly find any change in brightness and colour over these years. The average values are: $V^J = 9^m65 \pm 0^m03$ and $(B - V)^J = 0^m47 \pm 0^m02$. Only on one occasion (Oct. 29 – Nov. 2, 1991), the star seemed to dim by 0^m5 (Kovalchuk 1991). Because there are no data available for the 34 nights preceding Oct. 29 and for the 12 nights following Nov. 2, we can only state that the variation was limited to at most

Fig. 2. Observed (squares) and extinction-corrected (circles) SED of BN Ori based on the data of Feb’86. The L -band observation of Cohen (1973) is indicated by the “upper” triangle (with error-bar). The L -band observation from Table 4 is indicated by the “lower” triangle (with upperlimit). The solid line is the Kurucz model of $T_{\text{eff}} = 7150$ K, $\log g = 3.8$ and solar abundance, normalised to the extinction-corrected V -band flux of BN Ori. The dotted lines are the observed- and extinction-corrected UV-fluxes

51 nights. The variation is along the reddening-line with slope 3, so that this event could have been due to infalling circumstellar dust which evaporated in the neighbourhood of the star.

Since 1976 we have obtained only two observations in the NIR (Table 4), and in Fig. 2 we give a SED of BN Ori based on these data of Feb’86. After transformation of the magnitudes to fluxes and correction of these fluxes for foreground extinction with the law of Savage & Mathis (1979) and $E(B - V) = 0^{\text{m}}07$ (Sect. 4.3), the corrected SED could be fitted with a Kurucz (1991) model for $T_{\text{eff}} = 7150$ K and $\log g = 3.8$, corresponding to a spectral type of F0 III – IV (Sect. 5) and an $E(B - V) = 0^{\text{m}}17$. From Fig. 2 we note that we get a good agreement in the visual and NIR wavelength ranges, but that there remains an excess in the UV. This excess will be explained (Sect. 5) in terms of the contribution from a (hot) boundary layer between the star and accretion-disc. If we compare our NIR data of 1986 with those obtained before 1977 (Glass & Penston 1974; Kolotilov et al. 1977) we note no difference in the H and K magnitudes. However, our J -band flux is somewhat larger than that of Kolotilov et al. and our L -band flux is significantly smaller than the one Cohen (1973; $L \approx 7^{\text{m}}6$) measured in 1971. The earlier attempts to match the SED (Kolotilov & Zajtseva 1976; Brown et al. 1986) were based on this higher L -band flux. No IRAS point-source was detected at the position of

BN Ori, probably because the far-IR fluxes of the star are not higher than the background.

From the Walraven photometry (which has two pass-bands in the UV: W at $3236 \text{ \AA}$ and U at $3623 \text{ \AA}$), we can get a measure of the magnitude of the Balmer discontinuity (D_B). The mean of the 9 observations of Dec’85 – Jan’86 gives $D_B = 0^{\text{m}}80$. This is a deficiency of $0^{\text{m}}48$ with respect to the prediction of the Kurucz (1991) model for $T_{\text{eff}} = 7200$ K and $\log g = 3.5$ which we take for the classification F0 III (Sect. 5). If this is due to the contribution of recombination of H^+ free-bound transitions near the star, we can derive (Garrison 1978) that for a temperature of 10^4 K in this region the emission measure is $1.86 \cdot 10^{35} \text{ cm}^{-5}$. If we assume that this ionosphere is in hydrostatic equilibrium with a scale-height of $4 R_*$ we find within $2 R_*$ an electron density $N_e = 3.34 \cdot 10^{11} \text{ cm}^{-3}$.

For HR 5999 (A5 – 7 III) we used the Walraven photometry to derive a D_B equal to $1^{\text{m}}23$ which results in a deficiency of $0^{\text{m}}20$ when compared to a Kurucz (1991) model with $T_{\text{eff}} = 8000$ K. This gives an emission measure of $6.0 \cdot 10^{35} \text{ cm}^{-5}$, which corresponds to $N_e = 5.6 \cdot 10^{11} \text{ cm}^{-3}$ close to the star, so that N_e^2 is 2.8 times the value found for BN Ori.

3. Imaging

In the two-dimensional CCD spectrograms, of $H\alpha$ taken in Jan’95, weak nebular emission-lines were detected along the spatial direction of the CCD image, which

Table 5. Log of spectroscopic observations of BN Ori. Columns 8 to 10 denote the dispersion D ($\text{\AA mm}^{-1}$) the resolution R ($\text{\AA pix}^{-1}$) and the exposure time Δt (min). The IUE imagenumbers are given in Col. 5 and the first digit denotes the used camera (1 = LWP, 3 = SWP) and LAP means large aperture. Observers: AB - A. Brown, DW - D. de Winter, HC - H. Cuypers, HT - H.R.E. Tjin A Dje, MA - M.E. van den Ancker, VK - V. Kotyshev, VS - V.S. Shevchenko

Spectral Range ($\text{\AA}$)	Date	UT	RJD#	Observatory + Telescope	Spectrograph + Detector	D	R	Δt	Obs.
3700–7000	12/11/83	22:25	5651.4345	Maidanak 0.6 m	UAGS tube	90	2.5	60	VS
6000–8700	13/11/83	22:48	5652.4500	Maidanak 0.6 m	UAGS tube	90	2.5	60	VK
3800–7200	24/02/86	02:15	6485.5944	ESO 1.5 m	B&C IDS	172	1.7	2	HC
3600–6790	21/11/91	19:40	8582.3195	SAO BTA 6 m	MSS A700y	27	0.65	65	VS
4180–7860	07/12/92	06:11	8963.7576	ESO 1.5 m	B&C CCD	129	1.80	8	MA
6090–8720	08/12/92	04:44	8964.6972	ESO 1.5 m	B&C CCD	88	1.28	8	MA
5858–5910	16/12/94	02:27	9702.6021	ESO CAT 1.4 m	CES CCD	—	0.11	45	MA
3700–7090	16/12/94	03:58	9702.6653	ESO 1.5 m	B&C CCD	114	1.59	6	DW
5858–5910	17/01/95	01:49	9734.5757	ESO CAT 1.4 m	CES CCD	—	0.11	45	MA
6536–6591	17/01/95	02:46	9734.6153	ESO CAT 1.4 m	CES CCD	—	0.12	45	MA
7650–7715	20/01/95	01:08	9737.5474	ESO CAT 1.4 m	CES CCD	—	0.14	45	MA
6536–6591	20/01/95	02:05	9737.5867	ESO CAT 1.4 m	CES CCD	—	0.12	45	MA
1150–2000	22/01/84	10:04	5721.9819	IUE LAP 322075	Echelle videcon	—	7	180	HT
1800–3200	22/01/84	13:09	5722.0521	IUE LAP 102694	Echelle videcon	—	7	12	HT
1150–2000	11/10/86	06:09	6714.7979	IUE LAP 329420	Echelle videcon	—	7	120	AB
1800–3200	11/10/86	08:15	6714.8472	IUE LAP 109294	Echelle videcon	—	7	10	AB
1150–2000	11/11/86	04:08	6745.7451	IUE LAP 329657	Echelle videcon	—	7	210	HT, AB
1800–3200	11/11/86	07:59	6745.8361	IUE LAP 109508	Echelle videcon	—	7	10	HT, AB
1800–3200	12/11/86	19:43	6747.5924	IUE LAP 109512	Echelle videcon	—	0.2	780	HT, AB
1150–2000	13/11/86	10:00	6747.9792	IUE LAP 329660	Echelle videcon	—	7	190	HT, AB

JD–2440000.

demonstrates that BN Ori is surrounded by a very faint emission (reflection) nebula. This is another property which BN Ori shares with the class of Herbig Ae/Be stars. Since these weak lines extended over the entire CCD frame, the diameter of this nebula must be larger than that covered by this frame ($\sim 10''$). In order to get more insight in the morphology of this nebula, CCD images of BN Ori through *Bessell U* and *V*, *Gunn z*, and a narrowband ($\text{FW} = 13.5 \text{\AA}$, centered at $6558.88 \text{\AA}$) $\text{H}\alpha$ -filter (No. 674) were obtained in Feb'95 (de Winter 1995) with the Dutch 90 cm telescope at ESO. However, we did not detect nebulosity around BN Ori on any of these images, which may be caused by the fact that the bandwidth of the $\text{H}\alpha$ -filter is still too large. In these cases the contribution from other surrounding wavelengths may be too high to permit imaging of the nebulosity in $\text{H}\alpha$.

4. Visual spectroscopy

4.1. History

The spectroscopic information on BN Ori from the period before 1960 is scarce. The first spectral classification of A7, was made by Cannon (1931) for the HDE catalogue, from objective prism spectra on plates exposed between 1925 and 1931. This classification was later confirmed by Parenago (1933), Hoffmeister (1949) and Payne-Gaposhkina (1952). Herbig (1954) estimated a type A5 – A7 from a low-dispersion slit spectrogram, but from an additional spectrum ($D = 75 \text{\AA mm}^{-1}$, taken on Mar. 6, 1955), he noted that the spectrum of BN Ori is pecu-

liar and that it may be composite with types A5 – A6 and mid-F9 (Herbig 1960a). In 1968 and 1969 Zajtseva (1971) took a number of blue-slit spectra ($D = 140 - 250 \text{\AA mm}^{-1}$) from which she classified the spectrum of BN Ori as F0. A microphotometer tracing in that paper shows absorption lines near 4525, 5163 and $5265 \text{\AA}$ (identified by her as Fe I), Ca II K and Mg II at $4481 \text{\AA}$. From the slope of the continuum between 6000 and $4000 \text{\AA}$ a spectrophotometric temperature of 9700 K was derived, which is consistent with spectral type A7 – A9. Photoelectric spectral scans in the range $6600 - 3200 \text{\AA}$ made in Jan'75 allowed Kolotilov & Zajtseva (1976) to determine the residual strengths of the $\text{H}\gamma$, $\text{H}\delta$, $\text{H}\epsilon$ and Ca II K lines, which led the authors to a classification F2 – F3. The only emission line in the visual spectrum of BN Ori is $\text{H}\alpha$. Between Jul'71 and Dec'75, 18 spectrograms of $\text{H}\alpha$ ($D = 20 \text{\AA mm}^{-1}$, $R = 1 \text{\AA pix}^{-1}$) were taken by Kolotilov & Zajtseva (1976). The line profile of $\text{H}\alpha$ in these spectra is double-peaked with an absorption trough at -50 km s^{-1} . Its blue emission-component varies strongly and has been observed to change into an absorption-component (with maximum velocity -600 km s^{-1}) within 24^{h} .

4.2. Low-dispersion spectra

Since 1983 we have obtained a number of high-and low-resolution spectra of BN Ori. The observational details are listed in Table 5. We will compare the spectral information of BN Ori with that of FU Ori (Herbig 1966; Reipurth 1990) and that of the bright Herbig A5 – 7 IIIe

Table 6. Identification, equivalent widths ($\text{\AA}$), full widths at half maximum (km s^{-1}) and source ($\mathcal{S}$) of the lines in the red part of the visual spectra of BN Ori, HR 5999 and FU Ori. See Table 10 for the description of the used symbols

λ_0 ($\text{\AA}$)	Line id.	E_χ (eV)	$\mathcal{S}$	BN Ori		HR 5999					FU Ori	
				EW	FW	EW	FW	EW ⁵	⁵ FW ⁶	EW ⁶	EW	FW
5889.95	Na I D ₂	0.00	s	0.00 ^{1,8}	—	0.38 ⁸	31	—	—	—	2.53 ⁹	66:
			d	0.13 ^{1,8}	400	0.37 ⁸	250:	—	—	—	—	—
5895.92	Na I D ₁	0.00	s	0.00 ^{1,8}	—	0.30 ⁸	28	—	—	—	2.53 ⁹	66:
			d	0.09 ^{1,8}	400	0.35 ⁸	250:	—	—	—	—	—
6496.90	Ba II	0.60		0.42 ⁷	402	0.44 ⁴	419	—	—	—	—	—
6562.82	H α	10.20	pcs	—, 80 ^{1,8}	—	—, 8 ⁴	—	—	—	—	—	—
6707.89	Li I (1)	0.00	ps	0.30 ⁷	244	0.0	—	—	—	—	0.47 ³	—
7664.90	K I (1)	0.00	i	0.09 ⁸	—	—	—	—	—	—	—	—
7698.96	K I (1)	0.00	i	<0.04 ⁸	—	—	—	—	—	—	—	—
7771.94	O I (1)	9.14	s	0.22 ⁷ b	370	1.03 ⁴ b	270	1.38 b	240	0.64 b	—	—
7774.17	O I (1)	9.14	s	—	—	—	—	—	—	—	—	—
7775.39	O I (1)	9.14	s	—	—	—	—	—	—	—	—	—
8437.96	P18	12.04	p	0.07 ⁷ b	403	0.50 ⁴ b	622	0.10:	185	0.33	—	—
8446.25	O I (4)	9.48	s	—	—	—	—	0.19 b	110	0.17 b	0.3 ¹⁰ b	—
8446.36	O I (4)	9.48	s	—	—	—	—	—	—	—	—	—
8446.76	O I (4)	9.48	s	—	—	—	—	—	—	—	—	—
8498.02	Ca II (2)	1.69	s	0.10 ⁷ b	440	0.38 ⁴ b	500	—, 90	150	—	2.6 ¹⁰ b	124
8502.49	P16	12.04	p	—	—	—	—	—	—	—	—	—
8542.09	Ca II (2)	1.69	s	0.25 ⁷ b	359	1.82 ⁴ b	495	0.77	150	—	3.9 ¹⁰ b	185
8545.38	P15	12.04	p	—	—	—	—	—	—	—	—	—
8598.39	P14	12.04	p	0.05 ⁷	396:	2.21	662	—	—	—	0.5 ¹⁰ b	122
8662.14	Ca II (2)	1.69	s	0.26 ⁷ b	393	4.27 ⁴ b	700	—	—	—	2.4 ¹⁰ b	212
8665.02	P13	12.04	p	—	—	—	—	—	—	—	—	—

Fig. 3. Part of the low-dispersion blue spectrum of BN Ori, taken with the ESO 1.5 m telescope in Dec'94

star HR 5999 (Bessell & Eggen 1972; Tjin A Djie et al. 1989; Baade & Stahl 1989).

4.2.1. Blue spectra

Two low-dispersion blue spectra have been taken: one in 1983 at Mt. Maidanak and one in 1994 at ESO (Fig. 3). From the strength of the H γ , H δ , H ϵ and Ca II K lines and the presence of the *G*-band in the spectra we confirm the classification F2 – F3 by Kolotilov & Zajtseva (1976).

However, some additional lines, such as the strong Ca I 4227 Å line, may point to a later type, e.g. F3 – F5. These blue spectra again show many absorption lines, among which the Fe II multiplet 42, the *G*-band, the Na I D doublet and the Ba II (6497 Å) and Li I (6708 Å) lines which are also conspicuous lines in FUOR spectra (Reipurth 1990). The EW of the Li I line is comparable (Table 6) with that of Li I in the spectrum of FU Ori (Herbig 1965).

The red emission-component of H α is stronger than the blue one, in contrast with the H α -profile in the low-dispersion IDS spectrum of 1986, which shows roughly equal red and blue emission-components.

4.2.2. Red spectra

Two low-dispersion spectra in the far-red wavelength range have been secured by us: one in 1983 at Mt. Maidanak and one in 1992 at ESO. Figure 4 shows part of the spectrum obtained at ESO and Table 6 lists the EWs and FWs of the most important lines in this spectrum and in those of FU Ori (Shanin 1979) and HR 5999 (Tjin A Djie et al. 1989). Figure 4 shows the Ca II (2) IR-triplet (8498, 8542 and 8662 Å) in absorption, which is blended with the Paschen absorption lines P16, P15 and P13, respectively. We have used the method of Bychkov et al. (1978) to make a spectral classification from the EWs of the blends of the Ca II (2) IR-triplet and the EW of the unblended P14. In the assumption that none of

Fig. 4. Part of the low-dispersion red spectrum of BN Ori, taken with the ESO 1.5 m telescope in Dec'92, with the most prominent lines identified

these lines are filled-in by emission one can derive a lower limit for the effective temperature or the spectral type of the region of formation of these lines. From Table 6 we find for BN Ori an EW ratio of ~ 12 , which points to a spectral type around G5. With the same method Shanin (1979) classified FU Ori as a K0 star. A reticon spectrum of HR 5999 (Tjin A Djie et al. 1989) in the same spectral region gives us an EW ratio of 3.1, which indicates a spectral type around A5. High-resolution observations of only the 8498 and 8542 Å lines (Hamann & Persson 1992) show the unblended profiles with indications for some filling-in by emission. After correction for emission the EWs would be somewhat larger, which could move the spectral type of HR 5999 to a slightly later type, e.g. A7. Similar (unknown) emission corrections to the Ca II (2) IR-triplet for BN Ori and FU Ori could shift their classifications to types later than G5 and K0 respectively. In the far-red spectrum we also observed the two O I IR-triplets around 7774 and 8446 Å (blended with P18 at 8438 Å). The EWs of these lines can be compared with those of standard stars of well-known spectral class (Slettebak 1986; Figs. 2 and 3, Faraggiana et al. 1988). High-resolution profiles of these lines for HR 5999 have been given by Felenbok et al. (1988) and by Hamann & Persson (1992). The EW, measured from the best profile of the O I (1) IR-triplet is 1.38 Å, which according to Slettebak (1986; Fig. 2) is consistent with A2 – A7 IIIsh. A correction for the emission-component would not change this conclusion. The EW of this (unblended) triplet for BN Ori is 0.22 Å, which would classify the star as F6 – G0, unless the contribution by emission is very large. A comparison of the EW of the blended O I (4) IR-triplet for HR 5999 with Fig. 3 of Slettebak's paper gives again A2 – A7 IIIsh, even if the filling-in by emission (Hamann & Persson 1992) is taken into consideration. The very small EW of this line for BN Ori suggests again a type G, but F0 could be

possible if the correction for emission fill-in would raise the EW from 0.1 to 0.4 Å. For FU Ori the EW of this line is 0.3 Å (Shanin 1979). This could lead to a classification F3 IV. Since FU Ori has strong shell features and high luminosity-class (see next section) its spectral type must be later than A6 – G0 (Slettebak 1986; Fig. 3), unless the emission contribution to the O I (4) IR-triplet is very strong.

4.3. High-dispersion spectra

A high-dispersion visual spectrum of BN Ori was obtained on Nov. 21, 1991 with the main stellar spectrograph (MSS) mounted on the 6 m Big Azimuthal Telescope (BTA) of the Special Astrophysical Observatory (SAO) in the Northern Caucasus. Various parts of this spectrum are given in Fig. 5 and the values of the EWs and FWs of the stronger lines are listed in Table 11, together with those of HR 5999 determined from the Coudé spectrum G9359 ($D = 12.4 \text{ Å mm}^{-1}$, Tjin A Djie et al. 1989), and some qualitative information concerning line strengths from the Coudé spectra of FU Ori ($D = 16 \text{ Å mm}^{-1}$, Herbig 1966).

In this table the identification of the lines with wavelengths longer than 5200 Å is tentative, except for the Ba II (6497 Å) and the Li I (6708 Å) lines. From the width of several photospheric lines (Mg II (4), Fe II (42) and Fe I (43)) we estimate a rotation rate of $v \sin i = 180 - 230 \text{ km s}^{-1}$ for BN Ori. A similar estimate for HR 5999 gives $v \sin i \sim 135 \text{ km s}^{-1}$. However, a comparison with the Mg II (4481 Å) line-width with those of rotation standard stars (Slettebak et al. 1975), taken with the same instruments as used for HR 5999, leads to $v \sin i = 180 \pm 20 \text{ km s}^{-1}$ for this star (Tjin A Djie et al. 1989). This suggests that the rotation rate of BN Ori is probably somewhat higher, perhaps around 250 km s^{-1} . For FU Ori Herbig (1966) derived $v \sin i \approx 60 \text{ km s}^{-1}$.

The most important conclusion from the spectrum of BN Ori is that different lines suggest different spectral types for the star:

1. from a comparison of the EWs of the higher terms of the Balmer series with a statistical analysis made by Kopylov (1958) we estimate a spectral type A6 – A7 for stars with low and average luminosity,
2. the strength of many Fe II and Ti II lines, usually known as photospheric ones is consistent with spectral types A6 – F0,
3. the strength of the *G*-band near 4300 Å points to a type F0 – F2 or early G,
4. the EWs of the rather numerous Fe I lines are typical for spectral types F0 to G5,
5. the strength of the Mn I resonance triplet at 4033 Å suggests a late *G*- or early K-type sub-class.

Together with the classifications G0 from the O I (1) IR-triplet and G5 from the Ca II (2) IR-triplet (Sect. 4.2.2) this variety in spectral type indicates a considerable thermal stratification of the atmosphere of

Fig. 5. Various parts of the high-dispersion visual spectrum of BN Ori obtained at SAO in 1991. Shown are from top to bottom: • Ca II H and K, H ϵ to H14 and the Ti II lines at 3760 Å, • H δ and its blue neighbourhood (V II, Sr II, Fe I, Ti II, Mn I (2) triplet), • H γ and the red neighbourhood, • the red neighbourhood of H β . The identification of the marked lines can be found in Table 11

BN Ori, which must consist of an A6 – A7 photosphere, surrounded by a rather dense and cooler envelope or disc. Several lines such as Sr II (4078 Å) and the semi-forbidden Ti II (13) lines near 3760 Å are typical shell lines and are probably formed in the low-density outer part of the envelope.

Most of the lines mentioned above are also present in the spectra of FU Ori and HR 5999 which were obtained with comparable resolution. The visual spectrum of FU Ori has been classified as F2p:I – IIe (Herbig 1966). If we add the classification F6 – G0 from the O I (4) IR-triplet and K0 from the Ca II (2) IR-triplet we can conclude that also the atmosphere of FU Ori is thermally stratified. Similar to BN Ori the spectrum of FU Ori shows a strong *G*-band and strong photospheric lines of Ba II and Li I. However, in contrast with BN Ori, strong components with velocities around -50 km s^{-1} are present in the spectrum of FU Ori for all lines of Hydrogen and

neutral or singly-ionised metals (with exception of the Fe I lines with higher excitation levels). Their presence has led to the qualification peculiar in the spectral classification. Because of their difference in velocity with the photospheric lines these components are probably formed in an outer shell region. Since we have no EWs from the visual spectrum of FU Ori, with the exception of Li I, Na I D and H α (Table 6), we only give qualitative estimates from Herbig (1966). With exception of the emission in Ca II K and H α , the spectrum did not seem to vary significantly in time between 1945 and 1963.

The visual spectrum of HR 5999 has been classified as A5 – A7 IIIe (Bessell & Eggen 1972; Tjin A Djie et al. 1989). The classification from the far-red spectrum (Sect. 4.2.2) is again A7 III, which indicates an absence of significant thermal stratification of the envelope of HR 5999. This means that the stratification of the atmosphere as found in BN Ori and FU Ori can not originate from the disc component, because this component is significant in the case of HR 5999 (Sect. 5). We will discuss this further in Sect. 6.

In contrast with FU Ori and BN Ori we do not find a *G*-band and Li I line in the spectrum of HR 5999, but similar to FU Ori, it has strong blue-shifted (-30 to -50 km s^{-1}) components of the Balmer- and metallic-lines, which are formed in a cool, dense outer shell (Tjin A Djie et al. 1989). Such an dense cool circumstellar shell does not seem to be present around BN Ori.

This is confirmed by the high-resolution observations of the Na I D (Fig. 6) with the CAT at ESO ($R = 0.11 \text{ Å pix}^{-1}$) and the MSS at SAO ($R = 0.65 \text{ Å pix}^{-1}$) and the K I lines (not shown). The observations at ESO show the presence of interstellar components only, with a heliocentric-velocity of $+26 \text{ km s}^{-1}$, which is of the same order as those of other stars in the Orion complex. The interstellar Na I D lines have EWs equal to 0.13 Å (D_2) and 0.09 Å (D_1). Since these lines are not saturated, we can use the Strömgren (1948) method, with which we derive an interstellar (foreground) column density for Na I of $1.27 \cdot 10^{12} \text{ cm}^{-2}$. With the relation between $E(B - V)$ and Na I D column density of Hobbs (1974) we find for the foreground of BN Ori an $E(B - V)$ of 0^m07 . From the Na I D lines, observed at SAO in 1991, we obtain the same value. These values are in agreement with those determined for the Orion complex by Walker (1969). In contrast with the Na I D lines of BN Ori, those of HR 5999 and FU Ori have several velocity-components which are formed in the circumstellar envelope of the star. The velocities measured for HR 5999 are $v_{\text{max}} \sim -35 \text{ km s}^{-1}$, and for FU Ori $v_{\text{max}} \sim -100 \text{ km s}^{-1}$ (Bastian & Mundt 1985; Reipurth 1990). The circumstellar origin of the Na I D lines in the spectrum of HR 5999 is clear from the variability of their EWs and the absence of Na I D lines in the spectrum of the common proper motion companion HR 6000 (Tjin A Djie et al. 1989).

Fig. 6. High-resolution heliocentric-corrected Na I D spectra obtained at ESO in 1994 for BN Ori (top) and HR 5999 (bottom, see also Grady et al. 1996). The dotted lines indicate the continuum level. The spectrum of HR 5999 was used for the annotation and the difference in radial velocity between the two galactic directions of observation introduces a wavelength-shift in the figure for the spectrum of BN Ori

The K I resonance lines of BN Ori observed at ESO (Jan. 20, 1995) were very weak. The 7699 Å line is hardly distinguishable from the noise, while the 7665 Å line is in the wing of a rotational line of the telluric A band of O₂. The lines have a heliocentric-velocity of $\sim +20 \text{ km s}^{-1}$ and are of interstellar origin. The EWs of these lines are 8.5 mÅ ($\pm 30\%$) and $\leq 4 \text{ mÅ}$ ($\pm 50\%$) for the 7665 and 7699 Å line, respectively. If the 7665 Å line is optically thin we derive with the oscillator strength of the line, a column density of $2.3 \cdot 10^{10} \text{ cm}^{-2}$. The ratio of the column densities of Na I to K I in the direction of BN Ori is then 54, the same value as for the direction of AB Aur (Felenbok et al. 1983).

A peculiar feature of BN Ori is the presence of broad, shallow and symmetric components of the Na I D lines, with a FW of about 400 km s^{-1} . The corresponding $v \sin i$ is close to the rotation rate ($\sim 220 \text{ km s}^{-1}$) of the photo-

sphere of BN Ori, which has $T_{\text{eff}} = 7150 \text{ K}$. Because of the low ionization potential of Na I ($E_{\chi} = 5.14 \text{ eV}$), we do not expect to observe these lines from photospheres with $T_{\text{eff}} > 5500 \text{ K}$. However, the broad components can originate from the atmosphere of the inner part of the accretion-disc, which has a temperature below 5890 K (Table 7) and a $v \sin i$ which is close to the photospheric-rotation rate. A similar broad component can also be found in the high-resolution profiles of the Na I D lines of HR 5999. However, in this case its width and EW are more difficult to estimate because of the circumstellar emission-component in both Na I D lines. The values for HR 5999 in Table 6 are therefore probably lower limits. The large width of the circumstellar components in the Na I D profiles of FU Ori (Reipurth 1990) does not enable us to detect the presence of such shallow components for this star.

The H α -profile of BN Ori has been observed by us at three dates in high-resolution: in Nov'91 at the SAO, and twice in Jan'95 at ESO. An additional profile obtained on Nov. 10, 1989 by Fernández et al. (1995) is very similar to the one of Nov'91. The resulting profiles are also similar to those given by Kolotilov & Zajtseva (1976), but show more details. In order to estimate the chromospheric profile we divided the normalised fluxes in the observed profiles by the corresponding normalised fluxes of the profiles of 21 Vul (A7 – F0 IV, $v \sin i \sim 200 \text{ km s}^{-1}$), which has a very weak shell. The profile of 21 Vul was taken from Doazan et al. (1991) and a contribution from the shell to H α is only expected in the minimum of the profile. After this procedure, the SAO H α -profile shows a single emission peak with a single, broad absorption-feature with $v \sim -650 \text{ km s}^{-1}$, which agrees well with the velocities found by Zajtseva & Kolotilov (1973). One of the ESO H α -profiles has an almost symmetrical shape, with a relative central part which is almost equal to that of the SAO H α -profile. The other profile is less strong in its central part and has a depression near $+240 \text{ km s}^{-1}$. The three profiles and their “chromospheric” shapes are shown in Fig. 7. The shapes are different from those of HR 5999 (Tjin A Djie et al. 1989; Baade & Stahl 1989; Praderie et al. 1991), which show no high-velocity absorption-features. The H α -emission flux of BN Ori can be derived from Fig. 7 by integration and normalisation with the continuum flux near 6600 Å, obtained from the SED with the help of the distance to radius ratio and after correction for extinction (Sects. 2 and 4.3). In this way we find emission fluxes of $1.56 \cdot 10^5 \text{ W m}^{-2}$ for the observations of Nov. 10, 1989 and Nov. 21, 1991, and $1.22 \cdot 10^5 \text{ W m}^{-2}$ for the observations of Jan. 20, and Jan. 17, 1995. In the same way we may derive the H α emission flux of HR 5999 in its phase of maximum brightness $V^J = 6^{\text{m}}.8$ (Tjin A Djie et al. 1989), which after an estimated correction for the central absorption, results to $2.3 - 3.4 \cdot 10^6 \text{ W m}^{-2}$. For $V^J = 7^{\text{m}}.6$ it is $5.8 \cdot 10^6 \text{ W m}^{-2}$. The flux of HR 5999 is therefore larger than that of BN Ori by a factor which is in the range 22 – 28.

Fig. 7. Left: high-resolution $H\alpha$ -profiles of BN Ori obtained at SAO in 1991 (top) and at ESO on Jan. 17 1995 (middle) and Jan. 20 1995 (bottom). Right: corresponding profiles after re-binning and division by the normalised $H\alpha$ -profile of 21 Vul (from Doazan et al. 1991). Top-axis gives the velocity (km s^{-1}) relative to 6562.82 Å

The $H\alpha$ -profiles of FU Ori (Bastian & Mundt 1985; Reipurth 1990) have P-Cygni shapes, with a very broad and deep absorption trough. Outflow velocities as high as -350 km s^{-1} can be estimated from these profiles. The observed profile has been corrected for photospheric contributions with the use of calculated $H\alpha$ -profiles (Kurucz 1979) of a F0 – F2Ib photosphere ($T_{\text{eff}} = 7500 \text{ K}$, $\log g = 2.0$). The extinction-corrected surface-flux of the symmetrised $H\alpha$ -profile is then $3.8 \cdot 10^5 \text{ W m}^{-2}$. The $H\alpha$ -emission fluxes are collected in Table 9.

5. UV-spectroscopy

Several low-resolution UV-spectra of BN Ori have been obtained with the International Ultraviolet Explorer (IUE) satellite in 1984 and 1986. Details of the observations are given in Table 5. Before each exposure the brightness of BN Ori was measured by the Fine Error Sensor (FES) of IUE in the Field Camera mode (Barylak 1989). In all cases the resulting V^J magnitude was around $9^{\text{m}}68$, which is close to the results of the ground-based photometry in the periods around the IUE observations (Tables 3 & 12). The low-resolution UV-spectra of BN Ori, HR 5999 and several other Herbig Ae stars show strong emission lines of O I, C II, Si IV and C IV (Tjin A Djie et al. 1982; Brown et al. 1986) shortward 1600 Å. The high intrinsic radiation flux in these lines can probably only be supplied by accretion (Tjin A Djie & Blondel 1997) and it has been possible to derive information on the accretion parameters of A and F stars from the UV-continuum over the full wavelength range (1150 – 3200 Å) of IUE (Blondel & Tjin A Djie 1997). After the choice of a stellar spectral type and luminosity-class and addition of the observed visual magnitude, the distance and the fore-

ground colour excess, we have matched the observed UV-continuum with standard star spectra from the IUE spectral atlases for the photospheric and boundary-layer components and a optically-thick model for the accretion-disc (UV3C, Blondel & Tjin A Djie 1994, 1997).

The results of the parameter adjustments required for the matching of the low-resolution UV-spectra of BN Ori, HR 5999, BF Ori and FU Ori are collected in Table 7. The masses of the stars (M_*) were estimated from the stellar radii (R_* derived from the model calculation) and the photospheric T_{eff} (Schmidt-Kaler 1982) with the use of the evolutionary tracks of Palla & Stahler (1993). With this mass and radius, the width of the boundary layer (δ_{bl}) and its effective temperature, the corresponding mass-accretion rate ($\dot{M}$) was derived. Since the mass of FU Ori cannot be derived from the evolutionary tracks, we have assumed that its precursor was a $1.0 M_{\odot}$ T Tauri star. In general the stellar spectral type and luminosity-class appear to be strongly constrained (to 1 or 2 subtypes) by the observed UV-continuum. For BN Ori we estimated a distance of $\sim 400 \text{ pc}$ from the data of Artyukhina (1959) and a foreground $E(B-V) = 0^{\text{m}}07$ from the Na I D interstellar components.

Fig. 8. Low-resolution UV-spectrum of BN Ori after correction for the foreground extinction (grey line) with the accretion model calculation (black line). The used model parameters are listed in Table 7, and the “W” indicates the Walraven W-band flux (Table 2) after correction for the foreground extinction. The low S/N in the observed spectrum (2000 Å – 2400 Å) is due to the low sensitivity of the LWP camera in this range

The calculated spectrum and the SED corresponding to the parameters of BN Ori in Table 7 are given in Figs. 8 and 9. These results show that the UV3C-model gives a good agreement with the observations from the far-UV up to the L -band in the NIR. In general the model (with an optically thick disc up to $40 R_*$) gives higher values than observed for the fluxes in the K - and L -band. The disagreement could not be reduced by taking the disc

Table 7. Parameters used in the UV3C-model calculations with the low-resolution UV-spectra. For the B9 Iab component we used $T_{\text{eff}} = 10300$ K (Schmidt-Kaler 1982). The value given by E^{is} is the interstellar (foreground) $E(B - V)$, while the E^{tot} value is the total excess

star	Spec. Type	M_v	$V_{\text{line}}^{\text{fes}}$ (magnitudes)	E^{is}	d (pc)	R_* ($R_\odot$)	L_* ($L_\odot$)	M_* ($M_\odot$)	$v \sin i$ (km s^{-1})	age (Myr)	Other Designations	
BN Ori	F0 III	+1.30	9.67	0.07	390	3.04	21.9	2.1	220	4.	HD 245465	BD+06°971
HR 5999	A5 III	-0.40	6.71	0.03	230	5.26	107.	3.5	180	0.3	HD 144668	CD-38°10893
BF Ori	A7 III	+1.40	9.90	0.06	415	2.54	20.0	2.0	100	6.	—	BD-06°1259
FU Ori	F0 I	-2.00	9.30	0.06	500	11.8	441.	1.0	60	—	—	—

star	boundary layer		disc		A_v^{cs} (mag)	R_v^{cs} —	E^{tot} (mag)	Relative F_v			
	Spec. Type	δ_{bl} (R_*)	$T_{\text{max}}^{\text{d}}$ (K)	i (°)				star (%)	b.l. (%)	disc (%)	$\dot{M}$ ($10^{-8} M_\odot \text{yr}^{-1}$)
BN Ori	B9 Iab	0.002	5887	80	0.231	4.50	0.12	96.67	0.18	3.15	2.0
HR 5999	B9 Iab	0.005	6580	53	0.489	3.10	0.19	86.64	0.64	12.72	54.0
BF Ori	B9 Iab	0.040	5810	60	0.190	3.10	0.12	86.00	5.00	9.00	32.0
FU Ori	B9 Iab	0.020	6034	45	2.79	3.40	0.88	85.30	3.40	11.30	2300
				70	2.71	3.40	0.86	91.34	2.20	6.46

Fig. 9. SED of BN Ori. The fluxes derived from the photometry of Sect. 2 are indicated by squares. The (*) points correspond to the fluxes calculated with the UV3C-model (Table 7), obtained by matching the low-resolution UV-spectrum (Fig. 8). The K - and L -band fluxes (open star) show the effect of removing the disc contribution in the model-calculation. Circles indicate the extinction-corrected model results

optically thin but when we limit the outer radius of the disc to $2.0 - 2.5 R_*$ the NIRE almost disappears (Fig. 9). This suggest that the disc has been largely dissipated during the outburst of 1947. For the parameters in Table 7 the $E(B - V)$ is $0^{\text{m}}12$, which with an observed $(B - V) \approx 0^{\text{m}}45$ corresponds with $(B - V)_0 = 0^{\text{m}}33$. This value is slightly higher then the $0^{\text{m}}30$ for spectral type F0 III given by Schmidt-Kaler (1982) but not unacceptable as BN Ori may be not exactly F0 III. Both the small circumstellar colour excess ($0^{\text{m}}05$) and the negligible NIRE indicate that BN Ori has almost no circumstellar dust left.

Table 8. Identification, EW ($\text{\AA}$) and FW (km s^{-1}) of lines in the high-resolution UV-spectra of BN Ori, HR 5999 and FU Ori. See Table 10 for the used symbols

λ_0 ($\text{\AA}$)	Line id.	E_χ (eV)	S	BN Ori		HR 5999		FU Ori	
				EW	FW	EW	FW	EW	FW
2562.54	Fe II (64)	0.98	s	0.16	40	1.31	140	0.26	56
2576.11	Mn II (1)	0.00	is	0.22	46	0.98	135	—	—
2585.88	Fe II (1)	0.00	is	0.17	39	1.12	151	0.11	37
2591.54	Fe II (64)	1.04	s	0.15	46	0.97	207	0.21	25
2598.37	Fe II (1)	0.05	is	0.16	26	1.31	123	—	—
2599.40	Fe II (1)	0.00	s	0.22	46	1.18	138	0.31	61
2617.62	Fe II (1)	0.08	s	0.07	—	1.04	151	—	—
2625.66	Fe II (1)	0.05	s	0.13	39	1.09	192	0.21	43
2677.16	Cr II (8)	1.53	is	0.09	—	0.80	108	—	—
2684.54	Mn II (63)	4.14	s	0.10	51	0.46	85	0.36	48
2692.83	Fe II (62)	0.98	s	0.11	44	0.78	94	—	—
2724.88	Fe II (62)	1.04	s	0.10	—	0.79	84	0.24	45
2727.54	Fe II (63)	1.04	s	0.09	40	0.96	110	0.28	38
2743.20	Fe II (62)	1.09	s	0.12	43	1.05	175	—	—
2746.49	Fe II (62)	1.07	s	0.14	—	0.78	186	0.48	23
2755.73	Fe II (62)	0.98	s	0.11	—	1.06	141	0.17	29
2757.72	Cr II (6)	1.50	s	0.11	43	0.59	122	—	—
2795.52	Mg II (1)	0.00	is	—	—	—	—	—	—
2802.70	Mg II (1)	0.00	is	—	—	—	—	—	—
2843.24	Cr II (5)	1.52	s	0.08:	33	0.96	93	0.20:	28:
2849.83	Cr II (5)	1.50	s	0.09:	36	0.97	105	0.20	56
2852.12	Mg I (1)	0.00	s	0.09	14	1.05	124	0.26	56
			i	0.00	—	—	—	0.27	50

In addition to the continua of the UV-spectra of BN Ori, we have also information on the individual lines from the high-resolution LWP image obtained with IUE. In spite of its long exposure (13^{h}) the S/N ratio is very low in the less sensitive part of the LWP camera (shortward $2400 \text{\AA}$) but the region longward $2560 \text{\AA}$ is better exposed. Since the three low resolution UV-spectra of BN Ori show no differences (although they were taken at

different times) we assume that the high-resolution spectrum of Nov. 13, 1986 is representative for at least the period Jan'84 – Nov'86. The FES-magnitude ($V_{\text{IUE}}^{\text{fes}}$) during this observation agrees with a simultaneous ground-based photometric observation from DASA. From the comparison of the high-resolution UV-spectra of BN Ori, FU Ori and HR 5999 we can draw the following conclusions:

1. The presence of an extended cool shell around the three stars is revealed by the many low-excitation absorption lines of Fe II, Cr II and Mn II in their UV-spectra longward 2300 Å. The lines are strongest in the spectra of HR 5999 and the correlation of their EW-variations with the variations in brightness of HR 5999 (Blondel et al. 1989) shows that these lines are formed in the shell of the star. Because of the lower brightness of BN Ori and FU Ori the S/N ratio in their spectra is lower than in the spectrum of HR 5999. In spite of this we can give upper limits for the EWs of the lines in the BN Ori spectrum and rough estimates ($\pm 30\%$) of the EWs of the lines in the FU Ori spectrum. Table 8, in which the EWs and FWs of the three stars are listed, shows that the EWs and FWs of the BN Ori lines are smaller than those of the corresponding lines in the spectrum of FU Ori, and both are smaller than the EWs and FWs of HR 5999. Since the spectral types of the three stars are not too different we expect that the column densities in the shells will also decrease from HR 5999 through smaller values for FU Ori to almost negligible values for BN Ori.
2. The Mg I resonance line (2852.120 Å) of BN Ori has two components: an interstellar one (with EW = 0.21 Å) which is displaced by $+26.5 \text{ km s}^{-1}$ from its heliocentric position (determined from the Na I D interstellar lines) and a circumstellar one (with EW = 0.09 Å) with a velocity of -53 km s^{-1} with respect to the interstellar one (Fig. 11). Similar to the Na I D lines the continuum in the neighbourhood suggests that there exists a third, broad (FW = $\sim 400 \text{ km s}^{-1}$) and shallow component, centered at the location of the two narrow components. Because of its width this component could be formed either at the stellar photosphere or near the inner accretion-disc. The Mg I line of FU Ori also appears to be double. Both components have an EW of about 0.26 Å and the circumstellar component has a velocity of $\sim -67 \text{ km s}^{-1}$ with respect to the interstellar component. The EW of the circumstellar component is larger than the corresponding one for BN Ori, while the foreground interstellar components of FU Ori and BN Ori are of comparable strength. The Mg I components in the UV-spectra of HR 5999 are not resolved because of the large width of the circumstellar component. Its EW is about 10 times larger than the upper limit of the EW of the corresponding component for BN Ori and 3 – 4 times the corresponding EW for FU Ori.

3. The Mg II h (2802.7 Å) and Mg II k (2795.5 Å) lines in the high-resolution spectrum of BN Ori have broad absorption-troughs with weak emission-components inside (Fig. 10). An accurate determination of the emission-components is difficult because of the presence of a resseau mark at 2795 Å and an echelle order overlap between 2798 Å and 2801 Å. Nevertheless we have made an attempt to derive some information on the shell component by dividing the (normalised) observed fluxes in the Mg II profiles of BN Ori by the corresponding ones in the profiles of 21 Vul, obtained from the IUE archives (LWR 9037). This star has a spectral type A7 – F0 IV, a $v \sin i$ of $\sim 200 \text{ km s}^{-1}$ and a very weak shell component in the Mg II profiles.

Fig. 10. Observed Mg II h&k profiles of BN Ori (LWP 9512) and the residual profiles after normalisation to the 21 Vul (LWR 9037) profiles. Top-axis give the velocity (km s^{-1}) relative to the wavelengths of the Mg II h&k lines

The result is given in Fig. 10, which shows that the shell component of Mg II has a P-Cygni profile with outflow-velocities up to -250 km s^{-1} . We have made a rough estimate of the Mg II k emission-component (EW $\approx 15 \text{ Å}$) by assuming that the intrinsic emission (without the blue absorption trough) is symmetric. With the continuum flux near 2790 Å from the low-resolution UV-spectra of BN Ori

($2.5 \cdot 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$), the distance to radius ratio from the UV3C-model ($4.35 \cdot 10^9$) and the total extinction correction (a flux factor of 2.08) we derive an extinction-free surface flux of $8.8 \cdot 10^4 \text{ W m}^{-2}$ for the emission-component of the Mg II k line of BN Ori. In the same way we derive from the corresponding profile of HR 5999 in the phase of maximum visual brightness (Blondel et al. 1989) an extinction-free surface flux of $6.45 \cdot 10^6 \text{ W m}^{-2}$ ($V^J = 6^{\text{m}}8$) and $1.2 \cdot 10^7 \text{ W m}^{-2}$ ($V^J = 7^{\text{m}}6$). The ratio of the Mg II k emission fluxes of HR 5999 and BN Ori is therefore close to 70 – 140. This is higher than the ratio of the H α fluxes of the two stars (Sect. 4).

Fig. 11. Mg I 2852 Å components of BN Ori

Table 9. Comparison of emission fluxes (W m^{-2})

star	H α	Mg II	$\frac{\text{Mg II}}{\text{H}\alpha}$	V^J
BN Ori	$1.6 - 1.2 \cdot 10^5$	$8.8 \cdot 10^4$	0.63	$9^{\text{m}}7$
FU Ori	$3.8 \cdot 10^5$	$1.7 \cdot 10^6$	4.4	$9^{\text{m}}3$
HR 5999	$3.4 - 2.3 \cdot 10^6$	$6.5 \cdot 10^6$	2.4	$6^{\text{m}}8$
HR 5999	$5.8 \cdot 10^6$	$1.2 \cdot 10^7$	2.1	$7^{\text{m}}6$

The high-resolution Mg II profiles of FU Ori have been published by Ewald et al. (1986). The profiles have a P-Cygni shape, but the noise in the neighbouring continuum does not permit to determine an outflow velocity. The extinction-corrected surface flux in the symmetrised Mg II k emission-profile is $8.6 \cdot 10^7 \text{ erg cm}^{-2} \text{ s}^{-1}$ and the corresponding flux of the Mg II h emission is $7.1 \cdot 10^7 \text{ erg cm}^{-2} \text{ s}^{-1}$. This total Mg II emission flux of FU Ori is close to the value obtained by Ewald et al. With the use of the observed Mg II profile of the F0 Ib star α Car (Praderie et al. 1980), which has a $v \sin i = 0 \text{ km s}^{-1}$, we corrected the profile of FU Ori for the

photospheric contribution. The extinction-corrected surface-flux of the symmetrised Mg II k-profile then becomes $1.67 \cdot 10^6 \text{ W m}^{-2}$. Table 9 gives a survey of the emission fluxes of the 3 stars. Although the H α and Mg II profiles show variations on a short time-scale ($\sim 1^{\text{d}}$) the time variations in the integrated emission fluxes are small. This gives us a justification to use Table 9 in the following discussion, in spite of the fact that the H α and Mg II fluxes were not observed simultaneously.

6. Discussion

The light curve of BN Ori and its spectral type A7 (Cannon 1931) during the first half of the century suggest that in this period BN Ori was a Herbig Ae star with strong brightness-variations due to a variable circumstellar dust extinction. The recent detection of emission from a nearby reflection nebula (Sect. 3) and the value of the stellar mass (Sect. 5) supports its previous membership to this class of intermediate-mass pre-main-sequence stars, first introduced by Herbig (1960b).

Around 1947 the large-scale light curve of BN Ori changed drastically in a way which is similar to the transition in the light curves of classical FUORs. In particular the light curve of BN Ori has much in common with that of the FUOR V1515 Cyg due to its last active epoch of variations in brightness with the further rise typical for FUORs, a delay at the maximum phase and specifically a typical short minimum after the first maximum (Fig. 12). The sequence and scale of the events in the pre-maximum and post-maximum phases of the BN Ori light curve are also consistent with those of other classical FUORs. The only possible difference with the FUOR light curves is the large amplitude of the variability in the pre-maximum epoch of BN Ori. The light-variation level of the classical FUORs was less in this phase, but for the lack of any reliable information it cannot be argued that the range of brightness-variations in the pre-flare phase of FUORs was small. Therefore, as far as the light curve is concerned, we have every reason to consider BN Ori as an object which is related to FUORs.

The spectroscopic observations of BN Ori, described in Sects. 4 and 5, show that there are also spectral similarities between BN Ori and the classical FUORs, such as FU Ori:

1. The various spectral classifications of BN Ori by successive observers: A7 (Cannon 1931; Hoffmeister 1949; Payne-Gaposhkina 1952), A6 – A8 (Herbig 1954, 1960a), F0 (Zajtseva 1970) and F2 – F3 (Kolotilov & Zajtseva 1976) could raise the impression that BN Ori has changed to progressively later spectral types in the course of the years. However, as already suspected by Herbig (1960a), several spectral types can be present simultaneously in the spectrum of BN Ori. Our spectra (Sect. 4) show a variety of spectral types ranging from

Fig. 12. Comparison of the light curves of BN Ori (upper part; dots) and the FUOR V1515 Cyg (lower part; stars)

A6 – A8 from the higher Balmer terms, A8 – F0 from the Ca II K line, F0 – F2 from the *G*-band, F0 – G5 from the Fe I lines, F6 – G0 from the O I (1) IR-triplet G5 from the Ca II (2) IR-triplet until late-G to early-K from the strength of the Mn I triplet around 4033 Å. This suggests that the atmosphere of BN Ori is thermally stratified in the sense that it consists of an A6 – A7 photosphere, surrounded by a cooler envelope. Such a thermal stratification is also a characteristic feature of FUOR atmospheres, e.g. FU Ori has a photosphere of type F2:pi – iie (Herbig 1966), estimated from the Balmer lines and the low excitation lines of neutral and singly-ionised metals in the visual, an envelope (or disc) of type K from the Ca II (2) IR-triplet and a type K – M from the CO bands in the NIR part of the spectrum. However, in contrast to the situation for BN Ori and for FU Ori we find only a small range of spectral types, A5 – A7 III (Bessel & Eggen 1972; Tjin A Djie et al. 1989), for the visual and red parts of the spectrum of the Herbig Ae star HR 5999, which suggests a much lower degree of stratification of the atmosphere of this star.

2. Another similarity with classical FUORs is the presence of high-velocity outflow-components in the H α P-Cygni type profiles: -680 km s^{-1} for BN Ori and -550 km s^{-1} for FU Ori. The time-scale of the shape-variability of this profile may be less than 24^{h} (Kolotilov & Zajtseva 1976) for BN Ori, which is comparable with those observed for FUORs. This suggests that the line is formed in a region of small extension. The large width of the emission-component profile (Fig. 7) indicates that this region is within a distance of $1 R_{\star}$ from the stellar surface. Similar to the fast winds from FUORs (Crowell et al. 1987), the fast outflow from BN Ori is probably driven by strong magnetic fields, originating near the accretion-disc boundary layer (Pringle 1989). In contrast with this, we find

only relatively low-outflow velocity-components in the H α -profiles of HR 5999: in general $\sim -50 \text{ km s}^{-1}$ and occasionally $\sim -120 \text{ km s}^{-1}$ (Tjin A Djie et al. 1989). The time-scale of the H α shape-variability for HR 5999 is of the same order as that of BN Ori. The profiles of Mg II h&k are similar in shape to those of H α in the three stars. The velocity of the outflow-components in the Mg II profiles seems to be lower than that in H α ($\sim -250 \text{ km s}^{-1}$ for BN Ori) but these values are rather uncertain, due to the low S/N for the neighbouring continuum. Since only one high-resolution UV-spectrum has been obtained for BN Ori and two for FU Ori, the time-scales of variability of the Mg II profiles are unknown.

3. Several prominent photospheric lines in the spectra of FU Ori and the FUOR BBW 76 (Reipurth 1990): Li I (6708 Å) and Ba II (6497 Å) are also prominently present in the spectrum of BN Ori (Sect. 4.3) with comparable strength. In the spectrum of HR 5999, however, the Li I line is missing.

Besides these similarities between the spectrum of BN Ori and those of the classical FUORs there are also differences:

1. The spectrum of BN Ori is of luminosity-class III–IV while the FUOR spectra have luminosity-classes I–II.
2. The rotation rate $v \sin i$ of BN Ori is about 220 km s^{-1} , which is close to those of several intermediate-mass Herbig Ae stars ($v \sin i = 180 \text{ km s}^{-1}$ for HR 5999). In contrast with this, the rotation rates of classical FUORs are in the range of 60 km s^{-1} (FU Ori) which is more similar to those of their T Tauri precursors.
3. BN Ori has a more extended shell than FU Ori. This is illustrated by the FW distribution over the excitation energies (E_{χ}) of Tables 6, 11 and 8. If we limit ourselves to the unblended lines of these tables and if we can consider the FWs to be proportional to the $v \sin i$ of the regions of formation of these lines we can, assuming a Kepler motion, estimate mean distances of these regions to the stellar surface. The values of $M_{\star}$ and $R_{\star}$ needed for this transformation were taken from Table 7. The distribution of E_{χ} (of the lower-level) versus the mean Kepler distance of the line-forming regions (in $R_{\star}$) is given in Fig. 13 for BN Ori, FU Ori and HR 5999. For comparison the thermal stratification of the FUOR V1057 Cyg is indicated by the dotted line. Welty et al. (1990) showed that this stratification originates from the differential rotation in the disk. Figure 13 demonstrates that outside the stratified envelope there is an extended shell region for BN Ori, FU Ori and HR 5999. This is especially clear from the Fe II & Cr II absorption lines (with lower level $E_{\chi} \leq 1 \text{ eV}$) which are still formed far away from the star ($\sim 40 R_{\star}$ for FU Ori and HR 5999, and $> 400 R_{\star}$ for BN Ori). The difference of the shell extension is illustrated by the least-square fits for BN Ori and HR 5999 in Fig. 13. The uncertainty for the size

Fig. 13. Shell regions of BN Ori, HR 5999 and FU Ori; E_X vs. distance to the surface (in units of R_*). The two dashed lines are the least-square lines for BN Ori and HR 5999, using the values of the Fe II and Cr II lines together. The dotted line indicates the stratification of V1057 Cyg

of the BN Ori shell is due to the fact that the UV-lines are so narrow that the widths may be dominated by Doppler broadening and therefore only give an upper limit to the distances. Although the cool shell of BN Ori extends much further out than those of FU Ori and HR 5999 we note from Table 8 that for each line: $EW_{HR} > EW_{FU} > EW_{BN}$. As the corresponding column densities follow the same order (BN:FU:HR = 1.0:4.0:8.6), this means that BN Ori has the most diluted shell of these 3 stars. This suggests that if BN Ori had a Herbig Ae star (like HR 5999) as its precursor, the thick shell has been expanded (to the shell remnant now present) as a result of a (FUOR) outburst. This expansion had a cooling influence on the extended Mg II emission region and less (or no) influence on the H α emission region which is confined to a region closer to the star. The ratios in Table 9 are consistent with this scenario.

4. FU Ori and HR 5999 have very large excess fluxes in the NIR. These excesses are too large to be accounted for by the contribution of the accretion-discs only and therefore indicate the presence of significant quantities of radiating nearby circumstellar dust. Another indication for this are the large circumstellar colour excesses in Table 7. In contrast with this we find a very small NIRE and colour excess for BN Ori, which suggests an almost complete absence of circumstellar dust around this star.

After this comparison of the light curves and spectra of BN Ori, FU Ori and HR 5999 we propose the following scenario for the behaviour of BN Ori: The precursor of BN Ori was a Herbig A6 – A7e star, similar to HR 5999 but of somewhat lower mass (comparable with BF Ori) and with a slightly higher rotation rate. Around 1947 a FUOR type outburst occurred in the star-disc system with the result that the envelope around the inner part of the

accretion-disc expanded. Except for the part near the star where most of the H α and Mg II emission originates, the optically thin (shell) region at the outside of this envelope was expelled together with the outer part ($R > 2.0 R_*$) of the accretion-disc. In the spectrum of FU Ori the shell components of the lines indicate that the shell moves outward with a velocity around -50 km s^{-1} (Herbig 1966), but for BN Ori we have no radial-velocity measurements available. Most of the circumstellar dust was probably blown away after the break-up of the outer part of the magnetic field, which confined the dust to the circumstellar region (Il'in & Voshchinnikov 1993) before the outburst. The disappearance of this dust (or the smoothing of its distribution), may explain the levelling-off of the light curve after the outburst.

This scenario raises several questions, the most important being whether a FUOR outburst can occur in a Herbig Ae star. Recently Bell et al. (1995) have shown that recurrent FUOR outburst can occur in young stars with disc accretion as a result of a thermal-runaway in the inner part of the accretion-disc when the mass-accretion rate rises above a certain critical value. For $2 - 3 M_\odot$ pre-main-sequence stars, such as the Herbig stars, Bell (1994) predicted that this critical value is around a few times $10^{-7} M_\odot \text{ yr}^{-1}$. It may be interesting to note that from matching the low-dispersion UV-spectra of BN Ori, BF Ori and HR 5999 we found mass-accretion rates of 0.18, 3.2 and $5.4 \cdot 10^{-7} M_\odot \text{ yr}^{-1}$ respectively. The latter two values are close to the critical value of the mass-accretion rate, while the low rate for BN Ori (compared e.g. with that of FU Ori) may be due to the present lack of supply of inflow from the circumstellar shell region.

If we accept the FUOR character of BN Ori we are faced with the question why BN Ori is different from the classical FUORs. Two main reasons for differences may be proposed: First of all there is the difference in mass and rotation rate between Herbig Ae and T Tauri precursors which could influence the relative violence of the outbursts. The present low accretion rate of BN Ori (corresponding to an optically thin disc) compared to that of FU Ori may permit a more rapid expansion of its outer shell, which could explain the difference mentioned in point 3 discussed above. Secondly, successive outbursts in a recurrent FUOR have differences in their initial conditions and may therefore show differences in their post-flare appearance. Recurrent outbursts in BN Ori would facilitate a gradual exhaustion of the shell supply, as well as the accumulative production of sizable amounts of Li I at the surface of BN Ori, e.g. by spallation reactions induced by high fluxes of energetic protons in the FUOR flares.

Acknowledgements. The authors would like to thank Dr. A. Brown (JILA) for collaborating in the IUE observations and reductions of BN Ori. Furthermore, we are indebted to all the observers mentioned in Tables 1, 5 and 12 and to Dr. J.R.W. Heintze (RUU) for his efforts to develop and maintain the photometric facilities at DASA. This research has made use of the

Simbad data base operated at CDS, Strasbourg, France and of the IUE archives operated by ESA at Villafranca del Castillo, Spain.

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Table 10. Description of the symbols and references used in Tables 6, 11 and 8

Negative EW-values indicate emission			
Italic EW-values indicate (the range of) variability			
Line sources:		i	interstellar
p	photospheric	s	shell, c.s. envelope
c	chromospheric	d	disc
Line strengths:		:	uncertain value
b	blended	m	medium
vs	very strong	w	weak
s	strong	vw	very weak
References:			
1	BTA-spectrum Nov. 21, 1991		
2	Kolotilov & Zajtseva (1976)		
3	Herbig (1966)		
4	Tjin A Djie et al. (1989)		
5	Hamann & Persson (1992)		
6	Felenbok et al. (1988)		
7	ESO (1.5 m) low-resolution spectra Dec'92		
8	ESO CAT high-resolution spectra Dec'94, Jan'95		
9	Reipurth (1990)		
10	Shanin (1979)		

Table 11. Identification and source (*S*) of lines in the high-resolution visual spectra of BN Ori, HR 5999 and FU Ori. The equivalent widths (EW) in (Å) and full widths at half maximum (FW) in (km s⁻¹) are also given. Identification of the lines has been made with the help of the Tables of Zaidel et al. (1969) and excitation energies (*E_χ*) have been taken from Wehrse (1974). See Table 10 for the description of the used symbols

λ_0 (Å)	Line id.	E_χ (eV)	<i>S</i>	BN Ori EW ¹ FW	HR 5999 EW ⁴ FW	FU Ori EW ³
3608.86	Fe I (23)	1.01		0.09 193	— —	—
3721.94	H 14	10.20	p	1.62 —	1.70 —	—
3727.03	Fe I (668)	3.27		— —	— —	—
3727.20	Cr II (117)	4.78		— —	— —	—
3734.37	H 13	10.20	p	2.37 —	1.17 —	—
3741.63	Ti II (72)	1.58		— —	0.04 —	—
3750.15	H 12	10.20	p	3.54 —	2.44 —	—
3759.29	Ti II (13)	0.61	s	0.37 b 130	0.74 110	—
3761.32	Ti II (13)	0.57	s	— —	0.64 100	—
3770.63	H 11	10.20	p	3.01 —	3.5 —	—
3797.90	H 10	10.20	p	3.83 —	6.0 —	—
3813.39	Ti II (12)	0.61	s	0.20 b 310	0.48 b 160	—
3814.12	Fe II (153)	4.74		— —	— —	—
3814.58	Ti II (12)	0.57	s	— —	— —	—
3815.25	Fe I (45)	1.48		— —	— —	—
3835.38	H 9	10.20	p	7.41 —	9.1 —	—
3872.51	Fe I (20)	0.99		0.38 209	0.27 —	—
3889.05	H 8	10.20	ps	6.19 —	10.6 —	—
3905.53	Si I (3)	1.91		— —	— —	—
3906.04	Fe II (173)	5.57		— —	— —	—

Table 11. continued

λ_0 (Å)	Line id.	E_χ (eV)	<i>S</i>	BN Ori EW ¹ FW	HR 5999 EW ⁴ FW	FU Ori EW ³
3906.48	Fe I (4)	0.11		— —	— —	—
3933.67	Ca II K (1)	0.00	pc	5.45 440	4.1 76	st
3944.01	Al I (1)	0.00	ps	0.09 160	0.1 152	st
3968.47	Ca II H (1)	0.00	pc	7.70 b —	12.5 b —	st
3970.07	He	10.20	ps	— —	— —	st
3983.96	Fe I (277)	2.73		— —	— —	—
3997.39	Fe I (278)	2.73		0.17 240	0.17 170	—
4005.23	Fe I (43)	1.56	p	0.29 355	0.28 300	—
4014.53	Fe I (802)	2.57		— —	— —	—
4025.13	Ti II (11)	0.61		— —	— —	—
4030.76	Mn I (2)	0.00		0.78 391	0.60 b —	—
4033.07	Mn I (2)	0.00		— —	— —	—
4034.49	Mn I (2)	0.00		— —	— —	—
4035.67	V II (216)	1.79		— —	— —	—
4045.82	Fe I (43)	1.48	ps	0.41 390	0.50 297	st
4053.81	Ti II (87)	1.89		— —	— —	vw
4057.36	Fe I (277)	2.76		— —	— —	—
4057.50	Mg I (10)	4.34		— —	— —	—
4063.28	Fe I (698)	3.37		0.20 b 389	0.27 b 295	m
4063.60	Fe I (43)	1.61	p	— —	— —	vw
4077.72	Sr II (1)	0.0	ps	0.30 290	0.34 260	st
4085.31	Fe I (559)	3.24		0.07 232	— —	—
4101.74	Hδ	10.20	ps	3.77 —	11.2 —	st
4118.55	Fe I (801)	3.67		0.09 —	— —	—
4134.20	Fe I (217)	2.61		0.10 —	— —	w
4143.76	Fe I (43)	1.56		0.18 228	0.18 217	—
4154.50	Fe I (355)	2.03		0.24 b 110	0.21 b 289	—
4154.81	Fe I (694)	3.37		— —	— —	—
4156.78	Fe I (354)	2.88		0.24 110	— —	—
4173.45	Fe II (27)	2.58	s	0.26 189	0.38 287	—
4177.55	Y II (14)	0.41	s	0.18 b 200	0.36 b 251	—
4177.60	Fe I (18)	0.91		— —	— —	—
4178.87	Fe II (28)	2.58	s	— —	— —	—
4187.04	Fe I (152)	2.45		— —	0.17 b 287	—
4187.80	Fe I (152)	2.42		— —	— —	—
4202.76	Fe I (42)	1.48		— —	0.14 —	—
4215.52	Sr II (1)	0.00	ps	0.07 250	0.29 270	st
4226.73	Ca I (2)	0.00	ps	0.53 240	0.60 260	st
4233.17	Fe II (27)	2.58	s	0.16 163	0.36 215	—
4246.83	Sc II (7)	0.31	ps	— —	0.20 265	m
4252.62	Cr II (31)	3.86		— —	0.06 b 88	—
4254.33	Cr I (1)	0.00		— —	— —	st
4261.90	Cr II (31)	3.86		— 190:	0.25 b 230	—
4262.13	Cr I (178)	3.11		— —	— —	—
4271.76	Fe I (42)	1.49		0.60 b 444:	1.28 b 350:	—
4273.32	Fe II (27)	2.70		— —	— —	—
4274.81	Cr I (1)	0.00	ps	— —	— —	m
4284.21	Cr II (31)	3.05		— —	0.10 244	—
4290.22	Ti II (41)	1.16		0.18 245	0.32 210	—
4301.93	Ti II (41)	1.16		0.51 b 370:	0.56 b 366:	—
4307.91	Ti II (41)	1.16	p	0.31 230	0.21 210	w
4314.08	Sc II (15)	0.62		0.23 b 256:	0.24 b 220	—
4314.29	Fe II (32)	2.68		— —	— —	—
4314.98	Ti II (41)	1.16		— —	— —	—

Table 11. continued

Table 11. continued

λ_0 (Å)	Line id.	E_χ (eV)	S	BN Ori EW ¹ FW	HR 5999 EW ⁴ FW	FU Ori EW ³	λ_0 (Å)	Line id.	E_χ (eV)	S	BN Ori EW ¹ FW	HR 5999 EW ⁴ FW	FU Ori EW ³
4325.01	Sc II (15)	0.60		0.32 b 330	—	—	5031.02	Sc II (23)	1.36		0.11 188	— 190	—
4325.76	Fe I (2)	0.00		"	—	—	5041.08	Fe I (16)	0.96		0.14 b 240	0.33 b 309	—
4340.47	H γ	10.20	ps	3.95	—	11.8	—	5041.63	Ca I (34)	2.71	"	—	—
4354.76	Fe II (27)	2.70		0.18: 254	—	—	5041.76	Fe I (36)	1.48		"	"	—
4374.45	Sc II (14)	0.62		0.16 b 250	0.19 b 190	—	5051.64	Fe I (16)	0.91		0.09 219	0.19 237	—
4374.82	Ti II (93)	2.06		"	—	—	5079.23	Fe I (66)	2.20		0.10 b	0.08 b	—
4374.94	Y II (13)	0.41		"	—	—	5079.74	Fe I (16)	0.99		"	"	—
4383.55	Fe I (41)	1.48		0.65 b 360	0.90 b 274	—	5083.34	Fe I (16)	0.96		0.20 186	—	vw
4384.21	Fe II (32)	2.66		"	—	—	5098.70	Fe I (66)	2.18		0.12 b 124	0.13 b	—
4385.38	Fe II (27)	2.78		"	—	—	5100.66	Fe II (35)	2.81		"	"	—
4394.06	Ti II (51)	1.22		0.14 b 233	0.30 b 170	—	5139.26	Fe I (383)	3.00		0.11 b 184	0.13 b	—
4395.03	Ti II (19)	1.08	ps	"	—	—	5139.47	Fe I (383)	2.94		"	"	—
4395.83	Ti II (61)	1.24		"	—	—	5167.33	Mg I (2)	2.71		— b	— b	—
4416.82	Fe II (27)	2.70		0.33 b 285	— 238	—	5169.03	Fe II (42)	2.89	ps	0.80: b 387	0.72: 232+116	—
4417.72	Ti II (40)	1.16		"	—	—	5172.68	Mg I (2)	2.71		0.47: 193	0.36: 232	vw
4434.96	Ca I (4)	1.89		0.24 b 286	0.15 b 220	—	5208.44	Cr I (7)	0.04		0.20 b 121	—	—
4435.10	Fe I (2)	0.09		"	—	—	5208.60	Fe I (553)	3.24		"	—	—
4435.69	Ca I (4)	1.89		"	—	—	5226.56	Ti II (70)	1.57		0.33 b 271	—	vw
4443.80	Ti II (19)	1.08		0.21 b 214	0.25 b	—	5226.87	Fe I (716)	3.41		"	—	—
4444.56	Ti II (31)	1.12		"	—	—	5234.62	Fe II (49)	3.22		0.31 241	—	—
4459.12	Fe I (68)	2.18		—	—	—	5264.80	Fe II (48)	3.33		1.38 b	—	—
4468.49	Ti II (31)	1.13		—	0.30 b 201	—	5270.30	Fe I (37)	1.61		"	—	—
4469.10	Ti II (18)	1.08		—	"	—	5274.99	Cr II (43)	4.07		0.58 b	—	—
4481.16	Mg II (4)	8.89	p	0.34 b 317	0.50 b 250	—	5275.02	Fe I (1029)	4.07		"	—	—
4481.33	Mg II (4)	8.86	p	"	—	—	5316.61	Fe II (48)	3.22		0.10 b	0.32	—
4491.40	Fe II (37)	2.85		0.25 280	0.22 264	—	5328.05	Fe I (15)	0.91		0.70 b	0.28 b 168	—
4508.28	Fe II (38)	2.85		0.04 193	0.18 216	—	5329.99	Fe I (1028)	4.07		"	—	—
4529.46	Ti II (82)	1.57		0.25 300	0.17 250	—	5341.02	Fe I (37)	1.61		0.11 206	0.08	—
4533.97	Ti II (50)	1.24		0.30 b 300	0.32 b 280	—	5364.88	Fe I (1146)	4.44		0.27 176	0.15 112	—
4534.17	Fe II (37)	2.85		"	—	—	5371.50	Fe I (15)	0.96		0.45 b 293	—	—
4549.47	Fe II (38)	2.83	ps	0.19 b 312	0.66 b 363	—	5383.37	Fe I (1140)	4.31		0.26 234	—	—
4549.62	Fe II (82)	1.58		"	—	—	5397.13	Fe I (15)	0.91		0.37 b 116	—	—
4555.89	Fe II (37)	2.83		0.19 b 277	0.40 b	—	5405.78	Fe I (15)	0.99		"	—	—
4558.66	Cr II (44)	4.07		"	—	—	5466.41	Y II (12)	1.43		0.19 144	—	—
4563.77	Ti II (50)	1.22		0.14 242	0.19 131	—	5476.91	Ni I (597)	1.83		0.31 202	—	—
4571.97	Ti II (82)	1.57		0.18 330	0.12	—	5526.81	Sc II (31)	1.77		0.19 143	—	—
4583.83	Fe II (38)	2.81		—	0.32 290	—	5535.48	Ba I (2)	0.00		0.10 142	0.20	—
4618.83	Cr II (44)	4.07		—	0.28 130	—	5586.76	Fe I (680)	3.37		0.34 226	—	—
4629.34	Fe II (37)	2.81		—	0.09 146	—	5638.27	Fe I (1087)	4.22		0.37 b 171	—	—
4670.17	Fe II (37)	2.83		—	0.31 b 321	—	5644.14	Ti I (240)	2.27		"	—	—
4670.40	Sc II (24)	1.36		—	"	—	5658.83	Fe I (686)	3.40		0.15 b 167	—	—
4861.33	H β	10.20	pcs	3.0 ²	11.9	—	5662.16	Ti I (249)	2.32		0.17 123	—	—
4910.05	Fe I (687)	3.40		—	—	—	5774.54	Ti I (228)	2.25		0.19 137	—	—
4911.21	Ti II (114)	3.12		—	—	—	5785.98	Ti I (309)	3.32		0.14 164	vw 100	—
4923.92	Fe II (42)	2.89	ps	0.53 449:	0.64 292+107	—	6053.48	Cr II (105)	4.74		0.17 104	—	—
4934.10	Ba II (1)	0.00		0.78 b	—	—	6136.62	Fe I (169)	2.45		0.17 b 154	0.22 b	—
4936.34	Cr I (166)	3.11		"	—	—	6137.70	Fe I (207)	2.59		"	"	—
4957.30	Fe I (318)	2.85		0.28 b	0.17 b 193	—	6215.21	Ti I (293)	2.69		0.22 152	—	—
4957.61	Fe I (318)	2.81		"	—	—	6220.46	Ti I (293)	2.68		0.11	—	—
4982.51	Fe I (1867)	4.10		0.51 b 380:	0.23 240	—	6277.52	Ti I (144)	1.73		0.48 200	0.33	—
4984.13	Ni I (143)	3.80		"	—	—	6491.71	Mn I (39)	3.76		—	—	—
5005.72	Fe I (984)	3.08		0.33 b	0.31 b 240	—	6494.98	Fe I (168)	2.40		—	—	—
5006.12	Fe I (318)	2.03		"	—	—	6496.90	Ba II (2)	0.60		0.42 402	0.44 419	vs
5018.43	Fe II (42)	2.89	ps	0.56 440	0.74 287+120	—	6707.89	Li I (1)	0.00		0.10: 100:	—	0.47 b

Table 12. Johnson (*UBVR*) Photometric Data of BN Ori

RJD #	<i>V</i>	<i>U</i> − <i>B</i>	<i>B</i> − <i>V</i>	<i>V</i> − <i>R</i>	T, O
3135.3453	9.578	0.117	0.466	0.432	1,S
3154.4141	9.609	0.121	0.453	—	1,S
3188.3667	9.666	0.132	0.465	0.399	1,S
3418.4326	9.601	0.133	0.456	0.413	1,S
3445.4423	9.612	0.142	0.503	0.455	1,S
3411.4312	9.598	0.137	0.500	0.432	1,S
3464.3878	9.623	0.140	0.521	0.453	1,S
3478.4121	9.611	0.154	0.503	0.435	1,S
3493.3998	9.606	0.154	0.489	0.498	1,S
3780.3889	9.612	0.163	0.448	0.456	1,S
3782.4112	9.609	0.143	0.501	0.456	1,S
3784.3987	9.599	0.138	0.511	0.458	1,S
3788.4356	9.623	0.144	0.546	0.453	1,S
3811.3765	9.632	0.148	0.564	0.533	1,S
3843.3876	9.607	0.139	0.554	0.467	1,S
3876.3978	9.600	0.127	0.476	0.476	1,S
5261.3245	9.598	0.143	0.465	0.408	1,S
5267.3987	9.646	0.182	0.455	0.465	1,S
5365.4432	9.656	0.167	0.456	0.521	1,S
5398.4312	9.654	0.156	0.465	0.432	1,S
5449.4532	9.674	0.197	0.476	0.460	1,S
5780.3246	9.666	0.155	0.456	—	1,S
6047.2999	9.628	0.153	0.518	0.468	1,Y
6052.3910	9.646	0.146	0.507	0.459	1,Y
6055.2624	9.644	0.146	0.503	0.458	1,Y
6060.2455	9.651	0.155	0.514	0.458	1,Y
6061.2560	9.652	0.133	0.503	0.705	1,Y
6293.4701	9.645	0.262	0.420	0.493	3,G
6298.4769	9.640	0.115	0.468	0.430	3,G
6300.4735	9.692	0.177	0.479	0.503	3,G
6308.4909	9.601	0.148	0.472	0.472	1,C
6310.4623	9.666	0.136	0.462	0.463	1,C
6315.4504	9.640	0.193	0.466	0.468	1,C
6317.4803	9.648	0.116	0.476	0.449	1,C
6319.4789	9.650	0.139	0.482	0.461	1,C
6321.4769	9.610	0.147	0.471	0.468	1,C
6323.4713	9.652	0.154	0.474	0.462	1,C
6324.4423	9.629	0.146	0.480	0.470	1,C
6328.4949	9.652	0.147	0.440	0.484	3,M
6331.4356	9.643	0.135	0.441	0.461	3,M
6333.4264	9.648	0.133	0.426	0.456	3,M
6335.4276	9.653	0.094	0.467	0.445	3,M
6338.3967	9.654	0.142	0.398	0.448	3,M
6339.4466	9.649	0.119	0.453	0.437	3,M
6340.3722	9.604	0.154	0.464	0.451	3,M
6345.4571	9.695	0.168	0.461	0.459	3,M
6347.4125	9.658	0.135	0.458	0.448	3,M
6355.3875	9.654	0.135	0.441	0.454	3,M
6358.3858	9.628	0.134	0.480	0.459	3,M
6370.3468	9.675	0.052	0.442	0.500	3,M
6375.3989	9.652	0.149	0.470	0.463	1,I
6376.4511	9.641	0.131	0.510	0.434	1,I
6396.4591	9.603	0.059	0.455	0.424	1,I
6397.4574	9.654	0.103	0.478	0.483	1,I
6399.3980	9.615	0.131	0.467	0.445	1,I

Table 12. continued

RJD #	<i>V</i>	<i>U</i> − <i>B</i>	<i>B</i> − <i>V</i>	<i>V</i> − <i>R</i>	T, O
6680.4633	9.696	0.145	0.421	0.416	3,Y
6681.4910	9.631	0.112	0.474	0.459	3,Y
6682.4780	9.653	0.161	0.460	0.462	3,Y
6683.4625	9.672	0.143	0.458	0.459	3,Y
6691.4998	9.609	0.174	0.478	0.447	3,Y
6702.4133	9.685	0.150	0.451	0.454	3,Y
6708.4101	9.694	0.197	0.451	0.473	3,Y
6714.4086	9.678	0.126	0.480	0.469	3,Y
6722.4158	9.640	0.129	0.455	0.465	3,Y
6730.3997	9.685	0.118	0.491	0.448	3,P
8490.4883	9.615	—	0.497	0.421	3,M
8491.4728	9.646	—	0.500	0.437	3,M
8492.4814	9.637	—	0.499	0.448	3,M
8494.4881	9.634	—	0.496	0.437	3,M
8495.4806	9.647	—	0.479	0.467	3,M
8496.4796	9.666	—	0.486	0.462	3,M
8498.4674	9.640	0.163	0.494	0.472	3,M
8499.4777	9.668	—	0.481	0.468	3,M
8508.4373	9.670	0.166	0.476	0.455	3,G
8509.4540	9.646	0.147	0.497	0.437	3,G
8510.4423	9.639	0.141	0.498	0.430	3,G
8511.4572	9.662	0.170	0.480	0.467	3,G
8512.4271	9.653	—	0.485	0.452	3,G
8513.4342	9.647	0.148	0.486	0.461	3,G
8514.4398	9.647	0.152	0.501	0.460	3,G
8515.4488	9.666	0.148	0.487	0.461	3,G
8516.3688	9.650	—	0.488	0.449	3,G
8517.3853	9.644	—	0.494	0.456	3,G
8518.3947	9.657	0.148	0.493	0.459	3,G
8519.4116	9.635	0.140	0.510	0.479	3,G
8520.4186	9.614	—	0.520	0.411	3,G
8521.4207	9.665	—	0.512	0.455	3,G
8522.4230	9.617	—	0.508	0.444	3,G
8523.4076	9.640	—	0.488	0.479	3,G
8575.4053	9.642	—	0.499	0.449	3,G
8582.4644	9.627	—	0.495	0.477	3,G*
8584.4290	9.648	—	0.484	0.492	3,G
8585.3857	9.635	—	0.494	0.427	3,G
8589.4612	9.644	0.090	0.477	0.438	3,G
8871.4961	9.682	0.043	0.454	0.510	3,G
8872.4633	9.700	0.052	0.475	0.505	3,G
8873.4775	9.641	0.164	0.457	0.465	3,G
8874.4310	9.674	−0.032	0.494	0.504	3,G
8875.4425	9.669	−0.034	0.495	0.479	3,G
8876.4102	9.692	0.041	0.479	0.508	3,G
8877.4394	9.666	−0.042	0.486	0.487	3,G
8878.4343	9.695	−0.072	0.463	0.508	3,G
8879.4471	9.685	0.089	0.443	0.437	3,G
8880.4245	9.679	0.031	0.487	0.493	3,G
8881.4404	9.698	0.216	0.498	0.445	3,G
8882.3933	9.660	0.010	0.488	0.478	3,G
8883.3891	9.668	0.041	0.485	0.503	3,G
8885.4966	9.680	0.019	0.463	0.498	3,G
8886.4654	9.701	0.047	0.472	0.471	3,G
8888.4503	9.686	0.027	0.470	0.474	3,G

Table 12. continued

RJD #	V	$U - B$	$B - V$	$V - R$	T, O
8890.4338	9.690	0.037	0.468	0.505	3,G
8901.4808	9.651	—	0.486	0.474	3,M
8905.4986	9.644	—	0.487	0.462	3,M
8906.4914	9.625	—	0.478	0.449	3,M
8907.4664	9.677	—	0.467	0.472	3,M
8914.4577	9.641	—	0.483	0.453	3,M
8915.4545	9.625	—	0.494	0.441	3,M
8920.4546	9.639	0.156	0.497	0.446	3,M
8922.4626	9.655	0.146	0.480	0.440	3,M
8923.4692	9.647	—	0.499	0.454	3,M
8925.4663	9.634	—	0.505	0.450	3,M
8927.4360	9.632	—	0.491	0.469	3,M
8954.4840	9.718	—	0.476	0.481	3,G
9234.4364	9.685	—	0.476	0.480	3,G
9235.4589	9.690	—	0.471	0.469	3,G
9238.4258	9.692	—	0.458	0.481	3,G
9239.4933	9.697	0.049	0.472	0.481	3,G
9259.5155	9.650	—	0.487	0.457	3,M
9260.4928	9.631	—	0.485	0.455	3,M
9262.5115	9.654	—	0.483	0.452	3,M
9264.5126	9.655	—	0.484	0.450	3,M
9271.4970	9.654	—	0.495	0.447	3,M
9274.4727	9.661	—	0.478	0.455	3,M
9286.4853	9.640	—	0.499	0.446	3,M
9615.4277	9.649	0.167	0.470	0.468	3,G
9619.4415	9.638	—	0.496	0.468	3,G
9620.4566	9.644	0.155	0.503	0.466	3,G
9621.4657	9.646	0.134	0.485	0.476	3,G
9622.4624	9.626	0.158	0.503	0.450	3,G
9948.4587	9.676	—	0.468	0.502	3,G
9950.4549	9.724	—	0.480	0.514	3,G
9952.4697	9.700	—	0.476	0.488	3,G
9954.4556	9.623	0.157	0.501	0.443	3,G
9956.4432	9.661	0.155	0.503	0.480	3,G
9958.4530	9.664	0.143	0.466	0.459	3,G
9960.4466	9.648	0.146	0.490	0.468	3,G
9963.4463	9.623	0.150	0.497	0.444	3,G
9965.4696	9.668	0.146	0.489	0.456	3,G
9968.4461	9.656	0.147	0.472	0.459	3,G
9970.4159	9.628	0.158	0.486	0.477	3,G
9973.3948	9.642	0.202	0.467	0.477	3,G
9975.4000	9.633	0.139	0.493	0.457	3,G
9978.3992	9.655	0.161	0.481	0.438	3,G
9984.4238	9.646	0.140	0.488	0.453	3,G
9987.4242	9.670	0.117	0.487	0.473	3,G
# JD–2440000		<u>ROTOR observers</u>			
* simultaneous with the high-resolution spectrum from SAO (Sect. 4.3)		C:	A.V. Chernyshev		
		G:	K.N. Grankin		
		I:	M.A. Ibragimov		
		M:	S.Yu Melnikov		
<u>Telescopes</u>		P:	D.L. Portnov		
1: Zeiss 600 reflector (60 cm)		S:	V.S. Shevchenko		
3: AZT 14 reflector (48 cm)		Y:	S.D. Yakubov		