Observational aspects of Herbig Ae/Be stars and of candidate young A/B stars

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The $\beta$ Pictoris phenomenon among young stars: The case of the Herbig Ae star UX Ori

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Abstract. – In this paper we present the first results of the study of very young stars having non–periodic Algol type brightness minima. It is based on cooperative observations between the Crimean Astrophysical Observatory (CAO), the European Southern Observatory (ESO) and the National Solar Observatory (NSO). In August-September, 1992, a very deep ($\Delta V = 2^\circ.5$), long lasting minimum of the light of the isolated Herbig Ae star UX Ori occurred. At this event the star was observed photometrically ($UBVRI$) and polarimetrically at the CAO, and spectroscopically (high resolution: H$\alpha$, Na I D and He I$\lambda$5876) at the ESO. The spectroscopic observations were continued at the NSO with the McMath solar/stellar telescope in October-December, 1992, when the star returned to maximum brightness and again at the ESO in July and October, 1993, when the star was bright.

The main results of our observations can be briefly summarized as follows: (1) The photometric and polarimetric results are in agreement with the model according to which UX Ori is surrounded by an edge-on circumstellar disk-like envelope, and its variability is caused by variable obscuration of the star by opaque circumstellar dust clouds. (2) The double-peak H$\alpha$ profile observed at maximum light changed to single-peaked at deep minimum; obscuration of a part of the circumstellar gas by an optically thick dust cloud is causing this variation. (3) The inverse P Cygni and the variable redshifted absorption components have been observed in the Na I D lines indicating the infall of cool gas onto the star. (4) The accreting gas is visible up to 200 km s$^{-1}$ with velocity structure similar to $\beta$ Pic at the time the inner disk was minimal obscured by circumstellar dust. (5) When the accreting gas collides with the inner disk material, ionized gas can appear, which explains the observed variable redshifted absorption component of the He I$\lambda$5876 line.

We believe that, such as in the case of the star $\beta$ Pictoris, violent comet-like activity takes place in the young protoplanetary disk of UX Ori which causes the observed variability. Although the accreting gas in UX Ori, a 2–3 Myr old star, differs from that seen toward $\beta$ Pic in mass accretion rate and in the volatile to refractory gas ratio.

1. Introduction

According to Herbig & Bell (1988) the irregular variable star UX Ori belongs to the Orion population. UX Ori has typical properties of a Herbig Ae/Be (HAEBe) star (Herbig 1960); its spectral type is A3e, the H$\alpha$ line is in emission, and it is located close to a region of star formation. Furthermore, its large infrared excess is due to thermal radiation of circumstellar (CS) dust located at the outer parts of its extended CS disk. Using the wavelength at maximum IR-flux Tjin A Djie et al. (1984) have estimated that the temperature of the dust envelope is approximately 1,350 K and that its inner radius is about 3 AU.

UX Ori is actually not embedded in a nebulosity, such as the classical HAEBe stars. Therefore, it is neither included in Herbig's original list of young Ae/Be stars, nor in the later extended list by Finkenzeller & Mundt (1984). However, based on modern criteria UX Ori can be considered as an "isolated" HAEBe star. Furthermore, it is the prototype of the small subclass of HAEBe stars, having an unusual photometric behaviour: non–periodic brightness variation with deep Algol-type minima. The decrease in the $V$ pass-band sometimes amounts up to 2 to 3$^m$, and lasts a few days to a couple of weeks. This group of variable stars has been selected as a separate subclass in the pioneering papers by Hoffmeister (1949), Parenago (1954), Wenzel (1957), and Kholopov (1959). The members of it consist of HAEBe and T Tauri stars, and several stars of unknown evolutionary status.

Only a few visual spectroscopic observations of UX Ori can be found in the literature. Low resolution spectra by Zajtseva & Kolotilov (1973) of the H$\alpha$ line, and by Kolotilov (1977) of the H$\alpha$ and H$\beta$ lines. In the last mentioned paper, where the measurements at different brightness levels were also presented, it was concluded that the equivalent width of the H$\alpha$ emission line increases when the star fades. This result was confirmed by
Herbst et al. (1983) using narrow-band photometry and was interpreted by them as evidence of the increase of chromospheric emission at brightness minima.

The photometric behaviour of UX Ori was investigated by many authors (Zajtseva 1973; Herbst et al. 1983; Tjin A Djie et al. 1984; Kilkenny et al. 1985; Evans et al. 1989; Bibo & Thé 1990; Bibo & Thé 1991). An important feature of this behaviour is the so-called “turnaround” of its colour-index in the colour-magnitude diagrams $U - B$ vs. $V$ and $B - V$ vs. $V$, popularly named the “blueing effect”. In the beginning the star becomes redder when it fades, but from some brightness level on, its colour becomes bluer again when the star dims further. Such an unusual behaviour, which is also typical for several other stars of above mentioned subclass (see Herbst 1986; Bibo & Thé 1991) has been interpreted by Herbst et al. (1983) and Rydgren & Cohen (1985) as caused by the activity of a surface magnetic field. In this interpretation the blueing effect is due to the radiation of a chromosphere or of active regions above magnetic starspots (Herbst 1986; Evans et al. 1989; Hoffmeister et al. 1990). This interpretation is in agreement with the above mentioned results of Kolotilov (1977) and Herbst et al. (1983).

Another interpretation of the blueing effect in deep minima of UX Ori and other stars having the same behaviour, was suggested by Grinin (1986). In his model, which is compatible with the variable CS extinction model, it is assumed that the weak scattered light of the central star by small dust particles dominates, when the star is obscured by the CS cloud intersecting the line of sight. If the CS dust particles are small enough, the scattered radiation of the central star can be even bluer compared to the light of the central star itself. This has been observed in the case of UX Ori (see Bibo & Thé 1991). Support to this interpretation can be given by proving that the scattered light of these stars at deep minima is strongly linearly polarized. In 1986 simultaneous polarimetric and photometric observations of isolated stars was started at the Crimean (Ukraine) and Sun-glok (Tadjikistan) observatories. These observations lead to the confirmation that above mentioned dust-disk model is indeed correct. At two deep minima the light of UX Ori was linearly polarized up to 7.4% in the $V$ pass-band (Voshchinikov et al. 1988), whereas at maximum brightness the degree of polarization is less than 1%. Results of other stars were summarized by Grinin et al. (1991) and Grinin (1992). The general conclusion from our multi-year simultaneous observations of isolated stars with non-periodic Algol-type minima is, that these stars are surrounded by CS disks seen edge-on or nearly edge-on, in which at the outer parts protoplanetary dust clouds are revolving around the central star in elongated orbits. This means that a strong selection was already made by Hoffmeister and others, at the very beginning, when they recognized and defined above mentioned subclass.

The dust-disk model above recalls the coronagraphic observations of the well known star β Pic (Smith & Terrile 1984). In the case of β Pic the protoplanetary disk was spatially resolved in the telescope, in which the exclusion of the direct stellar radiation was obtained using a coronagraph (Paresce & Burrows 1987; Gledhill et al. 1991). In the case of UX Ori, however, the CS dust cloud acts as a natural coronagraph, which obscures almost completely the direct radiation of the central star. Consequently, in deep minima we are able to observe the highly polarized scattered stellar radiation by the dust particles in the outer parts of the protoplanetary disk.

It should be mentioned here that in the case of β Pic, the observations of the variable line profiles in its spectrum led to the conclusion that they are caused by in-falling comet-like bodies towards the star (Ferlet et al. 1987; Lagrange-Henri et al. 1988). Therefore, it is very important to investigate whether something like this is also happening in extremely young stars, where the accretion processes have been applied to the interpretation of different properties of these type of stars (Appenzeller & Mundt 1989). The HAEBe stars with deep Algol-type minima are the most suitable to be used for solving this problem, because their CS disks are seen, as in the case of β Pic, edge-on or nearly edge-on.

For our program we have concentrated on the four most photometrically active stars of this type: UX Ori, WW Vul, BF Ori and CQ Tau, and on two spectral lines for our spectral observations: the Na I D resonance doublet and the Hα emission line. The choice of the sodium lines is based on the fact that, due to the high ionization rate of the gas, these lines cannot be formed either in the atmosphere or in the stellar wind of Ae stars. Only the neutral gas, associated with the cool CS matter, can be responsible for the formation of the CS components of these Na I D lines.

During the first cooperative observations from ESO, CAO and NSO only one star, UX Ori, was observed at a deep minimum. Strong variations were found in both spectral lines mentioned above. In this paper we describe these variations and suggest tentative interpretations.

2. The observations

The first 1992 observation of UX Ori was made on August 22, 1992, at the CAO, with the five-channel $UBVRI$ photometer/polarimeter of the Helsinki University (Pirola 1975), mounted on the 1.25-m telescope. The comparison star BD = $-3\,999$ of Zajtseva (1973) was used; $V = 8^{m}38$, $U - B = 0^{m}13$, $B - V = 0^{m}10$, $V - R = 0^{m}13$, $V - I = 0^{m}16$. In 1992/93 the star was observed during 46 nights. The photometric data were transformed to the Johnson system. For the reduction of the simultaneously observed polarimetric data, standards for polarimetry were observed each month.

In the observation of August 22, 1992, we found UX Ori to be in a very deep minimum. This information prompted the spectral observations at ESO (see below) and with the IUE (Grady et al. 1995). In Fig. 1 the light curve, the degree of linear polarization, and the corresponding position angles in the $V$ pass-band, are shown. For comparison, the data obtained in two previous observational seasons, 1987 to 1988 and 1991 to 1992, are also given. The photometric data of all these seasons are used to construct the colour-magnitude diagrams in Fig. 2.

High dispersion spectra of UX Ori taken in the vicinity of Hα and the Na I D lines were obtained during the August minimum brightness phase, as well as in a following phase of maximum light. Technical data of these observations are given in Tables 1 and 2. The spectra, taken at UX Ori’s minimum brightness phase, were observed with the Coulé Auxiliary Telescope (CAT) at ESO using the short camera, equipped with an RCA high resolution CCD of $1024 \times 640$, $15 \times 15\mu m$, pixels. One spectrum, centered around Hα, is the result of a 60 min exposure on September 1, 1992, with a resolving power of 50,000. During the same night a 60 min spectrum of the Na I D lines and their neighbouring regions, were obtained with a resolution of 55,000. In a previous night, August 26, a Na I D spectrum
was also taken with the same exposure time. Due to limited visibility of UX Ori during these two nights, the spectra are underexposed and have a low S/N ratio (about 25). Therefore we use them only for qualitative analysis.

The spectral observations of UX Ori were continued in October-December, 1992, at NSO with the McMath 1.52-m solar/stellar telescope and stellar spectrograph having a circular aperture of 5″. Two spectra have been secured around the Na\textsc{i} D lines and one in the vicinity of the Hα emission line. The resolution of all these spectra is about 20,000 and the S/N ratio is about 70 - 100.

One Hα spectrum of UX Ori was obtained on March 1, 1993, when the star was already near its brightest state (see Fig. 1). For this observation the 2.6-m telescope at CAO, equipped with the Coudé spectrograph and CCD camera, were used; the spectral resolution was about 20,000 and the S/N ratio was about 50.

The spectral observations of UX Ori with the CAT were continued in July and October, 1993, (with exactly the same equipment) and were supported in October by photometric observations at CAO (see Table 1). The S/N ratio of these spectra was about 100. In all cases the heliocentric reference system was used. The wavelength region for all the observed Na\textsc{i} D spectra includes the He\textsc{ii}λ5876 line.

### 3. Analysis of the results

#### 3.1. Photometry and polarimetry

A comparison of the photometric observations at the Algol-type minimum of UX Ori, obtained in August-September, 1992, (Fig. 1) with those at other deep minima, observed during the previous five years of patrol observations of this star at CAO (Grinin et al. 1996a), and with the results of other authors (Zajtsev 1973; Herbst et al. 1983, 1987; Bibo & Thé 1991) shows, that the duration of the 1992 brightness change was extremely long and that the minimum was very deep. Note that the star had already faded before we started our observations at CAO. Therefore, we can only estimate a lower limit of the duration of the brightness decrease, until the return to maximum light. This is about two months. The other important feature observed at this minimum is the "turnaround" of the colour-indices in the colour-magnitude diagrams. As can be seen in Fig. 2 this blueing effect has been observed, not only in the visual V vs. U - B and V vs. B - V diagrams, as already known previously, but also in the red V vs. V - R and V vs. V - I diagrams. UX Ori was the first star in which this important feature was observed so clearly. The unusual shape of the red colour-magnitude diagrams (like an ice-hockey stick) agrees well with the theoretically predicted colour-magnitude diagrams by Voshchinnikov et al. (1988).
As our first simultaneous photometric-polarimetric observations in 1986 (Voshchinnikov et al. 1988), UX Ori again shows a distinct correlation between its brightness decrease and the increase in linear polarization, as is shown in Fig. 1. According to this figure a maximum degree of linear polarization of 6.7% was observed at the deepest part of the August brightness minimum. This value and that of the accompanying position angle are about the same as those at the deep minimum of 1986. As was stressed by Grinin (1986), the exact reproduction of the polarization parameters observed from minimum to minimum, is an important property of our model, summarized below. A more detailed discussion of the seven years of polarimetric and photometric observations of UX Ori will be given in a paper by Grinin et al. (1996b).

The photometric and polarimetric observations are in agreement with the model in which UX Ori is supposed to be surrounded by an edge-on CS disk-like envelope, in which many dust clouds, located at its outer parts, are revolving around the star. When a dust cloud intersects the line of sight to the central star, the radiation of this star is suppressed, and it is then pos-

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### Table 1. Log of spectroscopic observations taken with the ESO CAT/CES combination.

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
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<td>NaI D</td>
<td>Aug. 26, 1992</td>
<td>09:26</td>
<td>8860.8931</td>
<td>55,000</td>
<td>5858–5918</td>
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<td>11.94</td>
</tr>
<tr>
<td>NaI D</td>
<td>Sep. 01, 1992</td>
<td>08:32</td>
<td>8866.8556</td>
<td>55,000</td>
<td>5868–5918</td>
<td>60</td>
<td>11.95</td>
</tr>
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<td>8866.9041</td>
<td>50,000</td>
<td>6536–6591</td>
<td>60</td>
<td>11.95</td>
</tr>
<tr>
<td>Hα</td>
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<td>10:27</td>
<td>9184.9354</td>
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<td>6536–6591</td>
<td>35</td>
<td>–</td>
</tr>
<tr>
<td>NaI D</td>
<td>July 17, 1993</td>
<td>10:27</td>
<td>9185.9354</td>
<td>55,000</td>
<td>5861–5917</td>
<td>40</td>
<td>–</td>
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<td>July 19, 1993</td>
<td>10:21</td>
<td>9187.9313</td>
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<td>6536–6591</td>
<td>45</td>
<td>–</td>
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<tr>
<td>Hα</td>
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<td>05:43</td>
<td>9267.7382</td>
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<td>6536–6591</td>
<td>60</td>
<td>–</td>
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<td>NaI D</td>
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<td>09:11</td>
<td>9267.8826</td>
<td>55,000</td>
<td>5861–5917</td>
<td>54</td>
<td>–</td>
</tr>
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<td>55,000</td>
<td>5861–5917</td>
<td>60</td>
<td>–</td>
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<tr>
<td>Hα</td>
<td>Oct. 08, 1993</td>
<td>09:29</td>
<td>9268.8951</td>
<td>50,000</td>
<td>6536–6591</td>
<td>33</td>
<td>–</td>
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<td>05:43</td>
<td>9269.7382</td>
<td>55,000</td>
<td>5861–5917</td>
<td>50</td>
<td>9.98</td>
</tr>
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<td>Hα</td>
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<td>6536–6591</td>
<td>45</td>
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<td>06:00</td>
<td>9270.7500</td>
<td>55,000</td>
<td>5861–5917</td>
<td>50</td>
<td>10.07</td>
</tr>
<tr>
<td>Hα</td>
<td>Oct. 10, 1993</td>
<td>08:33</td>
<td>9270.8563</td>
<td>50,000</td>
<td>6536–6591</td>
<td>30</td>
<td>10.07</td>
</tr>
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<td>NaI D</td>
<td>Oct. 11, 1993</td>
<td>05:43</td>
<td>9271.7382</td>
<td>55,000</td>
<td>5861–5917</td>
<td>50</td>
<td>9.87</td>
</tr>
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<td>Hα</td>
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<td>08:06</td>
<td>9271.8375</td>
<td>50,000</td>
<td>6536–6591</td>
<td>30</td>
<td>9.87</td>
</tr>
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<td>9272.7188</td>
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<td>5861–5917</td>
<td>50</td>
<td>10.12</td>
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<td>05:27</td>
<td>9273.7271</td>
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<td>5861–5917</td>
<td>50</td>
<td>10.18</td>
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<td>NaI D</td>
<td>Oct. 14, 1993</td>
<td>05:18</td>
<td>9274.7208</td>
<td>55,000</td>
<td>5861–5917</td>
<td>50</td>
<td>10.16</td>
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<td>Hα</td>
<td>Jan. 11, 1994</td>
<td>01:34</td>
<td>9363.5653</td>
<td>50,000</td>
<td>6540–6590</td>
<td>60</td>
<td>–</td>
</tr>
</tbody>
</table>

Fig. 2. The colour-magnitude diagrams of UX Ori, based on CAO observations during three seasons: squares indicate 1987-88, circles 1991-92 and triangles 1992-93.
4) From this discussion we can conclude that these variations of the Hα line profiles, at deep minima and at bright states, have repeated twice. Hence they cannot be accidental. This important conclusion is supported by model calculations of Grinin & Tambovtsev (1995) (see below for a short description).

Our observations support the conclusion by Kolotilov (1977) that the equivalent width of the Hα line increases when the star fades; according to our data W(Hα) increased from 6.7 Å at bright state (March 1, 1993) to 19.5 Å at deep minimum (September 1, 1992). Note that for making the estimate of W(Hα), the photospheric absorption profile of a normal star of the same spectral type (β Eri) was employed.

During maximum brightness the spectra of Hα show short timescale V/R variations, with V/R > 1, see Fig. 4. When the R-component diminishes the V-component follows. Perfect reversed P Cygni profiles are then seen on 07/10/93. When the red-emission peak is getting stronger or more peaked, e.g. 19/07/93, 11/10/93 and 11/01/94, we notice extra emission in the violet peak or the central absorption diminishes. In the three mentioned cases the red- and blue-emission is peaked to lower velocities. The variations in both peaks seems therefore undoubtedly connected to each other. Either a mechanism of in-and out-flowing gas is present or a rotational effect play a significant role.

Using the results of the simultaneous photometry we have estimated the Hα luminosity of UX Ori at bright state (March 1, 1993) to be $5 \times 10^{31}$ erg s$^{-1}$, assuming its distance is 460 pc and the visual extinction $A_V = 0.3$ (Zaitseva 1973). The Hα flux decreased by a factor of about 1.7 from the bright state, which is the result of the screening of the inner part of

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**Table 2. Log of spectroscopic observations taken with the NSO-McMath telescope.**

<table>
<thead>
<tr>
<th>Central Line</th>
<th>Date</th>
<th>U.T.</th>
<th>JD -2440000</th>
<th>Resolution</th>
<th>Spectral Range [Å]</th>
<th>Exp. Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hα</td>
<td>Oct. 26, 1992</td>
<td>11:59</td>
<td>8921.9994</td>
<td>20,000</td>
<td>6530-6590</td>
<td>60</td>
</tr>
<tr>
<td>Na I D</td>
<td>Nov. 07, 1992</td>
<td>10:15</td>
<td>8933.9270</td>
<td>20,000</td>
<td>5865-5908</td>
<td>60</td>
</tr>
<tr>
<td>Na I D</td>
<td>Dec. 02, 1992</td>
<td>05:40</td>
<td>8958.7362</td>
<td>20,000</td>
<td>5865-5910</td>
<td>60</td>
</tr>
</tbody>
</table>

**Fig. 3.** The Hα line in the spectrum of UX Ori: (a) at its bright state (CAO, March 1, 1993, $V = 10^9.09$), and (b) in its deep minimum (ESO, September 1, 1992, $V = 11^9.95$). The vertical scales in both spectra are normalized in the same energetic units by using simultaneous photometry.

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3.2. Spectral variations

3.2.1. The Hα emission line

According to low-resolution spectral observations by Kolotilov (1977) at the bright state of UX Ori, the Hα emission shows an asymmetric two-component profile with the ratio $V/R > 1$, i.e. a reversed type III P Cygni profile. Only once he had observed this star at a deep ($V \approx 12^m$) minimum; the profile of the Hα line was then asymmetric and single-peaked. Fig. 3b shows that at the deep brightness minimum of August, 1992, a similar Hα emission-line profile was observed. When the star returned to its bright state the line re-gained a two-component asymmetric shape with $V/R > 1$ (Fig. 3a). The same two-component Hα profile has been observed also at NSO in October 26, 1992, and at ESO in July and October, 1993, when the star was bright (Fig. 4). From this discussion we can conclude that these variations of the Hα line profiles, at deep minima and at bright states, have repeated twice. Hence they cannot be accidental. This important conclusion is supported by model calculations of Grinin & Tambovtsev (1995) (see below for a short description).
the gaseous envelope by the CS dust cloud. Such a behaviour is quite natural in the case of variable CS extinction (see e.g. Zajtseva 1973): the central star was obscured completely by the opaque CS dust cloud, whereas this cloud screened the more extended gaseous envelope, where the Hα-line originates, only partially. Note that the Hα profiles in Fig. 4 are not corrected for the stellar brightness as in Fig. 3.

3.2.2. The sodium resonance doublet

Very interesting variations have been observed also in the Na\textit{i} D lines. At the bright state of UX Ori, observed at NSO on December 2 (Fig. 6), only narrow interstellar components of the Na\textit{i} D lines are seen, which is typical for most HAEBe stars (Finkenzeller & Mundt 1984). According to Finkenzeller & Jankovics (1983) the radial velocities of these lines coincides within a few kilometers per second with the radial velocities of the HAEBe stars.

In the spectrum observed at ESO at deep light minimum the lines of the resonance doublet have weak inverse $P$ Cygni profiles (Fig. 5), blended by sharp interstellar absorption lines. The radial velocities of the redshifted absorption components indicate infall of gas onto the star with a velocity up to 50 km s$^{-1}$. The radial velocities of the blueshifted emission components are about the same. More clearly redward-displaced absorption components of the Na\textit{i} D lines have been observed with higher S/N ratio at the NSO on November 7, when the star returned to its bright state (Fig. 6).

Interesting features in the spectrum of November 7 are the sharp emission components, which are seen in both resonance lines. These components are also seen in the ESO spectra of September 1, 1992, and of July and October, 1993 (before extracting the background). The analysis of the October, 1993, spectral images (which have the best S/N ratio) shows that these sharp emission components are the night sky (NS) lines. Note that the correction of the NSO spectra for the background radiation was impossible due to the circular aperture of the spectrometer. The same, time variable, sharp emission components are sometimes seen in sodium lines of stellar spectra observed with high spectral resolution (Crawford & Barlow 1991).

Strong and variable CS absorption components of the Na\textit{i} D lines have been observed also at ESO in July and October, 1993 (Fig. 5). They are all redshifted and well separated from the IS components. Their shape changes from night to night. The maximum equivalent widths of these components were observed on July 17, 1993; 0.60 Å and 0.41 Å for the D$_1$ and

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**Fig. 4.** The Hα line profiles in the spectra of UX Ori at bright phase on July and October, 1993. The September 1, 1992 Hα profile is shown for comparison. All profiles are normalized to the continuum level.

**Fig. 5.** The ESO spectra of UX Ori around the Na\textit{i} D lines at deep minimum of 1992 and in the bright state of the star at July and October 1993. Note the variable, mostly red-shifted, weak absorption line of He\textit{i} 5876 Å. Thin dashed lines correspond to the continuum level. The radial velocities are given in the heliocentric system.
D_2 lines, respectively. The maximum radial velocity is about 200 km s^{-1}. Comparison with the H\alpha line profiles, which were observed on the same nights (Fig. 4), shows that the radial velocities of these redshifted components are about the same as the radial velocities of the absorption component of the H\alpha line profile. When the Na\,i D absorption components are stronger and distributed over a smaller velocity range, e.g. 10/10/93 and 12/10/93, the same is seen for the blue peak of the quasi-simultaneous taken H\alpha profiles. Note that variable redshifted H\,i absorption profiles are also seen in most Na\,ID spectra, Figs. 5 and 6. A common behaviour between the observed lines is not clear.

It should be noted also that according to Table 1 the star was at its bright phase during the observations of October, 1993. There was no photometric support in July. Nevertheless, estimations based on the count rates show that the star was quite bright that night.

The radial velocity of the interstellar Na\,i D absorption components in the spectra of UX Ori is +19 \pm 2 km s^{-1}. From Figure 5 one can see that in all the October spectra the IS components are blended by the additional sharp, slightly redshifted CS absorption components whose radial velocity is +26 \pm 2 km s^{-1}. Thus, in the October spectra two different types of CS components were observed: the narrow components which are almost the same in all spectra, and the wide, variable redshifted components.

4. Interpretation of the results

Based on the analysis of the observations given in the previous section we present now a tentative interpretation of the results.

4.1. The screening effect and the variation of the H\alpha emission line

The observed variations of the H\alpha line (Fig. 3) at the deep minima of UX Ori can be well understood in the framework of the dust cloud obscuration model considered in detail in the paper by Grinin & Tambovtseva (1995). In this model the almost opaque dust cloud acts as a natural coronagraph, obscuring that part of the CS gaseous disk which produces the absorption in the centre of the H\alpha line.

The results of these model calculations are depicted in Fig. 7. It is assumed for simplicity that the hydrogen emission spectrum is formed in a flat accreting gaseous disk. The geometrical thickness of the disk is equal to the stellar diameter. The other model parameters are as follows:

- the radius of the central star \( R_* = 2 R_\odot \),
- the accretion rate \( M = 3 \times 10^{-9} M_\odot\text{yr}^{-1} \),
- the electron temperature \( T_e = 8,000 \text{ K} \),
- the radial and tangential velocity components of the flow are:
  \[ u(r) \sim r/r^{1/2}, u(R_a) = 250 \text{ km s}^{-1}, v(R_a) = 200 \text{ km s}^{-1}, \]
- the effective temperature of the star and the gravity are \( T_{\text{eff}} = 8,500 \text{ K} \) and \( \log g = 4 \), respectively.

The energy distribution and the photospheric H\alpha absorption profile were taken from Kurucz' (1991) models. The theoretical H\alpha line profile, obtained with above parameters, is in general agreement with the observed one at UX Ori's bright state (see Fig. 3a and Fig. 4). For the case of UX Ori at minimum brightness, it is assumed that the dust cloud intersecting the line of sight has a radius of \( R_{\text{cloud}} = 8 R_* \) and is completely opaque for stellar radiation. The faint continuum radiation seen in Fig. 7 at deep minimum is the scattered radiation of the central star by the dust particles in the protoplanetary disk. According to this figure the theoretical H\alpha line profile at minimum brightness of the star is also in general agreement with the observed one in the spectrum of UX Ori at a similar situation. Some "roughnesses" in the theoretical line profile in Fig. 7 are caused by the assumption that the obscuring dust cloud has sharp boundaries.

4.2. Dissipation of the CS clouds, evaporation of the star-grazing bodies and the non-stationary accretion

As is mentioned above the type III P Cygni profile of the H\alpha line in the spectrum of UX Ori is reversed. Such a profile is usually interpreted as the result of accretion of gas onto the star. The presence of the redshifted variable absorption components in the lines of the sodium resonance doublet show that accretion of cool gas takes place in the circumstellar gaseous envelope and is, probably, very irregular (clumpy) (see also Graham 1992).

The question arises: what is the source of this cool matter? It is natural to connect the cool gas in the line-of-sight with the circumstellar clouds. When such a cloud is far from the star, it can produce the sharp absorption components similar to those observed in October 1993. In the vicinity of a star the CS cloud can be destroyed by the tidal forces and evaporation.
Indeed, in order to be able to produce deep Algol-type brightness decreases, the minimum radius of a CS cloud, $R_\text{c}$, should be comparable with the stellar disk diameter (about 1000 km). According to Voshchinnikov & Grinin (1991) the masses of the large CS clouds can reach $M_\text{c} = 10^{21}$ g. In this case the CS cloud will be destroyed by tidal forces beginning at a distance from the central star of $r_\text{t} = 2(M_*/M_\odot)^{1/3}$, $R_\text{c} \approx 10$ AU and smaller, when we assume that $M_\star = 3.3 M_\odot$ (Hills 1975). Most probably part of this cool CS matter will fall onto the star.

We do not consider here the physical conditions in these clouds and the formation of the absorption components of the NaI D lines. These will be studied in more detail in forthcoming papers (Grinin & Tambovtseva 1995, and Grinin et al. 1996a). However, it is important to note that the process of the destruction of CS dust clouds, discussed above, reminds us of a similar phenomenon observed in a much weaker form today in our own Solar System. It is the well known process of partial dissipation of comets at their nearest passage to the Sun and the formation (together with the asteroidal dust) of the F-corona. It is also worth mentioning that the existence of the proto-comets around young stars was already proposed by Gahm & Greenberg (1983) and by Baade & Stahl (1989) for the interpretation of the photometric activity of young stars.

The other potentially important source of cool matter in the vicinity of UX Ori is the evaporated star-grazing bodies. The first observational evidence in favour of this interesting type of circumstellar activity was found for the star β Pic (see Lagrange-Henri et al. 1988; Ferlet et al. 1993 and references therein). In the case of UX Ori we have similar arguments in support of this idea:

i) The maximum infall velocities which we observed in the sodium lines reach about 200 km s$^{-1}$. For the stellar mass 3.3 $M_\odot$ and radius 3.2 $R_\odot$ (see Hillenbrand et al. 1992) it corresponds to the infall velocity at the distance of about 10 stellar radii from the star.

ii) UX Ori is a hot star (A3e) and neutral sodium will be ionized very quickly at that distance (seconds and less). This means that neutral sodium atoms have to be produced somehow immediately at this place. The most natural (and, probably, unique) way to do it is the evaporation of star-grazing bodies.

iii) The sodium resonance lines are usually not very strong in cometary spectra. However, they are quite intense in the spectra of sun-grazing comets in the vicinity of the Sun (Preston 1967; Spinrad & Miner 1968).

iv) In the case of gas accretion it is natural to expect the formation of hot regions in the gaseous streams. Therefore, the existence of the neutral helium line 5876 Å in the NSO spectrum of Dec. 2 (Fig. 6) and the CAT/CES spectra (Fig. 5, which is not typical for normal A stars) is not surprising: this line can be formed in the hot regions behind shock fronts.

5. Conclusion

Based on the first cooperative program for the study of the pre-main sequence Herbig Ae star UX Ori, which in August, 1992, was at a very deep Algol-type minimum, we can summarize our conclusions as follows.

For the first time, UX Ori has been observed spectroscopically at high spectral resolution (up to $R = 55,000$) during a deep brightness minimum. These observations have shown that four different mechanisms of the spectral variability can play a role in stars surrounded by young protoplanetary disks.

1. Obscuration of part of the circumstellar gas by an optically thick dust cloud, which intersects the line of sight, is causing variations in the Hα line profile. The double-peaked emission profile observed at a high brightness phase is transformed to a single-peaked asymmetric line at deep minimum.

2. Dissipation of dust clouds at their closest passage to the star, and the simultaneous infall of cool gas onto the star. We observed the manifestation of this interesting process in

![Fig. 7. The theoretical Hα line profiles at bright state and at deep minimum (see text for details). Vertical scales are normalized in the same way as in Fig. 3.](image-url)
the inverse $P$ Cygni profiles of the Na I D resonance doublet when the star was in deep minimum.

3. Evaporation of star-grazing bodies in the neighbourhood of a star. The consequence of this process is the formation of the variable redshifted absorption components in the sodium lines which were observed in the bright state of UX Ori.

4. If the accreting material collides with the inner disk-material, hot regions can exist of collisional ionized gas. This gas can explain the appearance of He I λ5876 redshifted absorption components.

The process of the destruction of the CS dust clouds observed in the neighbourhood of UX Ori, reminds of the process of partial dissipation of cometary matter in the inner part of our Solar System. If our assumption that UX Ori "absorbs" some part of the comet-like matter is real, an overabundance of the heavy elements in the atmosphere of this star is possible when it will go to the Main Sequence. The estimates by Kumar et al. (1989) show that the processes of such a type could be responsible for the chemical peculiarity in the atmospheres of Am and Ap stars. In this connection further observations of different spectral lines of UX Ori type stars will be very important for the diagnostics of cool matter associated with CS dust clouds.

The other potentially important consequence of the assumption mentioned above is the possibility of the accretional process onto a young star and formation of the disk-like gas envelope around it without the classical scenario of Lynden-Bell & Pringle (1974) of viscous disk accretion. In our case the mass accretion rate and the parameters of the CS gas envelope will depend on the parameters of the star-grazing bodies and the distribution of their orbits.

The primary difference between $\beta$ Pic and UX Ori are the higher accretion rate, as seen from the integrated red-shifted profiles, and the presence of volatile gases in the accreting material seen towards UX Ori. In Chapter A5 the location of UX Ori in the Hertzsprung-Russell diagram is compared to theoretical evolutionary tracks. From this we derive: $M_\ast = 3.3 \, M_\odot$ and an age of 2 - 3 $10^6$ yrs. Models for the infalling, evaporating bodies in the $\beta$ Pic system have suggested that the comet-like bodies are perturbed into high eccentric orbits by secular resonance with giant planets. If the formation of such orbits is a result of the gravitational perturbation produced by planets (Beust et al. 1991) then UX Ori is a real candidate of a star with a young protoplanetary system. Our data suggest that any giant planets must have formed within a few $Myr$, rather than the $10^7$ - $10^8$ years suggested for the formation of Jupiter.

The differences in the volatile/refractory gas behaviour in the UX Ori and $\beta$ Pic systems suggests that substantial chemical evolution of the disk occurs on timescales longer than 2 - 3 $10^6$ yrs, and thus provides a firm lower bound on the age of the $\beta$ Pic system. The similarities between the systems, however, tend to favor a comparative young $\beta$ Pic system.

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References

Wenzel, W. 1957, "Die Sterne" 33, 196.