THE ASTROPHYSICAL JOURNAL, 542:421–427, 2000 October 10

AN INTERESTING EPISODE OF ACCRETION ACTIVITY IN UX ORIONIS[1]

A. NATTA
Osservatorio Astronomico di Arcetri, Università degli Studi di Firenzi, Largo Enrio Fermi 5, I-50125 Firenze, Italy; natta@arcetri.astro.it

V. P. GRININ
Crimean Astrophysical Observatory, Crimea, 334413 Nauchny, Ukraine, and Department of Astronomy, St. Petersburg State University, 1, Uliyanovskaya Str., Petrodvorets, St. Petersburg, 198904, Russia

AND

L. V. TAMBOVTSEVA
Central Astronomical Observatory Pulkovo, M-140, 196140, St. Petersburg, Russia
Received 2000 February 22; accepted 2000 May 11

ABSTRACT

This paper presents observations of an episode of accretion activity in the pre–main-sequence star UX Ori. High-velocity, redshifted absorption is seen in several lines of H, Ca II, Na I, and Fe II during an interval of eight nights in the fall of 1996 with similar velocity and time evolution. A non-LTE analysis of the line optical depths shows that the infalling gas cannot be heavily hydrogen-depleted, as would be expected if it was produced by the evaporation of a solid body of chemical composition similar to solar system comets. On the contrary, the observations are consistent with gas of solar chemical composition at temperature ~6000–7000 K.

Subject headings: circumstellar matter — stars: formation — stars: individual (UX Orionis) — stars: pre–main-sequence

1. INTRODUCTION

The Herbig Ae/Be star UX Ori is the prototype of a small group of young stars (UXORs) of intermediate mass characterized by intense photopolarimetric variability, probably caused by variable circumstellar extinction (Grinin et al. 1991; Thé 1994; Eaton & Herbst 1995 and references therein). Their spectra are characterized by the presence of redshifted absorption components in a number of metal lines and in Hα due to gas infalling toward the star. The similarity of this spectral behavior to what is observed in β Pic has suggested that UXORs are closely related to the older β Pic systems, and that also in UXORs the infalling gas is produced by the evaporation of protocomets or planetesimals in star-grazing orbits (see, for example, Grady et al. 2000). However, several other characteristics of UXORs invite caution when pursuing this interpretation. In particular, the presence of a rather massive circumstellar disk in UX Ori (Natta et al. 1999) and the strong Hα emission commonly seen in the UXORs suggest a close similarity between UXORs and classical T Tauri stars, where gas infall is related to the presence of an accretion disk disrupted in the vicinity of the star by the stellar magnetic field (magnetospheric accretion models; Königl 1991; Hartmann, Hewett, & Calvet 1994; Ostriker & Shu 1995).

A clear test of these two models involves the determination of the chemical composition of the infalling gas. If the gas results from comet evaporation, it should be strongly depleted in hydrogen, while in the magnetospheric accretion hypothesis one expects the chemical composition to be roughly solar. Sorelli, Grinin, & Natta (1996) tried to discriminate between these two extreme cases by comparing the redshifted absorption observed in the NaD lines with model predictions for absorbing slabs of different chemical composition, with no conclusive result. Clearly, lines of different elements are needed.

[1] Based on observations obtained with the Nordic Optical Telescope.

In this paper we present observations of an infalling event detected in the spectrum of UX Ori. Redshifted absorption is seen simultaneously in several lines with similar velocity and time evolution. We use these observations to constrain the chemical composition of the infalling gas.

2. OBSERVATIONS AND RESULTS

High-resolution ($R = 25{,}000$) spectra of UX Ori were obtained with the Nordic Optical Telescope (NOT) and the echelle spectrograph SOFIN during the nights of 1996 November 25, 28, and December 2. These nights were part of a large program of monitoring the spectral variations of several UXORs by obtaining full spectra in the range 3909–8716 Å in time sequences with two-to-three nights separation, conducted during the years 1994–1996 at NOT. The observations and data reduction are discussed in detail in V. P. Grinin et al. (2000, in preparation). Simultaneous photometric observations obtained at the Crimean Astrophysical Observatory show that UX Ori was in its bright state during the three nights of interest ($V = 10.08$, 9.95, and 9.86 mag, respectively).

Among the spectra of UX Ori, the sequence of three nights discussed here presents the clearest evidence for an episode of gas infall toward the star, clearly detected in a number of circumstellar lines, as seen in Figures 1–4. Figure 1 shows the first four lines of the hydrogen Balmer series; Figure 2 shows the Na D doublet; Figure 3 shows the H and K lines of Ca II, and Figure 4 shows the Ca II IR triplet. The complete spectra can be found in V. P. Grinin et al. (2000, in preparation). Weak circumstellar absorption is seen in several other lines, mostly Fe II. In the majority of the cases, however, the absorption is too weak to derive the velocity profile. Circumstellar absorption, centered at zero velocity, is also observed in the He I λ5876 and O I λ7774 lines; these lines are likely associated with the infall/accretion process, but they originate in gas hotter than the other lines, having a different dynamical evolution, and will

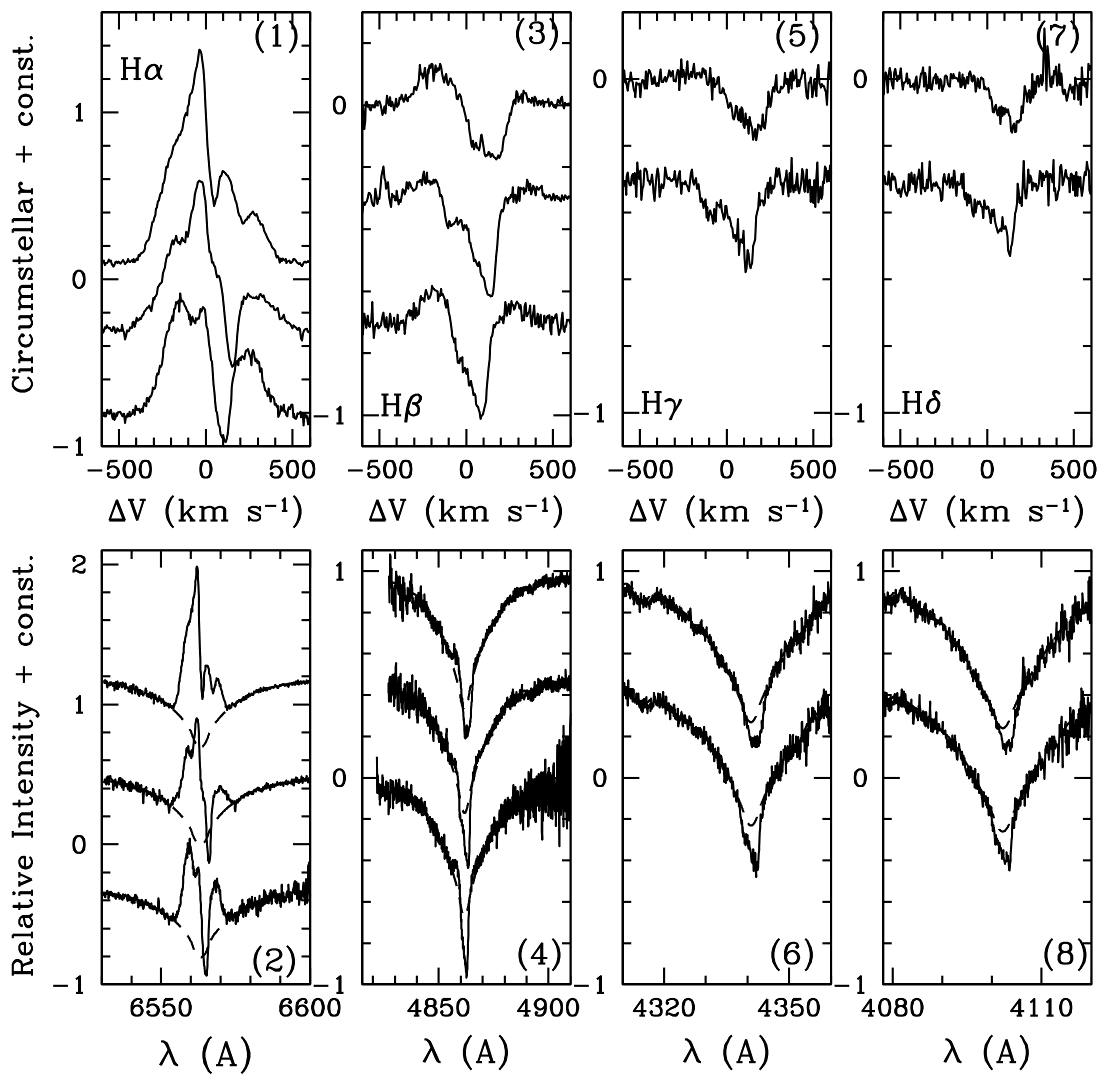

FIG. 1.—Hα, Hβ, Hγ, and Hδ. *Bottom* (*2, 4, 6, and 8*): solid lines plot the observed fluxes as the function of wavelengths for the three nights of November 25, 28, and December 2 (from top to bottom). The dashed lines show the photospheric component as predicted by a synthetic spectrum of UX Ori ($T_* = 9500$ K, $\log g = 4$). *Top* (*1, 3, 5, and 7*): show as a function of velocity shift the corresponding circumstellar components, computed as the difference of the observed minus the synthetic spectrum. The infalling event is seen in Hα at redshifted velocities of ~ 210, 163, and 125 km s^{-1} on November 25, November 28, and December 2, respectively. In Hβ the corresponding velocities are 170, 140, and 93 km s^{-1}, respectively. Note that in all the four lines there is evidence of additional, weaker, and less redshifted absorption components, seen, for example, at ~ 50 km s^{-1} in Hα and Hβ on November 25. Also in this case there is a tendency to move toward lower redshift with time. Hγ and Hδ were not observed on December 2.

not be further discussed here. The formation of these lines in UXORs will be the subject of a forthcoming paper.

To the best of our knowledge, this sequence of spectra is unique because on each night it provides simultaneous coverage of a very large spectral range. Previously published high-resolution spectroscopy of UX Ori was restricted to Hα and the region of the Na D doublet (Grinin et al. 1994).

Figures 1–4 plot the observed flux as a function of wavelength for each of the three nights (*solid lines*) overlayed on the synthetic spectrum corresponding to the UX Ori photosphere (*dashed lines*). The circumstellar component has been derived by subtracting the synthetic spectrum from the observed fluxes and is plotted as a function of velocity in the separate panels of the same figures. The synthetic spectrum has been computed using the Kurucz (1979) grid of model stellar atmospheres, together with the list of spectral lines from the database of Kupka et al. (1999). The calculations were performed using the codes SYNTHE and ROTATE by Piskunov (1992) for stars of different effective temperature and gravity. Each spectrum was convolved with different values of the projected rotation velocity $v \sin i$ until a good fit was obtained to the most stable features of the spectrum, measured over all the spectra we have acquired at NOT (a total of seven). They include the wings of the Balmer lines and several weak lines of Ti II, Fe II, and Mg I. Details of this procedure can be found in V. P. Grinin et al. (2000, in preparation). The resulting values of the stellar parameters are $T_* = 9500$ K, $\log g = 4$, and $v \sin i = 140$ km s^{-1}.

The circumstellar lines have complex profiles. Multiple absorption components are seen in all the strongest lines (such as Hα, Hβ, Hγ, Hδ, Na D, and Ca II). Emission is strong only in the Hα line; most of the other lines have inverse P Cygni profiles with very weak emission (see, for example, the lines of Na D, Ca II IR, and Hβ) or are seen

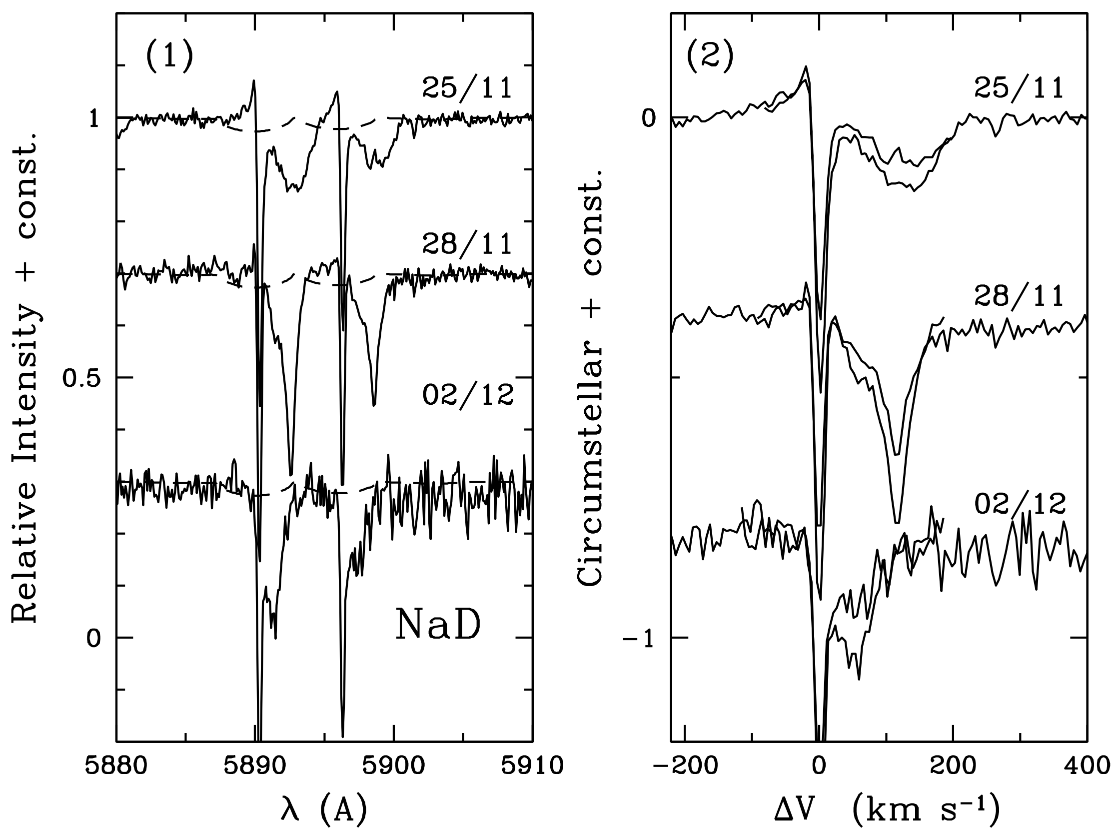

FIG. 2.—Same as Fig. 1 for the Na D doublet lines. Panel 2 shows the two components folded and plotted versus the velocity shift.

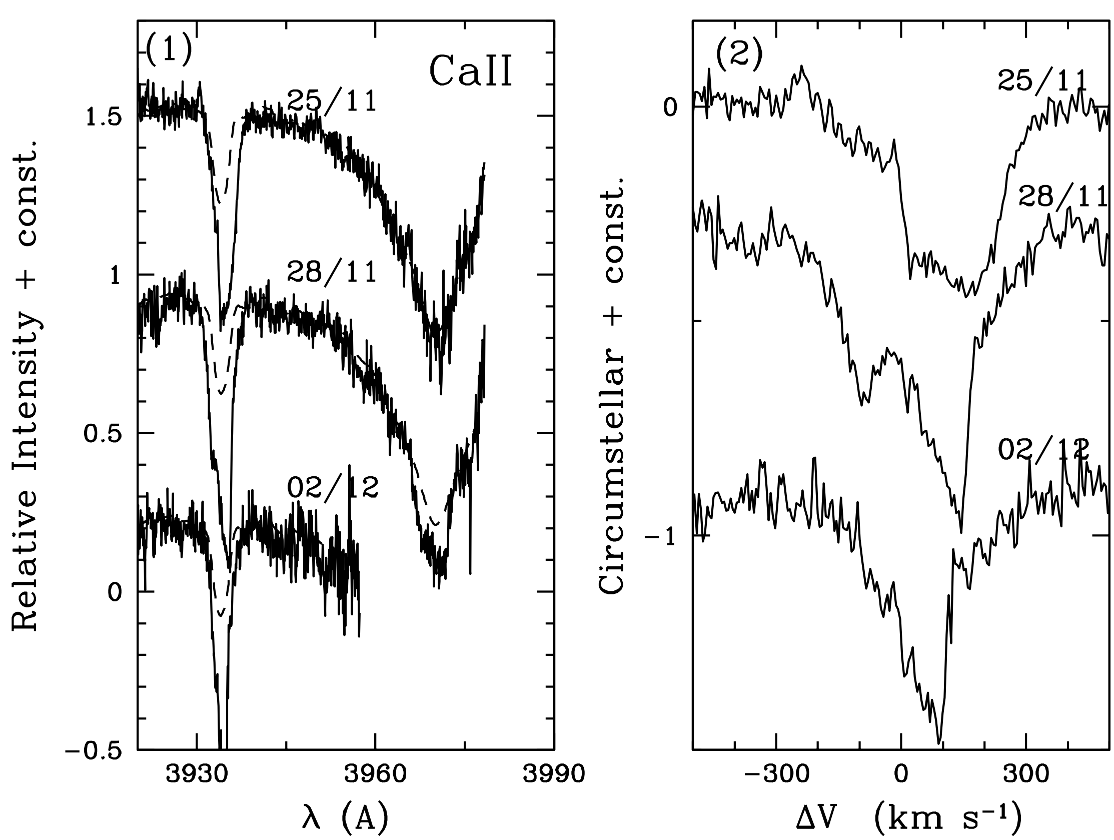

FIG. 3.—Same as Fig. 1 for the H and K component of Ca II. Panel (2) shows the velocity profile of the circumstellar component of the H line only.

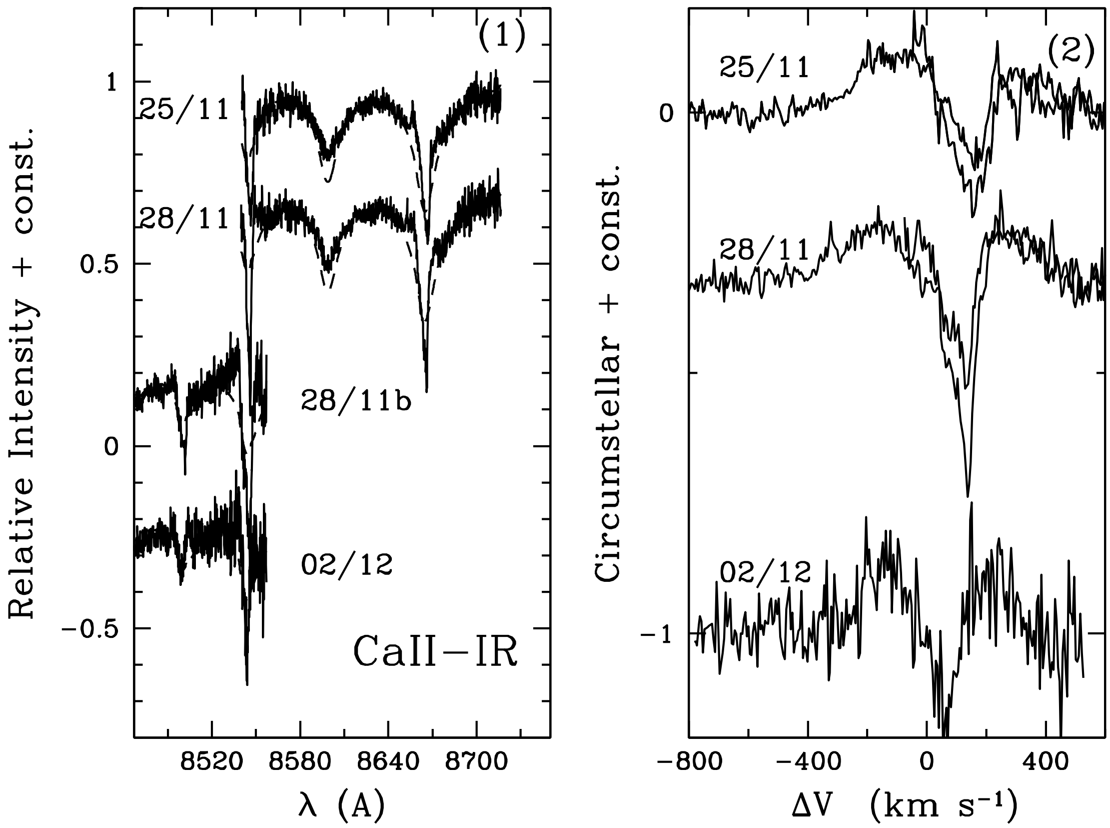

FIG. 4.—Same as Fig. 1 for the Ca IR triplet. Panel 1 shows two different spectra for November 28, obtained with different grating positions. The second one was also used on December 2 and includes the component at 8498 Å. Panel 2 shows the profiles (after subtraction of the photospheric component) of the two components at 8542 and 8662 Å for November 25 and 28, and of the 8542 Å one for December 2. This last spectrum has lower quality than the others. However, it is easy to see that it is possible to measure the redshift and the depth of this component on this night also. The absorption line seen at 8600 Å is Paschen 14.

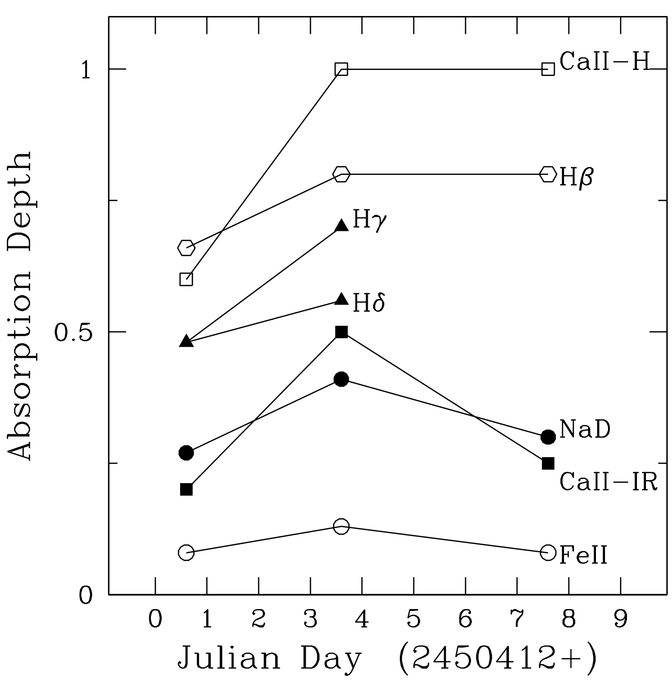

FIG. 5.—Depth of the redshifted absorption components as a function of the time of the observations. The depth has been computed with respect to the photospheric spectrum. We do not compute it for Hα, where there is strong circumstellar emission. Fe II refers to the λ5316.5 line, which has the strongest circumstellar absorption among Fe lines.

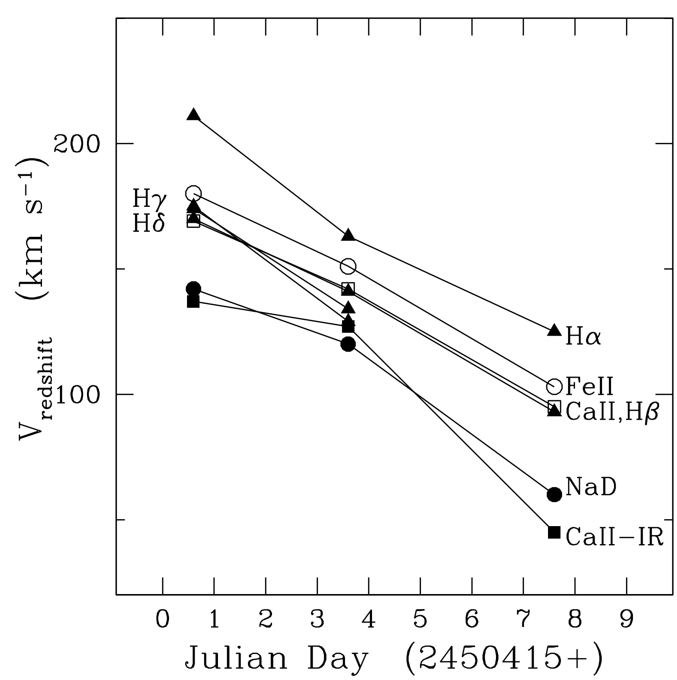

FIG. 6.—Velocity of the peak of the redshifted components as a function of the time of the observations.

only in absorption. Here we are interested in the accretion episode that is clearly seen in all lines, as described in the legends to the figures. Its properties are summarized in Figures 5 and 6. The depth of the circumstellar absorption component is defined as $1 - F_{obs}/F_{syn}$, where F_{obs} is the observed flux and F_{syn} is the photospheric flux at the peak wavelength. With this definition, a depth of ~ 1 means that the circumstellar line is saturated.

The redshifted absorbing gas does not have a very large optical depth in any of the lines, with the only exception being the Ca II H and K lines from November 28. In particular, the Na D lines are not saturated, as shown by the ratio of ~ 2 between the two components of the doublet, as is expected in the optically thin case (see Fig. 2). In this event, the stellar radiation is absorbed by a rather thin layer of gas, which very likely covers most of the stellar surface. In other words, we are not detecting an "occultation" event, where the different depth of the absorption components can be interpreted in terms of different covering factors for the various chemical species (Grady et al. 2000). Note, however, that previous observations (Grinin et al. 1994) have occasionally shown Na D redshifted absorption lines with a ratio close to unity.

Figure 6 shows the redshift of the absorption peak as a function of time. Weak absorption is seen at a redshift of about 100–200 km s^{-1} already on November 25; on November 28 the absorption components are much deeper. On December 2 they are again weaker and are systematically shifted toward a lower velocity (by about 50 km s^{-1}).

3. NON-LTE MODELS

The similarity of the velocity behavior of the absorption components that are seen in the hydrogen and Ca lines, in the Na D doublet, and in the Fe II line suggests that the features we observe, at least on each individual night, have a common origin. We have tried to estimate the chemical composition of this infalling gas in the following way. We consider a homogeneous and isothermal cloud of gas of fixed chemical composition that lies between the star and the observer and compute the optical depth in the lines of interest, varying the gas density n and temperature T. A given chemical composition is acceptable if there is a range of values of n and T that reproduce simultaneously the observed values of τ of all the lines. We select for our analysis three weak lines, namely Hγ, the Na D $3S$–$3P_{3/2}$ line, and the λ8542 component of the Ca II IR triplet. For these relatively weak lines, we can assume that the observed optical depth is roughly equal to the depth of the line, as defined in Figure 5. We will require for all of them that $\tau_{obs} \sim 0.2$–0.6, as was roughly observed on November 28. In general, all the models predict that $\tau(\mathrm{H}\alpha) \gg \tau(\mathrm{H}\gamma)$ and $\tau(\mathrm{Ca\,II\ H\ and\ K}) \gg \tau(\mathrm{Ca\,II\ IR})$, so any model that satisfies the requirements for the three weak lines will also automatically reproduce the much deeper absorption observed in the lower Balmer lines and in the Ca II H and K lines.

We make use of the code CLOUDY (Ferland 1996) to compute the non-LTE gas ionization and excitation of all the elements except sodium, for which we use a special, more accurate code developed by Natta & Giovanardi (1990). For each line of interest, we compute the expected optical depth, varying the density and the temperature of the cloud. The cloud is at distance of $D = 10R_*$ from the star, which has an effective temperature of $T_* = 9500$ K and a luminosity of $L_* = 55L_\odot$ (V. P. Grinin et al. 2000, in preparation). At $D = 10R_*$ the infall velocity is about 150 km s^{-1}, similar to the observed values. There are two additional parameters that need to be specified, namely the thickness of the cloud l and its internal velocity field Δv. A number of considerations (see Sorelli et al. 1996) suggest that the absorbing cloud must have a length of the order of R_*. As for the velocity field, we assume a velocity dispersion of ~ 50 km s^{-1}, based on the observed width of the absorption components. If $l \sim 1$–$10R_*$, the line optical depth is roughly proportional to l and inversely proportional to Δv. We consider densities in the range 10^8–10^{12} cm^{-3}, as derived by Sorelli et al. (1996) in their analysis of the Na D lines in the UXORs. Note that the high values of n are typical of gas at the base of a stellar wind ($n \sim 10^{11}\dot{M}_8$ cm^{-3}, where $\dot{M}_8$ is the mass loss rate in units of 10^{-8} $M_\odot$ yr^{-1}) or in accreting gas columns (Hartmann et al. 1994)

The results are shown in Figures 7 and 8, which plot the computed values of the optical depth of the three lines as a function of the gas temperature T for two different chemical compositions. In Figure 7 the gas has a solar chemical composition (metallicity index $m = 1$); in Figure 8 the gas is highly hydrogen depleted. More specifically, all the abundances (of a number relative to H) of elements heavier than He are multiplied by a factor of $m = 500$. This is similar to the composition of Halley's comet (dust and ice; Jessberger & Kissel 1991) and representative of comets in general (see Krishna Swamy 1997).

If we compare the results of the model calculations to the observed depth of the absorption components, we find that the three lines we have considered can be accounted for by gas with a solar chemical composition at $T \sim 6000$–7000 K. This gas will also have large optical depth ($\tau \gg 1$) in the lower Balmer lines and in the resonant Ca II lines, as observed. A large range of gas densities are compatible with

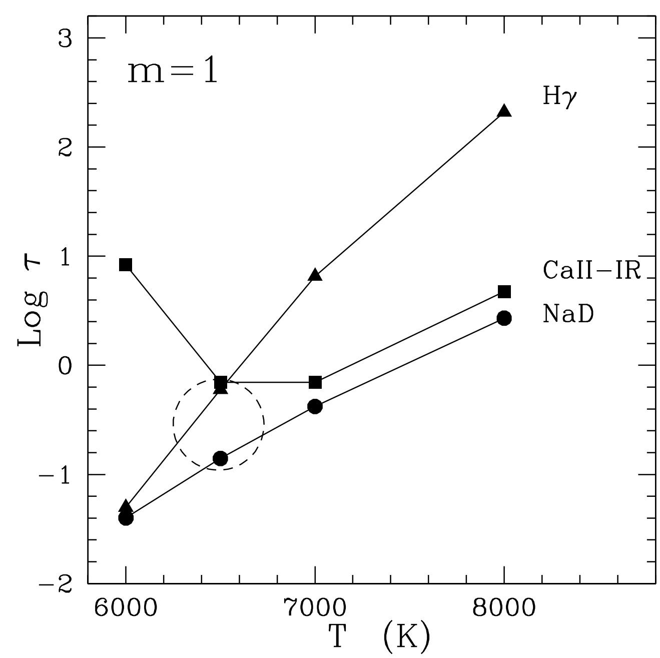

FIG. 7.—Model-predicted optical depth of selected lines for gas of solar chemical composition. The optical depth is shown as a function of the gas temperature. The lines are Hγ (*triangles*), Na D $3S$–$3P_{3/2}$ (*circles*), and the λ8542 component of the Ca II IR triplet (*squares*). The calculations are for a slab of gas of density $n_H = 10^{11}$ cm^{-3}, having a length $l = 3$ R_*. The dashed circle shows the region where the models approximately reproduce the observations.

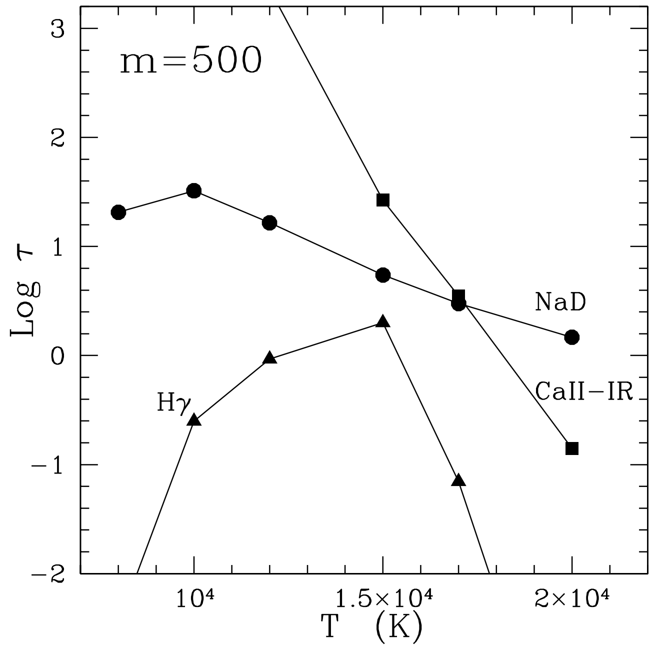

FIG. 8.—Same as Fig. 7 for gas of approximately cometary chemical composition (m = 500). The hydrogen density is $n_{\rm H} = 10^{10}$ cm^{-3} and l = 3 R_*.

the observations, given that the other parameters, such as l or Δv, are only poorly constrained. On the contrary, there is no possible solution if the gas is highly hydrogen depleted. In this case, the optical depth of the hydrogen lines is strongly reduced with respect to the metal ones, and any gas slab with τ(Hγ) $\sim$ 0.5 has at the same time an extremely large optical depth in the Na D and Ca II-IR lines. Moderate hydrogen depletion (e.g., $m \sim 10$) is consistent with the observations if the gas temperature is of order 9000 K (see Fig. 9).

The conclusion that large hydrogen depletion is inconsistent with the observations holds over a large range of gas

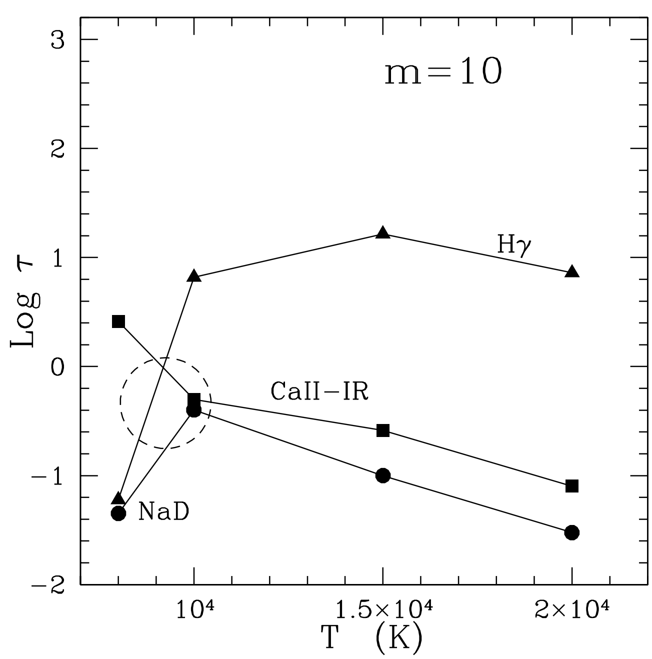

FIG. 9.—Same as Fig. 7 for moderately metal-rich gas (m = 10). The hydrogen density is $n_H = 10^{11}$ cm^{-3} and l = 3 R$_*$.

densities ($\sim 10^8$–10^{12} cm^{-3}). It is unlikely that a temperature and/or density gradient could reconcile the observations and the model predictions, since any layer of absorbing gas with nonnegligible τ(Hγ) will always produce too much absorption in the metal lines.

4. DISCUSSION AND CONCLUSIONS

The observations and analysis described in the previous sections do not support the idea that the infalling gas detected in the UX Ori spectrum on the nights of 1996 November and December is produced by the evaporation of a solid body similar in composition to the solar system comets. In estimating the chemical composition of the evaporated gas, we have made the assumption that both ices and grains are vaporized at the same time as the comet reaches the close vicinity of the star. This is probably justified, since at distances $\lesssim 10 R_*$ the dust temperature is higher than 2000 K. In fact, a significant fraction of ice may have already been lost by the comet, and the hydrogen depletion (with respect to refractory materials) may be even larger. Unfortunately, there is no information on the ratio of hydrogen-to-heavy metals in Sun-grazing comets in the immediate vicinity of the Sun that we could use to confirm (or invalidate) our assumption. While the hydrogen observed in comets is well accounted for by dissociation of molecular species such as OH and H_2O (Combi & Feldman 1998; Raymond et al. 1998), the origin and relative abundance of heavy metals such as Na is less clear (Combi, Di Santi, & Fink 1997). We hope that the recent observations of many star-grazing comets made by the *Solar and Heliospheric Observatory* will clarify this point in the future.

The lack of evidence for heavily metal-rich infalling gas is probably common to most of the UXORs. A test for this is whether infalling gas is seen not only in metal lines but also in the higher Balmer lines, such as Hγ and Hδ. Detection of Hα redshifted absorption does not discriminate between different models, given the very large optical depth of this line. Claims of cometary abundances in the infalling gas should be based on the presence of redshifted absorption in the metal lines and the simultaneous *absence* of absorption in the high Balmer lines. Note that in β Pic there is no evidence of circumstellar hydrogen absorption or emission at all (Lagrange, Backman, & Artymowicz 2000).

The possibility that the infalling gas in UX Ori is disk material driven onto the star, in analogous fashion to the magnetospheric accretion models proposed for T Tauri stars, needs to be confirmed by the comparison of the observations with specific model predictions. Sorelli et al. (1996) found, using very simplified models, that the Na D absorption in UXORs is consistent with accretion rate $\dot{M}_{\rm acc} \sim 10^{-7}\ M_\odot\ {\rm yr}^{-1}$. The corresponding accretion luminosity ($\sim 2\ L_\odot$) is only a few percent of the stellar luminosity. Of the usual accretion indicators, we can note that the UXORs have a strong infrared excess, while not all of them show forbidden lines, expected to form in a wind with a mass-loss rate of $\dot{M}_w \sim 0.1 \dot{M}_{\rm acc}$. In particular, UX Ori has no detected [O I] 6300 Å emission (equivalength width $\lesssim$0.04 Å; Böhm & Catala 1994). This is puzzling, also because blueshifted absorption, indicative of mass loss, is seen at times in UX Ori in the blue wing of Hα (see Fig. 1). We have examined the existing estimates of $\dot{M}_w$ for Herbig Ae/Be stars and found no correlation with the [O I] 6300 Å equivalent width (Corcoran & Ray 1997; Böhm & Catala 1995). Stars with the lowest measured [O I]

6300 Å equivalent width (of order 0.1 Å) have $\dot{M}_w$ varying in the interval $\sim 10^{-8}$ to $\gtrsim 10^{-5}$ $M_\odot$ yr^{-1}. Clearly, the problem of magnetospheric accretion in Herbig Ae/Be stars (and therefore in the UXORs) deserves further examination, and models more complex than those developed so far for T Tauri stars, which include the effects of the hotter stellar radiation field and higher stellar rotation, are needed (see also Kozlova, Grinin, & Rostopchina 2000).

An important point in assessing the different models is their capability to account for the dynamics of the infalling gas. To this purpose, it is of great importance to obtain denser time sequences than those described here in order to ascertain that one is observing the time evolution of a single clump of gas rather than a set of unrelated episodes. If the accretion event we have discussed is indeed a single "event," then we find that the gas seems to decelerate with time (see Fig. 6). This behavior is not unique, as seen, for example, in BF Ori where denser time sequences of high-resolution spectra were obtained by de Winter et al. (1999). Decelerating infall is occasionally seen also in β Pic (Petterson & Tobin 1999); models of comet evaporation by Beust et al. (1998) predict a pattern of acceleration in the infalling gas. However, "accelerating" infalling events are also observed at times in UXORs (see, for example, Kozlova et al. 2000 and V. P. Grinin et al. 2000, in preparation), and we do not have enough information at the moment to estimate if deceleration of the infalling gas is typical of UXORs or sporadic, while in most cases the accreting gas accelerates with time. Let us note, however, to avoid possible confusion, that our estimate of the chemical composition of the infalling gas does not depend on any assumption of its dynamical evolution over the eight night interval, since it is based on the November 28 spectrum only. In fact, the other two spectra just confirm our results. In summary, the results discussed in this paper do not support the case of solid body evaporation as the source of infalling gas in UXORs.

We thank G. P. Tozzi, M. Mumma, and P. Feldman for discussions on cometary chemical composition and O. Kozlova for the calculation of the UX Ori synthetic spectrum. This work was partly supported by ASI grant ARS-98-116 to the Osservatorio di Arcetri. V. P. G. was supported in part by RFFI grant 99-02-18520.

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