Astron. Astrophys. 363, 984–990 (2000)

ASTRONOMY AND ASTROPHYSICS

Occultation of young stellar objects by circumstellar disks

I. Theoretical expectations and preliminary comparison with observations

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Received 3 May 2000 / Accepted 7 September 2000

Abstract. The hypothesis that partial occultation of young stars by their circumstellar disks is responsible for UX Ori and T Tauri Type III photometric variability is quantitatively studied. We construct accretion disk models in which reprocessing of stellar and accretion luminosity leads to flaring of the disk (assumed to be in vertical hydrostatic equilibrium), and compute the probability to observe the star through the disk atmosphere. The mass accretion rate is found to primarily determine the range of view angles over which the star is fully or partially obscured by the disk. For average disk/star parameters relevant to active T Tauri stars, the probability of observing occultation events is $\sim$0.15, while it is typically 0.2 for parameters relevant to UX Ori. A preliminary analysis of available photometric data confirms these estimates and allows us to uncover in some stars cyclic variability on a time-scale of weeks to years that may tentatively be attributed to disk inhomogeneities or warps. These results suggest that direct observational study of the disk structure may be possible for a sizable fraction of young stellar objects.

Key words: accretion, accretion disks – stars: formation – stars: pre-main sequence – stars: variables: general

1. Introduction

The photometric variability of optically visible young stellar objects (YSOs) is well documented. Solar-type YSOs (T Tauri stars [1]) display light variations of up to a few magnitudes on many time-scales at all wavelengths (cf. Ménard & Bertout 1999). FU Orionis outbursts represent the most extreme case of variability in these objects. The more massive Herbig Ae/Be stars (HAEBESs) are comparatively less active but may display long-term cyclic variations with time-scales of years to decades (cf. Herbst & Schevchenko 1999). Physical causes of this intense activity have been investigated in the last two decades, leading to convincing identification of two main physical processes at work in these objects: magnetic activity and accretion power. A third cause of variability is suspected to be variable extinction caused by occultation of the stellar surface by circumstellar matter. The current state of understanding of these three physical processes is aptly summarized by Herbst et al. (1994), who define three types of photometric variability.

Type I: Rotational modulation caused by cold magnetic spots. These periodic variations are seen in all young solar-type stars, but are most easily detectable in WTTSs, because it is what causes the dominant mid-term variability in these stars. V410 Tau is the prototype star for this type of variability. The spots are often located at high-latitude in WTTSs, cover up to 40% of the projected surface, and are typically 1000K cooler than the remaining photosphere. In WTTSs, a single source of variability (the rotation of stars with cool spots) is sufficient to account for V, R, and I data. In U and sometimes B, short-term magnetic flaring is observed especially when the stars are faint (similar to what is observed in dMe flare stars). The maximum amplitude that can be attributed to cold magnetic spots is about 0.8 mag in V and 0.5 mag in I.

Types II and IIp: Variability caused by cold and hot spots. Type II variations are either irregular or periodic, in which case they are called Type IIp. Both kinds of Type II variations, which occur only on CTTSs, can be understood in terms of a changing mix of cool and hot spots on their surfaces. The localized hot zones on the stellar surface are attributed to accretion onto the star of circumstellar disk matter and may produce in part the spectroscopic veiling characteristic of the CTTS class. They are shorter-lived than the cold magnetic spots and can produce much larger amplitude variations of several magnitudes, particularly in the B and U filters, because temperatures of typically $7{\cdot}10^3$–10^4K are reached in the accretion zone. The geometry and distribution of accretion regions on the stellar surface remain unclear. Simple spot models indicate that the stellar fraction covered by hot spots is small, typically $\lesssim$1%.

Type III: Variable obscuration by circumstellar dust? This is the least understood variability type. While it occurs in some T Tauri stars with early K spectral types, such as RY Tau and RY Lupi, it is mainly observed in HAEBESs, in which case it is called UX Ori type variability after the best observed star displaying this sort of activity. It is characterized by large amplitude light variations in stars with no evident veiling or effective temperature variations. Type III variables appear to fluctuate

[1] There are two flavors of T Tauri stars: classical T Tauri stars (CTTSs) display conspicuous evidence for circumstellar accretion disks and weak-emission line T Tauri stars (WTTSs) lack evidence for disks but are magnetically active. A thorough discussion of both types is provided, e.g., by Bertout 1989.

around their high luminosity state most of the time while sometimes fading suddenly by several magnitudes before recovering their previous luminosity on a time-scale of days, and the fading episodes are suspected to be cyclic (Grinin et al. 1998; Rostopchina et al. 1999). The fact that the degree of linear polarization increases as the star becomes faint is a major argument supporting the idea that variable obscuration is responsible for the star's fading. The pros and cons of the different models proposed to explain this variability are discussed in some detail by Herbst et al. (1994).

Contrary to an earlier belief, it has recently become apparent that Type III variability might also be present in some CTTSs with late spectral-type, most notably AA Tau (Bouvier et al. 1999) and possibly UY Aur (Ménard & Bastien 1987), both of K7 spectral type. Chelli et al (1999) discuss possible evidence for occultation in the M star DF Tau, usually known for its Type II light variations. Interestingly, T Tau itself displays all three types of variability, and thus appears to be a true photometric prototype of the class. All this suggests that Type III variability might be present in the entire YSO mass spectrum, from low-mass objects such as AA Tau to the most massive HAEBESs, although its occurrence seems more likely in bright members of the Orion population. Herbst & Schevchenko (1999) were first to note the difficulty to extend the occultation model to the entire class of HAEBESs if disk material is the source of occultation, as it requires viewing the star at a grazing angle through the outer parts of its circumstellar disk, an apparently rare occurrence. To alleviate this difficulty while retaining the fruitful hypothesis that disks surround CTTSs and HAEBESs, they suggested that accretion is ultimately driving UX Ori variability.

This paper presents first results of an effort to assess the occultation model's merits for explaining Type III and UX Ori variability. Sect. 2 briefly describes the disk model used to study the frequency of full or partial occultation occurrences (for various combinations of star and disk properties), and presents probabilities of observing disks both edge-on and through their atmospheric layers. The basic assumption made throughout this work is that a star seen through its circumstellar disk atmosphere is expected to display variable occultation by disk material because the disk is likely to be inhomogeneous and possibly non-planar, as discussed in Sect. 3. Because of disk flaring induced by reprocessing of stellar and accretion radiation, the probability of actually viewing a young star through its circumstellar disk is surprisingly high. Sect. 3 gives a preliminary discussion of available observational evidence in the light of this finding. A full study of the extensive database of YSO photometric observations compiled by W. Herbst, which provides useful clues of the nature of mid-term variability (from a few days to a few years) in a sample of well-studied YSOs, will be discussed in a forthcoming paper.

2. The probability of observing YSO occultation

2.1. Disk model

The basic accretion disk model used in this investigation was described and used extensively earlier (e.g., Bertout et al. 1988; Basri & Bertout 1989). The main modification introduced for the present study concerns the disk's vertical structure. Local hydrostatic equilibrium is assumed at each disk radius, and reprocessing of stellar and accretion radiation is taken into account when computing the local disk temperature and the disk "flaring". Instead of calculating the disk vertical structure in full detail (e.g., Bell et al. 1997) we follow here the more tractable approach advocated by Hartmann & Kenyon (1987) and recently by Chiang & Goldreich (1997) (hereafter CG97); that is, we assume that the disk is isothermal at each radius, with the disk temperature T_D resulting from balancing the locally dissipated and emitted energy fluxes. While this is a good approximation for optically thin and passive disks, it can be questioned for the optically thick disks envisioned here, since the disk equatorial temperature T_c is expected to be given in the grey approximation by

$$T_c^4 \sim \frac{3}{8}\tau T_V^4 + T_A^4 \tag{1}$$

where τ is the frequency-integrated optical depth, σT_V^4 the energy flux due to accretion and σT_A^4 the flux of reprocessed radiation (Malbet & Bertout 1992; Dubus et al. 1999). However, one finds that departures from isothermality are much more important in the inner disk, where most of the accretion energy is deposited, than in the outer parts of the disk. Since we are primarily interested here in the disk flaring produced at a large distance from the star, the assumption of isothermality thus does not appear critical. We nevertheless monitored the ratio of height scales given by T_D and T_c throughout the computation as a check on this hypothesis' consistency.

The treatment of flaring basically follows CG97, but with two differences. First, the computation of the angle of incident stellar light on the disk allows for the fact that physical quantities describing an accretion disk vary as a function of radius[2]. Second, we explicitly take into account the effect of accretion luminosity on the flaring, assuming that half of the accretion luminosity is radiated away in an optically thick, axially symmetric fraction f of the stellar surface (here 1%). The 'equivalent effective temperature' T_e which replaces the stellar effective temperature T_{eff} in the expression giving the flaring angle is then

$$T_e = T_{eff}\left[1 + f\ \left(\frac{T_{acc}^4}{T_{eff}^4} - 1\right)\right]^{1/4} \tag{2}$$

where $T_{acc}^4 = GM_*\dot{M}\ /\ 8\pi\sigma R_*^3 f$, and M_* and R_* are the stellar mass and radius, respectively.

The vertical frequency-integrated optical depth[3] τ_x at height x is given by

$$\tau_x = \frac{\Sigma\kappa}{2}\left[1 - \mathrm{erf}\,(x)\right] \tag{3}$$

where Σ is the disk surface density, κ is the Rosseland opacity and x is the height in units of $h\sqrt{2}$, h being the local scale

[2] CG97 consider constant density disks.
[3] measured from the disk surface inwards.

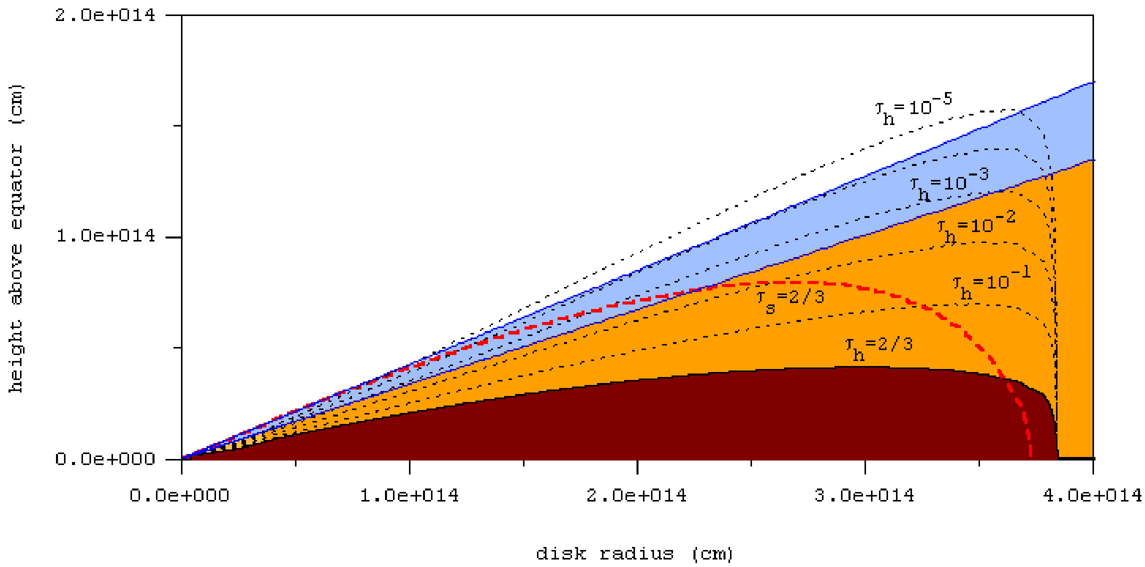

Fig. 1. CTTS disk profile. The dark-shaded (dark red) area shows the vertical disk photosphere ($\tau_h = 2/3$) while the thin dotted lines show contours of equal vertical optical depth τ_h with values ranging from 10^{-1} down to 10^{-5}. The medium-shaded (yellow) area indicated the range of view angles over which the central star is totally obscured by the disk. The light-shaded (light blue) area indicates the range of view angles where partial occultation of the star can be expected. The thick dotted (red) line, corresponding to $\tau_s = 2/3$, shows how deep into the disk an outside observer sees at each view angle s.

height. This expression is used to find the photospheric height $H = h\,(\tau_h = 2/3)$ which enters the equation giving the angle of incident stellar radiation (Eq. (5) in CG97). In writing Eq. (3), we assumed that κ is a function of temperature only, which is true as long as dust dominates the opacity, i.e., for $T \lesssim 1500$K. The temperature, opacity, mean molecular weight, and angle of incident stellar radiation are found iteratively, using a Newton-Raphson scheme. In the horizontal plane, the disk is assumed to extend up to the radius where the temperature goes down to 10K. Fig. 1 shows the resulting disk profile for a mass accretion rate of $3\ 10^{-8}\mathrm{M}_\odot \mathrm{yr}^{-1}$ (valid for a typical CTTS) and for a viscosity parameter $\alpha = 10^{-2}$. This value of α is currently favored in theoretical work on accretion disk MHD turbulence (cf. Balbus & Hawley 1998). Stellar parameters entering the computation represent a typical CTTS: $M_* = 0.5\ \mathrm{M}_\odot, R_* = 2.5\ \mathrm{R}_\odot$, and K7 spectral type. The dark area shows the optically thick disk (in the *vertical* direction) while the thin dotted lines delineate levels of constant vertical optical depths in the disk atmosphere, corresponding to $\tau_h = 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}$, and 10^{-5}.

Once the disk structure is computed, we set up a grid of sight lines and compute the total optical depth through the disk τ_t as a function of view angle s. It is then straightforward to estimate the probability

$$p_{\mathrm{thick}} = \int_{i_{\mathrm{thick}}}^{\pi/2} \sin i'\,\mathrm{d}i' \qquad (4)$$

to observe the central star through the optically thick disk, in which case the YSO will be completely obscured, and the probability

$$p_{\mathrm{thin}} = \int_{i_{\mathrm{thin}}}^{i_{\mathrm{thick}}} \sin i'\,\mathrm{d}i' \qquad (5)$$

to observe the central star through the disk outer layers.

In these definitions, i_{thick} and i_{thin} are respectively the minimum view angle at which the disk is still optically thick and the maximum view angle for seeing the star free from disk obscuration (see Fig. 1). If the disk atmosphere is inhomogeneous, a likely possibility, we then expect variable occultation of the star by disk matter when the system is viewed between i_{thin} and i_{thick}. The recurrence time-scale of occultations will depend on both the size of obscuring clumps and their location in the disk.

For the sake of illustration, we define p_{thin} somewhat arbitrarily by the range of view angles over which the disk has frequency-integrated optical depths τ_t ranging from 0.1 to 10 (light-shaded area in Fig. 1). We should mention here that the exact values of the integration limits are not critical in Eqs. (4) and (5) above for p_{thick} and p_{thin}. For the example shown in Fig. 1, the view angle for $\tau_t = 10$ is $\sim 72°$ while it is $\sim 70°$ for $\tau_t = 3$, and the difference in p_{thin} for these two values of the integration limit is only 0.03. Similarly, p_{thin} would be larger by 0.05 if the lower limit of integration were 0.01 instead of 0.1.

Note that p_{thin} could be determined empirically from the observed number of stars displaying occultations in a statistically significant sample of young stars.

2.2. Results

Fig. 2 displays three different observation probabilities as a function of mass accretion rate for the stellar parameters given above. They are p_{thick}, which represents the fraction of CTTSs that are missed in optical surveys since they are extincted by more than ~ 10 magnitudes, $p_{\mathrm{occ}} = p_{\mathrm{thin}}/(1 - p_{\mathrm{thick}})$ which is the probability of observing occultation events with the assumptions discussed above, and $p_{\mathrm{total}} = p_{\mathrm{thin}} + p_{\mathrm{thick}}$, the probabil-

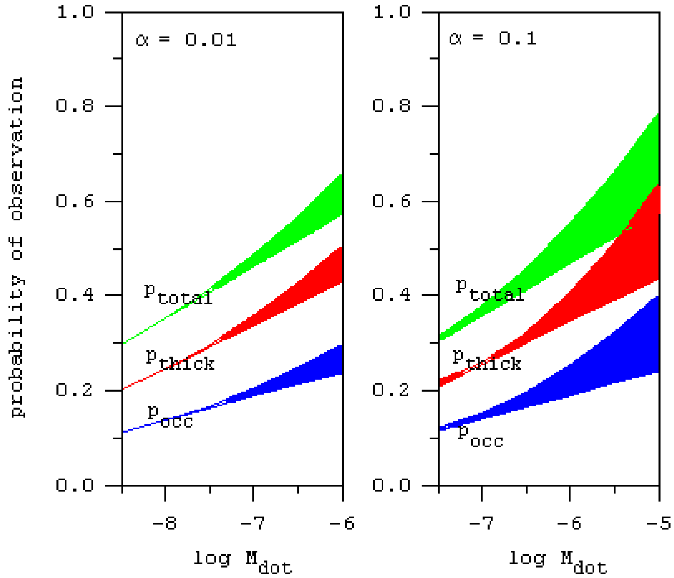

Fig. 2. Probabilities $p_{\rm occ}, p_{\rm thick}$, and $p_{\rm total}$ as a function of mass accretion rate for computation parameters appropriate for a typical CTTS, shown for two values of α. The shaded (colored) areas indicate the range of probabilities obtained when reprocessing only the stellar luminosity (lower values) and when both the stellar and the accretion luminosities are taken into account in the flaring computation (upper values).

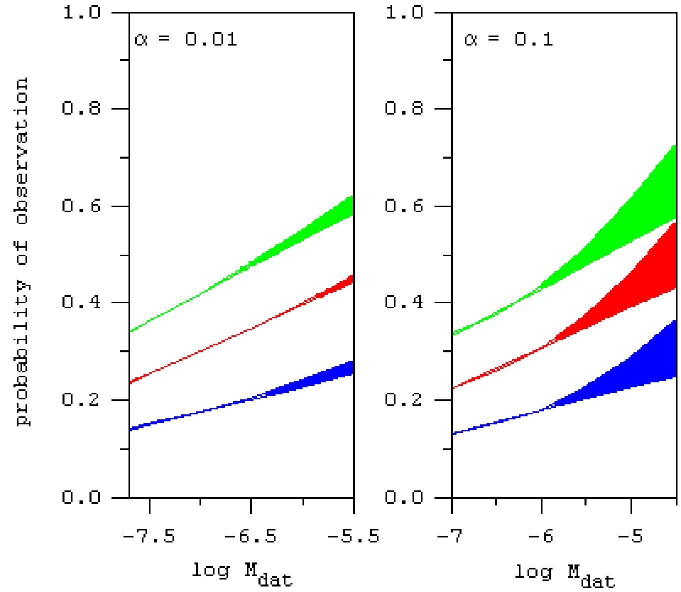

Fig. 3. Same as Fig. 2, but for computation parameters appropriate for UX Ori.

ity to view a disk either edge-on or through its atmosphere. In order to bracket the plausible range of observation probabilities, we consider two cases: (a) reprocessing due to stellar luminosity only, and (b) reprocessing due to both stellar and accretion luminosity, in the approximation explained above. These two values bracket the plausible range of probabilities, shown as shaded (colored) areas in Fig. 2. We consider two values of the (uncertain) viscosity parameter α, which controls the disk density. The left panel of 2 is for $\alpha = 0.01$, while the right papel is for $\alpha = 0.1$. Typical values of $p_{\rm occ}$ and $p_{\rm total}$ are 0.1-0.15 and 0.3-0.35 for moderately active CTTSs with $\dot{M} \sim 10^{-8}$M$_\odot$/yr and $\alpha = 0.01$, while the fraction of (optically) unseen stars is $\sim 25\%$. At these accretion rates, the accretion luminosity is smaller than the stellar luminosity and does not play an important role in the disk flaring properties. At the highest accretion rates envisioned here, the accretion luminosity is larger than the stellar luminosity and the disk mass becomes comparable to the mass of the central object.

Fig. 2 shows that all probabilities increase with the accretion rate, or more precisely with the ratio $\dot{M}/\alpha$, which determines the disk surface density. This is because the outer radius of the optically thick disk (and consequently the extent of flaring, which goes approximately as $r^{1.2}$) increases with disk surface density. Additionally, the flaring increases with increasing reprocessed accretion luminosity. When α decreases, the outer disk regions are less dense and flaring increases accordingly.

We now turn to stellar parameters representative of the UX Ori class: $M_* = 2.5$ M$_\odot$, $R_* = 3.5$ R$_\odot$, $T_{eff} = 8600$ K (Natta et al. 1999). Fig. 3 displays the results; typical values of $p_{\rm occ}$ and $p_{\rm total}$ are 0.2 and 0.45 for $\dot{M} \sim 3 \cdot 10^{-6}M_\odot$/yr and $\alpha = 0.01$, while the fraction of optically unseen stars is close to $\sim 35\%$. Note that for a given mass accretion rate, the occultation probability is somewhat lower for UX Ori than for a CTTS. This is because the gravitational pull exerted by the star on the disk is stronger (stellar radius does not increase as fast as mass), resulting in a smaller extent of the flare. In the framework of our simple model, the frequency of Type III variability is thus controlled primarily by the mass accretion rate. The different frequencies of Type III variability observed in HAEBESs and CTTSs (Herbst et al. 1994) then implies that mass accretion rates in UX Ori stars must be larger by one to two orders of magnitude than in CTTSs, in rough agreement with current estimates.

Summarizing, we find that the probability of observing occultation events in YSOs is typically 0.10-0.15 in late-type, low-mass CTTSs and 0.15-0.25 in higher mass UX Ori objects. These results suggest that direct observational study of the disk structure may be possible for a sizable fraction of YSOs and that stellar occultations by flaring circumstellar disks might be the only physical process needed to account for CTTS Type III and UX Ori variability. This last conclusion, however, needs to be confirmed by detailed studies of UX Ori objects in the light of the occultation model, as well as by statistical studies of the occultation occurrences.

3. Discussion and preliminary comparison with observations

3.1. Validity of model assumptions

The observation probabilities derived above depend on the properties of the investigated disk model. The main assumptions made in the computation are the vertical isothermality and the

Table 1. Properties of observed and model disks

Name	$R_{\rm out}^{\rm gas}$ (AU)	$R_{\rm out}^{\rm dust}$ (AU)	i	p	β	q	$\dot{M}_{acc}$ $\rm M_\odot yr^{-1}$	$p_{\rm total}$	$p_{\rm thick}$	$p_{\rm occ}$
HH 30	—	250	> 80	0.75	1.45	—	—	—	—	—
Model 1	250	250	—	1.0	1.25	~ 0.54	$7.5 \cdot 10^{-6}$	0.67	0.52	0.32
HK Tau/c	—	105	85	0.3–1.5	1.2	—	—	—	—	—
Model 2	100	100	—	1.0	1.25	~ 0.54	$1.9 \cdot 10^{-6}$	0.52	0.38	0.23

homogeneous mixing of gas and grains. As mentioned above, the assumption of isothermality in the vertical direction is incorrect in the innermost part of the disk for the highest values of the mass accretion rates envisioned here. Beyond a disk radius of a few AUs, however, heating due to dissipation of viscous energy becomes smaller than heating due to reprocessing of stellar and accretion luminosity and the vertical structure becomes isothermal in the outer disk regions where flaring is important. We therefore do not expect the isothermal hypothesis to strongly affect our results, which depend mainly on the outer disk structure. Similarly the assumption made in deriving Eq. (3) above is valid everywhere except in the innermost disk region, and is therefore uncritical here. There is some concern, however, that homogeneous mixing of gas and grains may lead to an overestimate of YSO extinction. Indeed, D'Alessio et al. (1999) find that their detailed vertical structure models assuming well-mixed gas and dust grains lead to an overestimate of extinction due to disk flaring. It is difficult to compare the simple model investigated here with the much more elaborate D'Alessio et al. (1999) model, which considers additional heating mechanisms and treats the radiative transfer in considerable detail. We note, however, that the extent of flaring we derive here is comparable or less than observed in disks imaged by HST and CFHT adaptive optics (see next section), so that the given probabilites to observe occultations are likely to be lower limits as well. Finally, we should mention that the disk colors will depend in good part on the scattering of stellar photons in the disk atmosphere, a process which is not currently included in the model but will be considered in subsequent work. Obviously, scattering should also work as to increase the probabilities of observing variability caused by non-axisymmetric disk structure in the photometric light curves.

3.2. Comparison with observed disks

The current status of YSO disk observations has recently been reviewed by Ménard & Bertout (1999). From their compilation, we reproduce in Table 1 the properties of two disks surrounding apparently single stars, HH30 and HK Tau/c, which we compare with typical properties of two models computed as described above. The three indices p, β, and q are defined by $\Sigma(r) = \Sigma_0(r/r_o)^{-p}$, $H(r) = H_0(r/r_o)^{\beta}$, and $T(r) = T_0(r/r_0)^{-q}$, while other table entries are self-explanatory. Stellar parameters are $M_* = 1$ $\rm M_\odot$, $R_* = 3.5$ $\rm R_\odot$, and K7 spectral type. The accretion disk model used here appears to approximately account for the observed p values; and the flaring resulting from vertical hydrostatic equilibrium is consistent with the value observed in HK Tau/c, although it is much lower than observed in HH30, where an additional physical mechanism must contribute to the local pressure. The probability of observing HH30 through its disk is therefore a lower limit. Index q is approximately equal to 0.54, which means that the disk IR spectrum is almost flat from 5 to 100 μm.

The probability of observing HH30 edge-on or through the disk atmosphere is ~ 0.7, a very high value indeed. It is ~ 0.5 for HK Tau/c, a difference that can be attributed to the lower mass accretion rate. The opening half-angle of the optically thick disk is $\sim 31°$ in Model 1, and $\sim 23°$ in Model 2. From the observations, we know that both disks are seen nearly edge-on, so that their central stars might well display Type III photometric variability. Note that we used a viscosity parameter $\alpha = 0.1$ in the above comparison, as smaller values would result in disk masses larger than a solar mass or so for the high accretion rates and extended disk radii envisioned here.

3.3. Disk flaring and Type III photometric variability

Whether occultation of the star by disk material will occur when the disk is seen at a grazing angle depends on the way matter is distributed within the disk, both in the equatorial plane and in the vertical direction. As discussed above, the model assumes that dust and gas are well-mixed throughout the disk, but it is likely that real disks are inhomogeneous (e.g., there are some indications for inhomogeneities in the HST HH30 images) and that some optically thick clumps will at times be located in the otherwise optically thin atmospheric layers.

While an investigation of the physical properties of clumpy disks requires numerical techniques well beyond the scope of this work, it is obvious that once a clump finds itself in the optically thin disk atmosphere, its frequency of oscillation about the disk plane in the local gravitational field $g = \Omega^2 z$ is equal to its period of revolution around the star. If one assumes that there are several such clumps at different radii in the inner disk, apparently aperiodic partial or full occultation may occur depending on both the clump size and its altitude at time of observation. Also, successive occultations will display a cyclic behavior mirroring the location of the main contributing clumps in the disk. These are very much the characteristics of UX Ori variability.

Alternatively, disk warps might easily produce partial or total periodic occultation of the central star when looking toward the disk at a grazing angle. In support of this possibility, Terquem & Papaloizou (2000) recently showed that the torque exerted on the disk by the stellar magnetic field, assumed to be an inclined dipole, leads to formation of a warp in the innermost parts of the disk that can explain the photometric observations of the CTTS AA Tau.

As a third possibility, one might also envision massive disks in which instabilities lead to the formation of fragmented spiral arms, perhaps with similar observational consequences (Pickett et al. 2000). In order to find clues allowing us to distinguish between these various possibilities for producing occultations, we will study in a forthcoming paper the mid-term variability of a reasonably large sample of YSOs.

As a first test of the ideas discussed here, we performed a preliminary study of available V photometric data for a number of YSOs, using Bill Herbst's photometric database (Herbst et al. 1994; Herbst & Schevchenko 1999) and looking for cyclic variability on time-scales of a few weeks to a few years. Because YSOs are known to display shorter-term variability, uncovering mid-term cycles is not an easy task, and we defer the full description of the time-series analysis to Paper II. Here, we merely describe preliminary results based on a careful, CLEANed periodogram analysis (Roberts et al. 1987) of the V data corroborated by an extensive search of preferred cycles using both χ^2 minimization techniques and robust wave variogram analysis (Eyer & Genton 1999).

We find that cyclic photometric variability occurs in a small but sizable fraction of young stars. Out of 36 (20) investigated CTTSs (HAEBESs), we find 6 (4) stars displaying cyclic V variations that deserve further study. This is apparently in rough agreement with the observation probabilities given above but there are severe biases in the data which need to be investigated further before a definite conclusion is drawn. Also, a more detailed study of photometric colors is needed to confirm that all suspected cyclic variations can be explained by occultations of stellar radiation by circumstellar matter.

Three examples of cyclic occultations are shown in Fig. 4, which displays the phase-folded V data for the K7 CTTS AA Tau (top panel), the HAEBES UX Ori (central panel), and the G2 CTTS SU Aur (bottom panel). The cycle length for AA Tau over the 11 years observation time span is 8.19d, in good agreement with the value found by Bouvier et al. (1999). Note that the irregular luminosity drops, which are resolved in the Bouvier et al. (1999) data, are unresolved in the present observations, and introduce much scatter in the light-curve. This is because these short time-scale occultation events, which are more likely to occur when the star is faint, are not regularly distributed in the phase diagram. Thus, the picture which emerges from the phase-folded data is a low-amplitude sine-like light variation between V=12.5 and 13.3 mag, with individual short-term occulting events superimposed. As mentioned above, a disk warp induced by the inclined stellar magnetic field accounts successfully for the observations (Terquem & Papaloizou 2000).

The preferred cycle for UX Ori has period 319.1d. Here, the data span 16 years and the light-curve resembles that of AA Tau but the deep minimum appears better defined in phase, suggesting a larger projected size of the occulting screen, located at $\sim$ 0.8AU from the star. The amplitude of the cyclic variability

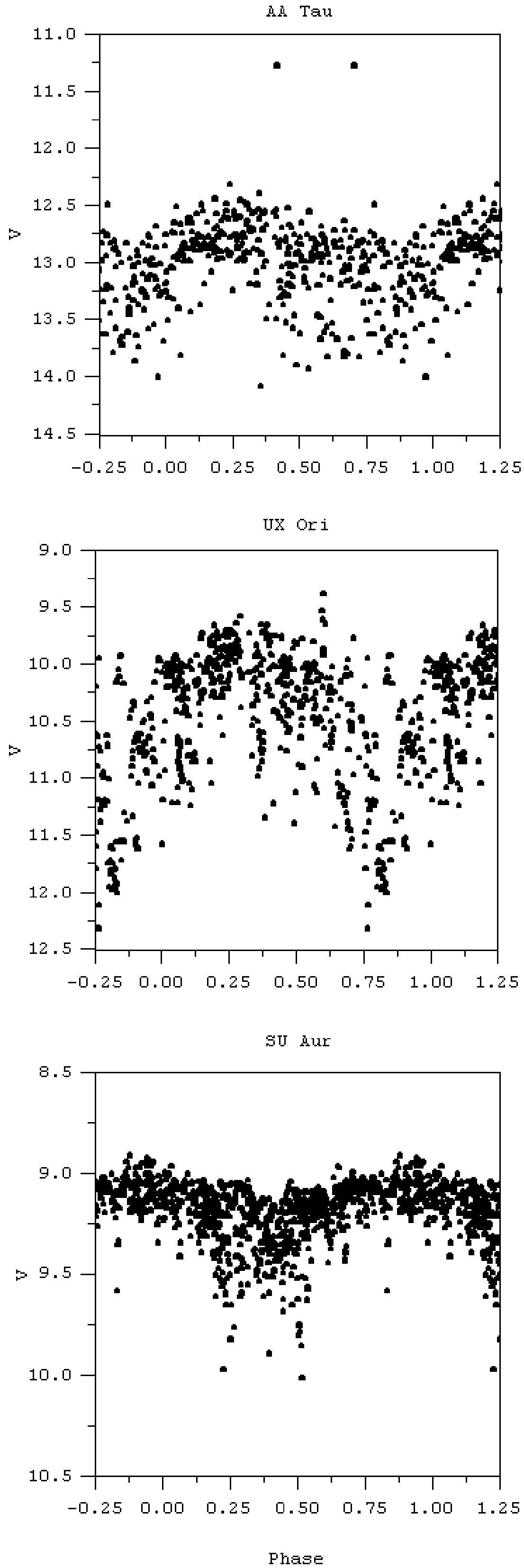

Fig. 4. Phase-folded V lightcurves for three Type III YSOs. Top Panel: AA Tau data folded with period 8.19d. Central Panel: UX Ori data folded with period 319.1d. Bottom Panel: SU Aur data folded with period 443.5d.

reaches 2 mag in V, compared to about 1 mag in AA Tau and SU Aur. The nature of the UX Ori occulting screen, which apparently is present on the sight line during about 40% of the phase, is quite puzzling.

Finally SU Aur displays a cycle length of 443.5d on V data spanning 16 years. The very low scatter of the sine-like low-amplitude light variation is truly remarkable (there are 1088 data points in this figure). The matter responsible for occultation is located at ~ 1.1 AU from the star. Besides the sharp drops in the light curve, which are characteristic of individual occultation events, there is again a low amplitude sine-like variability with the same period, and the sharp drops occur most often when the star is fainter, i.e., when the obscuring "wall" is highest on the observer's horizon. This is reminiscent of what one would expect from occultation by a disk warp (cf. AA Tau), with the sharp drops due to clumpy material located in the disk atmosphere flying across the stellar disk. The physical conditions needed to form and maintain a warp at 1AU are unclear at present, although a low-mass companion orbiting the primary star in a trajectory non-coplanar with the disk might be able to produce warps at such distances from the central star (C. Terquem, private communication).

As a conclusion, we can emphasize the following predictions of the model investigated here, which can all be tested by statistical analysis of YSO properties and detailed models of UX Ori-type objects.

– Direct observation of the circumstellar disk structure using photometric and spectroscopic techniques appears possible for 1/10th to 1/5th of all YSOs, and strong constraints on the nature of physical processes at work in protoplanetary disks are likely to follow from such studies.
– YSOs surrounded by disks with high mass-accretion rates are more likely to be observed edge-on than low mass-accretion rates objects.
– The larger frequency of UX Ori variability in early T Tauri stars and HAEBESs (compared to late-type, low-mass CTTSs) is caused by their larger mass-accretion rates.
– We expect to find Type III variability in perhaps 1/10th of late-type CTTSs, unless their mass accretion rates are much smaller than $\sim 10^{-8}$ $M_\odot$/yr. In other words, Type III variability might occur in a sizable fraction of late-type stars that also display the Type II variability typical of CTTSs. This is apparently more than currently observed (see Sect. 1), but the time-scales of both processes can be so different that a new examination of available data is in order.

Acknowledgements. It is a pleasure to thank Jérôme Bouvier, Sylvie Cabrit, Bill Herbst, Jean-Pierre Lasota, Caroline Terquem and Harold Yorke for helpful suggestions and comments concerning this work. Constructive criticism by referee Francesco Paresce is also gratefully acknowledged.

References

Balbus S.A., Hawley J.F., 1998, Rev. Mod. Phys. 70, 1
Basri G., Bertout C., 1989, ApJ 341, 340
Bell K.R., Cassen P.M., Klahr H.H., Henning T., 1997, ApJ 486, 372
Bertout C., 1989, ARA&A 27, 351
Bertout C., Basri G., Bouvier J., 1988, ApJ 330, 350
Bouvier J., Chelli A., Allain S., et al., 1999, A&A 349, 619
Chelli A., Carrasco L., Mujica R., et al., 1999, A&A 345, L9
Chiang E.I., Goldreich P., 1997, ApJ 490, 368
D'Alessio P., Calvet N., Hartmann L., Lizano S., Canto J., 1999, ApJ 527, 893
Dubus G., Lasota J.-P., Hameury J.-M., Charles P., 1999, MNRAS 303, 139
Eyer L., Genton M.G., 1999, A&AS 136, 421
Grinin V.P., Rostopchina A.N., Shakhovskoi D.N., 1998, Astronomy Letters 24, 802
Hartmann L., Kenyon S.J., 1987, ApJ 312, 243
Herbst W., Herbst D.K., Grossman E.J., Weinstein D., 1994, AJ 108, 1906
Herbst W.M., Schevchenko V.S., 1999, AJ 118, 1043
Malbet F., Bertout C., 1992, ApJ 383, 814
Ménard F., Bastien P., 1987, In: Appenzeller I., Jordan C. (eds.) Circumstellar Matter. IAU Symp. 122, Reidel, Dordrecht, p. 133
Ménard F., Bertout C., 1999, In: Lada C.J., Kylafis N.D. (eds.) The Origin of Stars and Planetary Systems. Kluwer, Dordrecht, p. 341
Natta A., Prusti T., Neri R., et al., 1999, A&A 350, 541
Pickett B.K., Cassen P., Durisen R.H., Link R., 2000, ApJ 529, 1034
Roberts D.H., Lehár J., Dreher J.W., 1987, AJ 93, 968
Rostopchina A.N., Grinin V.P., Shakhovskoi D.N., 1999, Astronomy Letters 25, 243
Terquem C., Papaloizou J., 2000, A&A in press