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EXPLAINING UX ORIONIS STAR VARIABILITY WITH SELF-SHADOWED DISKS

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ABSTRACT

In this Letter we propose a new view on the phenomenon of Algol-type minima in the light curves of UX Orionis stars (UXORs). The idea is based on the earlier proposal by various authors that UXORs are nearly edge-on disks in which hydrodynamic fluctuations could cause clumps of dust and gas to cross the line of sight. However, early models of protoplanetary disks were based on the notion that these have a flaring geometry. If so, then it is mostly the outer regions of the disk that obscure the star. The timescales for such obscuration events would be too long to match the observed timescales of weeks to months. Recent two-dimensional self-consistent models of Herbig Ae/Be protoplanetary disks, however, have indicated that for Herbig Ae/Be star disks there exists, in addition to the usual flared disks, a new class of disks: disks that are fully self-shadowed. For these disks only their puffed-up inner rim (at the dust evaporation radius) is directly irradiated by the star, while the disk at larger radius resides in the shadow of the rim. For these disks there exist inclinations at which the line of sight toward the star skims the upper parts of the puffed-up inner rim, while passing high over the surface of outer-disk regions. These outer-disk regions therefore do not obscure the star nor the inner-disk regions, and small hydrodynamic fluctuations in the puffed-up inner rim could cause the extinction events seen in UXORs. If this idea is correct, it makes a prediction for the shape of the SEDs of these stars. It was shown by Dullemond and Dullemond, Dominik, & Natta that flared disks have a strong far-IR excess and can be classified as "Group I" (in the classification of Meeus et al.), while self-shadowed disks have a relatively weak far-IR excess and are classified as "Group II." Our model therefore predicts that UXORs belong to the "Group II" sources. We show that this correlation is indeed found within a sample of 86 Herbig Ae/Be stars.

Subject headings: circumstellar matter — planetary systems: protoplanetary disks — stars: pre–main-sequence — stars: variables: other

1. INTRODUCTION

UX Orionis objects (UXORs; see, e.g., reviews by Thé 1994 and Waters & Waelkens 1998) are mostly intermediate-mass pre–main-sequence stars displaying a peculiar kind of photometric variability: their *V*-band light curves are characterized by sudden drops in brightness of up to 3 mag with durations of days to many weeks. These events are separated by relatively long periods of persistence. During these so-called Algol-type minima (the name refers to the similarity of the rapid decrease in brightness to those exhibited by eclipsing binaries such as Algol) their spectrum is reddened and is accompanied by a strong increase in polarization (Grinin, Rostopchina, & Shakhovskoi 1991). In very deep minima the star often becomes bluer again (e.g., Bibo & Thé 1991). The origin of these brightness drops and the bluing effect has been debated for a long time. The currently favored view is that variations of the column density of dust in the line of sight to the star is to be held responsible. This idea was first put forward by Wenzel (1969) and has since been worked out in more detail by many authors (e.g., Grinin 1988; Voshchinnikov 1990; Grinin, Rostopchina, & Shakhovskoi 1998). If these obscuration events are due to localized dust clumps of filaments passing through the line of sight, then all phenomenological properties are reproduced: the initial reddening due to dust absorption, and the increase of polarization and later bluing due to the unobscured scattered radiation. While this picture is attractive, it does not explain the nature and origin of these dust clumps or filaments.

One of the leading theories is that Herbig Ae/Be stars are surrounded by many large protocometary clouds or cometary bodies (Grady et al. 2000 and references therein). When one of these objects happens to cross the line of sight toward the star, then an absorption event is expected with precisely the characteristics seen in UXOR stars. The absorption initially reddens the stellar light, but for very large extinction the light scattered off other dust clouds starts to dominate, restoring the color again. One of the main problems of this model is making it consistent with the observed infrared SED. Most of these UXORs have rather strong far-IR excess, with $L_{\rm dust}/L_* \simeq$ 0.2–0.3. This ratio is an indication of the covering fraction of the dust with respect to the star, so that for UXORs at least 20% of the sky is covered with dust grains. If this all is due to comets, their orbits must be almost isotropically distributed, and there must be a very large number of cometary bodies orbiting around the star. Moreover, the chemical composition of gaseous material moving in and out of the line of sight does not appear to resemble that expected in comets (Natta, Grinin, & Tambovtseva 2000).

Currently, a more favored model for the obscuring clouds/filaments seems to be that of a protoplanetary disk seen nearly edge-on (Grinin et al. 1991; Grinin & Rostopchina 1996; Ber-

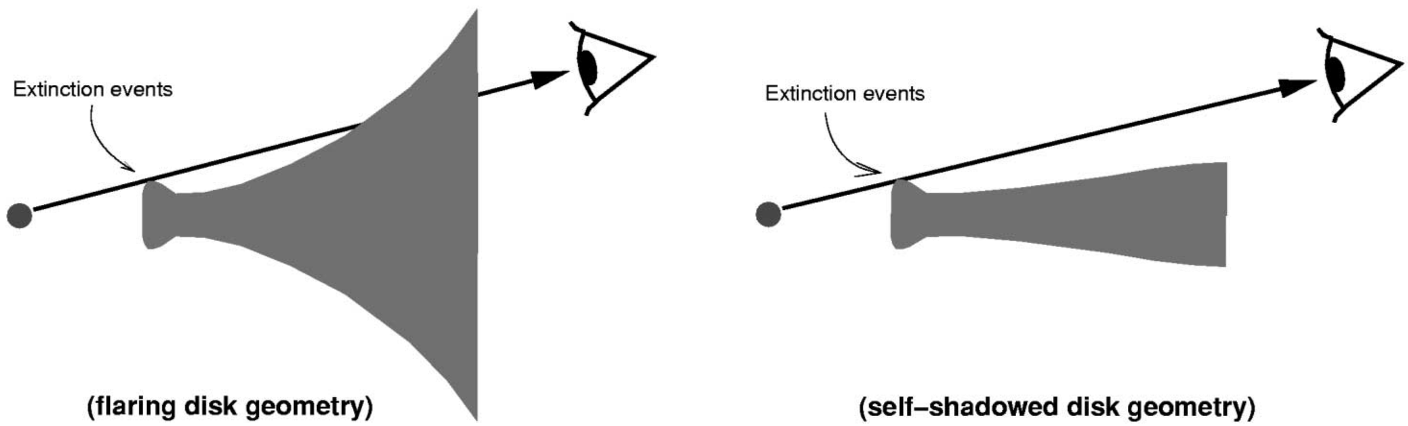

FIG. 1.—Pictographical illustration of the nearly edge-on disk model. The left panel shows that the puffed-up inner edge of the disk (a naturally arising phenomenon in models of Herbig Ae/Be disks; see DDN01) may be responsible for the UXOR extinction events, but that one needs inclination angles at which the outer flaring part would have already completely occulted both the central star and the inner rim. The right panel shows that the new disk solutions found by D02/DD03 (the "self-shadowed" disks) do not have this problem. Hydrodynamic fluctuations in the puffed-up inner rim can cause short-timescale extinction events, while the outer disk is not disturbing the view anymore.

tout 2000; Natta & Whitney 2000; Kozlova, Grinin, & Rostopchina 2000). If the inclination angle of the disk is so large that the line of sight toward the star skims the surface of the disk, then it is conceivable that hydrodynamic fluctuations of the surface of the disk could cause dust filaments to pass through the line of sight. Since protoplanetary disks are usually assumed to have a flaring geometry (Kenyon & Hartmann 1987), dust filaments held responsible for these obscuration events must reside in the outer regions of the disk (Thé 1994). A problem with this picture is that one does not expect obscuration events of this kind to be on a timescale of days or weeks. Turbulent eddies and filaments in the disk at 100 AU will tend to move across the star on a timescale of multiple years. One would have to invoke turbulent eddies that have a size of about 0.01 times the pressure scale height at 100 AU and that are very compact (hundreds of times the typical densities at those radii) in order to explain these phenomena with the outer edge of the disk.

In this Letter we propose a new version of the nearly edge-on disk hypothesis that does not suffer from the problems mentioned above and that in fact arises quite naturally from self-consistent models of protoplanetary disks around Herbig Ae/Be stars.

2. THE MODEL

The idea we wish to present in this Letter is inspired by recent models of passive disks around Herbig Ae/Be stars (Dullemond, Dominik, & Natta 2001, hereafter DDN01; Dullemond 2002). In these models, dust evaporation by the radiation of the central star has removed the dust inward of the dust evaporation radius. The dusty part of the disk therefore has an inner rim (at around 0.5–1 AU from the central star) that is irradiated frontally by the central star and has a puffed-up geometry (Natta et al. 2001; DDN01). This puffing-up is a result of the fact that the rim is much hotter than the rest of the disk, since the latter is only irradiated under a shallow angle (see e.g., Calvet et al. 1991; Chiang & Goldreich 1997). Bell et al. (1997) showed that viscous dissipation by accretion could also cause the inner regions of the disk to puff up. The puffed-up geometry of the hot inner rim makes it a good candidate for the origin of the obscuring clouds. The timescales are right: a Kepler timescale is a few months, so it is very well possible that turbulent filaments pass through the line of sight in a matter of days to weeks. Also the densities are right; the inner rim is expected to have a very high density, allowing that even relatively tenuous hydrodynamic perturbations can have optical depths much larger than unity. The fact that this puffed-up inner rim is a good candidate source for obscuring clouds was already suggested by Natta et al. (2001). However, they admit that for inclinations necessary for the inner rim to marginally obscure the star, the outer flaring disk must already strongly obscure both the star and the inner rim. The star would then not have been classified as a Herbig Ae/Be star. A pictographical representation of the idea and the corresponding problem with the flaring outer disk is shown in the left panel of Figure 1.

A solution to this flaring disk problem may lie in recent two-dimensional models of Herbig Ae/Be star disks (Dullemond 2002, hereafter D02; Dullemond & Dominik 2003, hereafter DD03). In these models the structure and SED of the disk is computed self-consistently by coupling two-dimensional continuum radiative transfer to the equations of vertical hydrostatic equilibrium. It was shown that, in addition to the flaring disk + inner rim geometry, there can also exist disks that have sunk entirely into the shadow of their own puffed-up inner rim. These "self-shadowed disks" have a similar inner-rim structure as the previous models, but they do not have the flaring outer regions. For these disks one can therefore easily find inclinations in which the line of sight skims the inner rim of the disk, *without* passing through a flaring outer disk. In this case the idea that hydrodynamic turbulent filaments from the puffed-up inner rim are the root cause of UXOR variability may in fact work. An illustration is shown in the right panel of Figure 1.

Interestingly, this hypothesis makes a prediction for the shape of the SEDs of UXORs. Self-shadowed disks were shown in D02/DD03 to have relatively weak far-IR excess. They may be classified as "Group II" sources, in the classification of Meeus et al. (2001).[1] Flaring disks, on the other hand, have a relatively strong far-IR excess and belong to the "Group I" sources. The hypothesis put forward in this Letter therefore predicts that UXORs belong to Group II. There may be marginal cases in which the flaring is present but weak enough to allow the observer to look through the flaring part without too

[1] Note that both Meeus et al. *Group* I and *Group* II sources are optically visible and hence belong to the Lada (1987) *Class* II YSOs.

strong extinction. But these should be a minority. The majority of UXOR sources should belong to Group II.

Incidentally, we note that emission from polycyclic aromatic hydrocarbons (PAHs), widely observed in Herbig Ae/Be stars, is believed to arise mainly in the part of the surface layer of the disk that is exposed to direct stellar radiation. Therefore, our two-dimensional models predict that Group II sources should have only weak or nonexistent emission of PAHs, while Group I sources may have strong emission of this kind (DD03). Our proposed model for UXOR variability therefore also predicts UXORs to have weak to nonexistent PAH emission.

3. SEDs OF UXORs AND OTHER HERBIG Ae/Be STARS

Guided by the hypothesis put forward in the previous section, we have investigated the correlation between the shape of the infrared energy distribution and the occurrence of UXOR phenomena in HAeBes. Following van Boekel et al. (2003), we characterize the infrared energy distribution of HAeBes by two quantities: the ratio of $L_{\rm NIR}$ (the integrated luminosity as derived from broadband *J*, *H*, *K*, *L*, and *M* photometry from the literature) to $L_{\rm IR}$ (the corresponding quantity derived from *IRAS* 12, 25, and 60 μm photometry), and the (non–color-corrected) *IRAS* [12]−[60] color. Since Meeus et al. Group I sources show an energy distribution closer to a power-law than the more "double-peaked" energy-distributions of their Group II sources, these two groups will naturally separate in a diagram of $L_{\rm NIR}$, $L_{\rm IR}$ versus the *IRAS* [12]−[60] color. This will be discussed in detail in R. van Boekel et al. (2003, in preparation). In Figure 2 the diagram is shown for a sample of 86 HAeBes.

Using *JHKLM* and *IRAS* photometry from literature, we have computed $L_{\rm NIR}/L_{\rm IR}$ and *IRAS* [12]−[60] for all probable HAeBes of spectral types B, A, and F from the catalog of Herbig Ae/Be stars by Thé, de Winter, & Perez (1994) for which sufficient photometry was available to compute these quantities. Empirically, we find that the line $L_{\rm NIR}/L_{\rm IR} > ([12] - [60]) + 0.9$ provides the best separation between the sources known from visual inspection of their energy distribution to belong to Group I and those belonging to Group II.

Using this relation, we find that our sample of 86 HAeBes contains 47 Group I sources and 39 Group II sources. If we define UX Orionis stars as stars of spectral type B9 or later (earlier-type stars do not show the UXOR phenomenon; Bibo & Thé 1991; van den Ancker et al. 1998) showing optical variations larger than 1 mag on timescales of days to weeks, 18 of the sources in our sample can be classified as UXOR. Of those, 14 are located in the part of the $L_{\rm NIR}/L_{\rm IR}$ versus *IRAS* [12]−[60] diagram occupied by Meeus et al. Group II sources, whereas the other four are close to the line separating groups I and II. If we limit ourselves to those sources for which we know that they are reasonably "isolated" (i.e., they are certain to be the dominant IR source in the *IRAS* beam), then there are 10 UXORs in Group II and one in Group I.

4. DISCUSSION AND CONCLUSION

On the basis of the findings of § 3 we conclude that the two-dimensional disk-model prediction, that UXOR-type phenomena should only occur in self-shadowed disks, i.e., the HAeBes with relatively modest far-infrared excesses, is consistent with the observational data present in literature.

We also note that a new study (B. Acke et al. 2003, in preparation) of all 48 Herbig Ae/Be stars observed spectroscopically by the *Infrared Space Observatory* finds that, while Group I sources often show strong PAH emission, these spectral features are absent or weak in Group II sources. Moreover, they find that the vast majority of the UXORs do not have strong PAH features in their infrared spectra. This is consistent with the model predictions.

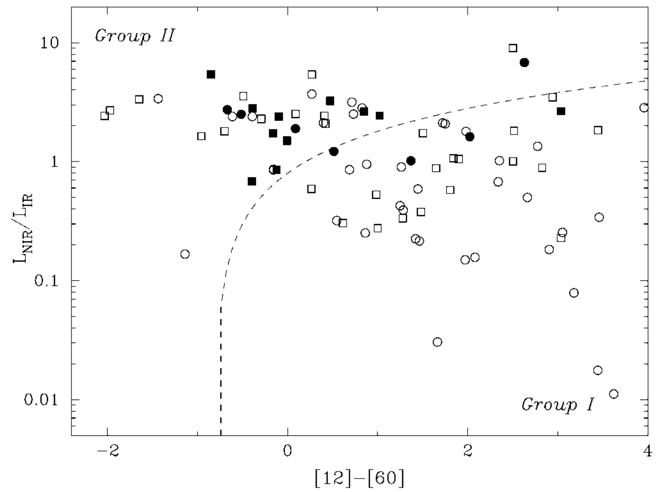

FIG. 2.—Distribution of the ratio of near-infrared to far-infrared luminosity vs. *IRAS* [12]−[60] color for 86 Herbig Ae/Be stars from the catalog of Thé et al. (1994). Filled symbols indicate UX Orionis stars. The dashed line indicates the empirical separation between stars with a "Group I" energy distribution (i.e., relatively strong Far-IR excess) and the "Group II" sources. The squares are the sources for which we know that they are reasonably isolated.

An important issue that we have not addressed so far is the percentage of Group II sources that we expect on the basis of our model to display UXOR-type variability. This question is difficult to answer, since this requires knowledge of the turbulent behavior of the disk. Typically, the surface height of the inner rim of such a disk is of the order of $H_{\rm rim} \sim 0.2R_{\rm rim}$. If hydrodynamic fluctuations are of the order of $\delta H_{\rm rim} \sim 0.1R_{\rm rim}$, then one expects about 13% of Group II stars to display UXOR variability. From Figure 2 it seems that about 33% of the Group II sources in the catalog of Thé et al. (1994) have UXOR variability. However, we note that the historical selection criteria for Herbig Ae/Be stars clearly favor strongly variable stars, such as UXORs. Therefore, it could well be that the real fraction of UXORs is smaller than the 33% in our current sample. Clearly, a study of the UXOR fraction in an unbiased sample of Herbig Ae/Be stars could place more stringent constraints on the magnitude of the hydrodynamic fluctuations required to explain the fraction of UXORs.

We stress that so far our model is not dependent on details of the dust properties. However, for an exact prediction of the degree of polarization and the detailed shape of color-magnitude diagrams, the scattering properties of the dust grains, in addition to the geometry of the disk, play an important role. In typical two-dimensional axisymmetric models of the structure of disks of Herbig Ae stars described in D02/DD03, we find that the disk covering fractions are within the range required by Natta & Whitney (2000) to reproduce the color magnitude diagrams and polarization behavior of UXORs. Therefore, we expect our model to be able to reproduce this aspect of the observational characteristics of UXORs as well.

Finally, for the model to work, the disk must have a puffed-up inner rim. For Herbig Ae/Be stars this is a natural consequence of the two-dimensional self-consistent model. For T Tauri stars there might exist such a rim as well, but it is far more difficult to find parameters for which the entire disk lies in the shadow of the inner rim. On the basis of these arguments it is therefore to be expected that T Tauri stars are only rarely seen to be UXOR-type stars. There appear to be some indications that this is indeed the case: Herbst et al. (1994) report that the dominant sources of photometric variations seen in T Tauri stars are rotational modulation due to cool spots on the stellar surface, and changes in the excess or veiling continuum. UXOR variations, although present in their sample, appear to be rare and are limited to stars with spectral type earlier than K0.

We conclude that the explanation for UXOR variability presented in this Letter seems to work better than explanations published in the literature so far. It is a natural consequence of self-consistent two-dimensional models of disks around Herbig Ae/Be stars, and it makes a number of predictions, which seem to be confirmed by observations.

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