1. INTRODUCTION

KH 15D is a pre–main-sequence (PMS) K7 star located in the young star cluster NGC 2264. Its large photometric variations are periodic and possibly interpreted in terms of eclipses by an opaque feature orbiting inside a circumstellar disk seen nearly edge-on (Herbst et al. 2002). It is likely connected to the UX Ori star family, characterized by large photometric and polarimetric variabilities (e.g., Natta et al. 1999) but is set apart from them with two important differences: no infrared excess polarimetric variabilities (e.g., Natta et al. 1999) but is set apart from them with two important differences: no infrared excess and also displays other important peculiarities: (1) ingress and egress are remarkably steep, indicating an occulting clump with a very sharp edge; (2) the minimum is not a flat land but contains a central bump with small-scale features and a reverse peak close to mid-eclipse; (3) when comparing two successive occultations, the reverse peak seems to shift from one side of the mid-eclipse to the other; (4) since the first series of observations, the occultation has clearly widened and deepened in secular fashion.

The various models suggested by Herbst et al. (2002) to explain these observations involve a companion, planet, or brown dwarf, able to “shepherd” gravitationally an extended swarm of solid particles (warped density wave or ring arc), which is responsible for the eclipses. Possibly these models could account for a number of the observed characteristics, but, so far, none of them has been developed far enough to reproduce the observed light curve and no observation has confirmed the presence of a “shepherd.”

In this Letter, we propose a new model in which KH 15D is periodically occulted by a dusty anticyclonic vortex persisting for a long time in a gas disk surrounding the star. The particles are confined inside the vortex by the gas friction, and no gravitational assistance is needed to keep them together into a clump. The swarm of the trapped particles is organized by the gas dynamics with an absorption profile that pretty well explains most properties of the observed light curve. The gaseous vortex associated to this dust swarm covers a wide azimuthal extent (see Fig. 1) that seems quite puzzling to explain but looks like those produced in recent numerical simulations (Klahr & Bodenheimer 2003). Our model is based on a scenario proposed by Barge & Sommeria (1994, 1995, hereafter BS94, BS95) in which the formation of planets begins inside persistent gaseous vortices; it relies on a number of recent works on the formation and evolution of vortices in circumstellar disks (Li et al. 2001; Klahr & Bodenheimer 2003).

2. THE PROPOSED MODEL

Our model starts from a circumstellar disk of gas and solid particles in which the mechanisms of planetary formation are still at work. The gas is assumed to spread into a flared disk following a simple hydrostatic equilibrium in the vertical direction with a scale height $H = C_s/\Omega$, where $C_s$ is the sound speed and $\Omega$ is the Keplerian orbital frequency. Protoplanetary disks are likely turbulent during a span of their lives and could host large-scale and long-lived vortices growing from turbulence by analogy with what happens in two-dimensional fluid dynamics, in which organized structures are known to emerge from random turbulence in rotating shear flows. Vortices spinning like the shear flow are robust and merge with one another, while those with the opposite sign are laminated by the shear (BS95 and references therein). However, such vortices may also result from some specific instabilities, for example: (1) the Rossby wave instability investigated by Li et al. (2001), which requires a strong local maximum in entropy and density; (2) a
global baroclinic instability, described recently by Klahr & Bodenheimer (2003) and which arises from a natural radial stratification of the gas flow.

A number of numerical simulations show that large-scale vortices can grow and survive for many rotation periods and look like either elongated structures stretched by compressibility effects (Godon & Livio 2000) or a single vortex dominating the whole disk (Klahr & Bodenheimer 2003). Highly elongated vortices are found also in the inner regions of MHD accretion disks (Tagger & Pellat 1998, and private communication) or as exact solutions of the incompressible Euler equation with different aspect ratios (Chavanis 2000). On the other hand, the radial extent of vortices cannot exceed the thickness of the disk ($R < H$) since the velocity of the vortex, $R\Omega$, must be less than the sound speed $C_s = H\Omega$ (BS95). Larger vortices would be destroyed by energy losses due to sound waves and density waves.

The solid particles embedded in the gas disk are subjected to a friction drag depending on the mean free path $\lambda$ of the gas molecules relative to the particle size (or radius) $s$. In the inner disk region ($r < 0.2$ AU) and for particles larger than a millimeter, the mean free path is less than size and the drag, caused by particle wake, reaches the Stokes regime (in the limit of particle Reynolds numbers $Re_p < 1$) with a stopping time (Chavanis 2000)

$$T_s = \frac{8s^2\rho_0}{9\sigma_{\text{gas}}\Omega\Lambda},$$

where $\sigma_{\text{gas}}$ is the gas surface density and $\rho_0 = 2$ g cm$^{-3}$ is the density of material particles are made of. In contrast, the Epstein regime is reached for smaller particle size $s < 9\lambda/4$. The particles are only subjected to star attraction and gas drag; their dynamical evolution depends on the single dimensionless friction parameter $\tau_f = \Omega T_s$; (1) the lightest particles ($\tau_f \ll 1$) come to rest rapidly with the gas and are driven by the flow; (2) the heaviest particles ($\tau_f \gg 1$) are nearly unaffected by the gas motion and keep a quasi-Keplerian motion.

The capture of particles by a gaseous vortex has been explored first by BS94 and BS95 using a simple model in which the velocity field is made up of concentric epicycles inside the vortex, while it matches a Keplerian flow at large distances. They found that such an anticyclonic vortex can capture and concentrate dust particles very efficiently: (1) light particles penetrate into the vortex and stop on streamlines close to the edge where they slowly shift toward the core; (2) optimal particles, with $\tau_f \sim 1$, sink deeply into the vortex and reach core streamlines. These results were confirmed for other velocity fields (Chavanis 2000; De la Fuente & Barge 2001). The vortex induces a segregation of the trapped particles (or a size sorting if the particles have the same composition) following the value of their friction parameter; this is illustrated in a number of numerical simulations (De la Fuente, Barge, & De la Fuente 2002).

The ultimate reason for this dynamical behavior lies in the sign of the vortex rotation. Indeed, in a reference frame rotating with the vortex center, the Coriolis force can overcome the centrifugal force and pushes the particles toward the core if the vortex is an anticyclone, whereas both forces are conspiring to eject the particles for a cyclone. This capture-in-vortex mechanism is a very efficient one and results in strong density enhancements inside the vortex, by at least 2 orders of magnitude in ~200 rotation periods. The capture rate is estimated under the assumption that the particles are continuously renewed near the vortex orbit due to the inward drift under the systematic headwind (Weidenschilling 1977; BS95). One obvious and important consequence of this density enhancement is that, inside a vortex, particle growth is made easier and will couple with confinement and segregation. On the other hand, dust is depleted from the region inside the vortex orbit as the particles either are feeding the vortex or are falling to the star under the systematic drift.

Inside the vortex, the trapped particles are also subjected to a background small-scale turbulence, which makes them diffuse and tends to reduce their global concentration. Chavanis (2000) investigated this question in terms of a diffusion equation in an idealized circular vortex and derived a time-dependent solution for the surface density inside the vortex:

$$\sigma_s \propto \frac{1}{l_s^2(1-k^2)} \exp \left[ \frac{-(r-k l_s)^2}{l_s^2(1-k^2)} \right].$$

The initial state being a delta function centered at $r_s$, $l_s$ is the characteristic time for a particle to reach the center of the vortex. In the case of light particles and very elongated vortices $T_{\text{capt}} \approx 2q/(3\Omega l_s)$ and $l_s \sim \left(\lambda,\mu/\eta,\tau_f\right)^{1/3} R_s$, where $R_s$ is the vortex radius and $q$ is its aspect ratio; $\alpha_s$ is the dimensionless parameter measuring the small-scale turbulence efficiency inside the vortex.

In order to estimate the size of the trapped particles, we will choose a standard model of nebula, the minimum-mass solar nebula, in which the surface densities (for both gas and particles) and the temperature are the decreasing power laws $r^{-3/2}$ and $r^{-1/2}$, respectively; at 1 AU the densities are set to 1700 g cm$^{-2}$ for the gas and 20 g cm$^{-2}$ for the particles, whereas the temperature is assumed to be 280 K. At 0.2 AU from the star and with our numerical values, the optimal size for particle capture is $s_{\text{opt}} \approx 31\tau_f^{1/2}(r/1\text{ AU})^{3/4} = 11$ cm, i.e., pebble size. Lighter nonoptimal particles with $\tau_f < 1$ can be also captured by the vortex but remain trapped at the periphery of the vortex.
These particles remain in the Stokes regime, at 0.2 AU from the star, so long as their size is larger than the critical size $s_c = 9\lambda/4 \approx 0.3$ mm.

3. FITTING THE LIGHT CURVE

We assume that the disk is seen nearly edge-on, under an inclination $i$ less than the flaring angle of the gas disk. The inclination must be small enough for the line of sight to cross the vortex in its vertical extent, but also large enough to avoid the prohibitive optical depths near the midplane layers. Of course, this inclination has to be consistent with the out-of-eclipse gray extinction $A_0 \sim 0.7$ mag deduced in § 1. In its motion around the star, the vortex periodically crosses the line of sight and the optical depth $\tau$ is a function of time varying from $A_0$ (out of eclipse) to $A_0 + 3.2$ during the eclipses. Assuming the absorption is due to spherical particles with sizes larger than a millimeter, the opacity $\kappa$ reduces to $\pi s^2 n$ and the optical depth $\tau = \int \kappa dl$ is the familiar dust column density, where $n$ is the local number density along the line of sight.

During an occultation $\tau$ is found to increase inside the vortex, from center to edge, then to fall down very steeply to reach the out-of-vortex level. This “opacity curve” has a peculiar shape that our model can easily reproduce.

First, one can guess that a circular blob of matter in which the opacity $\kappa(r)$ is radially increasing can conveniently mimic the optical depth profile. Then, we noticed that a simple linear dependence, $\kappa \propto 1 + ar$, with a cutoff at the outer boundary permits the data to fit pretty well (Fig. 2). In our fit the optical depth has been computed following two steps: (1) an integration of $\kappa$ along a path crossing an equivalent circular vortex (ECV) of radius $H$ and located at a distance $r_{out}$ from the star; (2) a circular anamorphosis by a factor of $q \approx 17$ (the result of an integration along a path at angle $u$ is reported to the direction of observation at angle $q \times u$). Figure 1 illustrates the ECV model with a sketch of the integration path and the density contours of the vortex based on the linear opacity law and the appropriate anamorphosis.

This absorption profile corresponds to a shell-like distribution of the solid particles inside the vortex, reminiscent of the spherical structures observed in H II regions. In our model such a density profile originates in the dynamics and the segregation of particles trapped in a vortex as described above.

Surprisingly, a simple cutoff at the vortex outer boundary can easily mimic the very steep fall during ingress or egress, consistent with an occultation by a sharp edge as proposed by Herbst et al. (2002). In fact, a cutoff cannot receive true physical justification and the resulting profile cannot connect smoothly the out-of-eclipse level. A more realistic fit of ingress and egress directly arises from our model. Indeed, light suboptimal particles are preferentially captured in the outer part of the vortex, where they accumulate and slowly diffuse toward the core. The fit is realized thanks to the Gaussian density profile presented in equation (2) with the following values of the parameters: the center of the Gaussian is close to the vortex boundary (at a distance from the core $\sim R_\nu = qH$); the 1/e half-width of the Gaussian is given by $L_s (1 - k^2)^{1/2} = 0.07 R_\nu$.

This is possible using the following assumptions: (1) the particles are renewed by capture every $\sim 10$ rotations of the vortex and have a friction parameter $\tau_* = 0.01$, consistent with a capture at the vortex periphery and a slow drift toward the core in a timescale $T_{\text{opt}} = 2q(30\Omega_\nu)$; (2) the parameter measuring the turbulence inside the vortex is $\alpha_\nu = 0.01$. As a result,

![Fig. 2.—Eclipses of KH 15D in $I_\nu$-band magnitudes, phased with the period of 48.36 days. The plotted points are weighted means per observation night from the 2001–2002 observation campaign (W. Herbst & C. Hamilton 2003, private communication). Dashed line is a fit obtained with the linear approximation $\kappa \propto 1 + ar$ and $a \sim 10$. Solid line is the best fit obtained assuming $\kappa \propto b^3 (b \sim 5) if \ r < H$, and $\kappa$ given by the Gaussian model described in the text if $r \geq H$.](image)

the corresponding size of particles confined in the outer regions is of the order of a centimeter.

4. DISCUSSION AND CONCLUSION

The proposed model can account for the main characteristics of KH 15D’s observations. It is able to reproduce the light curve and permits the data to fit pretty well.

1. The period and duration of the eclipses may be produced by the rotation around the star of a giant swarm of solid particles, trapped in a persistent gaseous vortex.

2. During totality, the rise up of the flux can result from a lower opacity of the central regions, possibly coming from a particle size segregation (the larger the particle, the deeper and faster the confinement inside the vortex).

3. The estimated size of the trapped particles ranges from 1 to 10 centimeters, consistent with the gray absorption observed in KH 15D. The presence and growth of bigger particles is very likely due to the high densities and the low relative velocities. This is in agreement with the expected predominance of large grains in PMS disks, which also seems required to explain submillimeter and millimeter disk observations (e.g., Natta et al. 1999).

4. The shift of the reverse peak observed in successive transits could be explained by gas rotation inside the vortex, the inner zone rotating at half the orbital frequency similarly to what happens in smaller vortices (Chavanis 2000).

We can also speculate that (1) “secular” changes of the light curve could result from a dynamical evolution of the swarm of particles and (2) the wavy behavior at egress could correspond to a turbulent wake of the vortex.

One of the main assumptions in our model is that the disk is seen nearly edge-on, at an angle $i \sim 2^\circ-3^\circ$, and with an optical depth $A_0 \sim 0.6-0.7$ mag during the out-of-eclipse periods. This is a possible situation if the dust particles have grown and settled down to the midplane, forming a flat subdisk dominated by large grains. The predominance of large particles in KH 15D is, indeed, completely consistent with our results. However, we want to stress that no numerical simulation is, currently, able to reproduce the huge azimuthal extent of the vortex required to fit the observations. Further hydrodynamical simulations and theoretical modeling of the particle dynamics are necessary to confirm and improve our model.
Finally, KH 15D appears a good target to test planetary formation models. This is presently the case with the scenario in which vortices can persist in a gas disk acting as traps for dust (protected against losses into the star) and as wombs for planetesimals. Of course, further observations of this object are required to constrain the model more firmly. The possibility of observing large-scale structures in circumstellar disks has been recently investigated by Wolf & Klahr (2002), extrapolating the capabilities of the future giant interferometer ALMA. KH 15D and other similar objects are good opportunities for the future space missions like CoRoT, Kepler, and Eddington.

A further piece of information was recently provided by Hamilton et al. (2003) using high-resolution UVES spectra, which confirmed that KH 15D is a weak-lined T Tauri star surrounded by an accretion disk with, possibly, a collimated bipolar jet. Such a configuration could favor the accretion-ejection model of Tagger & Pellat (1998) in which persistent vortices can form in the inner region of magnetized disks.

While submitting this Letter we learned that H. Klahr also claims the existence of a vortex in the disk of KH 15D to explain the peculiar light curve of this object. His work seems complementary to ours since he is focusing on the way a giant vortex forms and persists in hydrodynamical simulations, and not on the trapping of solid particles in gaseous structures.

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