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PROTOSTELLAR DISKS UNDER THE INFLUENCE OF WINDS AND UV RADIATION

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RESUMEN

La formación estelar y la creación de discos protoestelares ocurre generalmente en la vecindad de múltiples fuentes. Las estrellas jóvenes cercanas y proto-estrellas, pueden influenciar los discos de sus vecinas más cercanas a través de los flujos hidrodinámicos y de su dura radiación. Las mismas estrellas centrales pueden desarrollar vientos estelares y también producir radiación UV y de rayos X, lo suficientemente importante como para destruir los discos circunvecinos. Aquí se describen los resultados de simulaciones numéricas acerca de la influencia que una fuente externa de radiación UV y el viento de una fuente central puedan tener sobre el disco circunestelar. El método computacional (con simetría axial) es descrito en otra contribución. Encontramos que los discos circunestelares son destruídos en una escala de tiempo relativamente corta (∼ 105 años) a no ser que estén bien escudados de las estrellas O. Los vientos inicialmente isotópicos producidos por las estrellas T-Tauri no afectan sus discos significativamente y en su lugar, son enfocados hacia el eje de rotación por el viento de gas fotoevaporado del disco.

ABSTRACT

Star formation and the creation of protostellar disks generally occur in a crowded environment. Nearby young stars and protostars can influence the disks of their closest neighbors by a combination of outflows and hard radiation. The central stars themselves can have a stellar wind and may produce sufficient UV and X-ray to ultimately destroy their surrounding disks. Here we describe the results of numerical simulations of the influence that an external UV source and a central star's wind can have on its circumstellar disk. The numerical method (axial symmetry assumed) is described elsewhere. We find that protostellar disks will be destroyed on a relatively short time scale ($\sim 10^5$ yr) unless they are well shielded from O-stars. Initially isotropic T-Tauri winds do not significantly influence their disks, but instead are focused toward the rotation axis by the disk wind from photoevaporation.

Key Words: **H II REGIONS — STARS: FORMATION**

1. INTRODUCTION

I believe I first met Peter Bodenheimer in 1976 during his visit to the Max-Planck-Institut für Astrophysik in Munich. (Our paths may have crossed before this, but I just don't remember.) As a recent post-doc at MPIA I had just added an ionization/recombination module to the Yorke & Krügel (1977) code to calculate more realistically the formation phase of HII regions. (Up to this point initial conditions for HII regions assumed a constant density envelope and I wanted to begin the calculations with the density distribution resulting from the formation of a massive star.) The HII region module calculated the line-of-sight transfer of hydrogen-ionizing radiation together with ionization/recombination equilibrium, assuming that the ionized gas was hot ($T \sim 10^4$ K) and the neutral gas temperature was given by the dust temperature. When Guillermo Tenorio-Tagle (like me a recent post-doc at MPIA) gave a seminar talk at the institute, describing the "champagne phase", the rapid expansion of HII regions when the I-front crosses a boundary with decreasing density, I found another use of my HII region module and approached Peter. Couldn't this module easily be added to his 2D code to calculate the champagne flow for 2-D molecular clouds? Within a few weeks we had the first results and began writing the first in a series of papers on the subject (Bodenheimer, Tenorio-Tagle & Yorke 1979) Our first published results used a 40×40 grid (see Figure 1). This marked the start of long personal friendships and a series of fruitful collaborations between the three of us. We later added a stellar wind point source to the 2D code in order to include the effect of strong stellar outflows.

The calculations described here are directly related to these first multidimensional HII region calculations and conceivably some of the original coding

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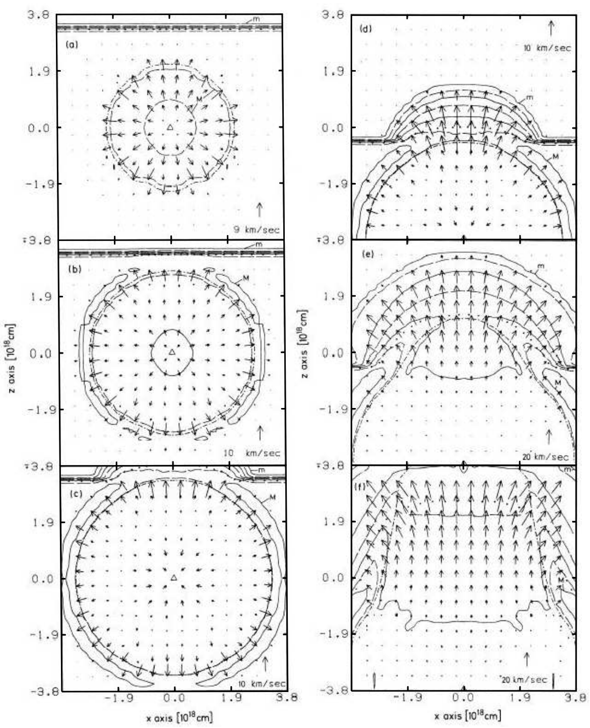

Fig. 1. Champagne flow developing from a expanding HII region after the I-front crosses the boundary of a molecular cloud (see Bodenheimer et al. 1979 for details).

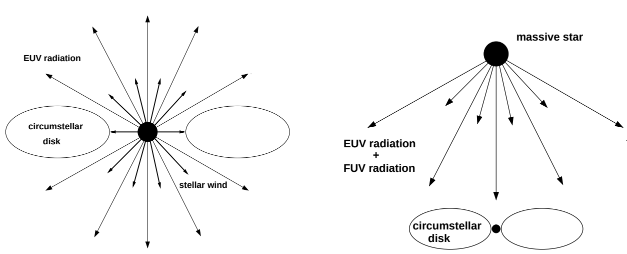

Fig. 2. Orientation of the UV source with respect to the disk for the two cases considered: 1) The disk is UV-illuminated by the disk's own central star [*left*] and 2) the disk is UV-illuminated by an external source [*right*]. In both cases an isotropic stellar wind from the disk's central star is specified as an inner boundary condition.

of that first ionization/recombination module and the stellar wind module can be found somewhere deeply buried within the modern code. Here, we describe the interaction of ionizing radiation and stellar winds on protostellar disks, using as a starting density configuration the results of Yorke & Bodenheimer (1999). We consider the case of disks UV-illuminated by an external source as well as disks UV-illuminated by their central star (see Figure 2).

2. THE NUMERICAL CODE

The modern code has experienced several generations of PhD students' and our own improvements (see e.g. Richling & Yorke 2000). The hydrodynamics is now 2^{nd} order in space and of order 1.5 in time on a series of multiply nested grids. It utilizes flux-limited-diffusion for the transfer of radiation in the diffuse infrared and several diffuse UV bands (see below). Angular momentum transport is approximated with a Sunyaev & Shukura α parameter, which is generally chosen to be $\alpha \sim 0.01$. Cells close to the origin are treated in a special way with a "wind generator" of specified mass loss rate $\dot{M}_W$, wind velocity v_W, and angular distribution (generally chosen to be isotropic).

The HII region module includes time-dependent heating and cooling via cooling lines using an escape probability formalism as well as time-dependent ionization and recombination of hydrogen and carbon. The direct line-of-sight transfer of H-ionizing and C-ionizing photons are included as well as the diffuse UV fields resulting from scattering of these photons by dust and by recombinations directly into the ground state (no "on the spot" approximation). The dust temperature is calculated (separately from the gas temperature) along with transfer of IR photons. Transfer of heat from the dust to the gas due to mutual collisions is included as one of the heating (or cooling) mechanisms. The lines of sight origin of EUV ($h\nu > 13.6$ eV) and FUV (6 eV $\leq h\nu \leq 13.6$ eV) radiation can be specified at the origin or at some external point along the rotational symmetry axis (see Figure 2).

3. RESULTS OF THE CALCULATIONS

Here we discuss three cases to illustrate use of the code. For case H we calculate the evolution of the ~ 0.6 M$_\odot$ protostellar disk around a young 0.85 M$_\odot$ star (case H of Yorke & Bodenheimer 1999 at an evolutionary age of 240,000 yr), illuminated externally by an O5 star at a distance of $D_{\rm UV} = 1$ pc from the disk. We have reset the evolutionary clock to $t = 0$, when the external ionizing source was turned on. For case I we also turn on the central star's stellar wind at $t = 100,000$ yr after the external UV source turn-on, when the basic flow pattern demonstrated in Figure 3 had been well established. Finally, for case S we assume the UV source is the central star itself (see initial parameters given in table 1).

The calculated evolution of the disk mass, the mass of neutral material within the ionization front, and the ionized mass within the grid is shown in Figure 4 for cases H and I. The SEDs of these cases

TABLE 1

PARAMETERS OF CASES CALCULATED

	H	I	S
M_* [$M_\odot$]	0.85	0.85	8.5
$M_{\rm disk}$ [$M_\odot$]	0.6	0.6	1.5
$\log S_{\rm FUV}$ [s^{-1}]	50.25	50.25	48.64
$\log S_{\rm EUV}$ [s^{-1}]	48.86	48.86	46.17
$D_{\rm UV}$ [pc]	1	1	0
$\log \dot{M}_W$ [$M_\odot$ yr^{-1}]	-7	-6.7	-8
v_W [km s^{-1}]	5	50	30

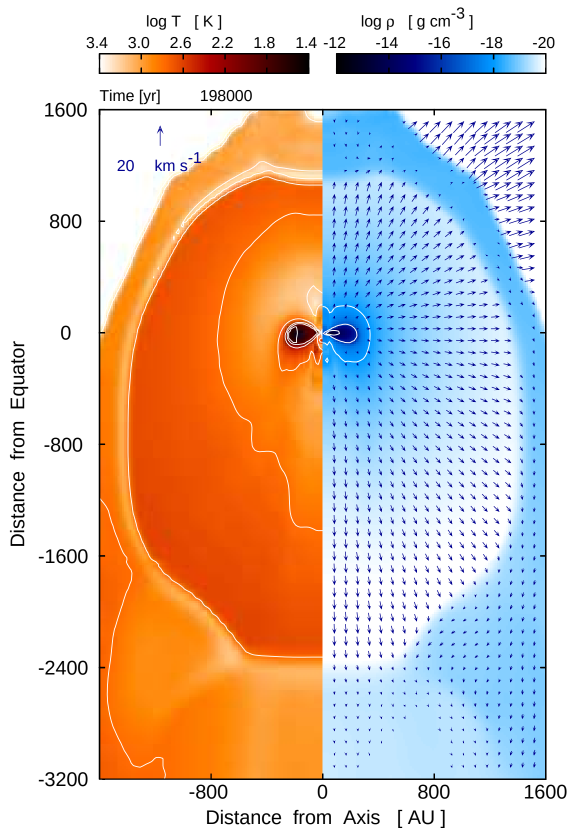

Fig. 3. Temperature (*left*), density (*right*) and velocity (*arrows*) structure of disk illuminated by an external UV radiation source (O star at 1 pc). The low density ($\rho < 10^{-20}$ g cm^{-3}) material in the upper corner is fully ionized and at a temperature $T \simeq 8000$ K. An I-front (not shown explicitly) separates it from the neutral material at higher density and lower temperature. The entire grid is 4×10^{17} cm squared — here we show the inner parts only.

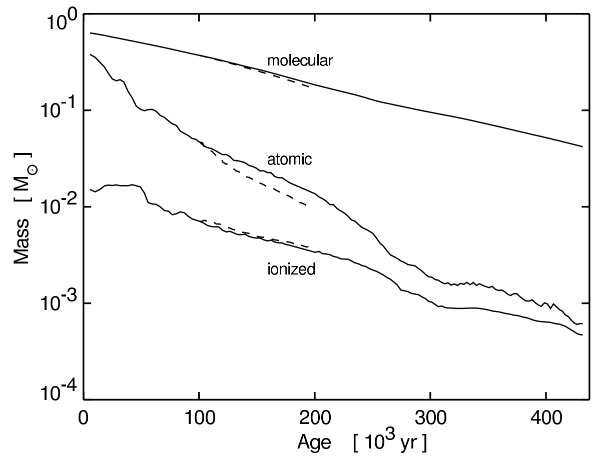

Fig. 4. Masses of disk (labeled *molecular*), atomic and ionized material during the course of evolution of case H (*solid lines*) and I (*dotted lines*).

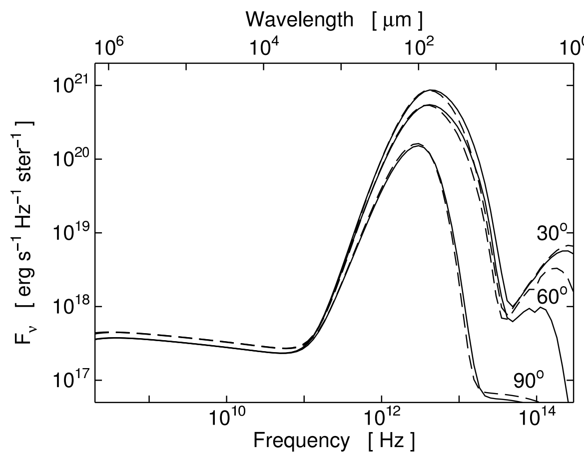

Fig. 5. SED (*solid lines*) of photoionized disk of case H at the time shown in Figure 3 as a function of viewing angle. The corresponding SEDs for case I *dotted lines*) are also displayed.

at $t = 198{,}000$ yr for selected viewing angles are shown in Figure 5. The decrease of disk mass is approximately exponential with an e-folding time of $t_{\rm photoevap} = 150{,}000$ yr. The SEDs are dominated by the far infrared peak, the maximum of which shifts slightly depending on inclination. The inferred bolometric luminosity also depends on view angle; the edge-on view appears to have a bolometric luminosity about a factor of 6 lower than the pole-on view displays.

For case S the assumed EUV flux was not sufficient to ionize a significant portion of the envelope; only the wind region remains ionized. The FUV, however, creates a disk wind via photoevaporation, which is able to focus the initially isotropic stellar wind into an (ionized) bipolar outflow (see Figure 6). The disk wind is heated to several 100 to several

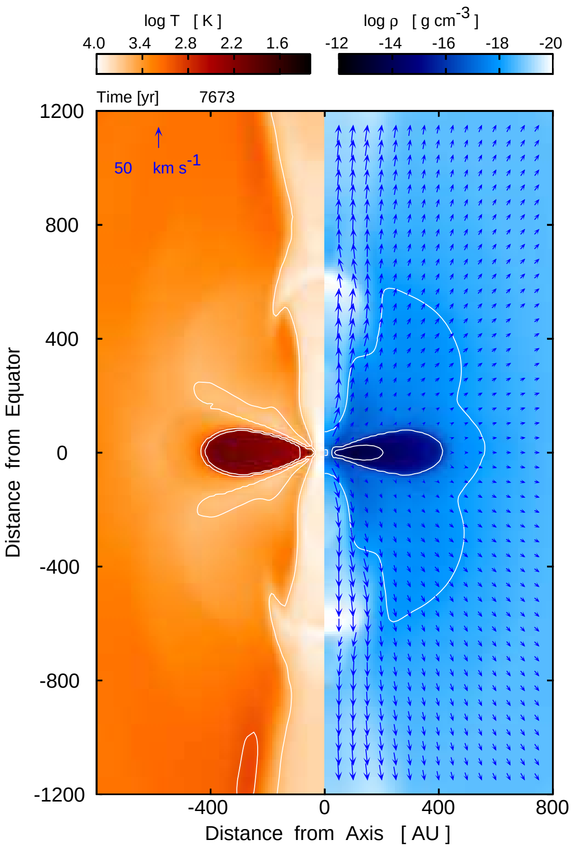

Fig. 6. Temperature (*left*), density (*right*) and velocity (*arrows*) structure of disk FUV-illuminated by its own central 8.5 $M_\odot$ star. An isotropic wind ($\dot{M}_W = 10^{-8}\ M_\odot\ yr^{-1}$; $v_W = 30$ km s^{-1}) originating at the star is focused by the photoevaporating disk material into a bipolar outflow.

thousands Kelvin, is neutral (atomic hydrogen) and without CO. The disk has a central hole.

For a disk around a more massive star the effects of radiation acceleration and winds are more prominent. Figure 7 depicts the inner accretion disk for such a configuration: inward radial flow is allowed in the equatorial plane. The inflowing material changes from molecular to atomic to ionized as it approaches the accreting central star. A polar cavity is evacuated by a combination of radiation and the stellar wind. The disk itself is self-shielded from the intense EUV field by an ionization front separating HII and HI gas and from the FUV field interior to the HI/H_2 interface by dust, molecular hydrogen, and CO. The dust is sublimated at $r_{\rm dust}$, well before it can experience the full UV irradiation of the star. Interior to $r_{\rm evap}$ even the ionized gas is gravitationally bound.

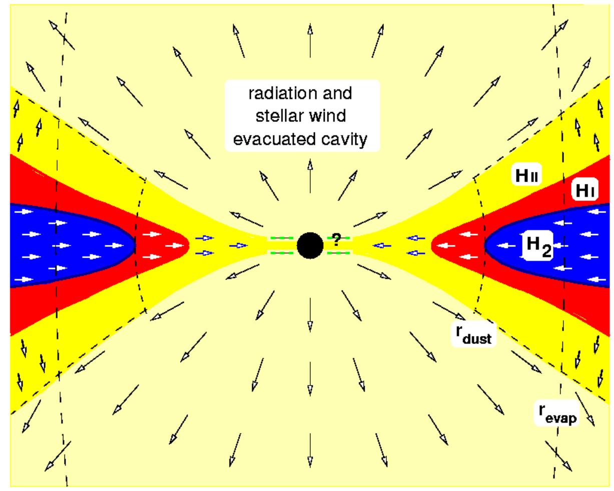

Fig. 7. Structure of disk surrounding a high mass star (schematic).

4. CONCLUSIONS AND DISCUSSION

The externally illuminated disks will be interpreted as proplyds if they are not deeply embedded within a dusty shroud and, if they are, could be interpreted as ultracompact HII (UCHII) regions. The lifetime of this configuration and the radio flux depend on the proximity and UV flux of the ionizing source. The most prominent UCHII regions will arise from disks extremely close to the UV source, possibly from their own circumstellar disk (see Figure 7) and will be able to exist for about 100,000 yr.

Case S probably best characterizes the expectation from Herbig HeBe stars. Their disks are short-lived (100,000 yr) due to FUV radiation from the central star. The neutral, atomic disk wind creates an approximately spherically symmetric $\rho \propto r^{-2}$ dusty envelope surrounding the star and disk (see Figure 6).

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