RevMexAA (Serie de Conferencias), **1**, 35-42 (1995)

THE EVOLUTION OF PHOTOIONIZED DISKS

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RESUMEN

El modelo más prometedor para la mayoría de las regiones HII ultra compactas (UCHII) involucra la fotoionización de un disco circunestelar alrededor de una estrella OB recién formada. La interacción de la estrella con el disco ocurre a través de la radiación ionizante del hidrógeno proveniente de la estrella y su viento estelar. Una serie de efectos adicionales jugarán también un papel en la evolución del disco. La fase UCHII en la evolución de estrellas masivas ocurrirá mientras el disco y la fuente central estén inmersos todavía en su nube molecular materna.

Se presentan y discuten nuevos resultados numéricos de tres casos: Uno con un viento estelar moderado, uno con un viento estelar muy fuerte, y uno con un viento despreciable. La colimación hidrodinámica a lo largo del eje de rotación tuvo lugar para el caso del viento moderado, mientras que el disco se perturbó significativamente en una escala de tiempo corta bajo la influencia del viento muy fuerte. El disco evolucionó en un toroide expandiéndose hacia afuera. Inestabilidades de Rayleigh-Taylor y Kelvin de tipo "ola" podrían dar lugar en este caso a la destrucción del disco. La fotoionización de los discos debería de ocurrir cuando existan suficientes fotones UV para fotoionizar el hidrógeno. Muchos de los procesos que se discuten aquí son también importantes para los "proplyds", los cuales están asociados con remanentes de material alrededor de estrellas recién formadas de masa pequeña en la vecindad de estrellas luminosas O.

ABSTRACT

The most promising model for the majority of ultracompact HII regions (UCHIIs) involves the photoionization of a circumstellar disk around a hot, newly formed OB star. The interaction of the star with the disk can occur via hydrogen-ionizing radiation from the star and its stellar wind. A number of additional effects will also play a rôle in the disk's evolution. The UCHII phase in the evolution of massive stars will occur while the disk and central source are still embedded in their parent molecular clump.

New numerical results are presented and briefly discussed for three cases, one with a moderate stellar wind and one with a very strong stellar wind, and one with a negligible wind. Hydrodynamic collimation along the rotation axis occurred for the moderate wind case, whereas the disk was significantly disturbed on a short time scale under the influence of the very strong wind. The disk evolved into an outward expanding torus. Rayleigh-Taylor and Kelvin "water wave" instabilities could lead to disk destruction for this case. Photoionization of disks should occur whenever sufficient hydrogen-ionizing UV photons are present. Thus, many of the processes discussed here are also relevant for "proplyds" which are associated with remnants of circumstellar material around newly formed low-mass stars in the vicinity of luminous O-stars.

Key words: **STARS: FORMATION — ISM: JETS AND OUTFLOWS — ISM: HII REGIONS**

1. INTRODUCTION

The formation of circumstellar disks is a common occurrence during the star formation process. Strom (1995, this meeting) estimates that the fraction of young ($t \ll 10^6$ yr), low-mass ($M \lesssim 1.5$ $M_\odot$) stars which have circumstellar accretion disks exceeds 80%. Presumably the precursors of massive stars ($M \gtrsim 10$ $M_\odot$ also possess massive disks. The lifetimes of circumstellar disks range from several hundred thousand years to several ten million (see Fig. 1), depending on the stellar mass. Evidence of inflated excess emission consistent with the existence of *optically thin* disks — analogous to the structures around Vega and β Pic — is found in stars of all masses. However, the fact that no massive circumstellar disk has been observed around an optically visible H-burning star gives an upper limit to the lifetime of this evolutionary phase, thus defining of location of the circles in Fig. 1 for $M_{\rm max} \gtrsim 3$ $M_\odot$. Based on the work presented by Strom (1995) at this meeting, we estimate massive disk lifetimes as ranging from about 10^6 yr ($M \approx 3$ $M_\odot$) to $\gtrsim 10^7$ yr ($M \lesssim 0.2$ $M_\odot$).

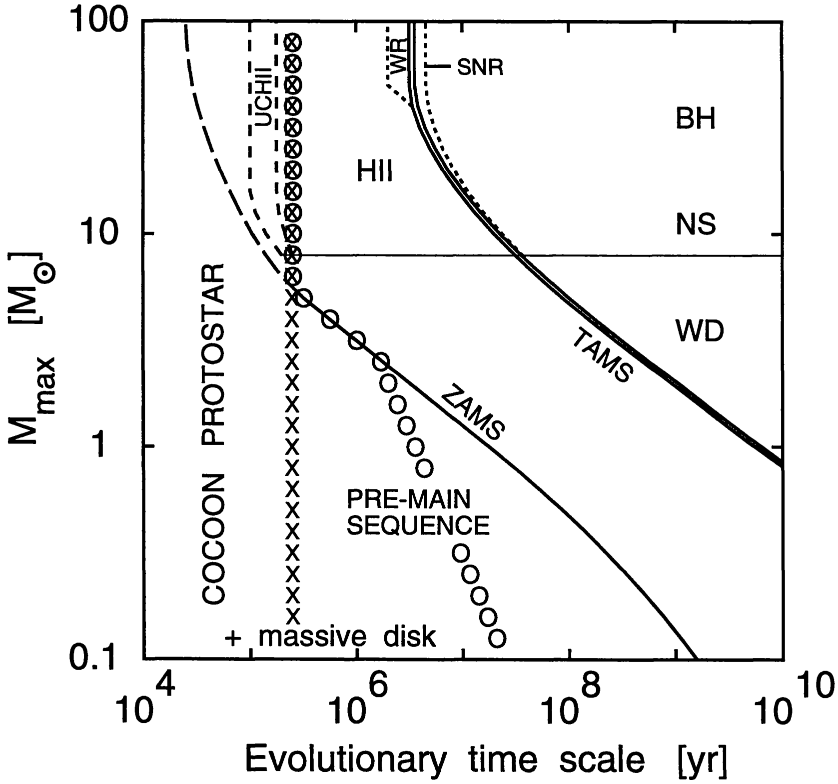

Fig. 1.— Evolutionary time scales after formation of the first protostellar core as a function of the maximum mass attained by the star M_{max} (adapted from Yorke 1986). The contraction time scale to the zero age main sequence (solid line labeled by ZAMS) is meaningful only for stars with masses $M \lesssim 5$ $M_\odot$. Stars more massive than about 5 $M_\odot$ begin H-burning (time denoted by long dashes) while still deeply embedded in their parent molecular clump (time scale indicated by X's). Our estimated maximum lifetime of massive disks is denoted by circles. Regions in the diagram are indicated where UCHIIs, Wolf-Rayet stars (WR), HII regions, and supernova remnants (SNR) can be found. The end of H-burning (TAMS) and of core nuclear burning (unlabeled) are shown as solid lines.

The detailed structure and evolutionary history of massive circumstellar disks has important consequences with regard to the early evolution of young stars. Massive disks provide a reservoir of material with specific angular momentum too large to be directly accreted by the central object. Only after angular momentum is transported outwards can this material contribute to the final mass of the star. The transition region disk-star will strongly influence the star's photospheric appearance and how the star interacts with the disk. The relative high densities in these disks provide the proper environment for the further growth and evolution of dust grains and may lead to the formation of planetisimals and ultimately to planets. Grain evolution will also affect the disk's opacity and consequently its energetics and appearance. Finally, the disk can be expected to interact with stellar outflows and is likely to be responsible for the outflows associated with star formation.

In the following we will consider the evolution of disks in the environment of H-ionizing photons and stellar winds. After first discussing the relevant physical processes, we briefly review current models. In particular, the numerical problem and several solutions are discussed.

2. PHYSICAL PROCESSES — A NON-EXHAUSTIVE CATALOGUE

2.1. Ionizing Sources

It is difficult to determine by theoretical considerations alone exactly how many ionizing photons are available in the vicinity of disks. Of course extensive catalogues of atmospheres exist (e.g. Kurucz 1979) which allow one to estimate the photospheric contribution, but as can be seen in Fig. 1, massive stars spend $\gtrsim 10^5$ yr of their H-burning lifetimes still embedded in their parent clumps. The atmosphere of an accreting star will certainly differ from a non-accreting one. Young low-mass stars are known to be more flare active than older stars of the same mass. Admittedly, the X-ray activity of young stars (see e.g. Casanova et al. 1995; Montmerle & Casanova 1995 in these Proceedings) appears to be anticorrelated with the existence of disks, but it is not inconceivable that such activity is concurrent with or has contributed to disk destruction. Powerful X-ray flares ($E_X \approx 10^{36.6}$ erg) have been observed in young, low-mass stars (Preibisch et al. 1993). Perhaps this is also true of more massive embedded stars. The existence of a disk may also contribute to the Lyc photon flux in the transition region at the disk/stellar surface interface. The disk itself may have an active photosphere or chromosphere. Finally, as in the case of proplyds, all the above mentioned can act as external sources of ionizing radiation.

2.2. The Circumstellar Disk

The vertical extension of the disk influences the ease with which it can be photoionized. "Fat" disks subtend a larger solid angle as seen from the central source and therefore can be better illuminated directly. The gas density at the edge of the ionization front separating the ionized gas from the neutral disk gas critically determines how many UV photons are lost due to recombinations. Because both the disk's vertical extension and the gas density depend on the local temperature, a combination of many physical processes in the disk is important for its photoionization history. Among these are the effects of magnetic fields, angular momentum transfer and the associated heating due to viscosity, the "passive" heating by the central source, convection, and the transfer of radiation. Critically important for radiation transfer is the opacity due to dust. Thus, dust evolution (coagulation, dust processing, and destruction mechanisms) will influence the disk's photoionization.

Evolution of the dust in the disk is influenced by the local environment. There are a number of physical effects which will lead to relative grain motions and thus enhance grain coagulation. Among these are: 1) differential sedimentation; 2) Brownian motion (Chokshi et al. 1993); 3) photon sputtering (Yorke 1988) and cosmic ray sputtering; 4) chemical processing on the grain surface (with expulsion of molecules); 5) partial sublimation of ice mantels; 6) suprathermal velocities due to random asymmetries of the grain surface and NLTE effects (Purcell 1979); 7) turbulent motions (Völk et al. 1980; Mizuno et al. 1988); 8) circulation and convective motions; 9) different azimuthal motions because the effective radial accelerations differ; 10) interactions between charged particles (Horanyi & Goertz 1990); 11) different radiative accelerations; and 12) different braking lengths behind accretion shocks (Yorke et al. 1993, 1995).

2.3. The Ionized Region

Models of photoionized disks must obviously consider the physics of the ionized region. The photoionization/recombination and heating/cooling processes are similar to those for more diffuse ($n_H \lesssim 10^4$ cm^{-3}) HII regions (see e.g. Osterbrock 1974; Yorke 1986), but there are significant differences. Due to "shadowing" effects the processes contributing to the diffuse UV field, such as scattering on dust, resonant scattering, and hydrogen-ionizing recombination photons, are especially important for the photoionization of disks. Contrary to the case of diffuse HII regions, the density of Ly_α photons may be so high that non-negligible ionization from the $n = 2$ level of hydrogen occurs. These processes also affect the heating of the ionized gas in a complex manner. For example, the diffuse UV component will have a spectral shape which differs greatly from the stellar photospheric

Table 1.— Parameters of various cases calculated. The resulting mass loss rates obtained from the numerical calculations $\dot{M}_{\rm evap}^{\rm num}$ is compared to the approximate formulae of Hollenbach et al. (1994).

Model	$\frac{M_\star}{\rm M_\odot}$	$\frac{\dot{M}_W}{10^{-8}\,\rm M_\odot/yr}$	$\frac{v_W}{\rm km/s}$	$\frac{L_W}{\rm L_\odot}$	$\frac{S_{\rm Lyc}}{10^{46}\,\rm s^{-1}}$	$\frac{\dot{M}_{\rm evap}^{\rm num}}{10^{-6}\,\rm M_\odot/yr}$	$\frac{\dot{M}_{\rm evap}^{\rm wW}}{10^{-6}\,\rm M_\odot/yr}$	$\frac{\dot{M}_{\rm evap}^{\rm sW}}{10^{-6}\,\rm M_\odot/yr}$
moderate wind Fig. 2	8.4	0.5	600	0.15	7.08	0.5	1.0	0.2
very strong wind Fig. 3	8.4	10.0	600	2.97	0.35	0.1	0.22	20
weak wind Fig. 4	8.4	2.0	60	0.006	7.08	0.4	1.0	0.2

component. Optical depth effects in lines will certainly influence the cooling. Local gravity, rotation, radiative acceleration, interactions with winds and relative motions of the star/disk system with respect to the ambient medium will also affect the evolution.

3. MODELS OF PHOTOIONIZED DISKS

First models of photoionized disks were discussed by Hollenbach et al. (1993, 1994), Yorke (1993) and Yorke & Welz (1993, 1994). Common to these models is the existence of a warm ($T \approx 10^4$ K), expanding ionized gas surrounding the neutral disk. The highest densities occur close to the disk and the time scales of disk photoevaporation are sufficiently long ($t_{\rm evap} \gtrsim 10^5$ yr) to explain the large number of observed UCHIIs. The detailed density and velocity structure of the ionized outflow depends on the assumed parameters (ionization rate, disk structure, stellar wind velocity and wind luminosity), so that one can in principle learn something about these parameters by studying the outflow.

3.1. Semi-Analytical Models

Hollenbach et al. stressed the importance of the diffuse ionizing component and by using a combination of analytical and semi-analytical methods was able to find simple expressions for calculating mass loss rates from the disks and disk destruction time scales over a wide range of disk and stellar parameters. In their model the disk was considered to be infinitely thin. They find disk mass loss rates $\dot{M}_{\rm evap}$ for the (1) "weak" stellar wind and the (2) "strong" wind cases:

$$\dot{M}_{\rm evap}^{\rm wW} = 1.3 \times 10^{-5}\,{\rm M_\odot\,yr^{-1}} \left(\frac{M_\star}{10\,{\rm M_\odot}}\right)^{1/2} \left(\frac{S_{\rm Lyc}}{10^{49}\,{\rm s^{-1}}}\right)^{1/2} \qquad (1)$$

$$\dot{M}_{\rm evap}^{\rm sW} = 6 \times 10^{-5}\,{\rm M_\odot\,yr^{-1}} \left(\frac{\dot{M}_W}{10^{-5}\,{\rm M_\odot\,yr^{-1}}}\right) \left(\frac{v_W}{1000\,{\rm km\,s^{-1}}}\right) \left(\frac{S_{\rm Lyc}}{10^{49}\,{\rm s^{-1}}}\right)^{-1/2}, \qquad (2)$$

where $M_\star$, $S_{\rm Lyc}$, $\dot{M}_W$ and v_W are the stellar mass, flux of H-ionizing photons, stellar wind mass loss rate and wind velocity, respectively.

3.2. Numerical Models

The models of Yorke & Welz (1993, 1994) are based on hydrodynamical calculations of the evolution of disks under the influence of an ionizing source and winds. In their 1994 paper and for the results presented

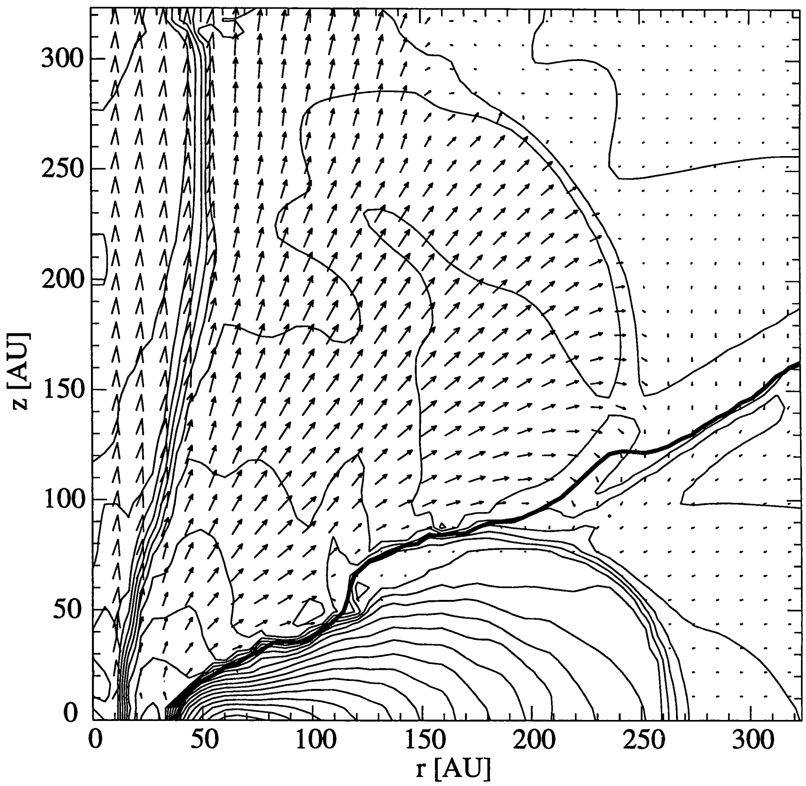

Fig. 2.— Density (solid contour lines) and velocity structure (arrows) of 1.6 $M_\odot$ disk surrounding a 8.4 $M_\odot$ star 39 yr after a central wind (velocity: $v_W = 600\ \mathrm{km\,s^{-1}}$; luminosity: $L_W = 0.15\ L_\odot$) and a central H-ionizing source ($S_{\mathrm{uv}} \approx 7 \times 10^{46}\ \mathrm{s^{-1}}$) have been turned on (see Tab. 1). The thick line denotes the location of the ionization front which separates the neutral disk material from the warm ($T \approx 10^4$ K) outflowing ionized gas. Velocities greater than 45 $\mathrm{km\,s^{-1}}$ are indicated by open arrowheads. Density contour intervals are $\Delta \log \rho = 0.4$.

here the following physical processes were taken into account: 1) 2D hydrodynamics (axial symmetry), 2) self-gravity, 3) time dependent ionization/recombination of hydrogen, 4) transfer of radially directed stellar photons, 5) production of and transfer of ionizing photons resulting from recombinations directly into the ground state of hydrogen (flux-limited diffusion), 6) time dependent heating/cooling (optically thin approximation for cooling in ionized region; temperature equilibrium with grains in neutral regions), and 7) a central stellar wind of a given velocity and mass loss rate. The use of flux-limited diffusion in a multi-grid hydrodynamic code is described by Yorke & Kaisig (1995). A complete description of the numerical problem and the results of several calculations including theoretical isophote maps are forthcoming. As starting conditions the disk resulting from the "standard" case of Yorke et al. (1995) was used.

The structure of the ionized region and the distribution of density and velocity obtained in three numerical simulations are shown in Fig. 2 ("moderate" stellar wind), Fig. 3 ("very strong" stellar wind), and Fig. 4 ("weak" stellar wind). Note that hydrodynamic collimation along the rotation axis occurred for the moderate wind case, whereas the disk was significantly disturbed on a short time scale under the influence of the very strong wind. The disk has evolved into an outward expanding torus. Estimates of mass loss due to photoevaporation obtained from the numerical calculations (see Tab. 1) are comparable to the semi-analytical "weak wind" estimates of Hollenbach et al. (1994). The "strong wind" formula does not apply for the "very strong" wind case depicted in Fig. 3, presumably because the necessary prerequisites (the wind should have little effect on the disk structure) do not apply. Rayleigh-Taylor and Kelvin "water wave"-type instabilities could lead to disk destruction for this case. For the case depicted in Fig. 4 a steady-state ionized outflow resulted. The disk became slightly more flattened during the course of evolution.

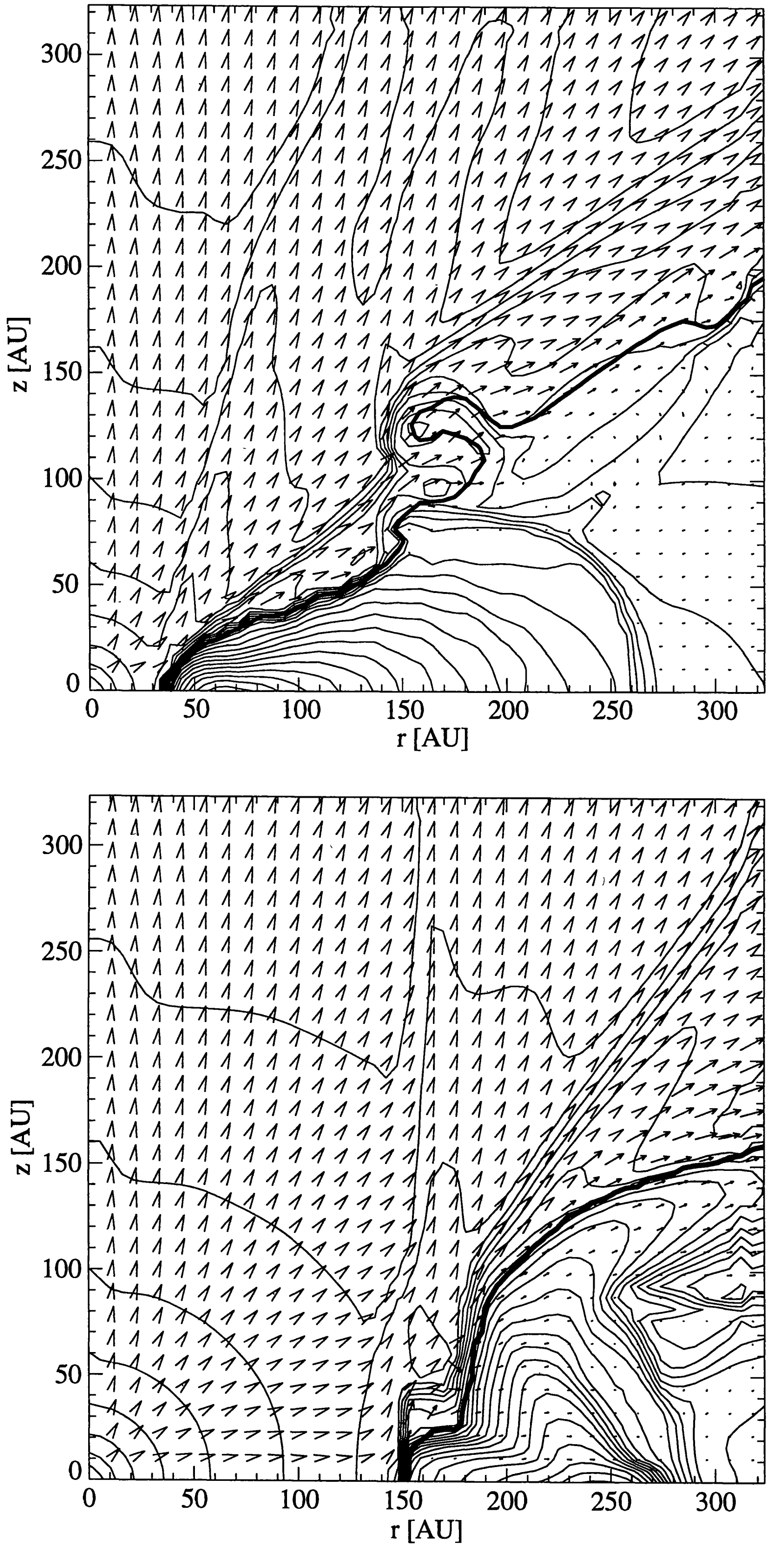

Fig. 3.— Same as Fig. 2, except for a higher assumed wind luminosity $L_W = 2.97$ $L_\odot$ and a lower ionization rate ($S_{\rm uv} = 0.35 \times 10^{46}$ s^{-1}). Two evolutionary times, $t = 41$ yr (top) and $t = 150$ yr (bottom) are shown.

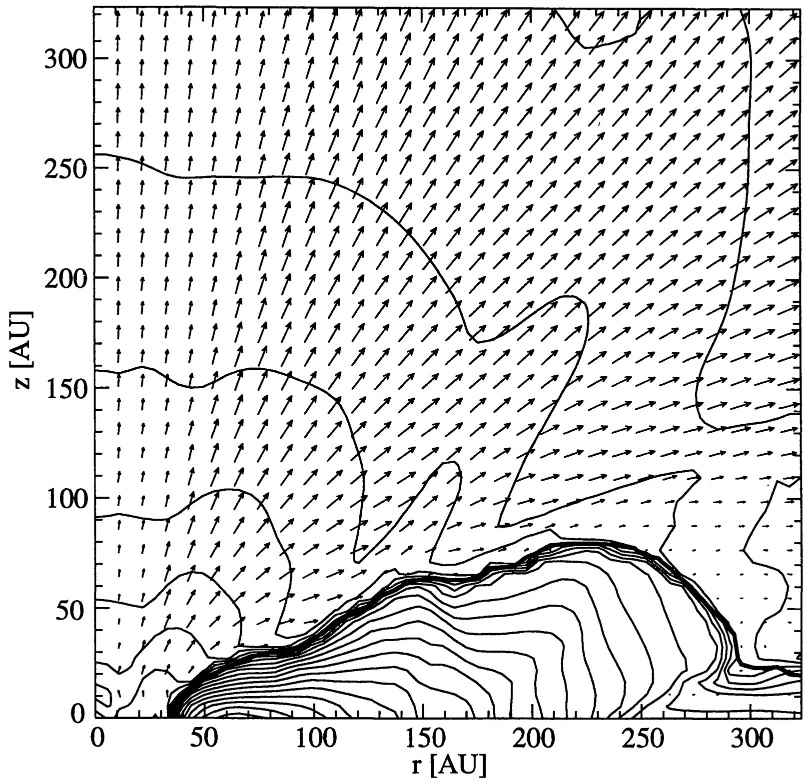

Fig. 4.— Same as Fig. 2, except that a negligible wind was assumed. The evolutionary time t = 575 yr is shown.

4. SUMMARY

The results can be summarized as follows: 1) The case shown in Fig. 2 demonstrates that hydrodynamically confined jets are possible. 2) If disks are a common phenomenon of massive star formation, photoionized disks must be an important evolutionary phase. Presumably many UCHII can be identified with this phenomenon. 3) As shown in Fig. 3 the existence of powerful stellar winds could seriously affect the structure of circumstellar disks on a much shorter time scale than by photoionization alone. This may be the limiting mechanism for disks around high mass stars and explain why no such disk around an O star has been detected. 4) Because external sources of ionizing radiation are available and because many young low mass stars display a high degree of activity which lead to ionizing radiation, photoionized disks may be a more general phenomenon associated with star formation, extending also to lower mass star/disk systems. The presence of hydrogen-ionizing radiation and/or stellar winds can affect the disk structure significantly. Detailed numerical modeling of proplyds will have to include these effects.

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