The Influence of External UV Radiation on the Evolution of Protostellar Disks

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Abstract

We investigate the interaction of an external UV radiation field with protostellar disks of low-mass stars using 2D radiation hydrodynamical simulations. The disks are gradually destroyed via photoevaporation as the UV photons heat the gas in the outer layers of a disk to thermal escape velocities. Beside the UV flux and the luminosity of the stellar wind from the central star, the evolutionary state of the star-disk system at the onset of the external illumination determines the size and the form of the ionized envelope and the resulting spectral appearance of the object. Disks irradiated before one free-fall time after the collapse of the parental molecular cloud lose much of the associated material during the first 10^4 yr of evolution. The star-disk systems remain extremely small in comparison to star-disk systems first irradiated at later evolutionary phases, where the central objects are more massive and much of the clouds mass is already bound in the accretion disk. These results suggest that an early UV illumination favors the formation of low-mass cluster members.
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1. Numerical Methods

We follow the evolution of protostellar disks under the influence of an external radiation field (Fig. 1.) by means of a 2D radiation hydrodynamics code. The code assumes axial symmetry and solves the hydrodynamical equations on nested grids (Yorke & Kaisig, 1995). The transfer of direct UV photons is calculated along lines of sight centered at the star located outside the computational domain. Diffuse UV photons originating from the recombination of hydrogen into the ground state and from scattering on dust grains are treated with the flux-limited diffusion approximation. Simultaneously, we determine the ionization of hydrogen and carbon. A detailed description of the code is given in Richling & Yorke (1998, 2000).

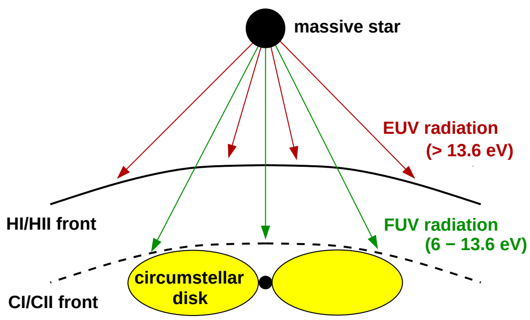

Figure 1: The ionizing radiation of a massive star interacts with a protostellar disk nearby. Both UV components are important.

In a second step, we use the density and temperature distribution of the gas and the velocity field obtained with the hydrocode to calculate emission line maps, continuum maps and spectral energy distributions via a ray-tracing procedure (Kessel et al., 1997). These diagnostic radiative transfer calculations allow us a direct comparison with observations.

2. Ionized Envelope and Micro-Jets

The calculations start with star-disk systems resulting from collapse simulations (Yorke & Bodenheimer, 1999). After the initial launch of a neutral disk wind by FUV photons, the carbon ionization front envelopes the densest parts of the disk. The hydrogen ionization front is prevented from reaching the disk surface by the interaction with the neutral wind and finally forms an envelope with the typical head-tail structure (Fig. 2a). This structure is the natural outcome of our self-consistent simulations and its properties are comparable to the proplyds observed in the Orion Nebula. The size of the ionized envelope and the photoevaporation rate of the disk depend on the distance from the ionizing star. Disks exposed to a UV radiation field are expected to survive no longer than several 10^5 years (Hollenbach et al., 2000; Richling & Yorke, 2000).

If we consider an isotropic stellar wind emerging from the protostar within the disk, we are able to reproduce another feature of proplyds. The spherically symmetric stellar wind is hydrodynamically focused into a jet due to the pressure of the neutral disk wind. The opening angle of the counter-jet is wider, because the neutral wind on this side of the disk shadowed from direct UV photons is

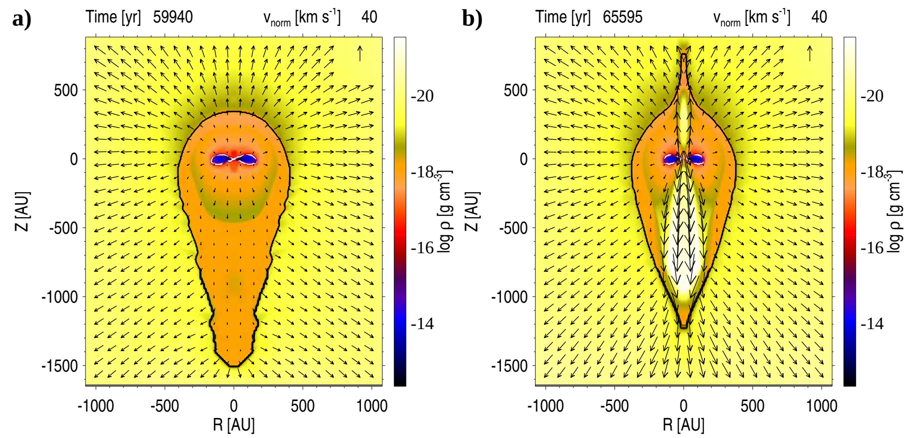

Figure 2: Density distribution, velocity field (arrows), hydrogen ionization front (black contour lines) and carbon ionization front (white contour lines) of a protostellar disk illuminated by an external UV radiation field. a) without a stellar wind b) with an isotropic stellar wind of 100 km/s.

less powerful. The jet changes the form of the ionized envelope as shown in Fig. 2b. In the corresponding emission line maps, the finger in the ionization front appears as a spike emerging from the objects head resembling the micro-jets extending from several proplyds in the Orion Nebula (Fig. 3).

3. The Evolutionary State of the Protostellar Disk

Table 1: Starting models: Elapsed time t since the beginning of collapse, disk radius r_d and mass of the protostar $M_\star$ are given.

Model	$t/10^3$ yr	t/t_ff	r_d/AU	$M_\star/M_\odot$
Y	107	0.5	130	0.64
M	240	1.2	640	0.94
O	438	2.2	1700	1.14

Massive stars evolve relatively fast and reach the main-sequence when low-mass cluster members may still be in earlier phases of evolution. In order to investigate the effect of UV illumination during earlier phases of a protostellar collapse we used three star-disk models at different evolutionary phases all

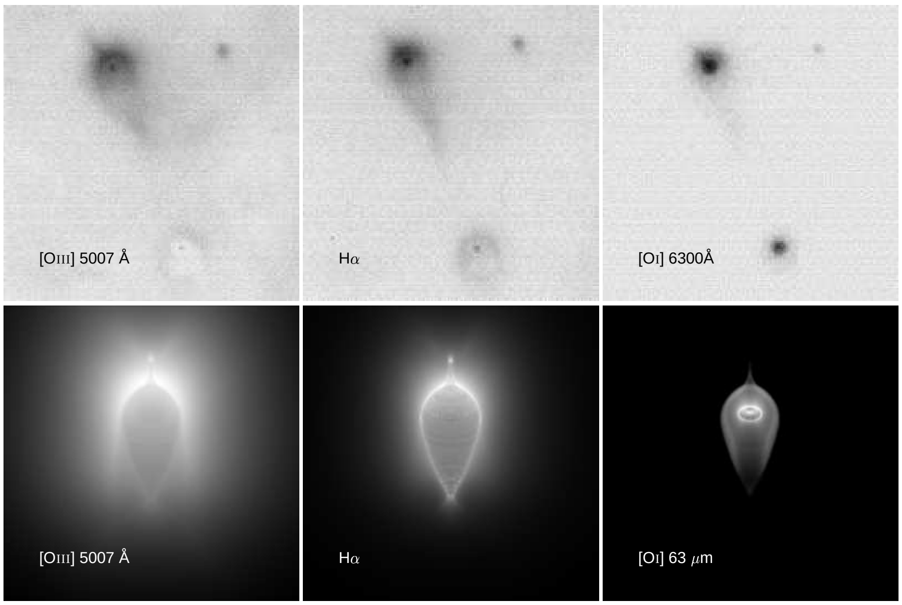

Figure 3: First row: Observed emission line maps of the proplyd HST 2 in M42 (Bally et al., 1998, Fig. 7a). Second row: Calculated emission line maps of the numerical result shown in Fig. 2b. The length of the object is ~ 1500 AU which is about twice as large as HST 2.

resulting from a single collapse simulation of a 2 $M_\odot$ rotating molecular cloud (Table 1).

Fig. 4 shows continuum maps of the three models after 5×10^4 yr of external UV illumination. In the first row are 2 cm radio maps of the whole object. They trace the free-free emission of the dense ionized gas around the head-tail envelope. In the second row are 100 μm maps of an inner part of the domain as indicated in the radio maps. They show the dust emission of the disk itself. The evolution of the mass and the radius of the disk are shown in Fig. 5.

Model Y is younger than one free-fall time of the parental molecular cloud core. Most of the material in its environment is ionized and swept away with the ionized wind during the first 10^4 yr of the evolution. Only a small object remains which will be photoevaporated relatively quickly. The older the starting model the larger is the ionized envelope and the length of the tail. Since the

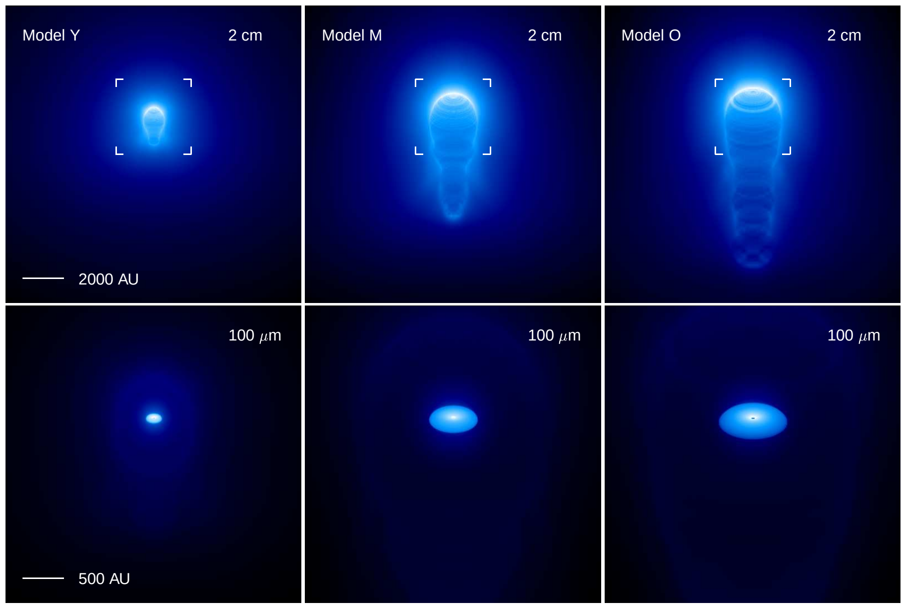

Figure 4: Continuum maps of the models Y, M and O (see Table 1) after 5×10^4yr of external UV illumination.

photoevaporation rate depends on the surface of the disk, model M will survive longer than model O because model O has a larger disk radius during the first 10^5 yr of evolution.

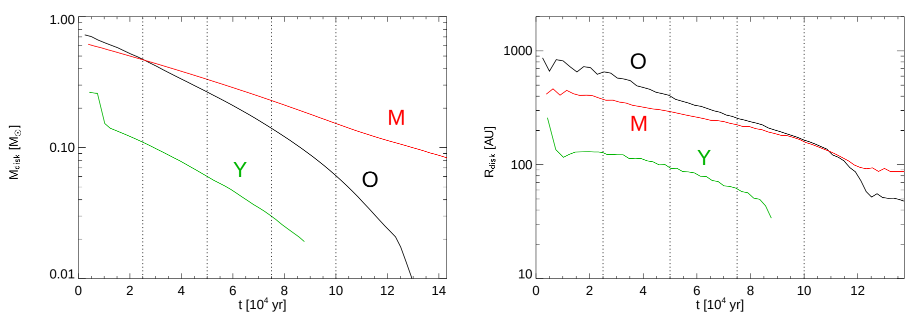

Figure 5: Evolution of mass and radius of the disk.

4. Conclusions

The photoevaporating disk model can explain the observed features of proplyds, e.g. the head-tail structure, the stand-off of the ionization front and the appearance of micro-jets. Photoevaporation is an important disk dispersal mechanism with a time scale of several 10^5 yr which is an upper limit for the time available for planet formation.

The evolutionary state of the protostellar disk at the time when the external UV illumination begins also determines the size and the spectral appearance of the resulting object. UV irradiation during early phases of a protostellar collapse removes the material that otherwise would be accreted onto the disk and finally onto the protostar itself. Thus, an early UV illumination favors the formation of low-mass cluster members and possibly is a mechanism for brown dwarf and brown dwarf disk formation.

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