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WWW DATABASE OF MODELS OF ACCRETION DISKS IRRADIATED BY THE CENTRAL STAR

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RESUMEN

Anunciamos la publicación de un catálogo de modelos físicos de discos de acreción alrededor de estrellas jóvenes, irradiados por la estrella central, los cuales están basados en las técnicas de modelización de D'Alessio et al. El catálogo WWW incluye $\sim$ 3000 modelos de disco para diferentes estrellas centrales, tamaños del disco, inclinaciones del disco, contenidos de polvo y tasas de acreción de masa. Para cada uno de ellos, los perfiles radiales de las propiedades físicas del disco y distribuciones espectrales de energía sintéticas se pueden consultar o descargar desde la página web para compararlos con observaciones. El catálogo está accesible en `http://cfa-www.harvard.edu/youngstars/dalessio/` (EEUU), `http://www.astrosmo.unam.mx/~dalessio/` (México), y en `http://www.laeff.esa.es/models/dalessio/` (España).

ABSTRACT

We announce the release of a catalog of physical models of irradiated accretion disks around young stars based on the modelling techniques by D'Alessio et al. The WWW catalog includes $\sim$ 3000 disk models for different central stars, disk sizes, inclinations, dust contents and mass accretion rates. For any of them, radial profiles of disk physical parameters and synthetic spectral energy distributions can be browsed and downloaded to compare with observations. The catalog can be accessed at `http://cfa-www.harvard.edu/youngstars/dalessio/` US), `http://www.astrosmo.unam.mx/~dalessio/` (México), and at `http://www.laeff.esa.es/models/dalessio/` (Spain).

Key Words: **ACCRETION DISKS — ASTRONOMICAL DATA BASES — STARS: PRE-MAIN SEQUENCE**

1. INTRODUCTION

The old idea that stars are born surrounded by disks, which may form planetary systems, has found strong observational support in the last couple of decades. The properties of these disks are quantified from the comparison between different observations and models. For instance, disk mass accretion rates have been inferred from the analysis of the short wavelength excess, modeled as produced by accretion shocks at the stellar surface (Hartigan, Edwards, & Ghandour 1995; Gullbring et al. 1998; Calvet & Gullbring 1998; Hartmann et al. 1998). Also, mass accretion rates and inner disk radii have been estimated from models of different line emission profiles thought to form in the magnetospheric flows connecting the disks to their central stars (Muzerolle et al. 1998a, b, and c; Muzerolle et al. 2001). Kinetic information on disks, central star masses, details of the vertical temperature distribution and molecular abundances are quantified from detailed analysis of different molecular lines (e.g., Dutrey et al. 1996; Dutrey, Guilloteau, & Guelin 1997; Guilloteau & Dutrey 1998; Simon, Dutrey, & Guilloteau 2000; Najita et al. 2000; Dartois, Dutrey & Guilloteau 2003; Aikawa et al. 2002, 2003; Qi et al. 2003; Carr, Tokunaga, & Najita 2004). Other disk properties, such as masses, degree of flaring of the disk surface and dust properties, are inferred from the spectral energy distributions (SEDs) of young stars, from near IR to radio-frequencies, using different kinds of disk mod-

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TABLE 1

PARAMETERS FOR THE CENTRAL STARS AND DISKS IN THE LIBRARY OF DISK MODELS

Central Star						Irradiated Accretion Disk Models			
$T_{\rm eff}$ K	SpType	Age Myr	L_* $L_\odot$	R_* $R_\odot$	M_* $M_\odot$	$\dot{M}$ $M_\odot$ yr^{-1}	$L_{\rm acc}$ $L_\odot$	$R_{\rm wall}$ AU	$R_{\rm wall}$ R_*
4000	**K7**	**1**	1.60	2.64	0.70	1×10^{-9}	0.009	0.11	8.65
						1×10^{-8}	0.087	0.11	8.88
						1×10^{-7}	0.869	0.13	10.68
						1×10^{-6}	8.694	0.27	21.58
4000	**K7**	**10**	0.31	1.16	0.80	1×10^{-9}	0.022	0.05	8.97
						1×10^{-8}	0.217	0.06	11.31
						1×10^{-7}	2.167	0.13	24.52
						1×10^{-6}	21.67	0.39	73.05
4500	**K4**	**1**	3.76	3.20	1.40	1×10^{-9}	0.014	0.16	10.92
						1×10^{-8}	0.137	0.17	11.15
						1×10^{-7}	1.375	0.19	12.80
						1×10^{-6}	13.75	0.35	23.63
4500	**K4**	**3**	1.60	2.08	1.34	1×10^{-9}	0.020	0.11	11.06
						1×10^{-8}	0.202	0.11	11.67
						1×10^{-7}	2.024	0.16	16.54
						1×10^{-6}	20.24	0.39	40.61
4500	**K4**	**10**	0.60	1.28	1.10	1×10^{-9}	0.027	0.07	11.18
						1×10^{-8}	0.270	0.08	13.17
						1×10^{-7}	2.700	0.15	25.65
						1×10^{-6}	27.00	0.44	74.19
5000	**K1**	**1**	14.86	5.14	3.00	1×10^{-9}	0.018	0.32	13.56
						1×10^{-8}	0.184	0.33	13.64
						1×10^{-7}	1.834	0.34	14.37
						1×10^{-6}	18.34	0.48	20.26
5000	**K1**	**10**	1.72	1.75	1.40	1×10^{-9}	0.025	0.11	13.64
						1×10^{-8}	0.251	0.12	14.50
						1×10^{-7}	2.514	0.17	21.25
						1×10^{-6}	25.14	0.43	53.52
6000	**G0**	**1**	59.10	7.13	3.50	1×10^{-9}	0.015	0.65	19.49
						1×10^{-8}	0.154	0.65	19.51
						1×10^{-7}	1.542	0.65	19.74
						1×10^{-6}	15.42	0.73	21.88
6000	**G0**	**10**	5.91	2.25	1.60	1×10^{-9}	0.020	0.20	19.56
						1×10^{-8}	0.223	0.21	19.89
						1×10^{-7}	2.234	0.24	22.92
						1×10^{-6}	22.34	0.45	42.70

TABLE 1 (CONTINUED)

Central Star						Irradiated Accretion Disk Models			
$T_{\rm eff}$ K	SpType	Age Myr	L_* $L_\odot$	R_* $R_\odot$	M_* $M_\odot$	$\dot{M}$ $M_\odot$ yr^{-1}	$L_{\rm acc}$ $L_\odot$	$R_{\rm wall}$ AU	$R_{\rm wall}$ R_*
7000	**F1**	**1**	130.39	7.78	4.00	1×10^{-9}	0.016	0.96	26.53
						1×10^{-8}	0.161	0.96	26.54
						1×10^{-7}	1.615	0.97	26.69
						1×10^{-6}	16.15	1.02	28.12
7000	**F1**	**10**	11.02	2.20	1.70	1×10^{-9}	0.024	0.28	27.30
						1×10^{-8}	0.243	0.28	27.57
						1×10^{-7}	2.428	0.31	30.13
						1×10^{-6}	24.28	0.50	48.81
8000	**A6**	**1**	165.08	6.70	4.0	1×10^{-9}	0.019	1.08	34.71
						1×10^{-8}	0.188	1.08	34.71
						1×10^{-7}	1.879	1.09	34.90
						1×10^{-6}	18.79	1.14	36.63
8000	**A6**	**10**	12.62	1.85	1.9	1×10^{-9}	0.032	0.30	34.75
						1×10^{-8}	0.322	0.30	35.15
						1×10^{-7}	3.227	0.33	38.89
						1×10^{-6}	32.27	0.56	65.46
9000	**A2**	**1**	215.39	6.05	4.0	1×10^{-9}	0.021	1.23	43.84
						1×10^{-8}	0.207	1.23	43.86
						1×10^{-7}	2.077	1.24	44.05
						1×10^{-6}	20.77	1.29	45.91
9000	**A2**	**3**	71.00	3.47	2.7	1×10^{-9}	0.024	0.71	43.90
						1×10^{-8}	0.244	0.71	43.94
						1×10^{-7}	2.445	0.72	44.64
						1×10^{-6}	24.45	0.82	50.89
9000	**A2**	**10**	17.08	1.70	2.0	1×10^{-9}	0.037	0.34	43.99
						1×10^{-8}	0.370	0.35	44.41
						1×10^{-7}	3.697	0.38	48.46
						1×10^{-6}	26.97	0.62	78.16
10,000	**B9.5**	**1**	251.94	5.30	4.0	1×10^{-9}	0.024	1.33	54.13
						1×10^{-8}	0.237	1.33	54.15
						1×10^{-7}	2.371	1.34	54.38
						1×10^{-6}	23.71	1.40	56.62
10,000	**B9.5**	**10**	29.20	1.80	2.3	1×10^{-9}	0.040	0.45	54.30
						1×10^{-8}	0.402	0.46	54.63
						1×10^{-7}	4.015	0.48	57.87
						1×10^{-6}	40.15	0.70	83.62

els (e.g., Kenyon & Hartmann 1987; Beckwith et al. 1990; Calvet et al. 1991, 1992; Malbet & Bertout 1991; Beckwith & Sargent 1991; Chiang & Goldreich 1997, 1999; D'Alessio et al. 1998, 1999; D'Alessio, Calvet, & Hartmann 2001; Dullemond, Dominik, & Natta 2001; Dullemond, van Zadelhoff, & Natta 2002; Dullemond 2002; Malbet, Lachaume, & Monin 2001; Lachaume, Malbet, & Monin 2003). These models go from simple power-law descriptions of the disk mass surface density, temperature and opacity, to detailed models where different heating mechanisms are included, and where the radiative transfer and dust opacity are calculated with different degrees of sophistication. Disks have been also imaged at near IR (e.g., Stapelfeldt et al. 1998; Koresko 1998; Malbet et al. 1998; Weinberger et al. 1999; Padgett et al. 1999; Tuthill et al. 2002; Colavita et al. 2003), mid IR (e.g., McCabe, Duchêne, & Ghez 2003) and millimeter wavelengths (Dutrey et al. 1996; Wilner, Ho, & Rodríguez 1996; Rodríguez et al. 1998; Mannings & Sargent 2000). Analysis of these observations with different models has given information about the radial and vertical structures of the disks. In general, models with some degree of complexity are required to fit multi-wavelength observations of a given object (e.g., Lay, Carlstrom, & Hills 1997; Wilner & Lay 2000).

In the present paper we describe a database with a series of models of disks around pre-main sequence stars. These models, which are described in detail in Merín (2004), are self-consistently calculated given the properties of the central star, the disk and its dust, using the methods developed by D'Alessio et al. (1998, 1999, 2001). We make these models available with the hope that they can be useful for fitting observations of young stars, helping to extract more information than simpler and usually faster approaches. In a forthcoming paper (Merín et al. 2005), relationships between disk, star and dust parameters and observable quantities such as spectral indices, colors, etc., will be presented and discussed in detail, to enable a faster search for the best model fit to the observations of a given disk or a survey of disks. In addition, comparison of models in this database with other modelling efforts will be helpful to test the underlying assumptions in each set of models. Finally, we hope that this database will help to increase our knowledge of the intrinsic properties of the disks around young stars.

2. DISK MODELS

The disk models from D'Alessio et al. (1998, 1999, 2001) have the following characteristics:

- Energy is transported by radiation, convection and a turbulent flux, the first one being the most important mechanism given the disk parameters we have explored in this work.
- The disk mass surface density distribution is a consequence of conservation of angular momentum flux given the functional form of the viscosity coefficient and the disk mass accretion rate.
- The gas and dust are in thermal balance, and are heated by viscous dissipation, stellar irradiation, and ionization by energetic particles (from cosmic rays and radioactive decay). For the set of parameters of models in the database, viscous dissipation is important in regions close to the star and at the disk midplane, while stellar irradiation is important for most of the disk.
- The fraction of the stellar radiative flux intercepted by the disk is evaluated at the surface where the mean radial optical depth to the stellar radiation is unity. This surface is self-consistently calculated given the disk structure and properties of its dust, and the intercepted flux is used as a boundary condition in the integration of the radiative transfer equation.

The models are based on the following simplifying assumptions:

- The disk is in steady state, with a mass accretion rate $\dot{M} = dM/dt$.
- The disk is geometrically thin: $H/R << 1$, where H is the gas scale height of the disk and R is the radial distance. With this assumption, the vertical and radial structures can be calculated separately.
- The viscosity coefficient is given by $\nu = \alpha\, H\, c_s$, following the α-prescription from Shakura & Sunyaev (1973), where c_s is the local sound speed and α is the viscosity parameter, assumed to be constant through the disk. The turbulent flux of energy is calculated consistently with the α prescription, assuming a Prandtl number $P_r = 1$.
- Dust and gas are well mixed in the entire disk, i.e., the dust to gas mass ratio of each dust ingredient and the grain size distribution are both taken to be constant in those regions where the temperature is lower than the sublimation temperature.
- Dust and gas are in thermal equilibrium and a unique temperature is calculated for both components.
- The radiation field is considered in two separate regimes: stellar radiation (UV, optical and near IR) and disk radiation (IR to radio wavelengths), and we use mean opacities calculated with appropriate weighting functions to describe the interaction of both fields with the disk material.

- The radiative transfer in each regime is calculated by solving the two first moments of the radiative transfer equation.
- The inner disk is truncated at the dust destruction radius and the inner cylindrical surface ("the wall") emits as a blackbody of 1400 K (Natta et al. 2001; Muzerolle et al. 2003). This is a new feature added to the models, which has not been included in the models described in the previous papers (D'Alessio et al. 1998, 1999, 2001). We follow the prescriptions in D'Alessio (2003) to calculate the emission from the wall, taking into account the contributions of the stellar and accretion luminosities to calculate the position of the dust destruction radius, and the dependence on inclination of the emitting area. More specifically, we compute the inner disk radii with eq. (3) from Muzerolle et al. (2003) where we take $q\chi_d/\kappa_d = 2.5$, which gives the best fits to the excess near-IR continuum in classical T Tauri disks. Then, we assume a fixed ratio between the height of the wall and the scale height at the dust destruction radius, $z_{\rm wall} = 4H$. However, we list separately the disk and wall contributions, allowing the user to include different heights or radii for the wall.

2.1. *Comparison with Observations*

The synthetic SED of a model calculated for typical stellar parameters, mass accretion rate, disk radius, inclination angle and a dust grain size distribution with millimeter-sized grains, fits the median observed SED of the classical T Tauri stars in the Taurus Molecular Cloud (see D'Alessio et al. 2001). Also, Merín et al. (2004) used the models to fit the detailed SEDs of two HAeBe stars (namely HD 34282 and HD 141569) and showed that not only the age was responsible for the disk evolution but also that the metallicity could play an important role.

Allen et al. (2004) have constructed color-color diagrams for different clusters using observations from IRAC-Spitzer. They find three distinctive regions in the diagrams: one corresponding to stars without IR excess, other for classical T Tauri stars and another for embedded objects. The synthetic IRAC colors of a subset of models from this library ($T_* = 4000$ K and age=1 Myr) agree very well with those of observed classical T Tauri stars (see also Sicilia-Aguilar et al. 2005; Hartmann et al. 2005).

It is important to mention that it is very difficult, if not impossible, to constrain the model parameters by considering only the SED of a given object. The main problem is that the SED is given by the monochromatic flux emerging from whole disk, i.e., it is a *spatially integrated* quantity. Thus, detailed information on the spatial distribution of the emergent intensity, which is more directly related to the disk structure, is hidden in the flux. Fortunately, different parts of the SED are sensitive to different combination of disk parameters, but more than one of these combinations can produce the same emergent flux from the disk in a particular wavelength range. For instance, the near IR SED is dominated by the emission of the wall at the dust sublimation radius. For a given sublimation temperature, different silicate composition, grain sizes, total (stellar and accretion shock) luminosities result in different values of the sublimation radius, but different inclination angles and wall heights can be assumed to obtain a similar wall SED. In principle, a SED which spans a wide range of wavelengths (from UV to radio-frequencies) might help to disentangle some of the disk properties when a self-consistent model is used. For instance, the continuum at mid-IR emerges from optically thick zones of the disk. In this spectral range, the emergent flux depends on the disk mass accretion rate (if the accretion luminosity is similar to, or larger than, the stellar luminosity), the disk inclination angle, and the grain composition and size distribution (which determines the height of the irradiation surface). The 10 and 18 μm silicate bands reflect the silicate composition and grain sizes in the atmosphere; thus, a self-consistent model should have the same type of grains producing the observed features and absorbing the stellar radiation which determines the disk vertical temperature distribution and its mid-IR emergent continuum. However, not all the degeneracy can be removed by modelling the SED alone, specially if the dust at the midplane in the outer disk has a size distribution different from that of the dust in the atmosphere in the inner disk, which is expected if dust is settling and growing in disks. The only way to remove all possible degeneracies is when the SED and images of a self-consistent model are compared to multi-frequency high angular resolution observations. In this first release of the catalog we are making available only SEDs, but intensity distributions at different wavelengths can be calculated upon request for a given set of model parameters.

3. WEB-BASED MODEL LIBRARY

We have constructed a grid of models for different central stars and a range of values for the physical parameters of the disk and its dust.

For the central stars, we chose 17 stars with spectral types from K7 to B9 ($T_{\rm eff} = 4000 - 10,000$ K, respectively) and ages of 1 and 10 Myr. Stellar parameters were taken from the pre-main sequence tracks by Siess, Dufour, & Forestini (2002).

For the disk, we considered four values of the accretion rate, namely $\dot{M} = 10^{-6}, 10^{-7}, 10^{-8}, 10^{-9}$ $M_{\odot}$/yr, a typical viscosity parameter $\alpha = 0.01$, three values of the disk radius $R_{\rm disk} = 100, 300, 800$ AU and two inclination angles $i = 30, 60$ degrees.

For the dust we use the abundances proposed by Pollack et al. (1994), a grain size distribution given by $n(a) = a^{-p}$ with $p = 3.5, 2.5$, with a minimum size typical of interstellar grains ($a_{\rm min} = 0.005\,\mu$m) and six different maximum grain sizes $a_{\rm max} = 1$, 10, 100 μm, 1 mm, 1 cm, 10 cm.

Columns (1) to (6) of Table 1 show the stellar effective temperatures, spectral types, ages, radii, masses and luminosities for the central stars in the grid of disk models, Column (7) lists the mass accretion rates of the disks, Column (8) has the accretion luminosity, and Columns (9) and (10) show the wall radius, in astronomical units and in stellar radii. Notice that, for a given central star, the wall radius increases with mass accretion rate, reflecting the fact that we are including the irradiation from the accretion shocks at the stellar surface as an additional heating source of the dust (see Muzerolle et al. 2003).

The disk models were computed in parallel with Linux PCs at the Harvard-Smithsonian CfA (MA, US), LAEFF (Madrid, Spain) and the Linux cluster `nostromo` at the CRyA (Morelia, México) and used a total CPU time of approximately 8000 hours.

4. CONCLUDING REMARKS

The WWW catalog contains currently more than 3000 model SEDs and disk structures. We hope this library of models will be a valuable tool for analyzing the SEDs of young stars surrounded by accretion disks. It is a dynamical website. We plan to continue filling the catalog with the emission maps and new disk models with different degrees of dust settling to the midplane.

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