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ACCRETION DISKS AROUND YOUNG LOW MASS STARS

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RESUMEN

En la pasada década se ha vuelto claro que casi la mitad de las estrellas de baja masa pre-secuencia principal poseen discos, que son los responsables de los excesos de emisión observados en el infrarrojo y en el óptico-UV. La caracterización de la estructura de los discos circunestelares es crucial para entender la evolución temprana de estrellas y la formación de planetas. La tésis que se resume en esta contribución presenta modelos físicos de la estructura detallada de discos de acreción en torno a estrellas T Tauri. Los discos se suponen en estado estacionario, en equilibrio hidrostático en la dirección vertical y con un coeficiente de viscosidad turbulenta descrito por la prescripción α. Hemos considerado diferentes mecanismos de calentamiento, como disipación viscosa, calentamiento por ionización debido a rayos cósmicos y decaimiento radioactivo, e irradiación del disco por la estrella central o por una envolvente en colapso. La energía es transporatada en la dirección vertical por radiación, convección y flujo turbulento. Dada la estructura de un disco, calculamos su emisión integrando la ecuación de transporte radiativo considerando una orientación arbitraria del disco respecto a la visual. Los espectros (SEDs) e imágenes se comparan con observaciones, y se infieren o constriñen sus propiedades físicas.

ABSTRACT

In the past decade, it has become clear that almost half of the low mass pre-main sequence stars are surrounded by disks, which are responsible for the observed infrared and optical-UV excess emission. The characterization of the structure of circumstellar disks is a crucial step towards understanding the early stellar evolution and planet formation. The thesis summarized here presents physical models of the detailed structure of accretion disks surrounding T Tauri stars. The disks are assumed to be in steady state, in vertical hydrostatic equilibrium, and with a turbulent viscosity described by the alpha-prescription. We consider different heating mechanisms: viscous dissipation, heating by cosmic rays and radioactive decay, irradiation by the central star or irradiation by an infalling envelope. The energy is transported in the vertical direction by radiation, convection and the turbulent flux. Given the disk structure, we calculate its emission by integrating the radiative transfer equation for an arbitrary orientation of the disk relative to the line of sight. Spectral energy distributions (SEDs) and images are compared with observations, and disk properties can be inferred or constrained.

Key Words: **ACCRETION: ACCRETION DISKS — PHYSICAL DATA AND PROCESSES —STARS: CIRCUMSTELLAR MATTER — STARS: FORMATION — STARS: PRE-MAIN SEQUENCE**

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1. INTRODUCTION

There is a compelling set of observational evidence of the presence of disks around young stars. For instance, the geometry of the Solar System suggests it has been formed by a flat distribution of mass. Moreover, the Sun has 98% of the total mass of the system, but only 2% of the total angular momentum, and the planetary orbits are almost circular. These properties support the idea that the Solar Nebula was a *viscous* disk, in which angular momentum was transported outwards, energy was dissipated, and a fraction of disk mass fell towards the central proto-Sun (Pringle 1981).

Also, Classical T Tauri Stars (CTTS) show an excess of emission with respect to a photosphere with the same spectral type (inferred in the optical range). This excess can be seen in optical-ultraviolet wavelengths (Smak 1964) and at longer wavelengths, $\lambda > 2\ \mu m$ (Rucinski 1985; Beckwith et al. 1990). The long wavelength excess is explained as emission of dust with a wide temperature range $T \sim 10 - 2000$ K. In particular, the lack of a correlation between the excess of emission and the optical extinction coefficient towards the central star, suggests a flat distribution of dust (Strom et al. 1989; Beckwith et al. 1990). So, disks and not spherical envelopes, seem to be responsible for the IR-mm excess in CTTS, with some exceptions [e.g., HL Tau, T Tau, see Calvet et al. (1994)]. The short wavelength excess is thought to arise from an accretion shock at the surface of the star. The magnetospheric model (Königl 1991) proposes that the accretion disk is disrupted at a few stellar radii by the magnetic field of the central star, and disk material falls onto the star along the magnetic field lines at supersonic velocities. This material is incorporated into the stellar surface through an accretion shock (Calvet & Gullbring 1998). The material falling towards the star at nearly free-fall velocities produces emission lines with inverse P Cygny profiles and other properties (see Muzerolle et al. 1998a,b,c, and references therein) which have been observed (e.g., Edwards et al. 1994). The luminosity of these lines and the luminosity of the veiling continuum in the optical-UV range are strongly correlated (Muzerolle et al. 1998c), as predicted by the magnetospheric model. The spectra of CTTS also show forbidden lines from [OI], [SII], etc, with asymmetric and blue-shifted profiles. The current explanation of this result is that forbidden lines are formed in the wind, and the disk acts as an opaque screen, which absorbs the emission from the receding part of the wind (Appenzeller et al. 1984; Edwards et al. 1987).

With the advent of mm interferometers and *HST*, it became possible to obtain direct images of disk-like structures surrounding pre-main sequence objects. Observations of the CTTS HL Tau in radio wavelengths using different interferometers (VLA, JMCT-CSO, BIMA) resolve an elongated structure with $R \sim 60-150$ AU, perpendicular to the optical jet (Rodríguez et al. 1992; Lay et al. 1994; Wilner, Ho & Rodríguez 1996). *HST* observations of Orion show disk-like structures seen in silhouette against the bright nebular background, with low-mass pre-main sequence stars at their centers (McCaughrean & O'Dell 1996). *HST* has also imaged edge-on disks in HH 30 (Burrows et al. 1996) and HK Tau/c (Stapelfeldt et al. 1998); in these cases, the disk blocks out direct light from the star, but stellar light scattered by the disk curved atmosphere is seen as an extended nebula.

In the current paradigm for formation of a single low mass star (see Shu, Adams & Lizano 1987; Hartmann 1998), a fragment of a molecular cloud collapses because its self-gravity cannot be counteracted by any other force. Since the angular momentum of the fragment is non-zero, it forms a flat structure (Terebey, Shu & Cassen 1984). Turbulent viscosity in this disk transports angular momentum outwards, dissipates energy and in this way, a fraction of disk matter can fall into the gravitational potential well. It is an *accretion disk*, which is heated by the energy produced by viscous dissipation (Lynden-Bell & Pringle 1974; Pringle 1981), but also by the impinging radiation from the central star (e.g., Kenyon & Hartmann 1987) or by the ambient medium (Natta 1993; Butner et al. 1991).

In the thesis (D'Alessio 1996), we construct physically motivated models of accretion disks around young low mass stars and quantify observables (e.g., SEDs, colors, images) which can be used as diagnostics of disk properties. In this contribution we summarize the basic results of this thesis and some of the applications of our models to understand specific observations.

2. MODEL

We assume that the disk is in steady state, i.e., all its properties are time independent. In particular, we take its mass accretion rate ($\dot{M}$) as constant in time and space, and it is one of the parameters which characterize the disk model. The disk is considered to be in vertical hydrostatic equilibrium, and is assumed to be geometrically thin, so the radial energy transport is neglected and the vertical and radial structures are decoupled (Lynden-Bell & Pringle 1974; Pringle 1981). The viscosity is described using the α prescription (Shakura & Sunyaev 1973), with a viscosity coefficient written as $\nu_t = \alpha c_s H$, where c_s is the local sound speed, H is the local scale height of the gas and α is the viscosity parameter, which is the other important parameter that characterizes a given disk model. The scale height is $H = c_s(T)/\Omega$, where Ω is the angular Keplerian velocity and T is the local temperature. A characteristic scale height of the disk is H_c, calculated with the sound speed evaluated at the midplane temperature T_c. The disk has azimuthal symmetry, and its equations are written in cylindrical coordinates (R, z), where R is the radial distance from the star, in a direction parallel to the disk midplane, and z is the vertical distance from the midplane, in a direction parallel to the rotation axis. We neglect the disk self-gravity, so the angular velocity of the disk material is taken as Keplerian.

In the thesis, we have considered several cases, characterized by different sets of equations and boundary conditions: (i) a non-irradiated accretion disk; (ii) an accretion disk irradiated by a tenuous dusty envelope, possibly a remnant of the original cloud core or formed by the wind; (iii) an accretion disk irradiated by an infalling envelope; and (iv) an accretion disk irradiated by the central star. Each of these cases are expected to represent different evolutionary phases or, perhaps, disks surrounded by different ambient media.

3. NON-IRRADIATED ACCRETION DISK

In this model, we consider that the disk is heated by viscous dissipation and ionizations produced by energetic particles (cosmic rays and particles from radioactive decay). The equations we integrate to find the disk vertical structure are the following:

- The disk is assumed to be in Hydrostatic Equilibrium,

$$\frac{dP_g}{dz} = -\rho g_z + \frac{dP_{rad}}{dz}\,, \tag{1}$$

  where P_g is the gas pressure, P_{rad} is the radiation pressure, g_z is the z-component of the stellar gravitational field and ρ is the volumetric density of mass.

- The Energy Balance equation can be written as

$$\frac{dF}{dz} = \frac{9}{4}\alpha\Omega P_g + \Gamma_{cr}\,, \tag{2}$$

  where F is the energy flux, the first term on the right hand side represents the viscous dissipation (e.g., Frank et al. 1992), and Γ_{cr} is the heating by energetic particles.

- The transport of energy by radiation is described using the first two moments of the radiative transfer equation (see Mihalas 1978),

$$\frac{dF_{rad}}{dz} = 4\pi\kappa_P\rho\left[\frac{\sigma T^4}{\pi} - J\right], \tag{3}$$

$$\frac{dJ}{dz} = -3\chi_R\rho\frac{F_{rad}}{4\pi}\,, \tag{4}$$

  where F_{rad} and J are the flux and the mean intensity of the radiation field, both integrated in frequencies, and κ_P and χ_R are the Planck and Rosseland mean opacities, respectively.

- The energy is also transported by a turbulent flux, self-consistently calculated given the viscosity coefficient used to describe the viscous energy dissipation, and by convection, described by the mixing length theory, taking into account that the convective elements lose energy by radiation and turbulent flux,

$$\frac{dT}{dz} = -\frac{T}{P_g} g_z \rho[\zeta\nabla_A + (1-\zeta)\nabla_{RC}]\,, \tag{5}$$

where T is the temperature, ζ is the efficiency of convective transport, ∇_A is the adiabatic gradient and ∇_{RC} is the radiative gradient, modified to account for both radiation and turbulent transport of energy.

The boundary conditions to solve these equations are: at $z = 0$, $F_{rad} = F = 0$ and at $z = z_\infty$, $P_g = P_\infty$, $F = F_{rad} = D_{vis} + D_{cr}$ and $J = J_\infty(F_{rad})$, where P_∞ is the pressure of the ambient medium, D_{vis} and D_{cr} are the total fluxes produced by viscous dissipation and energetic particles, and z_∞ is the height of the disk surface, which is unknown *a priori*. We take z_∞ as an eigenvalue of the problem and solve the equations using a relaxation method (Press et al. 1989). Details about these equations, related quantities and the integration method can be found in D'Alessio (1996).

A non-irradiated disk is not a realistic picture of a pre-main sequence disk, which is always irradiated by the star or by the ambient medium. However, it is a good approximation for small disks with high $\dot{M}$. Examples of this are the compact disks resolved in L1551-IRS5 by Rodríguez et al. (1998), using the VLA at $\lambda = 7$ mm, with a beam size of 0.05" (which corresponds to ~ 7 AU at the distance of the source, $d = 140$ pc). This is a binary system of disks, which also seems to be surrounded by a circumbinary ring (Looney et al. 1997). We have found a disk model for each source, which fits their mm SEDs, the maximum intensity at 7 mm, the apparent sizes and the bolometric luminosities (see Rodríguez et al. 1998). Both disk models have mass accretion rates $\dot{M} \sim 5 \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$ and a disk maximum radius $R_d \sim 10$ AU. The high brightness temperature observed at 7 mm is due to the high mass accretion rate of the disk and the fact that mm observations penetrate deeply in the disk, being sensitive to the physical conditions close to the hotter midplane. The mass of the northern disk is $M_{dn} \approx 0.06 M_\odot$ and the mass of the southern disk is $M_{ds} \approx 0.03\ M_\odot$, both larger than the minimum mass required to form a planetary system similar to our own.

4. DISK IRRADIATED BY A TENUOUS ENVELOPE OR BY AN OPTICALLY THICK INFALLING ENVELOPE

Natta (1993) proposed that the SED of some CTTS can be explained if the disk is surrounded by an infalling dusty envelope which scatters radiation from the star towards the disk. We have extended this model to account for scattering back the disk's own radiation and developed an useful analytic formulation for this problem. The results are sensitive to the density distribution of the envelope, but for plausible distributions, the temperature of the outer regions of the disk increases with respect to the non-irradiated case. This increment in temperature increases the disk IR excess. However, this effect could explain the observed SEDs of CTTS only for envelopes with extinction coefficients towards the central star $A_V \gtrsim 1$, high compared with the typical values of CTTS in Taurus-Auriga (Kenyon & Hartmann 1995), taking into account that there is additional extinction produced by the ISM between the source and the observer. See D'Alessio (1996) and Cantó, D'Alessio & Lizano (1995) for details.

Some CTTS show flat SEDs in the IR range, which cannot be explained as a non-irradiated disk model nor a disk irradiated by a tenuous envelope or by the star. In the case of HL Tau, a typical flat-spectrum source, Calvet et al. (1994) show that an infalling envelope model can explain its mid and far IR SED. However, the envelope cannot account for the observed mm flux since it does not contain enough mass at small scales. On the other hand, a disk can explain the observed mm emission of HL Tau if the outer disk temperature is sufficiently high. We construct a model of an accretion disk irradiated by an infalling envelope which successfully explains the long wavelength observations.

For a disk irradiated by a tenuous envelope or infalling envelope, we solve the same set of equations described in §3 , modifying the boundary conditions. In particular, an irradiation flux F_{irr} at the disk surface $z = z_\infty$ is included. This model is used in the case of HL Tau (see D'Alessio 1996; D'Alessio, Calvet & Hartmann 1997), with F_{irr} calculated from the envelope models proposed by Calvet et al. (1994) and Hartmann, Calvet & Boss (1996), which accounts for the IR SED and images of HL Tau. We fit the long wavelength SED and the visibility at 1 mm of HL Tau (reported by Lay et al. 1994) with an irradiated disk model with $\dot{M} = 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$, $\alpha = 0.04$, $M_d = 0.15\ M_\odot$, and $R_d = 125$ AU, assuming a typical T Tauri central star.

5. DISK IRRADIATED BY THE CENTRAL STAR

From detailed UV-optical observations, the typical mass accretion rate of CTTS in Taurus-Auriga is $\dot{M} \sim 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ (Gullbring et al. 1998). Such a small $\dot{M}$ implies that heating mechanisms other than viscous dissipation can be dominant, specially in the outer parts of the disk, and one of the most plausible heating sources is the radiation from the star. The first irradiated disk models assume that the disk is flat, with all the dust deposited at the midplane (Friedjung 1985). The temperature distribution is $T \propto R^{-3/4}$, which is coincidently the same distribution of a viscous non-irradiated disk. However, most CTTS show SEDs which require a higher temperature at the outer regions of the disk, i.e., a flatter temperature distribution. Kenyon & Hartmann (1987) propose that if gas and dust are well mixed in the disk, its surface is flared, which increases the amount of stellar radiative flux intercepted by its outer regions. Assuming the disk is vertically isothermal, and that the surface height is a constant multiplied by the gas scale height, the temperature distribution is $T \propto R^{-3/7}$ (D'Alessio 1996). Calvet et al. (1991, 1992) found that a large fraction of the impinging stellar radiation, characterized by a shorter wavelength than the disk's own radiation, is deposited in the upper disk atmosphere producing a temperature inversion (see also Malbet & Bertout 1991; Chiang & Goldreich 1997). In the thesis we calculate a zero order approximation, solving the equations described in §3, but including the intercepted stellar flux in the boundary condition. This kind of model cannot account for the temperature inversion at the disk atmosphere, but relaxes the assumption of vertical isothermality, and the height of the surface is self-consistently calculated.

D'Alessio et al. (1998) constructed a detailed model of the disk structure, including the radiative transfer of stellar radiation through the disk. The radiation field is separated into two frequency ranges, one characteristic of the stellar effective temperature and the other corresponding to the local disk temperature. The disk structure, irradiation flux and detailed temperature distribution of the atmosphere, are calculated self-consistently. We find a photospheric disk temperature $T_{phot} \propto R^{-1/2}$ for $R > 5$ AU and the SED of the CTTS AA Tau is well fitted with the fiducial model. D'Alessio et al. (1999) calculate the structure and emission properties of irradiated disk models in a wide range of $\dot{M}$, α and R_d. The SEDs and images for all inclination angles are compared with observations of the entire population of CTTS and Class I objects in Taurus. We find that the median near-infrared fluxes can be explained with most recent values for the mean accretion rate for CTTS. We also find that the majority of the Class I sources in Taurus cannot be Class II sources viewed edge-on (as suggested by Chiang & Goldreich 1999) because they are too luminous and their colors would only be consistent with disks seen in a narrow range of inclinations. Our models appear to be too geometrically thick at large radii, as suggested by: (a) too much far-infrared disk emission compared with the typical SEDs of T Tauri stars; (b) wider dark dust lanes in the model images than in the images of HH30 and HK Tau/c; and (c) larger predicted number of stars extincted by edge-on disks than consistent with current surveys. The large thickness of the model is a consequence of the assumption that dust and gas are well mixed, suggesting that some degree of dust settling may be required to explain the observations.

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REFERENCES

Appenzeller, I., Oestreicher, R., & Jankovics, I. 1984, A&A, 141, 108
Beckwith, S. V. W., Sargent, A. I., Chini, R. S., & Guesten, R. 1990, AJ, 99, 1024
Burrows, C. J., et al., 1996, ApJ, 473, 437
Butner, H. M., Evans, N. J. II, Lester, D.F ., Levreault, R. M., & Strom, S. E. 1991, ApJ, 376, 636
Calvet, N., Patiño, A., Magris, G., & D'Alessio, P. 1991, ApJ, 380, 617
Calvet, N., Magris, G., Patiño, A., & D'Alessio, P. 1992, RevMexAA, 24, 27
Calvet, N., Hartmann, L., Kenyon, S. J., & Whitney, B. A. 1994, ApJ, 434, 330
Calvet, N., & Gullbring, E. 1998, ApJ, 509, 802
Cantó, J., D'Alessio, P., & Lizano, S. 1995, in Disks, Outflows and Star Formation, ed. S. Lizano & J. M. Torrelles, RevMexAASC,1, 217
Chiang, E. I., & Goldreich, P. 1997, ApJ, 490, 368
Chiang, E. I., & Goldreich, P. 1999, ApJ 519, 279
D'Alessio, P. 1996, Ph.D. Thesis, Universidad Nacional Autónoma de México, México
D'Alessio, P., Calvet, N., & Hartmann, L., 1997, ApJ, 474, 397

D'Alessio, P., Cantó, J., Calvet, N., & Lizano, S. 1998, ApJ, 500, 411
D'Alessio, P., Calvet, N., Hartmann, L., Lizano, S. & Cantó, J. 1999, ApJ, submitted
Edwards, S., Cabrit, S., Strom, S.E., Ingeborg, H., Strom, K.M., & Anderson, E., 1987, ApJ, 321, 473
Edwards, S., Hartigan, P., Ghandour, L., & Andrulis, C. 1994, AJ, 108, 1056
Frank, J., King, A.R., & Raine, D. J., 1992, Accretion power in Astrophysics, Cambridge: University Press, p.72.
Friedjung, M. 1985, A&A, 146, 366
Gullbring, E., Hartmann, L., Briceño, C, & Calvet, N. 1998, ApJ, 492, 323
Hartmann, L., Calvet, N., & Boss, A, 1996, ApJ, 464, 387
Hartmann, L. 1998, Accretion Processes in Star Formation, Cambridge: University Press
Kenyon, S. J., & Hartmann, L. 1987, ApJ, 323, 714
Kenyon, S. J.,& Hartmann, L. 1995, ApJS, 101,117
Königl, A. 1991, APJ, 370, L39
Lay, O. P., Carlstrom, J. E., Hills, R. E., & Phillips, T. G. 1994, ApJ, 434, 75
Looney, L. W., Mundy, L. G., & Welch, W. J. 1997, ApJ, 484
Lynden-Bell, D., & Pringle, J. E. 1974, MNRAS, 168, 603
McCaughrean, M. J. & O'Dell, C. R. 1996, AJ, 111, 1977
Malbet, F., & Bertout, C. 1991, ApJ, 383, 814
Mihalas, D. 1978, Stellar Atmospheres, San Francisco:Freeman
Miyake, K., & Nakagwa, Y. 1995, ApJ, 441, 361
Muzerolle, J., Calvet, N. & Hartmann, L. 1998, ApJ, 492, 743
Muzerolle, J., Hartmann, L., & Calvet, N. 1998, AJ, 116, 455
Muzerolle, J., Calvet, N. & Hartmann, L. 1998, AJ, 116, 2965
Natta, A. 1993, ApJ412, 761
Press, W. H., Flannery, B. P., Teukolsky, S. A., & Vetterling, W. T. 1989, Numerical Recipes, (Cambridge:University Press)
Pringle, J. E. 1981, ARA&A, 19,137
Rodríguez, L. F., Cantó, J., Torrelles, J. M., Gómez, J. F., & Ho, P. T. P., 1992, ApJ, 393, L29
Rodríguez, L. F., et al., 1998, Nature, 395, 355
Rucinski, S.M. 1985, AJ, 90, 2321
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24,337
Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A,25,23
Stapelfeldt, K. R., Krist, J. E., Ménard, F., Bouvier, J., Padgett, D. L., & Burrows, C. J. 1998, ApJ, 502, L65
Terebey, S., Shu, F. H., & Cassen, P. 1984, ApJ, 286, 529
Smak, J., 1964, ApJ, 139, 1095
Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., & Skrutskie, M. F. 1989, AJ, 97, 1451
Wilner, D. J., Ho, P. T. P., & Rodríguez, L. F. 1996, ApJ, 470, 117