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OPACITY PROBLEMS IN ACCRETION DISKS AROUND YOUNG STELLAR OBJECTS

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RESUMEN. Los discos de acrecimiento alrededor de los objetos estelares jóvenes son fríos y densos; las fuentes más importantes de opacidad provienen del polvo y de las moléculas. Los cálculos de la estructura interna y atmosférica y de los espectros sintéticos de estos discos no han sido satisfactorios hasta ahora debido a la ausencia de datos confiables de opacidad. Se discuten problemas específicos.

ABSTRACT. Accretion disks around young stellar objects are cool and dense; dust and molecules constitute the most important opacity sources. Calculations of internal and atmospheric structure and of synthetic spectra for these disks have been hindered by the lack of appropriate and reliable opacity data. Specific problems are discussed.

Key words: ACCRETION – OPACITIES – STARS: PRE-MAIN-SEQUENCE

1. BRIEF OVERVIEW OF STAR FORMATION

In the present picture of star formation, disks are formed around young stellar objects (YSO) as a result of the collapse of molecular cloud cores possessing a certain small amount of angular momentum (see Shu, Adams, and Lizano 1987). Inside the molecular clouds in the plane of the galaxies, cores are found with typical sizes of 0.1 *pc* and masses of 1 to 10 $M_\odot$. When all mechanisms of support are overwhelmed by gravity, gravitational collapse starts. This is an "inside-out" collapse where, at a given time t, all the matter inside a radius $\approx c_s t$, where c_s is the sound velocity, is nearly in free fall. The collapse is almost radial far from the center, but inside the so-called centrifugal radius (defined by the condition that the centrifugal forces balance gravity on the plane perpendicular to the axis of rotation) matter falls onto a disk at a distance from the center determined by the specific angular momentum of the infalling matter. The result of this collapse process is a Classical T Tauri System (CTTS), which comprises a central object surrounded by a disk (see Bertout 1989, and references therein) and, further out, an infalling envelope which feeds the disk. The envelope may or may not hide the central parts of the system depending on the viewing angle; when it does, the central object is seen as embedded and the system is called a protostar (Barsony and Kenyon 1991).

Disks are then a natural result of the process of gravitational collapse. If the viscosity in the disk is high enough, there will then be accretion of disk matter onto the star, and the disk will be an accretion disk. The disk rotates with differential velocity, approximately Keplerian, and the transport of angular momentum between adjacent layers results in viscous torques and local heat dissipation. To compensate for the loss of energy, matter sinks deeper in the potential well (Pringle 1981). Since the disks around young objects are turbulent, viscosity is high enough to produce a significant accretion of matter onto the star. In fact, it is estimated that 10 to 20 % of the matter of the star is acquired through the disk (Hartmann, Kenyon, and Hartigan 1991). For steady, physically thin, optically thick accretion disks, it can be shown that the temperature in the disk, $T(R)$, goes like $R^{-3/4}$ and that the luminosity of the disk is given by half of the accretion luminosity; that is, $L_{disk} = (1/2)\, GM_*\dot{M}/R_*$, where M_* and R_* are the central object mass and radius, and $\dot{M}$ is the constant mass accretion rate.

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Disks are not necessarily stable. The flow of matter through the disk is controlled by viscous processes, that is, by local characteristics. In contrast, the influx of "fresh" material is controlled by the characteristics of the infalling envelope. These two processes are not necessarily matched; they may produce an accumulation of material at some radius which may lead to instabilities in the disk.

The FU Orionis objects may be examples of such an instability. These objects are thought to be CTTS where the accretion disk has suffered an instability that has resulted in an increase of $\dot{M}$ from $\approx 10^{-7}$ $M_{\odot}\,yr^{-1}$, a typical value for CTTS, to $\approx 10^{-4}$ $M_{\odot}\,yr^{-1}$, producing an increase in the luminosity of the system by a factor of $\approx 100 - 1000$. After the FU Ori outburst only the disk is seen because the star is hidden by the luminous disk (Hartmann, Kenyon, and Hartigan 1991, and references therein). The best evidence that the energy in FU Orionis objects comes from a bright disk lies in the variation with wavelength of the measured rotational broadening in spectral lines. In an accretion disk $T(R) \propto R^{-3/4}$; therefore, the hot inner annuli of the disk will emit mainly in the optical, while outer, cooler regions will emit mainly in the infrared. The disk rotates differentially with a rotational velocity $\Omega \propto R^{-3/2}$. Lines in the optical should therefore show a larger rotational broadening than lines in the infrared. This effect is indeed observed in FU Orionis spectra. The rotational velocity determined for atomic lines at $\approx 0.6\mu$m is larger than that determined for the CO lines at 2.3μm, by an amount which is consistent with a disk in Keplerian rotation (Kenyon, Hartmann, and Hewett 1988).

2. YSO DISK CHARACTERISTICS AND OPACITY PROBLEMS

The study of YSO disks involves two aspects: the determination of the internal structure and its evolution, and the determination of the atmospheric structure and the resulting spectrum. Figure 1 shows the location in the density–temperature diagram of the midplane of the disk and of several optical depths in the atmosphere for a system consisting of a star with $M_* = 1$ $M_{\odot}$, $R_* = 3R_{\odot}$, and effective temperature of 4000 K, surrounded by a steady disk with $\dot{M} = 10^{-7}$ $M_{\odot}\,yr^{-1}$; these are typical characteristics for a CTTS. (The midplane values have been kindly provided by K. R. Bell.) Calculations are shown at several distances from the star. Typical temperatures for YSO disks are of the order of, or smaller than, 4000 K while densities are $\leq 10^{-5}$g cm^{-3}. Below $T \approx 1500$ K dust is present. Above this temperature, it evaporates or has not condensed yet, so that the matter is mostly in the form of molecules. Hence, for the range of temperatures and densities found in YSO disks, the most important contributors to the opacity are dust and molecules.

Figure 1 shows the region where dust opacity is important as determined by Pollack, McKay, and Christofferson (1985, PMC85). The temperature at which dust becomes important is density dependent because different species are formed at different densities, but it is found to be around 1500 K. Since the main topic of this conference is gas opacities, I will refer to problems related to molecular opacities in what follows, although the need for accurate dust opacities is as urgent as that for the gaseous component.

In the calculation of the internal structure, the diffusion approximation is generally used for the radiative flux, so that the Rosseland mean opacity, κ_{Ross}, is relevant (see, for instance, Lin and Papaloizou 1985). In the atmospheric structure calculations, a grey approximation in terms of the optical depth calculated with κ_{Ross} has been used (Calvet *et al.* 1991a,b). A plot of the Rosseland mean opacity as a function of temperature for various densities is shown in Figure 2. The abrupt jump at 1500 K indicates the temperature value below which dust opacity dominates. Between ≈ 1500 K and ≈ 3200 K, opacities fall to low values and are dominated by H_2O and to lesser extent by TiO. As the temperature increases, the electron density increases and H^- opacity sets in, so that κ_{Ross} increases again.

Among the published opacities, the most widely used by workers in the field are those by Alexander and collaborators (Alexander 1975, A75; Alexander, Johnson, and Rypma 1983, AJR83; Alexander, Augason, and Johnson 1989, AAJ89). However, several problems are found in the use of Alexander's tables.

The first problem is that the tables do not cover the complete range of temperatures and densities found in YSO disks. To overcome this deficiency, one of the solutions adopted is to use the analytic fits to Alexander's tables by Lin and Papaloizou (1985). These fits were meant to be used in analytical treatments of disk internal structure solutions, and sometimes fail badly outside the range of the tables. Another solution is to calculate approximate values for κ_{Ross} (as those shown in Figure 2) based on published opacities for different molecules, which generally give means over small wavenumber intervals using various approximations for the way the mean is taken.

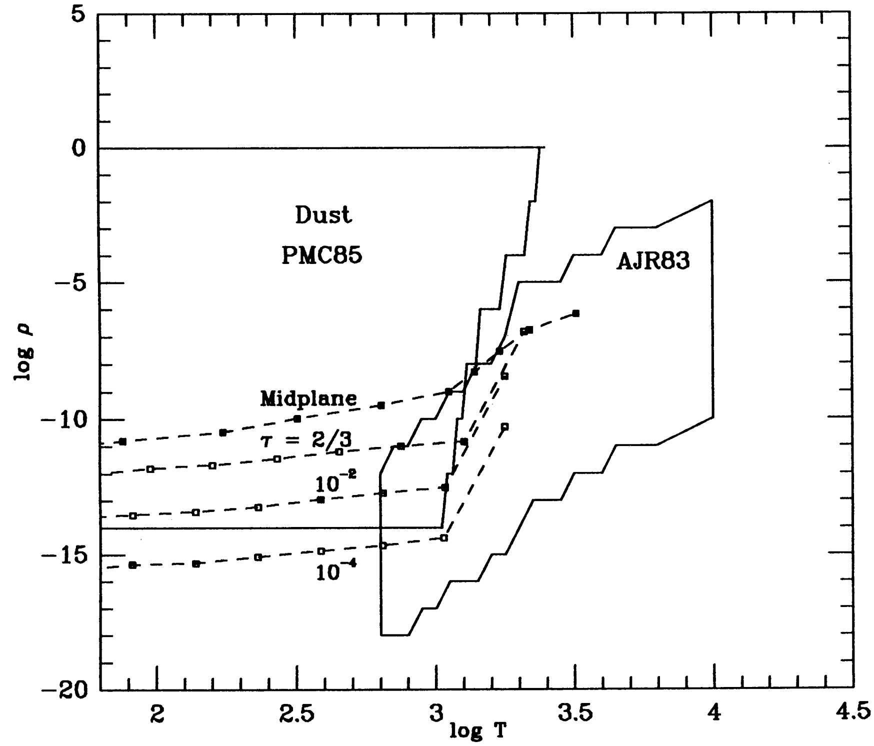

Figure 1. Location in the $\rho - T$ of characteristic regions in the disk for $M_* = 1\mathrm{M}_\odot$, $R_* = 3R_\odot$, $T_* = 4000$ K, and $\dot{M} = 10^{-7}$ $\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. Each square corresponds to a radius in the disk, $R/R_* = 2, 4, 8, 16, 32, 64, 128, 256, 512$. The smallest radius is at the right. Filled squares: midplane, open squares: atmosphere at several Rosseland optical depths, as shown. In the region marked by PMC85, dust opacity dominates. The region marked by AJR83 is the region covered by the Rosseland mean opacity tables of Alexander, Johnson, and Rypma (1983).

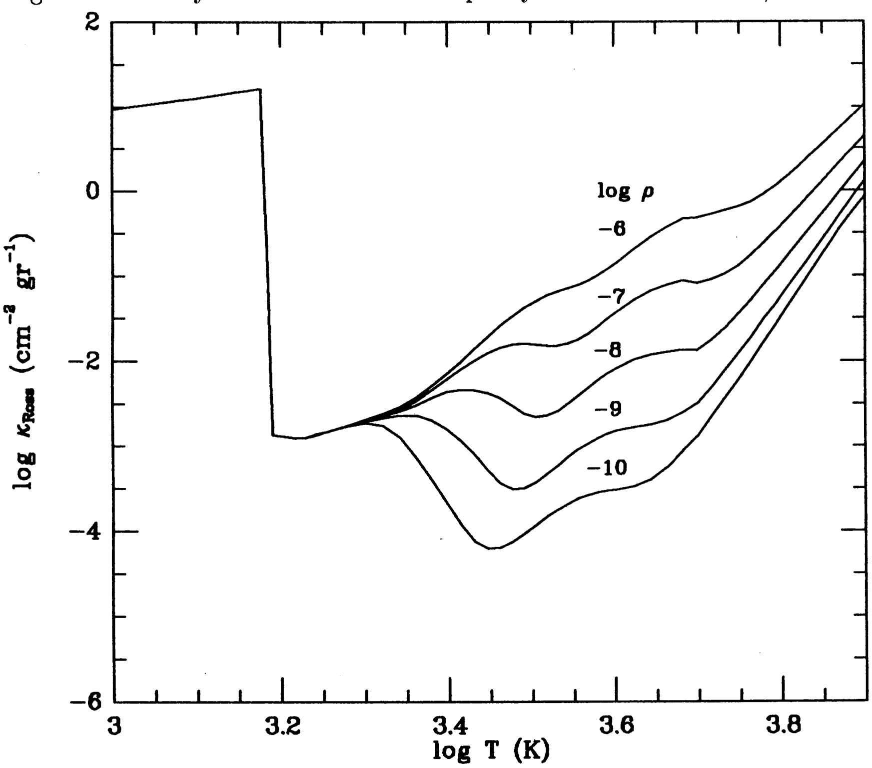

Figure 2. Rosseland mean opacities for various densities (opacity contributors from Calvet *et al.* [1991b]).

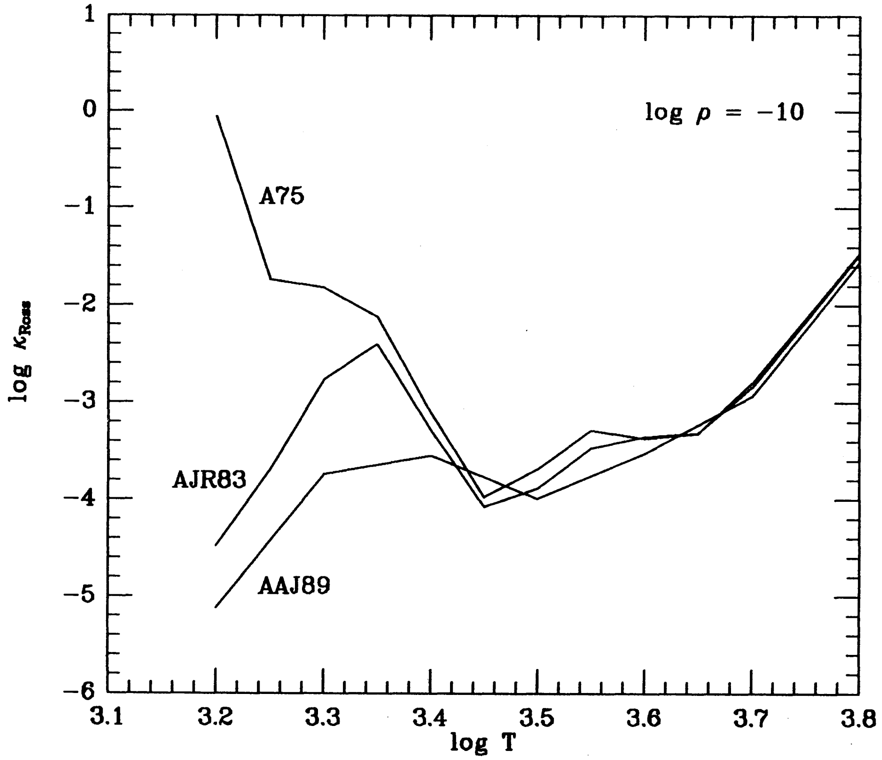

Figure 3. Rosseland mean opacities for $\rho = 10^{-10}\,\mathrm{g\,cm^{-3}}$, from different opacity tables: A75, Alexander (1975); AJR83, Alexander, Johnson, and Rypma (1983); AAJ89, Alexander, Augason, and Johnson (1989).

A second problem lies in the treatment of the critical region between $1000 < T < 2000$ K, where dust grains form/evaporate. In this temperature region, what is usually done is to match Alexander's tables to those of Pollack, McKay, and Christofferson (1985). The problem is that Alexander assumes a mixture of dust appropriate to the interstellar medium, consisting of silicates and graphite. In the solar nebula, however, no graphite is found. There are regimes, then, where the tables of Pollack *et al.* have no dust as Alexander's do, which results in artificial values for the opacity or in difficulties in matching the tables. Moreover, there is no proper accounting for the depletion of heavy elements in the transition region where dust begins to evaporate/condense. It would be ideal to have tables of κ_{Ross} calculated specifically for the conditions found in YSO disks.

In the range $1500 \leq T \leq 3000$ K, the most important contributor to the opacity is water vapor. In A75, the H_2O opacity is taken from Auman (1967), who uses a harmonic-mean average over 100 $\mathrm{cm^{-1}}$ intervals; AJR83 calculate straight-mean averages over 100 $\mathrm{cm^{-1}}$ intervals to calculate the H_2O opacity; finally, AAJ89 use an opacity-sampling technique for H_2O. In each case, individual line opacities were calculated from different theoretical approximations and laboratory data. The values for κ_{Ross} as a function of temperature at a representative density of $10^{-10}\,\mathrm{g\,cm^{-3}}$ are shown in Figure 3. In the relevant temperature range, opacities have changed by a factor of 100 in the published tables. These changes are basically due to the different ways of estimating the H_2O opacity.

The ambiguity in κ_{Ross} for the range of temperatures found in YSO disks has brought great uncertainties into the calculation of the disk structure. As an example, I will refer to a work in progress by K. R. Bell and D. N. C. Lin, who are studying the instabilities that appear in YSO accretion disks which may originate FU Orionis outbursts; that is, instabilities that may produce an increase of the mass accretion rate by factors of 100–1000.

Bell and Lin construct at a given radius in the disk a series of thermal equilibrium models for increasing values of $\dot{M}$. Physically, this is equivalent to considering at a given radius R the mass flux through it, $\dot{M}$, and the response to a varying mass inflow from a nearby annulus, $\dot{M}_{in}$. As $\dot{M}_{in}$ increases, the structure of the given annulus adjusts itself to the new mass flux, increasing the mass column density Σ. The result of three of

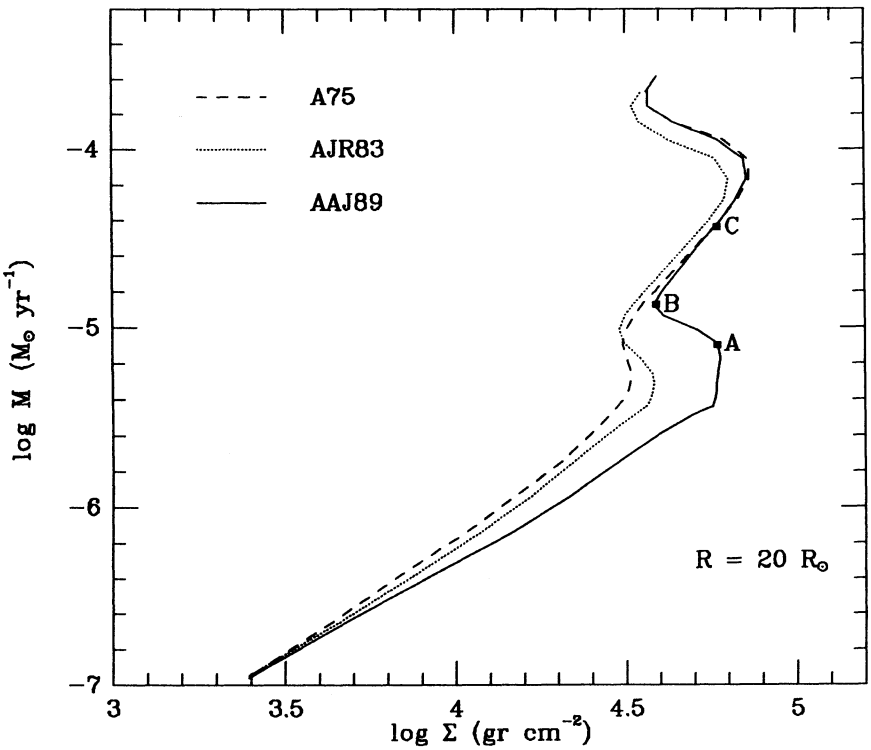

Figure 4. Mass accretion rate vs. mass column density for a series of thermal equilibrium models (K. R. Bell, private communication), calculated with the different opacity tables in Figure 3.

such series of calculations for conditions appropriate to CTTS is shown in Figure 4, where $\dot{M}$ is plotted against Σ. The $\dot{M}$ vs. Σ line shows inflection points, as that represented in one of the curves shown in Figure 4 by the letter A. Between A and B in the figure, $d\dot{M}/d\Sigma < 0$, and no thermally stable model can exist. For these models, the cooling rate cannot compensate the heating rate, and the annulus continues heating until it gets to the upper thermally stable branch, represented by point C (Lin and Papaloizou 1985), which corresponds to a much higher $\dot{M}$. The unstable regions correspond to regions where κ_{Ross} falls rapidly with decreasing temperature to very low values, so that the disk becomes marginally optically thin (Lin and Papaloizou 1985). Therefore, the value of $\dot{M}$ at which the transition occurs and the final stable value of $\dot{M}$, which are crucial predictions of the study, are highly dependent on the adopted values of κ_{Ross}. The three relations $\dot{M}$ vs. Σ shown in Figure 4 are calculated with the three tables by Alexander mentioned above. As κ_{Ross} decreases, two well defined instability regions have appeared, and the lower instability region corresponds to mass accretion rates closer to the values observed in CTTS. Moreover, with the newest opacities, the value of Σ at each inflection point has become more similar, suggesting that the magnitude of the outburst may span both instability regions. The need for reliable values of κ_{Ross} to determine the feasibility of this mechanism to explain FU Orionis outburst becomes obvious.

Besides Rosseland mean opacities, other relevant quantities are necessary. Planck mean opacities are required for a better treatment of the radiation transfer. In addition, monochromatic opacities are required for an accurate treatment of the energy conservation equation, and very specially, wavelength dependent opacities are needed for spectral energy distribution calculations. In the first case, since the quantities needed are integrals over frequency, a high level of accuracy is not required. However, in the calculation of synthetic spectra for comparison with high-resolution observations, an accuracy of $\approx$ 0.5 Å is necessary. Information on individual lines is needed to take into account effects such as turbulent broadening, rotational broadening, and expansion velocities due to winds. Such information is only available in the literature for a small number of molecules. The need for monochromatic opacities becomes more urgent since the calculations of Calvet *et al.* (1991a,b) indicate that the presence and strength of the TiO, H_2O, and CO bands in the near infrared are good indicators of disk mass accretion rates. This assertion has been confirmed for the case of the highest $\dot{M}$, the FU Orionis objects, where the calculated H_2O bands and the CO bands in the near infrared show good agreement with observations (Calvet, Hartmann, and Kenyon 1991).

3. FINAL COMMENT: A PLEA

In the conditions found in accretion disks around young stellar objects and in the solar nebula, dust grains and molecules are the important contributors to the opacity. However, these opacities, especially the latter, are poorly known. To study properly the disk structure and to calculate synthetic spectra for comparison with high-resolution observations, the important needs are: (1) to obtain the required transition moments and laboratory data to improve the knowledge of important molecules such as H_2O and TiO, which provide most of the molecular opacity in the relevant temperature range; (2) to determine the appropriate mechanisms for line broadening; (3) to settle the question of the most appropriate way of calculating opacity means; and (4) to determine the mechanisms of condensation/evaporation of grains in the appropriate conditions and the effects on the equation of state. A collective effort by people calculating molecular opacity would be warmly welcomed, as would direct contact with those applying such opacities to various problems. Publication of even partial results would also be greatly appreciated.

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