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THE OPTICAL-NIR OPACITY LAW IN YSO DISKS AND ENVELOPES: EVIDENCE FOR DUST GROWTH?

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RESUMEN

La ley de opacidad del óptico-NIR representa un diagnóstico clave de crecimiento de granos en discos protoplanetarios. Discutimos recientes determinaciones de la ley de opacidad del óptico-infrarrojo cercano a partir de imágenes de alta resolución de discos vistos de perfil. El ajustar simultáneamente la ley de opacidad y la geometría, y considerando un rango adecuadamente amplio de geometrías, aparentemente proporciona resultados robustos. En HV Tau C no encontramos ninguna evidencia de que la ley de opacidad entre 0.8 y 2.2 difiera de aquella para el polvo del MIE. Por el otro lado, en HH 30 existe una fuerte evidencia de que la ley de opacidad entre 0.44 μm y 2.0μm es mucho más plana que la del polvo del MIE, aunque no es completamente gris. No está claro por qué el polvo en estos dos objetos es tan diferente. Discutimos planes para ampliar nuestra muestra e investigar si lo que estamos viendo es la evolución de las propiedades del polvo entre una HV Tau C más joven y una HH 30 más vieja.

ABSTRACT

The optical-NIR opacity law is a key diagnostic of grain growth in protoplanetary disks. We discuss recent determinations of the optical-NIR opacity law from high-resolution images of edge-on disks. Fitting simultaneously for the opacity law and the geometry, and considering an adequately wide range of geometries, yields apparently robust results. In HV Tau C, we find no evidence that the opacity law between 0.8 μm and 2.2 μm differs from that for ISM dust. On the other hand, in HH 30 there is strong evidence that the opacity law between 0.44 μm and 2.0 μm is much flatter than that for ISM dust, although is it not completely gray. Why the dust in these two objects should be so different is not clear; we discuss our plans to enlarge our sample and investigate if we might be seeing evolution in dust properties between a younger HV Tau C and an older HH 30.

Key Words: **PLANETARY SYSTEMS: PROTOPLANETARY DISKS — STARS: CIRCUMSTELLAR MATTER — STARS: INDIVIDUAL (HH 30 AND HV TAU C) — STARS: PRE-MAIN SEQUENCE**

1. INTRODUCTION

One of the key issues in the study of disks around young stars is the extent to which their dust grains have grown beyond the sub-micron sizes characteristic of the interstellar medium (ISM). Grain growth is expected in the dense disks, as grain-grain collisions are much more frequent than in the ISM. Furthermore, grain growth is probably the first step in the process of planet formation. For this reason, there has been intense interest in finding evidence for grain growth in circumstellar disks, with many observational claims for its discovery (Beckwith et al. 1990; Beckwith & Sargent 1991; Mannings & Emerson 1994; Throop et al. 2001; Cotera et al. 2001; D'Alessio, Calvet, & Hartmann 2001; Calvet et al. 2002; Wood et al. 2002; Wolf, Padgett, & Stapelfeldt 2003; Watson & Stapelfeldt 2004) but also indications that in some disks the dust is not too different from ISM dust (Silber et al. 2000; Stapelfeldt et al. 2003; Wolf, Padgett, & Stapelfeldt 2003).

Our only observational handle on circumstellar grains is through their dielectric properties. Grain growth is expected to increase the opacity at long wavelengths and decrease the opacity at short wavelengths. In both regimes the opacity law $\kappa(\lambda)/\kappa(\lambda_0)$ is expected to flatten. The opacity is expected to become completely grey (i.e., constant with wavelength) in the geometric limit of the minimum grain size being much larger than the wavelengths in question.

Unfortunately, in the equations of radiation transfer the opacity always appears in a product with the density. This means that an absolute determination of the opacity require an independent determi-

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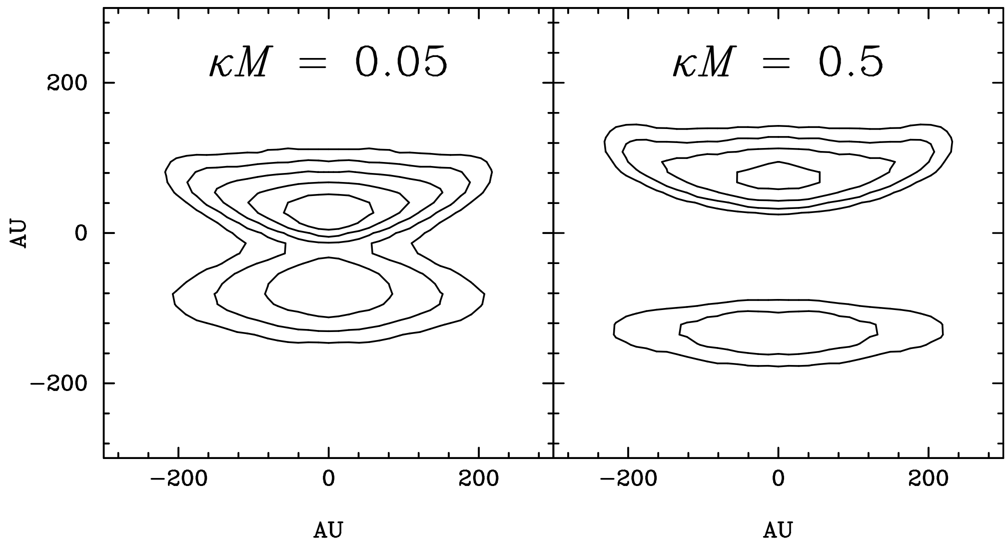

Fig. 1. Model scattered-light images of edge-on disks. The left-hand model has $\kappa M = 0.05$ cm^2 g^{-1} M$_\odot$ and the right-hand model has $\kappa M = 0.5$ cm^2 g^{-1} M$_\odot$. Otherwise, the disk parameters are the same as model A1 of Burrows et al. (1998). As the opacity-mass product decreases, the dark lane narrows.

nation of either the density or the mass. For this reason, it is notoriously difficult to make absolute measurements of the dust opacity in young circumstellar disks. Even when the disks are optically thin, as is thought to be the case at millimeter wavelengths, the emergent flux densities depend on the product of the opacity and the disk mass; since the latter cannot generally be determined independently, the absolute dust opacity is highly uncertain.

In the millimeter region, most workers have taken the differential approach of attempting to determine the opacity law $\kappa(\lambda)/\kappa(\lambda_0)$. As grains grow and the opacity law flattens, the spectral index of the millimeter continuum thermal emission is also expected to flatten. Beckwith et al. (1990), Beckwith & Sargent (1991), and Mannings & Emerson (1994) found that the spectral index from a sample of disks was shallower than would be expected for ISM dust, and interpreted this as evidence for an enhanced population of large grains in disks around T Tauri stars.

2. EDGE-ON DISKS IN THE OPTICAL-NIR

At shorter wavelengths, the situation is more complex because young disks are highly optically thick and so determining the opacity is more difficult than in the optically thin regime. In the far-infrared, disks are spatially unresolved and little progress can be made. In the visible, near-infrared, and mid-infrared, disks are still optically thick, but can now be resolved, which gives additional information and allows for progress. Edge-on disks are the simplest cases, for the extent of the dark lane between the scattering layer at the upper and lower surfaces of the disk depends on the product of the dust opacity and the disk mass.

As in the millimeter region, the absolute value of the opacity cannot be determined because of our ignorance of the disk mass, but changes in the dark lane width with wavelength can be used to restrict the opacity law. If the dust is completely grey in the visible and near-infrared (i.e., the opacity is independent of wavelength), the dark lane thickness should be constant with wavelength; if the dust is chromatic (i.e., the opacity changes with wavelength), the dark lane should appear narrower at wavelengths at which the opacity is lower. Figure 1 illustrates this effect. It shows a two models of edge-on disks in which the opacity-mass product differs by a factor of 10. One might consider this as modeling images of the same disk at wavelengths between which the dust opacity differs by a factor of 10. When the opacity is lower, the dark lane is narrower.

Edge-on disks whose dark lanes are known to narrow toward longer wavelengths include Orion 114-426 (McCaughrean et al. 1998), IRAS 04302+2247 (Padgett et al. 1999), HH 30 (Cotera et al. 2001), and HV Tauri C (Stapelfeldt et al. 2003). Similarly, Shuping et al. (2003) recently found that outer radius of the Orion 114-426 silhouette disk decreases toward longer wavelengths. Together, these observations *qualitatively* indicate that the dust opacity in

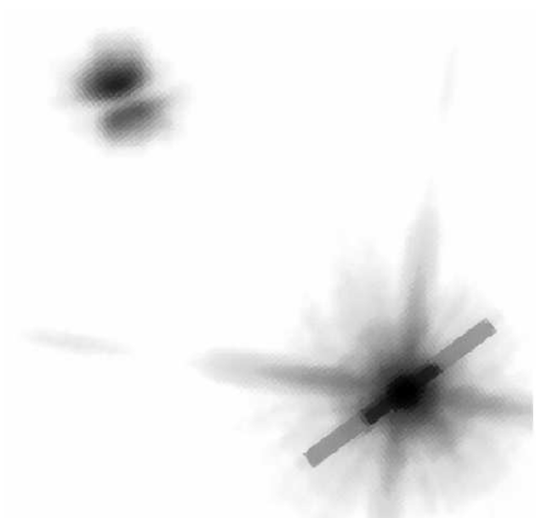

Fig. 2. HST/WFPC2 images of HV Tau system (Stapelfeldt et al. 2003). The image is about 6″ (840 AU) to a side. The saturated image of HV Tau A and B is in the lower right and HV Tau C is to the upper left. Note the large vertical extent of the nebula, which can only be adequately explained by an envelope component.

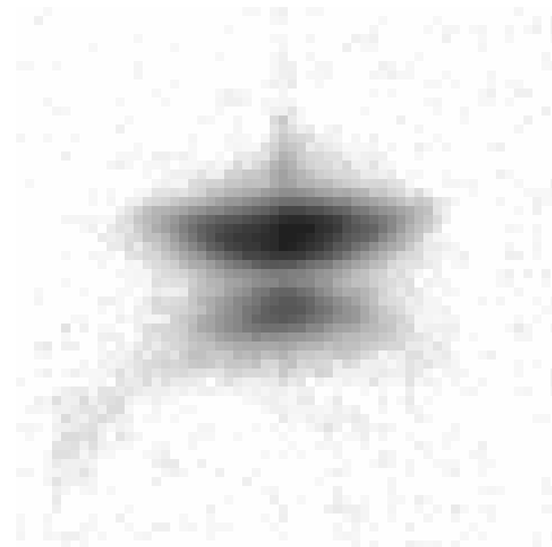

Fig. 3. HST/WFPC2 images of HH 30 system (Watson & Stapelfeldt 2004). The image is about 6″ (840 AU) to a side.

the outer regions of these disks is not completely grey but instead decreases toward longer wavelengths. This suggests that small grains still dominate the visible and near-infrared opacity in the outer regions of these young disks. (A further relevant observation is the imaging polarimetry of GG Tauri circumbinary ring by Silber et al. 2000, where the observed polarization strength indicates that small particles are the dominant scatterers.)

3. DETERMINATION OF THE OPACITY LAW

Visible and near-infrared images of edge-on disks also provide the opportunity for *quantitative* measurements of the dust opacity law through comparison with scattered light models. If the disk's internal density distribution and source of illumination can be adequately modeled, then specific predictions can be made for the wavelength dependence of the dark lane thickness (or outer disk radius). In this way, the opacity law over a range of wavelengths can be determined, the dust size distribution function can be constrained, and even small changes in dust properties can be identified. Cotera et al. (2001) applied this technique to images of HH 30 at 1.10, 1.60, and 2.04 μm, finding that the opacity law between 1 and 2 μm was flatter than in the ISM. In contrast, Wolf, Padgett, & Stapelfeldt (2003) performed a similar analysis of IRAS 04302+2247, again at 1.10, 1.60, and 2.04 μm, but found that the opacity law in this object was very similar to that in the ISM. Both of these efforts considered only very restricted density models when fitting for the dust properties and made no quantitative attempts to optimize the fits. Therefore, they leave unaddressed the question of whether their conclusions are robust to reasonable changes in the disk density distribution.

A better approach is multi-wavelength disk image fitting where both the density distribution and dust parameters are *simultaneously* allowed to find their optimum values. In Stapelfelt et al. (2003) and Watson & Stapelfeldt (2004), we have performed such fits for the edge-on disks around HV Tau C and HH 30.

HV Tau C is the widest component in a hierarchical triple system (see Figure 2). Stapelfelt et al. (2003) report HST/WFPC2 images in V and I and CFHT/PUEO/KIR adaptive-optics images in J, H, and K. They generated model images of disk and disk-plus-envelope systems using the Pinball Monte-Carlo code (Watson & Henney 2001) and determined the best parameters by minimizing the χ^2. They found that the large vertical extent of the disk required the presence of an envelope component. Simultaneous fitting of I and K images suggests that the opacity drops by a factor of about 3.5 from 0.8 to 2.2 μm. This is entirely consistent with the properties of ISM dust (Cardelli, Clayton, & Mathis 1989).

HH 30 was the first edge-on disk in Taurus seen clearly at optical wavelengths (Burrows et al. 1998). Watson & Stapelfeldt (2004) report new

HST/WFPC2 B and I images, and combined these data with the HST/NICMOS K image of Cotera et al. (2001). They also performed χ^2 fitting of Pinball models to the images, varying the geometry quite widely. They were able to fit the HH 30 disk without resorting to an envelope component. As expected, given the degeneracy between the indicies α and β of the midplane density and scale-height (Burrows et al. 1998), they were unable to identify a single best-fit set of parameters. However, by considering all of the reasonable fits, they were able to show that the median change in the opacity between 0.44 and 2.0 μm is less than a factor of 2. This is inconsistent with ISM dust, in which the opacity drops by at least a factor of 8 (Cardelli, Clayton, & Mathis 1989). We suggest that this result is the first robust, quantitative measurement of a non-ISM optical-NIR opacity law in a circumstellar disk.

4. TOWARDS AN EVOLUTIONARY SEQUENCE?

Watson & Stapelfeldt (2004) mentioned the possibility that HV Tau C and HH 30 might illustrate an evolutionary sequence of disks. HV Tau C is a composite disk-plus-envelope system and shows no evidence for grain growth. HH 30 appears to be a pure disk system and shows strong evidence for grain growth. The envelope in HV Tau C might suggest that it is younger than HH 30, which in turn might explain why the dust in HV Tau C appears to be unevolved.

On the other hand, one might note that HV Tau C is a member of a hierarchical multiple system and HH 30 appears to be a single star (although we cannot rule out the possibility that it is a very close binary), and perhaps conclude that this is the explanation for the difference in dust properties.

With results for only these two disks, we cannot draw strong conclusions, and these ideas are no more than intriguing suggestions. To make progress, we must expand the sample size of disks in which we understand the opacity law, and then examine trends in the opacity law. We hope to collect high-resolution images of a sample of about 10 edge-on disks from B or V to K and determine of the opacity law in each. In this, HST is essential, both to obtain the optical images necessary to give us a long lever-arm in wavelength and because many of these disks are in dark clouds and lack adequate guide stars for adaptive optics observations.

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