Investigating Circumstellar Disk Geometry and Dust Properties with Coronagraphic Polarimetry

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Abstract.

High-angular resolution coronagraphy and imaging polarimetry have both proved to be valuable tools for studying the properties of circumstellar disks around young stars, but only recently has it become possible to combine these techniques together. Coronagraphic polarimetry observations, obtainable with ACS and NICMOS on Hubble, and some adaptive-optics-corrected telescopes on the ground, are now providing new constraints on light scattered on subarcsecond scales within disks. When combined with multiwavelength numerical radiative transfer models, these data can yield insight into both the overall disk geometry as well as the size distribution and other properties of their constituent dust grains. We present initial results from several recent HST programs studying disks around young stars, summarize ongoing modeling efforts, and discuss future prospects.

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INTRODUCTION

The study of circumstellar disks has long made use of both coronagraphy and polarimetry [e.g. 1, 2], but only in recent years has it become possible to combine both techniques with diffraction-limited imaging to study circumstellar material at high angular resolution and contrast. Such observations have now been obtained for several young disks using both adaptive optics and the Hubble Space Telescope. These data can be used to assess the grain growth processes which work within protoplanetary disks to build up planetesimals and planets from primordial material, as well as the collisional processes which counter this growth by grinding larger bodies down to dust. The equilibrium between these processes causes dust grain populations within disks to evolve over time as systems shift from protoplanetary to transitional to debris disk phases. When light is scattered from circumstellar dust, a signature of the scattering bodies is written into the resulting pattern of polarization. If we can invert this process, high angular resolution polarimetry lets us infer the nature of the scattering bodies and assess grain growth within the disk.
However, this relationship is not one-to-one, and if only limited observables are available (say, percentage polarization alone) then degeneracies between model parameters limit the constraints that can be placed. Thus coronagraphic polarimetry’s proper place is as one tool of many in a broadly multiwavelength toolkit which includes imaging, polarimetry, spectroscopy and photometry across the electromagnetic spectrum. Scattered light observations are most sensitive to grains with size comparable to the wavelength (thus primarily $\lesssim 1 - 2 \mu m$ for optical and near-infrared studies). Thus in order to assess the full grain size distribution, scattered light images must be combined with submillimeter to radio data which probe the largest grains (perhaps better called “pebbles” or even “snowballs” at those macroscopic sizes). Together with modern numerical radiative transfer codes, these diverse observables can place complimentary constraints on circumstellar disk properties, ultimately allowing robust determination of both the overall geometry and structure of the disk and the nature of its constituent particles.

The first section of this presentation reviews the physics of polarization by dust-scattered light, and how we can use that to infer the nature of scattering bodies. This is followed by a brief discussion of observational methods. We then present examples of both protoplanetary and debris disks observed with coronagraphic polarimetry, before closing with a look ahead at future challenges and opportunities.

**POLARIZATION BY SCATTERING FROM DUST**

When scattered from circumstellar dust, intrinsically unpolarized thermal radiation typically becomes polarized perpendicular to the scattering plane, giving rise to the familiar “bulls-eye” centrosymmetric pattern of linear polarization. This scattering process can be represented mathematically as a matrix acting on the electric vector [See 3, and references therein.]. The values of the terms within these scattering matrices generally depend on both the nature of the scattering body and the angle of scattering.

An empirical model for the angular dependence is given by the Henyey-Greenstein function, which has free parameters $g$ (parametrizing the relative degree of isotropic versus directional scattering ) and $l$ (the maximum linear polarization). More realistic models for scattering are available from laboratory experiments or calculations using Mie theory. Such calculations show that compact grains whose size is small relative to the wavelength typically polarize light strongly, while grains larger than the wavelength are less polarizing (see Figure 1).

The presence of non-spherical grains (such as the porous, fractal grains produced by ballistic collision aggregation) complicates this picture. The optical properties of such grains can be modeled by treating them as spheres with indices of refraction close to 1 (i.e. spheres with a large volume fraction containing vacuum). Such porous grains retain an ability to strongly polarize light, even for grain sizes much larger than the wavelength, and thus can mimic the presence of small grains. However, large porous grains will in general be more strongly forward-scattering than compact grains (thus will have higher $g$ parameters in the Henyey-Greenstein formalism). Thus by measuring both the maximum polarization and the degree of forward scattering (as constrained by the spatial dependence of disks’ surface brightness), we can break the degeneracy and place constraints on both particle size and composition.
FIGURE 1. Polarization dependence of dust scattering as a function of scattering angle and dust properties. Plotted is the ratio of two terms from the scattering matrix calculated according to Mie theory, and giving the linear polarization induced in dust-scattered light. In general polarization is highest for scattering angles near 90°, and smaller grains give the greatest polarization. For compact grains, larger sizes lead to much lower polarizations, but for porous grains this is not the case.

OBSERVATIONAL METHODS FOR HIGH CONTRAST POLARIMETRY

Placing such constraints requires imaging polarimetry with high contrast and high angular resolution. To date, few adaptive optics instruments have combined both a good AO coronagraph plus a polarimetry mode; many coronagraphs lack polarimetry (e.g. NIRC2, NICI) while other instruments which do have dual-channel polarimetry lack coronagraphy (IRCAL). One of the few instruments which incorporates both modes is Subaru’s CIAO. Imaging polarimetry of Beta Pictoris using CIAO showed that the disk has a lower degree of polarization in the infrared (∼10%) than in the optical [4]. Tamura et al. interpreted these data as consistent with scattering by ice-filled fractal aggregates of submicron grains.

Two factors limit AO polarimetry today: (1) the challenge of obtaining a sufficiently small inner working angle; and (2) the need for accurate absolute polarization fractions. Dual-channel polarimetry provides a powerful technique for rejecting atmospheric speckle noise to reach the photon-noise limit very near stars [5, 6], but only for polarized intensity \( P \) and not for the total intensity \( I \). Therefore the absolute percent polarization cannot be accurately measured unless other forms of PSF calibration are available [7, 8].

Thus at present most detailed disk models have relied on data from space, where the Hubble Space Telescope’s great PSF stability provides excellent contrast and accurate polarization fractions, using both ACS and NICMOS [9]. The coronagraphic polarimetry mode of NICMOS, combined with careful PSF subtraction, can reach \( \lesssim 2\% \) polarimetric accuracy and inner working angles as small as 0.3" at 2 microns. As of this writing, ACS and NICMOS are both disabled by hardware failures, but there is hope for their revival during the upcoming HST servicing mission. However, before their failures, a coordinated series of campaigns made use of both ACS and NICMOS to observe nearby disks across a range of masses and ages.
STUDIES OF DEBRIS DISKS

Graham et al. [10] presented HST ACS polarimetry of AU Mic’s disk revealing moderately high linear polarization, 40-50% in F606W. They model these observations following a dynamical model of a birth ring from which dust is dispersed by radiation & Poynting-Robertson drag [11]. Fitting the surface brightness profile and polarization simultaneously requires grains with very low index of refraction, implying high porosity. In particular, the observations are consistent with porous water ice grains $\sim 600$ nm in size and with a 90% vacuum fraction porosity. To produce such grains as debris, the parent bodies must not be compactified, and therefore are likely no more than a few centimeters in size.

Similar observations have recently been obtained for Beta Pic using HST NICMOS [12], measuring low polarizations consistent with the Subaru data on larger scales. After straightforward adjustments for disk size and stellar properties, the dynamical model used for AU Mic also can fit the Beta Pic data. Initial modeling attempts found that good agreement with both polarization and brightness requires adopting the optical constants of dirty ice instead of pure water ice, suggesting greater radiative weathering of grains at Beta Pic due to the more intense radiation environment there.

Observations of several additional debris disks were obtained with NICMOS during Cycles 15-16 and are currently being analyzed for presentation in the near future [9].

STUDIES OF PROTOPLANETARY DISKS

Likewise approximately a dozen T Tauri and Herbig Ae/Be systems have been observed with NICMOS coronagraphic polarimetry. Initial analyses of a subset of the Herbig Ae stars show a substantial range in apparent maximum polarization fractions, from 50-60% for AB Aur to $\sim 20\%$ for HD 100546. At first glance these data appear consistent with decreasing polarization fraction as a function of age, as suggested by some grain growth models, but the small sample size makes this conclusion very tentative. Analysis and interpretation of the complete data set remains ongoing, but the optically-thick nature of these disks makes this process significantly more challenging than in the debris disk case. Here we present one example demonstrating the value of having accurate measurements of polarization fraction, as provided by HST.

Previous coronagraphic polarimetry of AB Aurigae using the AEOS telescope and Lyot Project coronagraph [8] showed a bright polarized nebula approximately 300 AU in radius, corresponding to the inner region of the large disk/envelope structure seen around AB Aur on larger scales. Intriguingly, a region of lower polarized intensity was seen towards PA $\sim 330^\circ$. Oppenheimer et al. interpreted this region as the sign of a physical clearing or gap in the disk, presumably due to the formation of a companion object orbiting $\sim 100$ AU from the star. Our NICMOS observations reveal the exact same pattern of polarized intensity, complete with the region of low polarization - but now we also have measurements of total intensity and thus polarization fraction. We find that the darker area seen in polarized intensity is not a physical gap (which would show up as a region of decreased total intensity) but instead a region of lower polarization fraction. The observed position angle is precisely coincident with the far-side minor axis of the
The diffraction-limited imaging resolution of the system is approximately 0.25 mas with the Lyot Project coronagraph. Each measurement is a series of six dual-beam polarized images (60 s exposures) with different liquid-crystal retarder settings; see Appendix B) are also added together to form a separate polarimetric image. The spatial variation of the scattering is a sensitive measure of variations in the properties around these targets requires accurate polarization fractions, not just images or scattering bodies.

**FUTURE PROSPECTS FROM SPACE AND GROUND**

In the near term, there remains a large body of not-fully-analyzed data likely to continue yielding insights into disk structure and evolution. Analysis and modeling of these data remains time consuming, but new computational facilities and improved radiative transfer codes may help speed progress (see articles by Menard and Wolf in this volume).

This article has focused primarily on assessing disk properties based on space polarimetry, but upcoming high-contrast AO systems are poised to make great contributions. Such systems are expected to be able to image polarized light at fainter levels and closer to the star than is currently possible with HST. Simulations indicate polarimetry with the Gemini Planet Imager will be sensitive to disks with optical thickness \( > 10^{-5} \) on angular scales of 0.2-2\(^{\prime}\). Similar capabilities will be available with the SPHERE and HiCIAO instruments. These instruments will resolve in polarized light many disks which have thus far only been detected photometrically. However, measuring dust scattering properties around these targets requires accurate polarization fractions, not just images in polarized light. Good constraints on grain properties will likely only be possible for disks which are bright enough to be detected in total intensity as well as polarized light.
In the more distant future, the picture becomes bleaker: polarimetry will not be available from the James Webb Space Telescope, nor any other currently approved space mission. A small or medium space mission with a focus on high contrast imaging, including polarimetry, could make an important contribution here. In particular, exozodiacal light levels pose a major challenge for any future terrestrial planet finder. An Exoplanet Probe with an optical coronagraph and polarimeter could measure zodiacal light levels while also imaging Jovian planets in scattered light. In the longer term, polarimetry deserves to be included as a general purpose capability (for disk studies and many other areas of astrophysics) on any future flagship mission such as the proposed ATLAST concept.

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