Imaging Spitzer-selected edge-on protoplanetary disks in nearby star-forming regions

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1. Scientific Justification

Imaging protoplanetary disks

Most young stellar objects (YSOs; ages of a few Myrs) are born with massive protoplanetary disks which eventually give birth to the planetary systems commonly discovered around Main Sequence stars (e.g., Petigura et al. 2013). Spatially unresolved infrared and millimeter dust continuum emission (e.g., Andrews & Williams 2005; Ribas et al. 2014) allow to determine some of the basic disk properties, most notably the total disk mass, but high-resolution imaging is absolutely necessary to characterize them in detail considering the ≈150 pc distance to the closest star-forming regions. While millimeter interferometers have provided important clues about the disk structure (Williams & Cieza 2011), their typical spatial resolution remains limited to several tens of AU.

The clearest and most detailed images of YSO disks produced to date are high-resolution optical/near-infrared scattered light images from Hubble Space Telescope and adaptive optics on large ground-based telescopes as these can achieve a superior angular resolution, down to a few AU (Watson et al. 2007). At these wavelengths, unfortunately, the bright glare of the directly visible starlight presents a very steep observational challenge and only two dozens disks seen at moderate inclinations have been successfuly imaged to date (e.g, Krist et al. 2000; Pinte et al. 2008).

Because disks are randomly oriented (Ménard & Duchêne 2004), a subset of protoplanetary disks are seen nearly edge-on ($i \gtrsim 80$ deg), in which case the bright central star is naturally occulted from view. In this situation, images reveal a characteristic absorption lane bisecting an extended reflection nebulosity, with starlight being scattered off the outer disk's upper layers (see Fig. 1). These edge-on disks offer a unique opportunity as their vertical structure, which is directly related to the local disk temperature and the possibility of dust settling toward the midplane, is in direct view. Detailed comparison of scattering models with the images has allowed to measure the disks' scale heights, their total dust masses and their grain properties (e.g., Burrows et al. 1996; Stapelfeldt et al. 1998, 2003; Duchêne et al. 2010; McCabe et al. 2011). Interesting differences are already apparent: the scale height in the disk of HH 30 is significantly larger than that of HK Tau B, possibly indicating strong settling in the latter disk (Duchêne et al. 2003). Dust grains appear to have ISM properties in IRAS 04302+2247, but are larger in HH 30 (Watson et al. 2007). Edge-on systems are thus uniquely valuable laboratories for the study of protoplanetary environments.

Identifying new edge-on disks

Given the typical opening angle of protoplanetary disks and their random orientation, we expect that about 15% of all young stars with disks should be observed in this edge-on configuration. However, although many hundreds of disk-hosting young stars are known in nearby star-forming regions, only two dozens edge-on disks have been imaged to date; several of these discoveries were serendipitous (e.g. Burrows et al. 1996; Monin & Bouvier 2000; Neuhauser et al. 2009). In fact, only one of these was listed in the Herbig-Bell catalog of young Hα emission stars, due to the magnitude limits of previous optical surveys. It is therefore clear that many more edge-on disks remain currently unrecognized in nearby molecular clouds. By identifying and imaging more of these uniquely valuable objects, a major window will open up on trends in disk structure and evolution.

While previous discoveries of edge-on disks were obtained by chance, the legacy of the *Spitzer* mission offers a much more powerful selection criterion. Large mapping projects have covered most of the nearby star-forming regions, identifying all the infrared excess sources in these clouds. Thorough color-magnitude vetting effectively rejected contaminating background objects (Harvey et al. 2007) and lead to the discovery of many new YSOs that are too faint or spatially confused to have been found by prior IRAS and ISO surveys. Critically, mapping whole clouds, rather than targeting predefined samples enabled the discovery of new YSOs that are extremely faint in the optical/near-infrared and were previously ignored, a key characteristics of edge-on disks.

Through our involvement in the 'c2d', 'Taurus' and 'Gould Belt' surveys (Evans et al. 2009; Rebull et al. 2010; Allen et al. 2007), which together mapped all nearby star-forming regions, we have generated the complete SEDs of known edge-on disks (see Fig. 2), which revealed a characteristic double-peak shape. At $\lambda \lesssim 10\,\mu$m, edge-on disks are underluminous by 2.5-4 mag but their colors are similar to other YSOs (as a result of roughly neutral scattering and little foreground extinction, unlike embedded protostars, e.g., Watson & Stapelfeldt 2007). At longer wavelengths, the disk's thermal emission finally penetrates the 50-5000 mag of extinction along the disk plane, leading to a far-infrared peak whose brightness is similar to that of disks at lower inclinations. All of the known edge-on disks share this characteristic SED shape.

Armed with this powerful selection tool, we have inspected the more than 2000 young stars identified in the c2d, Taurus, and Gould Belt surveys (d $\lesssim$ 300 pc), and found 70 objects whose SEDs possess the aforementioned characteristics of the previously identified edge-on disks. Our goal is now to use high-resolution scattered light images to confirm their nature. In a Cycle 19 HST project, we have targeted 21 targets that are inaccessible to ground-based adaptive optics (even in LGS mode) and confirmed that 11 of them were edge-on disks. While we did identify some outliers (such as embedded protostars and background galaxies), this $\gtrsim$50% success rate is unprecedented for protoplanetary disk imaging surveys and undesrcores the effectiveness of our selection strategy.

Immediate objectives

We now propose to take advantage of the the new capabilities of the ShaneAO system to perform a reconnaissance of a new sample of candidate edge-on disks. Our selection criteria are identical to those of our successful HST program except for the feasibility of LGS AO observations. We have identified 10 targets in the Perseus, Taurus and Auriga star-forming regions. Our immediate goals is to confirm several new edge-on disks. Even though the angular resolution achieved by ShaneAO is not as high as that of 8-10 m telescope, it is sufficient to resolve edge-on protoplanetary disks: the most compact such disk known to date (HV Tau C, 75 AU-radius; Monin & Bouvier 2000; Stapelfeldt et al. 2003; Duchêne et al. 2010) was first identified in AO images from the 3.6m CFHT.

For disks that are well resolved, we will engage in thorough modeling using our well-developed disk image and SED modeling tools to extract disk structural parameters and dust properties, building on our groups extensive experience in this area (Stapelfeldt et al. 1998, 2003; Krist et al. 2000, 2005; McCabe et al. 2002, 2011; Duchêne et al. 2004, 2010; Wolf et al. 2003; Watson & Stapelfeldt 2004; Perrin et al. 2006, 2009; Pinte et al. 2008; Sauter et al. 2009). In addition, thanks to the vetting enabled by these ShaneAO observations, we will be in an ideal position to present strong proposals to use other facilities for follow-up at higher resolution and/or in other wavelength regimes (Keck AO, SMA, ALMA, ...), similar to what we are currently pursuing for the objects identified in our HST program (2 ALMA projects were accepted in Cycle 2).

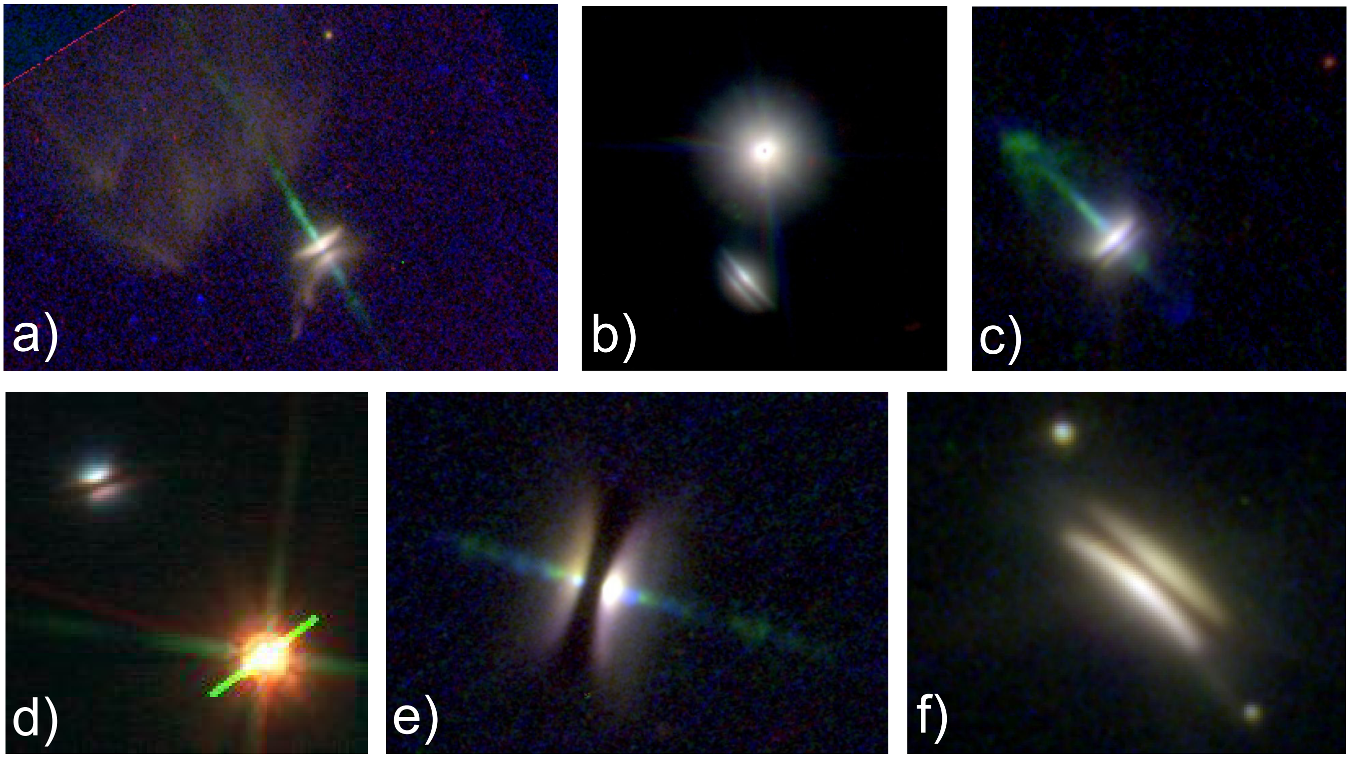

Fig. 1.— Scattered light images of edge-on protoplanetary disks, illustrating the diversity of morphology, from highly flared (panels a and e) to apparently very flat and presumably settled (panels b and c). These color images combine HST optical images with near-infrared AO observations from large ground-based telescopes when available (panels b, d and e). **a)** HH 30 (Burrows et al. 1996); **b)** HK Tau B (Stapelfeldt et al. 1998; McCabe et al. 2011); **c)** a new edge-on disk discovered with HST in Chamaeleon (Wolff et al., in prep.); **d)** HV Tau C (Stapelfeldt et al. 2003; Duchêne et al. 2010); **e)** SSTtau 0420201.4+281349 (Duchêne et al., in prep.); **f)** a new edge-on disk discovered with HST in Ophiuchus (Krist et al., in prep.)

References:

Allen et al. 2007 AAS 211 8919 – **Andrews & Williams** 2005 ApJ 619 175 – **Burrows et al.** 1996 ApJ 473 437 – **Duchêne et al.** 2003 A&A 400 559 – **Duchêne et al.** 2004 ApJ 606 969 – **Duchêne et al.** 2010 ApJ 712 112 – **Evans et al.** 2009 ApJS 181 321 – **Harvey et al.** 2007 ApJ 663 1149 – **Krist et al.** 2000 ApJ 538 793 – **Krist et al.** 2005 AJ 130 1378 – **Mathews et al.** 2013 A&A 556 A66 – **McCabe et al.** 2002 ApJ 575 974 – **McCabe et al.** 2003 ApJ 588 L113 – **McCabe et al.** 2011 ApJ 727 90 – **Melis et al.** 2011 ApJ 739 L7 – **Ménard & Duchêne** 2004 A&A 425 973 – **Monin & Bouvier** 2000 A&A 356 L75 – **Neuhauser et al.** 2009 A&A 496 777 – **Petigura et al.** 2013 PNAS 110-48 19273 – **Perrin et al.** 2006 ApJ 645 1272 – **Perrin et al.** 2009 AJ 137 4468 – **Pinte et al.** 2006 A&A 459 797 – **Pinte et al.** 2008 A&A 489 633 – **Rebull et al.** 2010 ApJS 186 259 – **Ribas et al.** 2014 A&A 561 A54 – **Sauber et al.** 2009 A&A 505 1167 – **Silber et al.** 2000 ApJ 536 L89 – **Sitarski et al.** 2013 ApJ 770 134 – **Stapelfeldt et al.** 1998 ApJ 502, L65 – **Stapelfeldt et al.** 1999 ApJ 516 L95 – **Stapelfeldt et al.** 2003 ApJ 589

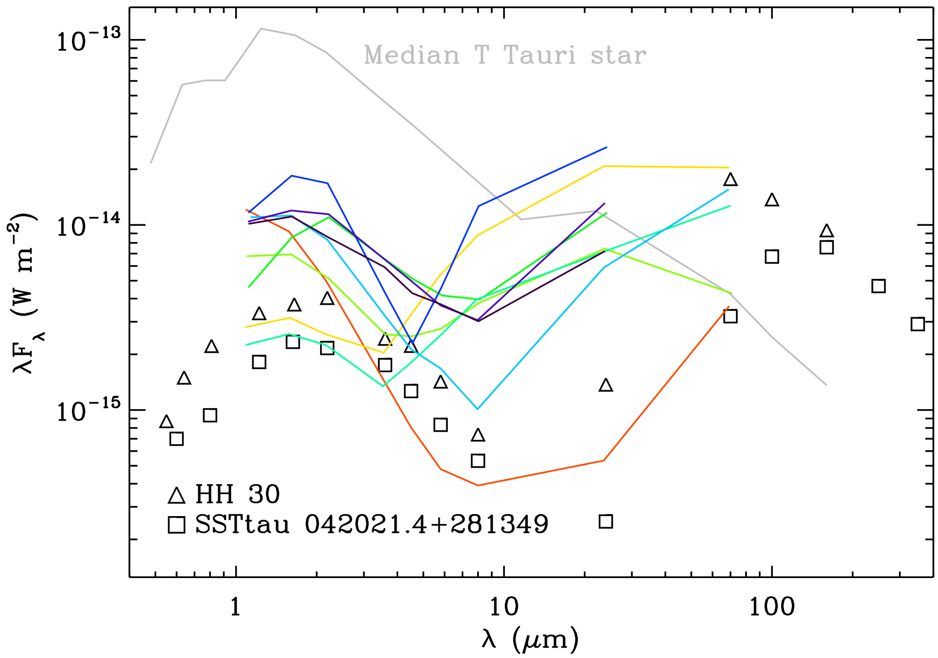

Fig. 2.— SEDs of the targets to be observed in this survey (colored curves) compared to the well-known edge-on protoplanetary disks HH 30 and SSTtau 042021.4+281349 (Fig 1a and e) and the median SED of all Taurus protoplanetary disks irrespective of inclination (from Mathews et al. 2013). To allow for a direct comparison, the SED of targets in Perseus and Auriga have been rescaled to the distance of Taurus assuming distances of 230, 300 and 140 pc, respectively. Notice how the optical/near-infrared colors of known edge-on disks are similar to those of normal T Tauri stars. All of the new targets share the same double-peak SED structure and near-infrared faintness as known edge-on disks; the difference in the wavelength of the "turnaround" point is indicative of the range of optical depths through the disks.

410 – **Watson & Stapelfeldt** 2004 ApJ 602 860 – **Watson & Stapelfeldt** 2007 AJ 133 845 – **Watson et al.** 2007, in Protostars & Planets V, 523 – **Williams & Cieza** 2011 ARA&A 49 67 – **Wolf et al.** 2003 ApJ 588 373 – **Wolf et al.** 2008 ApJ 674 L101

2. Technical Remarks

2.1. Targets and exposures

As discussed above, our targets have been selected based on 1) their near- through far-infrared double-peaked SED characteristics of edge-on protoplanetary disks, and 2) the availability of a sufficient bright stars nearby to serve as a tip-tilt star (in some cases, this is the target itself. For the latter criterion, we have searched within about $45''$ and set a minimum brightness of $R = 17$. The median tip-tilt star brightness and distance are $R = 15.7$ and $25''$, respectively, and we thus expect that we will get good adaptive optics correction under reaonsably good observing conditions.

The basic observing strategy will consists in acquiring the guide star and taking a few snapshot images to check that the adaptive optics system provides sufficient quality. We will then offset to the target and acquire a series of K band images, adjusting the integration time to the actual surface brightness of the object and using a dithered pattern for sky subtraction. In cases where the source is immediately confirmed as an edge-on disk, we will acquire additional images in the H and J filters to study the colors of the objects and the chromaticity of the dark lane (which stems from the underlying dust opacity). In addition, surface brightness permitting, we will take a few deep in the H_2 narrow band filter to image the jet that often is seen in edge-on disks (see Fig 1). Finally, in order to evaluate the potential for PSF elongation when observing far from the tip-tilt star, we will also take images of unrelated point sources at similar distances as our targets. In total, we estimate that we will spend an average of 1h on source per target.

In addition to the ten new targets listed in the top part of Tab. 1, we will also take images of 5 known edge-on disks in Taurus. These images will serve as tests of the performance of the new ShaneAO system for this project. These objects represent a range of tip-tilt star brigthness and distance from the target. While these objects already have been imaged with HST and/or adaptive optics on large ground-based telescopes, obtaining new images is scientifically valuable as edge-on protoplanetary disks are known to undergo significant variability in their surface brightness distribution as a result of variable illumination by the central star (e.g., Watson & Stapelfeldt 2007).

In total, we thus request $\sim$15h of laser time, which requires two nights considering the limits set in laser usage. Based on the range of RA of our targets, and the 10pm–5am window to propagate the laser, this program is best scheduled in November.

2.2. Backup Program

If observing conditions are such that the performance of ShaneAO on the faintest and/or most distant tip-tilt stars are insufficient (i.e., significant broadening of the PSF well beyond the diffraction limit), we will focus on the objects with the brighter/closer tip-tilt stars. If the laser is entirely ineffective or not operating, we will obtain data on the objects that can be observed in natural guide star mode ($R \lesssim 13.5$). If conditions are marginal and only bright stars can be observed, we will observe a sample of late-B star in open clusters and field stars in an effort to search for their lowest-mass stellar companions (the PI has a ShaneAO-NGS proposal to do this in semester 2015B).

Table 1: Target list. The second column indicates the star-forming region in which the source resides, while the thirs and fourth column indicate the R magnitude and distance of the proposed tip-tilt star to the target.

Object	SFR	R_{TT}	D_{TT}	Note
New candidate edge-on disks				
SSTc2d J032858.3+312209	Perseus	15.0	25″	
SSTc2d J032906.1+303039	Perseus	14.5	43″	
SSTc2d J033035.5+311559	Perseus	15.5	42″	target itself is $R = 17.0$
SSTtau 041332.3+291726	Taurus	15.8	on axis	
SSTtau 043349.5+291528	Taurus	15.7	45″	target itself is $R = 16.8$
SSTtau 043559.4+223829	Taurus	11.4	9″	
SSTgbs J041212.9+384202	Auriga	16.8	20″	
SSTgbs J042838.4+362451	Auriga	16.9	on axis	
SSTgbs J043025.3+354518	Auriga	16.0	39″	
SSTgbs J043027.0+354550	Auriga	16.0	13″	target itself is $R = 16.8$
Known edge-on disks				
DG Tau B	Taurus	9.5	50″	
Haro 6-5 B	Taurus	13.7	20″	
HK Tau B	Taurus	13.9	2.″4	
HV Tau C	Taurus	13.7	4″	
SSTtau 0420201.4+281349	Taurus	15.9	30″	

2.3. Supplementary observations

Assuming that our sample selection is as effective as in our previous HST program, the observations proposed here will provide images for a half-dozen new edge-on protoplanetary disks. With these data alone, we will start characterizing the disks (outer radius, degree of flaring, ...) and will then prepare follow-up proposals to obtain higher-resolution images at Keck and with submillimeter arrays (SMA, ALMA). Therefore the ShaneAO observations are both stand-alone and a key stepping stone in building effective proposals on high-pressure facilities. We note that conducing this vetting process with Keck adaptive optics, while possible in principle, would be an inefficient use of that facility, and we would rather focus our time request there on confirmed edge-on disks. Thus, the contribution of these Lick observations will go beyond simply detecting new edge-on disks but will serve as a key stepping stone.

2.4. Status of Previously Approved Lick Programs

The PI of this project has had a Lick LGS and NGS AO observing runs accepted in semesters 08A, 09A, 09B, 10A, 10B, 11A, 11B and 12A. The bulk of these runs (09A through 11A) have been conducted as an ancillary program to the Herschel DEBRIS program. This study has been published in Rodriguez et al. (2015, MNRAS, 49, 3160), with the PI of this proposal and a former UC Berkeley undergraduate student as co-authors. In semesters 12A and 12B, the PI also led observing run with the FIRST visiting instrument (in collaboration with Observatoire de Paris and SETI). Data acquired during these and previous FIRST runs (on which Duchene was a coI) were published in Huby et al. (2012 A&A 541 A55; 2013 A&A 560 A113) and an additional publication is in preparation with a former UC Berkeley undergraduate student. The PI also has had a successful Shane/KAST run in semester 10B; data analysis is completed and folded into a multi-observatory monitoring campaign (again with strong contributions by two undergraduate students). The results from that survey have been presented at the AAS meeting in January 2015 and will be submitted for publication by the end of the Spring semester (both undergraduate students will be co-authors).

3. Personnel & Ressources

Gaspard Duchêne is an Assistant Researcher at UC Berkeley who has a long record of studying protoplanetary disks with high-resolution imaging devices from the optical to the millimeter regime, with particular emphasis on adaptive optics imaging (e.g., Duchêne et al. 2003, 2004, 2010; McCabe et al. 2002, 2003, 2011; Melis et al. 2011; Perrin et al. 2006; Silber et al. 2000; Sitarski et al. 2013). He is part of the development team of MCFOST, a 3D radiative transfer code developed to produce synthetic scattered and thermal images, as well as SEDs, of protoplanetary disks (Pinte et al. 2006). The other members of the team are Carolina Gould, a UC Berkeley undergraduate student working with the PI on the analysis of the recent HST optical images of some known edge-on protoplanetary disks and who will be directly involved in the observing, data reduction and analysis aspects of this program, and Karl Stapefeldt, Chief of the Exoplanets and Stellar Astrophysics Laboratory at NASA/Goddard, who has been studying edge-on disks since the first HST image of HH 30, and PI of the successful Cycle 19 HST program (Burrows et al. 1996; Stapelfeldt et al. 1998, 1999, 2003; Watson & Stapelfeldt 2004, 2007; Wolf et al. 2003, 2008).