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The Disk Substructures at High Angular Resolution Project (DSHARP) III: Spirals in protoplanetary disks around single stars

Jane Huang[1] and others

[1] *Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*

ABSTRACT

We present an analysis of the three spiral-armed protoplanetary disks hosted by single stars from the DSHARP. The the T Tauri stars Elias 27, IM Lup, and Wa Oph 6 host disks featuring spiral arms dominated by the $m = 2$ mode. In addition, each disk features ringlike substructure in close proximity with the spiral arms. Two spiral arms stretch throughout much of the extent of the Elias 27 disk and each crosses the annular gap at a radius of $\sim$ 69 AU. The IM Lup and WaOph 6 disks appear to have "spur"-like features branching off the spiral arms.

To be continued....

Keywords: protoplanetary disks—ISM: dust—techniques: high angular resolution

1. INTRODUCTION

(Author note: I think the premise of this paper may have to be worded a bit differently because we don't know 100 percent if there's no external companion? But I guess these are all spirals in single disk systems?)

-origins of spirals still not well-understood

-detection of spiral arms comparatively rare in millimeter continuum

-mm detections are important because they trace the midplane

2. OBSERVATIONS AND DATA REDUCTION

We analyze high angular resolution 1.3 mm continuum observations of the Elias 27, IM Lup, and WaOph 6 protoplanetary disks from the DSHARP survey presented in Andrews et al. (in prep), hereafter DSHARP1. The stellar host properties and data calibration are described in DSHARP1. The imaging procedure is described in Huang et al. (in prep), hereafter DSHARP2.

-Describe how azimuth-radius plots are made

3. DISK FEATURES

3.1. *Number and extent of arms*

-All sources dominated by $m = 2$ mode

-Elias 27 has two spiral arms that appear to extend from $\sim$50 to 230 AU?

-WaOph 6 has 2 arms, with possible spurs/branching?

-IM Lup has at least 2 arms, possibly up to 6, with additional spurs/branching

Corresponding author: Jane Huang
jane.huang@cfa.harvard.edu

-Not sure if spiral arms extend all the way into inner disk. If optical depth is sufficiently high, then arms could still be present? Also possible distortion by PSF.

-Comment on whether arms are trailing or leading

3.2. *Relationship between spiral and ring structure*

-Gap crossing arms in Elias 27

-Present different scenarios for IM Lup (ambiguity between ring and spiral structure)

-Arms in WaOph 6 seem to be nested inside ring

3.3. *Spiral arm pitch angles*

-methodology description

-measurements

-address possible variation in pitch angle in Elias 27

-address ambiguity in IM Lup (is the pitch angle of the spiral changing or are the arms just merging into the ring?)

-there doesn't seem to be an obvious pattern to the relative locations of rings and spirals, except that in all cases they seem to overlap or occur in close proximity (i.e., there don't seem to be any cases where the spirals and rings are well-separated from one another)

3.4. *Spiral arm contrasts*

-methodology description

4. DISCUSSION

4.1. *Comparison to spiral arm observations in other disks*

4.1.1. *Observations in millimeter continuum*

MWC 758 (Ruobing Dong) HT Lup, AS 205 (Nico's paper)

comment on pitch angles, number of arms

Figure 1. *Top*: ALMA 1.3 mm continuum images of the Elias 27, IM Lup, and WaOph 6 disks. *Bottom:* Azimuth-radius plots

Figure 2. Azimuth-radius, mean-subtracted azimuth-radius plots, and deprojected image of Elias 27 highlighting gap-crossing spirals

Figure 3. Show images of IM Lup with different combinations of spiral and ring scenarios overlaid

Figure 4. Modeled pitch angles plotted over azimuth-radius plots and original disk images

Figure 5. Plot of contrast as function of radius for the three disks

4.1.2. *Observations in scattered light*

-Ruobing's new overview paper

-AB Aur (Hashimoto et al. 2011), HD 142527 (Casassus et al. 2012), SAO 206462 (Muto), MWC 758 (Grady et al. 2013, Benisty et al. 2015), HD 100546 (Boccaletti et al. 2013, Follete et al. 2017) HD 100453 (Wagner 2015, Benisty 2017), Oph IRS 48 (Follete et al. 2015) -Am I missing anyone?

-comment on pitch angles, number of arms

-Scattered light observations are all transition disks around early type stars vs. "full" T Tauri disks in the millimeter sample. To date there have been no confirmed spiral arm detections in scattered light for K and M stars (IM Lup is ambiguous)

-Comment that ALMA observations of disks with scattered light spirals often look quite different

4.1.3. *Observations in molecular emission*

AB Aur (Corder et al., Tang et al), MWC 758 (Boehler), HD 142527 (Christiaens)

comment on pitch angles, number of arms

4.2. *Possible origins of spiral structure*

4.2.1. *Companion-induced structure*

Discuss Goldreich and Tremaine 1979, Bae and Zhu 2018 issues with trapping? Can we put even rough upper limits on the masses of companions?

4.2.2. *Gravitational instability*

-Discuss previous mass estimates (Cleeves et al. 2016, Perez et al. 2016) - generally suggest these disks are gravitationally stable, but masses might be higher for different assumptions?

-Comment on spur features in IM Lup and WaOph 6

-Discuss Zhu et al. 2012, Meru et al 2017, Forgan et al. 2018

4.2.3. *Other hypotheses*

Illumination?

4.3. *How common are spiral arms in protoplanetary disks?*

-Spirals seem rarer than rings so far, but could be due to sensitivity/angular resolution requirements? Note the relatively modest contrast of spiral arms compared to some observed ring structures

-Impact of selection bias; if the origins are gravitational instability, then spirals would be even rarer among the smaller disks? Not sure what direction things will go in if the structures are companion-induced.

5. SUMMARY

This paper makes use of ALMA data ADS/JAO.ALMA#2016.1.0 We thank the NAASC and JAO staff for their advice on data calibration and reduction. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. J.H. acknowledges support from the National Science Foundation Graduate Research Fellowship under Grant No. DGE-1144152 and from NRAO Student Observing Support.

Software: `CASA` (McMullin et al. 2007), `AstroPy` (Astropy Collaboration et al. 2013), `analysisUtils` (https://casaguides.nrao.edu/index.php/Analysis_Utilities)

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Facilities: ALMA