Characterizing New Transitional Disks in the Taurus Star Forming Region

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Abstract

We present a multi-wavelength study of two new transitional disks in the Taurus star forming region. It is thought that when planets form in young disks, they clear out material in the disk and leave behind signatures in the form of holes, thus it is important that we constrain the parameters of these disks in order to develop a deeper understanding of planetary evolution. Here we model the spectral energy distributions (SEDs) of these disks. For these two objects (V410 X-ray 2 and IRAS04125+2902) we also present high resolution SMA images. We obtained estimates of the hole sizes of these two disks through the use of the models and the images. Our results are show that for IRAS04125+2902 the most likely cause of the hole is planetary formation but the possibility of a close stellar companion cannot be ruled out. For V410 X-ray 2, our results show that the hole could be caused by either the formation of planets or by the effects of photoevaporation.

Subject Keywords: Circumstellar Disks, Transitional Disks, Taurus

1 Introduction

It is our current understanding that large gaseous clouds around young stellar objects form circumstellar disks and then eventually form planetary bodies. However, the way in which these disks form planets is relatively poorly understood. With recent advances in observational telescopes (such as the Kepler space telescope), the abundant existence of exoplanets in our Galaxy has been confirmed (Ford et. al 2012; Meschiari 2012). Planets have even been imaged in 100 Myr old debris disks; showing that there is a link between disk evolution and planetary formation (Marois et. al 2010). However, in order to understand how these planets form, we need to observe much younger disks where planetary formation could be occurring.

The younger stars that may be exhibiting planetary formation in its earliest stages are known as T Tauri stars. T Tauri stars are a class of young variable pre-main sequence stars that are grouped into two overarching subclassifications. There are classical T Tauri stars (CTTS) which are accreting from their circumstellar disks and there are weak T Tauri stars (WTTS) which are not accreting and do not have circumstellar disks. There are three main types of circumstellar disks around stars: full disks, pre-transitional disks, and transitional disks. Full Disks have no clearings in the disk and they are radially continuous. Pre-transitional disks have a cleared gap within the disk, and transitional disks have inner holes in the disk (see Figure 1). There are tell-tale signs of each different disk in their spectral energy distributions (SEDs). Full disks are characterized by having data in the optical that agrees with the stellar photosphere but at longer wavelengths the emission is higher than the stellar photosphere due to re-emission from dust in the disk. Transitional disks are typically characterized by their deficits of near & mid-infrared flux and their excesses at longer wavelengths, however, there are disks with SEDs that look like full disks but millimeter imaging shows that they have large holes (Andrews et al. 2011). Pre-transitional disks are similar to transitional disks, however, they exhibit strong near infrared emission which indicates gaps in the disk (Hartmann, Accretion Processes in Star Formation).

There are three mechanisms that could be causing the holes in transitional disks: planetary formation, the presence of a companion star, and photoevaporation. We do not consider grain growth as a possible mechanism because it is shown to be a gradual process in the disk that cannot account for the drastic changes seen in SMA imaging (Birnstiel et. al, 2012). When a planet forms in a disk it intercepts and accretes material which therefore causes a hole or gap to clear in the disk (Hartmann, Accretion Processes in Star Formation). Recent work has also shown that there is the potential for multiple planets to form in the disk and clear out holes that are tens of astronomical units large (Zhu et. al 2011). This could therefore be in agreement with observations of transitional disks with very large holes. The presence of a close companion star (a factor of ~ 10 AU separation) could also clear out holes in a disk that can appear to have been caused by a planetary companion (Kraus et. al 2012). The final mechanism considered is photoevaporation. The relevant form of photoevaporation that has the potential to clear out holes in the disk of a star is photoevaporation due to high energy radiation from the central star (either X-ray, ultraviolet, or extreme ultraviolet). During this process, the radiation heats the gas in the disk until it is unbound from the disk and a small gap opens in the disk (Clarke et al. 2001 & Hollenbach et al. 1994). The material left interior to this gap in the inner disk is then accreted onto the star and the end result is a hole in the disk. However, models show that photoevaporation cannot explain all transitional disks and that it can generally only account for stars with small holes and low accretion rates (Owen et al. 2011).

The stars in our sample are located in the Taurus star forming region. These stars were first identified as having transitional disks in Luhman et al. 2010 and we then followed up this analysis with SED modeling and millimeter data. This region is around 1-2 Myr old and contains many young stars. The Taurus star-forming region is around 140 pc from Earth. In this study, we focus on newly discovered T Tauri stars with potential transitional disks in these regions. The purpose of this study is to complete the millimeter sample of objects with transitional disks in the Taurus star-forming region (Andrews et. al 2011).

In order to understand the root cause of the holes in these disks it was necessary to constrain the physical parameters of these transitional disks. One method of finding the radius of these holes involves extensive model fitting of the SEDs of these objects. This method can then be compared to imaging of the disks of two objects in Taurus. The more that we know and understand about the parameters of these circumstellar disks, the more insight we are given into the mechanisms behind their disk evolution.

Section 2 will focus on the compilation of the SEDs. Section 3 will detail the modeling of our data. Section 4 will briefly go over the Data Reduction and SMA millimeter imaging. Section 5 and 6 will contain a discussion and summary of the results found in this study.

2 Analysis

2.1 Spectral Energy Distributions (SEDs)

A spectral energy distribution (SED) is a plot of the flux density of an object versus the wavelength of light from the object. We produced SEDs for V410-Xray 2 and IRAS04125 using Spitzer IRS, IRAC, and MIPS data found from Luhman et. al, 2010 as well as J/H/K data found using the 2MASS all sky survey. The SEDs for these objects (see figures 2 & 3) give preliminary evidence that these are transitional disks. This is evident from the lack of disk emission at wavelengths where it matches the stellar photosphere until rising in emission towards longer wavelengths. The data in the optical and the mid-infrared agrees with the stellar photosphere but at longer wavelengths the emission is higher than the stellar photosphere due to re-emission from dust in the disk. This again indicates that there is a hole or absence of dust in a portion of the disk which shows that these disks are potential transitional disks.

3 Models

The disks were modeled using the disk code of D'Alessio et. al, 2006. The assumptions behind this model are that the object is steadily accreting, the disk is geometrically thin and in vertical hydrostatic equilibrium, and that the dust and gas in the disk are thermally coupled. It is likely that the dust and gas are thermally coupled only in the lower layers of the disk. The code also assumes that the viscosity is defined by α through the prescription of Shakura & Syunyaev (1973).

The disk code also requires several input parameters. The code requires the input of previously derived stellar properties such as luminosity, radius, and effective temperature. These properties were previously derived when producing the original SEDs. We adopted the same values for these parameters as the values used in Furlan et al. 2011. The code also requires the input of the viscosity (α), and the properties of the dust. The final input required by the disk code is the input of stellar mass accretion rates. We did not have access to data that could be used to determine the accretion rates for these objects. Thus, in the grid we used accretion rates of $3 \times 10^{-9}\ M_{\odot}/yr$ as found in Espaillat et. al 2012. This accretion rate was found to be the average accretion rate for transitional disks in the Taurus, Chamaeleon, and NGC2068 star forming regions. The value that was selected for these models is the value for the median transitional disks.

In order to obtain good fits for our data, we varied the wall temperature and the maximum grain size for the disks. The wall temperature effects the location of the peak disk emission while the grain size effects the height and shape of this peak. After a good fit was obtained, the disk hole radius was calculated using this best-fit temperature following D'Alessio et al. 2005. The hole radius uncertainties depend on the dust opacities used in the model which will be discussed later in this section.

The parameters for the disk modeling of IRAS 04125+2902 and V410 X-ray 2 can be seen in Table 1. The best-fit models to the SED can be seen in Figures 4 and 5.

We will now discuss the model for the outer disk. We made a grid of several disk models of D'Alessio et al. for the two objects. The inclination was set at 60^o, which is taken to be the average inclination angle of disks in star forming regions such as Taurus. The parameter for the maximum grain size was set at a constant of 0.25 microns in the upper disk layers and 1 millimeter in the disk midplane. The outer disk radius was taken to be 300 AU in all cases. Both the α and ϵ values were varied to produce the fits for the grid. Here, α is the Shakura & Sunyaev viscosity parameter and ϵ is the dust settling parameter. The α value adjusts the width of the outer disk model while the ϵ values effect the height and shape of the curve. Table 3 describes these values and Table 4 describes the values of the parameters that provided the best fit.

4 Data Reduction and SMA Imaging

We observed IRAS04125+2902 and V410 X-ray 2 with the Submillimeter Array (SMA) on October 26, 2011 in the compact configuration, August 19, 2011 in the extended configuration, and September 08, 2011 in the very extended configuration. We reduced Compact (270 Ghz), Extended, and Very Extended (345 GHz) data from the sub-millimeter array (SMA) using the MIR Software package for SMA. MIRIAD is a data reduction package used for radio interferometry.

The data was then visualized using the software DS9. According to this image, the hole radius of IRAS 04125+2902 is approximately 25 AU. The image for V410 X-ray 2 does not show signs of having a clear hole and thus the hole is likely too small to be imaged using the SMA. This is because the limit of hole imaging for the SMA is 20 AU. These images can be seen in Figures 6 & 7.

5 Discussion

5.1 Hole Size Agreement

For IRAS04125+2902 the hole size derived from the SED modeling was larger than the hole size seen in the millimeter imaging. The SED model indicates that the hole size should be 62 AU while the SMA image indicates that the hole size should be closer to 25 AU in radius. The large discrepancy seen here could be due to the dust opacities being a degeneracy in the model. According to Espaillat et al. 2010, degeneracies in the adopted dust opacities could cause the model to be off by 10-20 AU. This is because the dust opacity determines the amount in which the disk flares which then determines the fraction of the stellar radiation that is captured by the disk. The amount of radiation captured by the disk then impacts the heating of the disk which causes the amount of disk emission to be strongly dependent on the dust opacity (Espaillat et al. 2010).

Discrepancies such as this have been seen before. For example, DM Tau was measured to have a hole radius of 7 AU through modeling by Calvet et al. 2005 and was then measured to have a hole radius of 20 AU through millimeter imaging by Andrews et al. 2011. It could be possible that both the imaging and the models are correct if it is the case the large and small dust grains have different distributions. The models are highly dependent on data at shorter wavelengths for the fits and therefore the models mostly trace the distribution of smaller dust grains. The millimeter imaging, however, uses data at longer wavelengths that traces the distribution of larger dust grains. This is derived through the knowledge that dust emits at a wavelength that is roughly equivalent to its size. Thus, if the distribution of small grains is different than large grains then it could be possible that both methods of measuring hole radius are accurate in their own right. This is still an active area of research, however, and as of yet no one has looked at this in detail.

For V410-Xray 2 the hole size derived from the SED model more closely matches the hole size as approximated from the millimeter imaging. The SED model indicates that the hole size is 7 AU and the hole is not visible in the millimeter image. This is consistent because a hole of 3 AU is too small to see in an image of this type because the SMA can only resolve holes with a radius greater than 20 AU.

5.2 Mechanisms

5.2.1 Planet Formation

The very large cavity in IRAS 04125+2902 is consistent with the hole size that would be seen due to the formation of multiple planets (Zhu et. al, 2011). Recent research on planetary formation mechanisms has shown that this type of multiple planet formation is possible and can indeed account for large cavities seen in transitional disks.

The cavity in V410 X-ray 2 is too small for the previously mentioned multiple planet formation process. The smaller hole in the disk of V410 X-ray 2 could be accounted for due to planetary formation with a single planet.

5.2.2 Photoevaporation

Photoevaporation has been shown to account for certain transitional disks, however, according to models done by Owen et al. 2011 photoevaporation can only be used to explain cavities that lie in a region of typical to low accretion rates and have small cavities (Figure 8). A low accretion rate is needed for this mechanism to work because photoevaporation causes the loss of the inner disk due to its previous accretion onto the star. Therefore, the current accretion rate should be small due to the lack of this inner disk in close proximity to the stellar mass.

If the cavity in IRAS 04125+2902 is as large as the SED model indicates then the cavity is too large to be explained by photoevaporation regardless of the accretion rate of this object. However, if it turns out that the cavity is closer to the radius seen in the millimeter imaging then it is possible that photoevaporation could be the cause of the hole, although this depends dramatically on the accretion rate of the object.

Photoevaporation cannot be ruled out as the cause for the hole in V410 X-ray 2 because the size of the cavity of this object means that it is in the range where the cavity could very likely be caused by photoevaporation. However, without the true accretion rate for this object it is not possible to definitively say that the cause of the cavity is photoevaporation.

5.2.3 Stellar Companions

We know from multiplicity studies that IRAS 04125+2902 is a binary. According to Adam Kraus (private communication, 2012), IRAS 04125+2902 is a 4″ binary which corresponds to a binary with a separation of 560 AU. Thus, this binary could not be causing the cavity in the disk. IRAS 04125+2902 has also been probed down to 7 AU in the disk and another companion star has not be found. If a companion star were to be found at 6 AU it could clear out a hole of around 20 AU in the disk (Artymowicz & Lubow 1994). Therefore, if the millimeter imaging is the most accurate measure of the hole size then this could be a possibility. However, if the SED modeling is more accurate then this could be ruled out.

In the case of V410-Xray 2 there have not been any studies of whether or not this object is a member of a stellar binary. Therefore, no conclusions can be drawn in this regard.

6 Summary

- We chose two new, and relatively bright, potential transitional disks in the Taurus star forming region.
- Through the analysis of the SEDs and images for these two disks we have confirmed that V410 X-ray 2 and IRAS 04125+2902 are indeed transitional disks.
- V410 X-ray 2 has a small hole that is likely caused by the formation of a planetary mass, by photoevaporation, or by an unknown companion star.
- IRAS 04125+2902 has a larger hole that is likely caused by the formation of a multiple planetary system but could possibly be caused by an unknown, close stellar companion.
- Through further constraints of these disks we can more accurately determine the cause of the holes in the disks.

7 Acknowledgements

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8 References

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9 Tables & Figures

Object	A_v	Spectral Type	T_* (K)	M_* ($M_\odot$)	R_* ($R_\odot$)
IRAS 04125+2902	2.66	M1.25	3720	0.47	1.74
V410 X-ray 2	19.6	M0	3850	0.56	4.11

Table 1: This table shows the stellar parameters for each star.

Object	T_{wall} (K)	a_{max} (μm)	R_{hole} (AU)	Disk Mass ($M_\odot$)
IRAS 04125+2902	75	0.25	62	0.04
V410 X-ray 2	230	1.0	7	0.01

Table 2: This table shows the best fit parameters for the model fitting of these objects and the fitted radius of the hole in each disk.

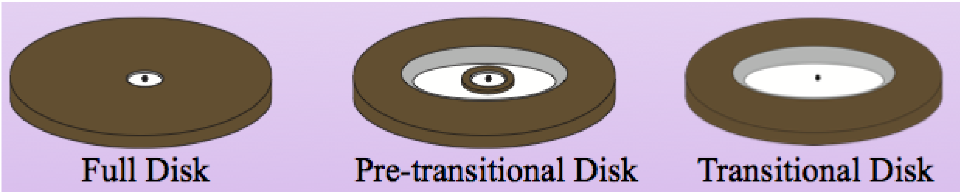

Figure 1: This figure shows the three classes of circumstellar disks. Full disks are radially continuous, pre-transitional disks have a gap while transitional disks have large central holes.

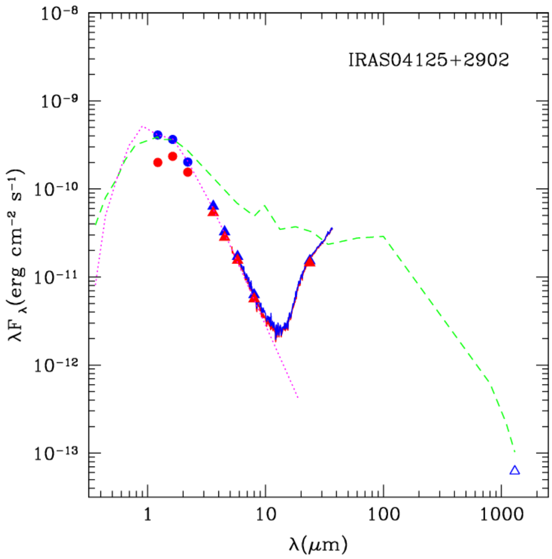

Figure 2: This figure shows the SED for IRAS 04125+2902. The magenta line represents the stellar photosphere. The green line is the median SED of T Tauri stars in Taurus with disks and is taken to be representative of a full disk. The red data points represent the observed values that are not corrected for extinction and the blue data points represent dereddened data. To deredden the data, we used extinctions from Furlan et al. 2011 and the extinction law from McClure 2009. The circle points were taken from 2MASS, the triangle points were taken from Luhman et al. 2010 and they represent IRAC and MIPS and the blue line represents Spitzer IRS data also taken from Luhman et al. 2010. The open triangle point at longer wavelengths represents the SMA photometry that we measured.

Object	α value	ϵ value
IRAS 04125+2902	0.0001	0.001
	0.0001	0.01
	0.0001	0.1
	0.001	0.001
	0.001	0.01
	0.001	0.1
	0.01	0.001
	0.01	0.01
	0.01	0.1
	0.01	0.001
	0.03	0.001
	0.04	0.001
	0.002	0.001
	0.004	0.001
	0.006	0.001
	0.008	0.001
	0.0012	0.001
	0.0014	0.001
	0.0016	0.001
	0.0018	0.001
V410 X-ray 2	0.0001	0.001
	0.0001	0.01
	0.0001	0.1
	0.001	0.001
	0.001	0.01
	0.001	0.1
	0.01	0.001
	0.01	0.01
	0.01	0.1
	0.01	0.001
	0.004	0.001
	0.006	0.001
	0.008	0.001

Table 3: This table shows the parameters used in the grid models to fit the outer disk of the SED for IRAS 04125+2905 and V410 X-ray 2.

Object	α value	ϵ value
IRAS 04125+2902	0.0012	0.001
V410 X-ray 2	0.004	0.001

Table 4: This table shows the best fit parameters of α and ϵ to fit the outer disk of the SED for IRAS 04125+2905 and V410 X-ray 2.

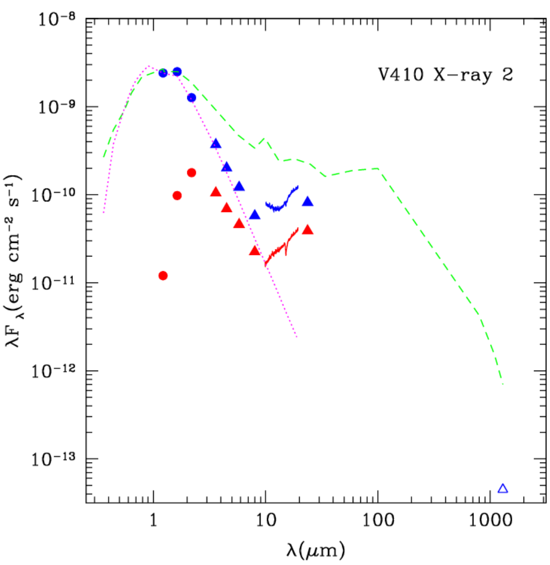

Figure 3: This figure shows the SED for V410 X-ray 2. The symbols and lines used here follow those described in Figure 1.

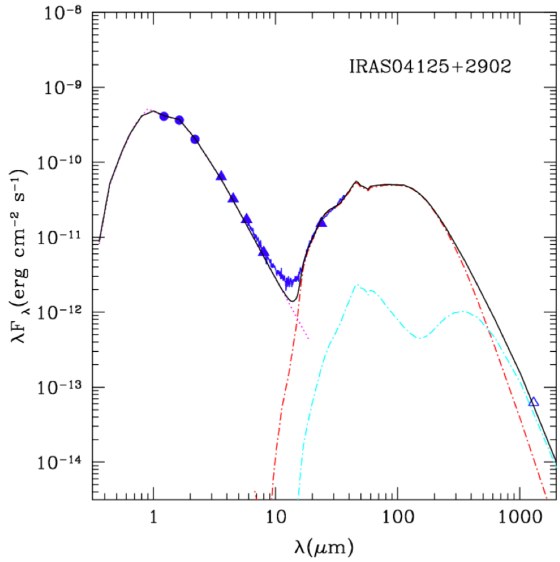

Figure 4: This figure shows the modeled SED for IRAS 04125+2902. The black line represents the complete disk model. The blue here again represents the dereddened data. The red line represents the emission from the inner wall while the turquoise line represents the emission from the outer disk.

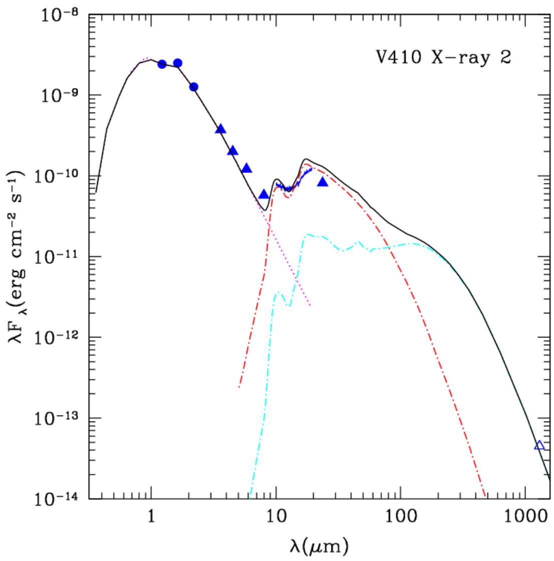

Figure 5: This figure shows the modeled SED for V410 X-ray 2. The symbols and lines used here follow those described in Figure 3.

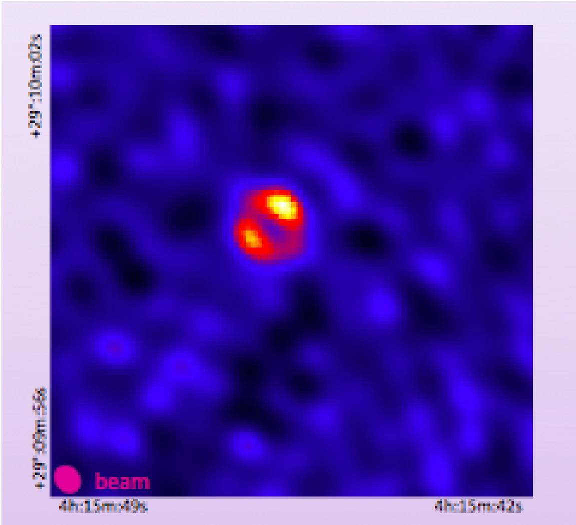

Figure 6: This figure shows the imaged disk for IRAS 04125+2902 at 345 GHz. There is a visible hole present in the disk with an approximate size of 25 AU.

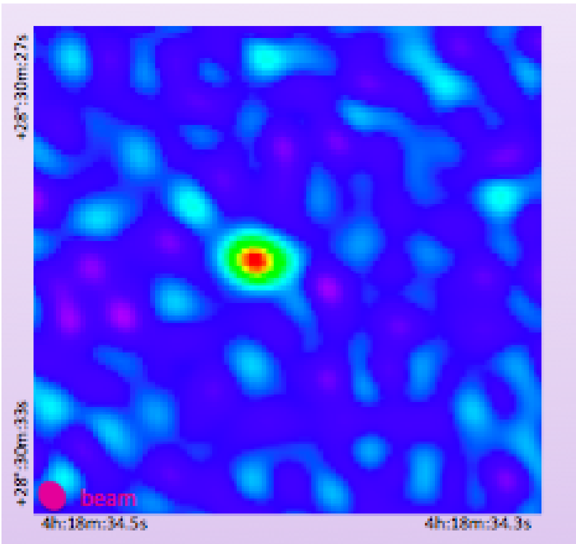

Figure 7: This figure shows the imaged disk for V410 X-ray 2 at 345 GHz. There is not a visible hole present which means that the hole is not large enough to be imaged.

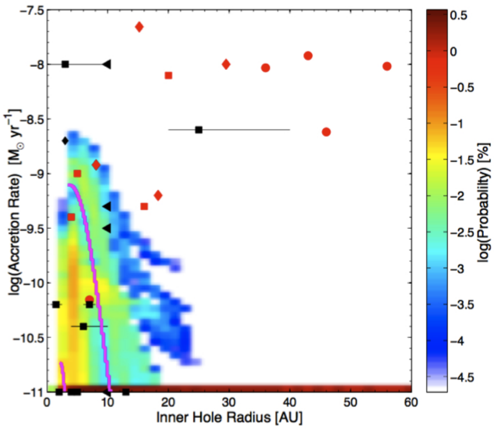

Figure 8: This figure shows the types of transitional disks (colored portion of the graph) that have a hole that could be caused by photoevaporation. This graph was taken from Owen et al. 2011.