An Analysis of the Planetary Disk and Gap Structure around HL Tau

A Major Qualifying Project Submitted to the

Faculty of Worcester Polytechnic Institute

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Degree in Bachelor of Science In Physics

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Abstract

The goal of this project was to analyze gap structures found in the proto-planetary disk around the star-HL Tauri. Data from the ALMA Radio Telescope was downloaded and analyzed using CARTA. A hypothesis was generated to predict the cause of the gaps. I generated plots to map observed gaps to the condensation fronts of particles commonly found in the proto-planetary disk of young stars.

Acknowledgements

I would like to thank my advisors Rudra Kafle and Douglas Petkie for guiding this project and showing tremendous support throughout its completion. I would also like to thank my friends for helping me understand Linux terminal.

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Chapter 1: Introduction

As a star grows, so does its radiation pressure. This outward force pushes much of the lighter compounds out from the inner solar system, leaving behind heavier materials. As lighter compounds are pushed, they eventually fall into stable orbits around the star known as condensation fronts, where larger than normal quantities of a singular material appear within the protoplanetary disk.

As the protoplanetary disk evolves, the various materials within it begin to collide and fuse. The eventual collisions of the fused materials results in the creation of pebbles, and then much larger rocks *(NAOJ, 2016)*. With more and more collisions, these rocks eventually become several hundred kilometers wide, at which point they are large enough to be considered planetesimals. These planetesimals collide over time, creating planets like those we find in our solar system today.

Section 1.1: Objectives

This project had 6 main objectives:

- Gain familiarity with astronomical observation methods.
- Practice using tools to analyze astronomical data, such as CARTA.
- Expand my theoretical knowledge of Astrophysics, particularly pertaining to the study of proto-planetary disks.
- Investigate the gap structure surrounding HL Tauri.
- Provide a hypothesis for the cause of the location of these gaps.
- Make predictions about planet formation in these gaps and draw comparisons to planets in our own solar system.

This project has served as my first experience conducting astronomical research. As such, many of my objectives involve getting familiar with how to conduct astronomy research and getting familiar with programs that more experienced astrophysicists would be familiar with. For this project I chose to research exoplanet formation, so I began researching existing theories about planetary formation, particularly focusing on the formulas that are used to model solar systems. Next, I began to research the system that I was interested in, HL Tauri and its protoplanetary disk. The ALMA website has a plethora of research papers about this system, after dissecting a few of these papers, it became time to begin my own research.

Chapter 2: Background

Section 2.1: A Brief Introduction to Planetary Formation

The life cycles of planetary systems, like our own solar system, begin after a molecular cloud collapses to form a protoplanetary disk (*Czekala, 2011*). These disks are composed of large quantities of tiny dust grains, along with gaseous and other solid materials that orbit around protostars (*Inamdar, 2016; Takemura, 2016*). The exact amount of gaseous and solid materials varies across protoplanetary disks and these materials are what will eventually form planets (Inamdar, 2016).

Section 2.1.1: What are Condensation Fronts?

As a star grows, so does its radiation pressure. This outward force pushes much of the lighter compounds out from the inner solar system, leaving behind heavier materials. As light compounds are pushed, they eventually fall into stable orbits around the star known as condensation fronts, where larger than normal quantities of a singular material appear within the accretion disk.

As the protoplanetary disk evolves, the various materials within it begin to collide and fuse (*Takemura, 2016*). The eventual collisions of the fused materials results in the creation of pebbles, and then much larger rocks (*Takemura, 2016*). With more and more collisions, these rocks eventually become several hundred kilometers wide, at which point they are large enough to be considered planetesimals (*Encyclopedia, 1998*). These planetesimals may continue to collide with each other, eventually becoming large enough to be considered a protoplanet (*NAOJ, 2016*). These protoplanets will either remain in stable orbits, free of collision from other protoplanets, or they will continue to collide, creating much larger protoplanets (*NAOJ, 2016*).

Section 2.1.2: Protoplanets and Planets

As protoplanets orbit the star they begin to collect nearby material through gravity, clearing out large portions of the proto-planetary disk. In the outer solar system, where much of the gas found stable orbits, this results in larger gas giants, like Saturn and Jupiter (Landau, n.d.). The inner solar system has much less gas and is left with mostly rocky material to form planets, typically resulting in significantly smaller planets.

Chapter 3: Theory and Findings

While looking to begin my research I focused on topics within the field of astrophysics that were of interest to me, notably blackholes and exoplanets. The ALMA website is a good source of publications on various topic sets. After reading a few papers, I decided to focus on exoplanets. One of the papers that I had read was on HL Tauri, abbreviated HL Tau, a young star with a protoplanetary disk surrounding it.

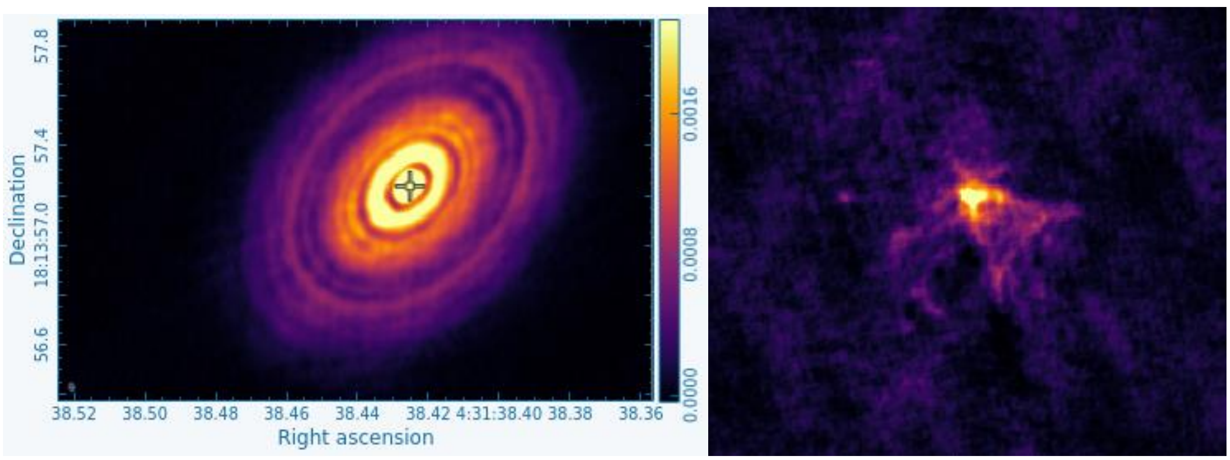

Figure 3.0.1: Flux density measured by ALMA band 6 and 7, observing a wavelength of 1.3mm (on the left). Flux density measured by band 3 (on the right). Each of these measurements was taken in 2011.

After further investigation, I learned about the gap structure in the protoplanetary disk, as can be seen in left image *Figure 3.0.1*. The cause of these gaps was unknown but was hypothesized to be due to planetary formation. The most recent publications on this system were mapping the condensation fronts of different materials to see if a correlation exists between these fronts and the location of the gaps. I sought to follow this research and generate a plot clearly mapping the condensation fronts of common compounds and the observed dips moving radially from HL Tau.

While reading about HL Tau, I observed that most researchers were treating the star as a blackbody to allow for calculations the govern black body radiation. A blackbody is a simplification of an object, if any radiation that impacts its surface is absorbed. Since the star is in thermodynamic equilibrium, the absorbed radiation is the emitted. When a blackbody emits radiation, known as blackbody radiation, models such as *Plank's Law for Black Body Radiation*, can be used to study emissions and predict the temperature of regions of known wavelength. The following graph, *Figure 3.0.2*, depicts the wavelength of radiation emitted by a black body at different temperatures *(Ling et al., 2018).*

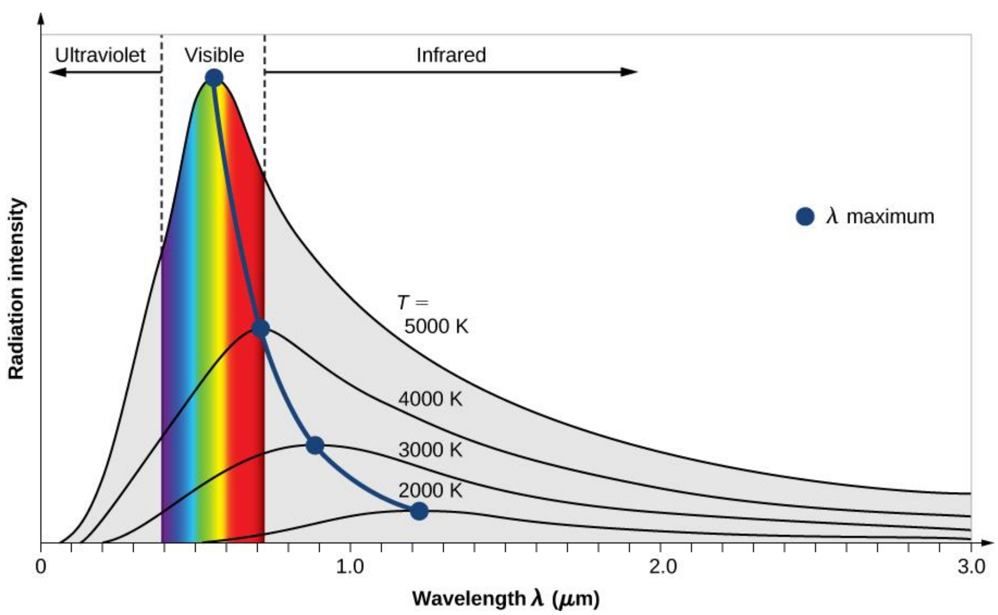

Figure 3.0.2: The intensity of a given wavelength emitted by a black body at the given temperatures. Notice lower temperature blackbodies give off less radiation overall. Emitted wavelengths shift toward infrared as temperatures decrease (Ling et al., 2018).

Section 3.1: Data Analysis

After downloading the data on HL Tau from ALMA, ALMA measured the Flux Density in a given region. I began to analyze it using CARTA, generating the plot shown in *Figure 3.1*. The dips in temperature are visible in this preliminary graph. Throughout the following sections I discuss how I analyzed the data to create predictions for the midplane temperature and brightness temperature of the system.

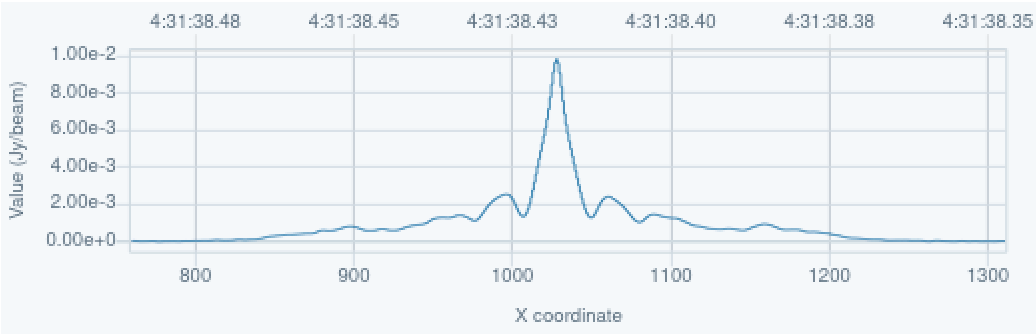

Figure 3.1: Plot exported from CARTA depicting the flux density as a function of the x coordinate, measuring in pixels, as shown in the left image of Figure 3.0.

In *Figure 3.1*, the dips in flux density correspond to the darker bands visible in *Figure 3.0*, while the higher points relate to the whiter parts of the image. The flux density is measured in terms of jansky per beam size.

Section 3.1.1: Flux Density to Brightness Intensity

The first step in analyzing the data was to normalize the data and change the *flux density* to the *intensity*. As can be seen in *Figure 3.0*, the plane of HL Tau is at an inclination angle relative to earth. Previous research papers have found the inclination angle *i = 46.72 degrees (Zhang, 2015)*. Using trigonometry, adjustments can be made to shift the data to account for this shift.

Once the data is shifted, it is straightforward to find the intensity. The beam size allows for the conversion from flux density ($I_{Jy/beam}$) to surface intensity (I_{λ}). For ALMA, the beam size depends on the band being used. For the bands used in 2011, bands 3, 6, and 7, the beam size is given by (*ALMA Basics*):

$$Beam\ Size = 4\frac{\ln(2)}{\pi\theta} \qquad (1)$$

$$\theta = 3.76111 * 10^{-5} degrees \qquad (2)$$

In the above equation, θ denotes the total angle observed by ALMA while collecting data on HL Tau. This can be found by finding the difference in ascension, between the left most and right most data points. Use the beam size and flux density in the following equation to receive the *surface intensity, I_{λ}*.

$$I_{\lambda} = \mathrm{I}_{Jy/beam}(Beam\ Size) \qquad (3)$$

The surface intensity allows for simple calculations of the brightness temperature, or the temperature along the surface of the protoplanetary disk using *Planks Law for Blackbody Radiation* as follows. In the below equation, c is the speed of light, and h is Planck's constant. λ is the wavelength of radiation collected in Band 7, in this case λ is equal to 1.3mm. I_{λ} is the surface intensity in a given area.

$$T_{SB} = \frac{hc}{k_B\lambda}\left[ln\left(1 + \frac{2hc^2}{I_{\lambda}\lambda^5}\right)\right]^{-1} \qquad (4)$$

Section 3.1.3: Midplane Temperature and Condensation Fronts

The midplane temperature is the theoretical temperature at the center of the protoplanetary disk as one travels out radially from the star. This value can be calculated by modeling the star as a black body and is useful for calculating the position of condensation fronts throughout the protoplanetary disk. The midplane temperature is modeled by the following equation (*Zhang 2015*):

$$T_{HL\,Tau} \approx 650K$$

$$T_{Mp} = T_{HL\,Tau}R^{-0.6} \qquad (5)$$

In the previous equation, R is the distance in AU from the temperature source, HL Tauri. $T_{HL\ Tau}$ denotes the midplane temperature distribution, which can be thought of as the temperature emitted by the star. Using the condensation temperature of different compounds, the position of condensations can be found even if the protoplanetary disk is thinner in those regions, due to planet formation or other disturbances to the protoplanetary disk.

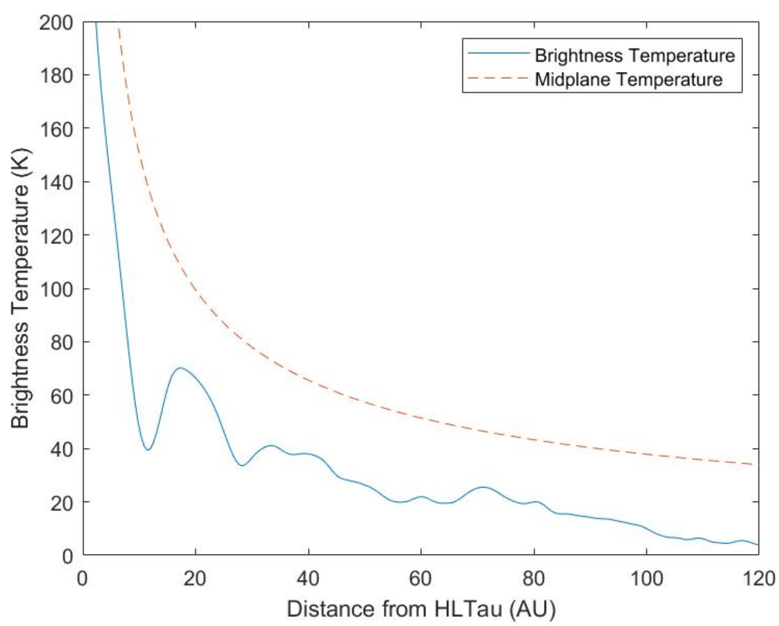

Figure 3.1.3: A plot depicting the surface brightness as a function of distance from the star.

In Figure 3.1.3, the blue line plots the measured brightness temperature. The orange line plots the projected Midplane Temperature, as if HL Tau was a black body, allowing predictions to be made for the condensation front of different elements.

Viewing *Figure 3.1.3*, a relation between midplane temperature and the brightness temperature is evident. The brightness temperature follows a similar trajectory to the midplane temperature but is shifted downwards. This shift is due to the different depth that the temperature is measured at. The brightness temperature is observed from the top of the protoplanetary disk, while the midplane temperature predicts conditions within the disk.

The midplane temperature will allow for calculations regarding the condensation fronts of various materials. The brightness temperature allowed me to compare the location of the brightness dips to the position of condensation fronts.

The final step is to choose which condensation fronts might correspond to the location of the dips. While studying exoplanet formation I found a table containing the midplane temperature that different compounds condensate at. The table can be found in Figure 3.1.4. After inspection of the graph that I generated, the condensation fronts of H_20, ammonia, methanol, and hydrogen sulfide aligned best the dips in intensity found at ~13AU and ~28AU.

Condensation Temperatures of the Major Volatiles in Disks

Species	T^a_{cond} (K)	E_b (K)	Cometary Abundance % of H_2O	References
H_2O	128–155	5165	100	1, 5
CO	23–28	890	0.4–30	1, 5
CO_2	60–72	2605	2–30	1, 5
CH_4	26–32	1000	0.4–1.6	2, 5
CH_3OH	94–110	4355	0.2–7	1, 5
N_2	12–15	520	…	2, 5
NH_3	74–86	2965	0.2–1.4	1, 5
HCN	100–120	4170	0.1–0.6	3, 5
H_2S	45–52	1800	0.1–0.6	4, 5
$NH_3{\cdot}H_2O$	78–81	…	…	6
$H_2S^{\star}$	77–80	…	…	6
$CH_4^{\star}$	55–56 (69–72)	…	…	6, 7
$CO^{\star}$	45–46 (58–61)	…	…	6, 7
$N_2^{\star}$	41–43 (55–57)	…	…	6

*Figure 3.1.4: The condensation temperature of different materials commonly found in protoplanetary disks. * Denotes clathrate-hydrate a type of crystalline structure the solid version of these compounds form. (Zhang, 2015)*

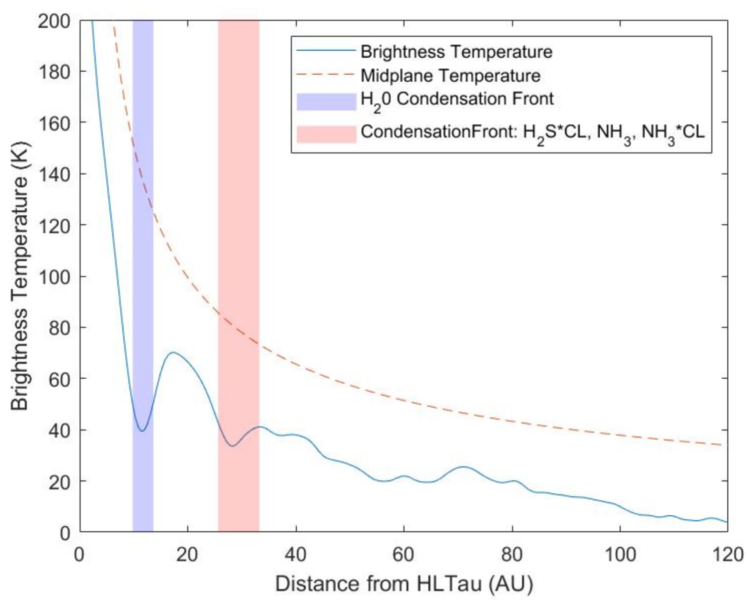

Figure 3.1.5: The surface brightness as a function of distance from the star.

In Figure 3.1.5, the blue line plots the measured brightness temperature. The orange line plots the projected Midplane Temperature, as if HL Tau was a black body, allowing predictions to be made for the condensation front of different elements. The condensation fronts of H_20 (in blue), Ammonia, Methanol, and Hydrogen Sulfide (in red) are shown to align with the larger dips in the observed brightness temperature. CL is an abbreviation for clathrate-hydrate, denoting the type of crystalline structure the solid version of these compounds form.

Chapter 4: Discussion

Section 4.1: Relations to Our Solar System

The condensation front of H_2O can be seen to correspond with the position of the first dip in Temperature. A potential planet forming in this region would collect the gas found in this region, resulting in less flux and thus less surface temperature, as viewed from Earth. Predictions made for the evolution of this solar system would place larger gas giants at distances of ~13AU, and 28AU from the star. A smaller planet may form ~63 AU from HL Tau. As a point of comparison, Saturn is ~9AU on average from the Sun, while Neptune is ~30AU on average from the Sun. These distances roughly correspond to the distance between HL Tau and the brightness dips.

Based on the position of condensation fronts, predictions can be made regarding the chemical makeup of these planets. The planet that forms ~13 AU from the star will likely have proportionally larger quantities of H_2O, in the form of ice, vapor, and potentially liquid water then other planets in the solar system. In our solar system, this condensation front roughly aligns with the asteroid belt, a large collection of icy asteroids between Mars and Jupiter. The asteroid belt is home to many icy planetesimals, like Ceres and Vesta, that are kept to a smaller size, due to Jupiter's gravity.

The planet forming at a distance of ~28AU will likely have a larger ratio of methanol and ammonia than are found in other planets. In our solar system Jupiter and Saturn have the highest ammonia content, likely forming near our solar systems' ammonia condensation front (NASA Astrobiology). It is important to note that throughout the evolution of a solar system, planets tend to move around, the place where they form isn't necessarily where they fall into a stable orbit.

Chapter 5: Conclusions

Overall, I feel that this project successfully completed its objective of allowing me to study topics not regularly studied as part of the WPI curriculum. I developed many new skills, from gaining a better understand of programming, to learning new methods of data analysis. Throughout the project, I learned about exoplanets and planetary formation, a topic that I hope to continue studying in graduate school. I studied the theories the govern planetary formation and made real world predictions about planets forming in distant star systems.

This paper makes use of the following ALMA data sets: ADS/JAO.ALMA#2011.0.00015.SV. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. The authors gratefully acknowledge support provided by the NSF Astronomy & Astrophysics, NSF INSPIRE (AST-1344133), and NASA Origins of Solar Systems grant programs.

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Appendix A: MATLab Code to Generate Graphs

```
clear

%Make Sure to put in the same folder as the excel file!!!%%%%

filename = xlsread('HLTau_B6B7-X-profile-.xlsx');

sheet = 1;

%Reading Full Data set from Excel

xDistAU = xlsread('HLTau_B6B7-X-profile-.xlsx',1,'D7:D600');

TempBrightK = xlsread('HLTau_B6B7-X-profile-.xlsx',1,'H7:H600');

%Positive X Distance from the star

XDistPosAU = abs(xlsread('HLTau_B6B7-X-profile-.xlsx',1,'D52:D275'));

%Measured Surface Brightness

TempBrightPosAU =  abs(xlsread('HLTau_B6B7-X-profile-.xlsx',1,'H52:H275'));

%Surface Brightness Theoretical

SBTemp = abs(xlsread('HLTau_B6B7-X-profile-.xlsx',1,'G52:G275'));

%Condensation Fronts

H20CondDist = xlsread('HLTau_B6B7-X-profile-.xlsx',1,'L6:L7');

H2SCondDist = xlsread('HLTau_B6B7-X-profile-.xlsx',1,'L20:L21');

NH3CondDist = xlsread('HLTau_B6B7-X-profile-.xlsx',1,'L12:L13');

%%-----Plots-------

plot(XDistPosAU,TempBrightPosAU,XDistPosAU,SBTemp, '--')

xlim([0 120]);

ylim([0 200]);

hold on
```

```
%H20 Condensation Front
Hx1 = H20CondDist(1,1);
Hx2 = H20CondDist(2,1);
H20CondensationFront = fill([Hx1,Hx1,Hx2,Hx2],[-1,250,250,-
1],'b','LineStyle','none','FaceAlpha',0.2);
%CH3OH Condensation Front
NH3x1 = NH3CondDist(1,1);
NH3x2 = NH3CondDist(2,1);
NH3CondensationFront = fill([NH3x1,NH3x1,NH3x2,NH3x2],[-1,250,250,-
1],'r','LineStyle','none','FaceAlpha',0.2);
%Plot Format
xlabel('Distance from HLTau (AU)')
ylabel('Brightness Temperature (K)')
legend('Brightness Temperature','Midplane Temperature','H_20 Condensation
Front','CondensationFront: H_2S*CL, NH_3, NH_3*CL ')
hold off
```