Investigation of Accreting Protoplanets in LkCa 15's Transition Disk

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Abstract

In this study Sallum et. al. demonstrate the ability to detect the formation of planets around distant stars. These protoplanets form from transition disks which are the dust and ice that surround a young star that have an area of clearing. The transition disk is in transition from a complete disk of dust and particles to one that contains formed solar satellites as is seen in a "mature" solar system such as ours. The detection of exoplanets, fully formed planets that orbit other stars, has been an extremely exciting advancement in astronomy. At the current time almost 2,000 of these exoplanets have been identified (Akeson et al 2013). The scientists involved in this research have made advances in the ability to detect protoplanets. Prior observations of transition disks have demonstrated areas of inner clearing (Andrews et al 2011, Strom et al 1989, Calvet et al 2005) which are felt to be the result of accreting protoplanets which are protoplanets that are actively acquiring more mass (Bryden et al 1999). Other prior studies have seen disk asymmetries (Isella et al 2013, Perez et al 2014) or infrared emissions from inner clearings which are felt to be caused by protoplanets. The astronomers surmised that such a star system would be a good place to try and more definitively detect the active formation of planets. LkCa 15 is a star with these transition disk characteristics and is suspected to contain protoplanets. (Kraus et al 2012, Ireland et al 2014)

1 Introduction

In this paper I will be discussing the accreting protoplanets within the LkCa 15 transition disc as described by Sallum et al (2015). It is unusual to find exoplanets that are in the process of formation. After a new star forms there can be a gas and dust disk surrounding the star where protoplanets form. The protoplanets form by accreting material from the disk. They accrete material from their orbiting path resulting in a gap in the disk. I will explain the method by which the astronomers obtained their data and their results which demonstrates some of the characteristics of the protoplanet accretion disk and the motion of the protoplanets.

2 Study Design

The telescopes used in this research were: 1) The Large Binocular Telescope, (LBT) which is, as the name implies, two telescopes mounted side by side. Each telescope has an 8.4 meter mirror with the centers of the two mirrors 14.4 m apart. The LBT is located on Mount Graham in Arizona and has the ability to study planets outside our solar system.[1] 2) The Magellan Telescope with an Adaptive Optics System (MagAO) are two 6.5 m telescopes 60 m apart on a 2,516 meter mountain in Chile.[2] The adaptive optics is a specialized secondary mirror that has 585 actuators that can quickly (1,000 times a second) adjust to compensate for atmospheric turbulence. This makes it possible to resolve details as small as 0.02 arcseconds.[3]

For the LBT, a non-redundant mask technique was used. The mask is a plate with multiple holes. It blocks a significant amount of the incoming light but will cause interferometric fringes. These fringes are what we learned in Physics with Young's double slit experiment. The double slit experiment produced bright and dark bands with the distance between the sinusoidal max-min of λ/d where d = distance between the slits. These images are then compared to similar images of several other stars which are used as a reference. Then subtraction is used to block out the light from the central star and collect data for objects adjacent to the star. The LBT measurements used two wavelengths of light. One they depicted in blue (referred to as K_λ = 2.16 micrometers) and the other depicted in red (referred to as L_λ = 3.7 micrometers). They detected two sources, LkCa 15b and LkCa 15c, in both bands. A fainter source, LkCa 15d, was detected but only with the L_λ light so the main focus of the article was on LkCa 15 b and c. The area of clearing in the transitional disk extended to a stellocentric radius of 56 AU (Thalmann et al 2014) and all the objects were within the zone of clearing.

The method of data collection from the MagAO telescope utilized the collection of hydrogen-alpha, H_α emissions. H_α corresponds to the first level of the Balmer series. To eliminate the relative glare of the star, the H_α from LkCa15 was subtracted from the image. This allowed the astronomers the ability to resolve the fainter emissions from the protoplanet.

[1] http://www.jpl.nasa.gov/missions/large-binocular-telescope-interferometer-lbti/
[2] http://obs.carnegiescience.edu/Magellan
[3] http://www.gizmag.com/magao-adaptive-optics-highest-resolution-astronomical-images/28801/

3 Protoplanet Accretion Disks

Each protoplanet has its own accretion disk. The gas and particles in this disk are heated as they accelerate into the protoplanet. This heat energy in turn results in the emission of light. The temperature of the gas falling into LkCa 15b was measured to be approximately 10,000 K. Using the Wien Displacement Law:

$$\lambda_{max} = \frac{b}{T}$$

$$where\, b = 2.898E - 3\; K \times m$$

The peak wavelength corresponding to this black body temperature would be 290nm.

The authors obtained additional information by calculating the infrared fluxes to quantify the amount of light being emitted from each source. The amount of energy is proportional to the mass of the matter accreting into the planet over a given area. For an accretion disk of radius $2R_J$ the planet mass times accretion rate $M_p \times \frac{dM}{dt}$ was calculated to be $1 \times 10^{-5} M_J^2 yr^{-1}$. It is reported that the large uncertainties of the fluxes means that these results could vary by a factor of 2 or 3.

The data was then compared to accretion disk models (Zhu 2015) and hot start models (Spiegel 2012) of planet formation and it was felt that the observations more closely fit the accretion disc model. It is theorized that giant planets can form in two ways. The first is when a solid core forms first. When this core is about ten times the mass of the Earth it will enlarge by accreting gasses but in a way that the entropy of the gas is lost via a luminous shock wave and the growing planet stays cool. Thus, this first method is called the cold start, or accretion disk model. Early in their formation, cold start giant planets have a temperature of about 500K to 700K. In the second model, the planet forms when the protoplanetary disk becomes unstable and collapses into a giant planet. In this model the planet starts out ”hot”, in the range of 1,000K to 2,000K. Regardless of the start, for planets of the same mass both models gradually yield identical planets after about 100 million years. (Spiegel 2012)

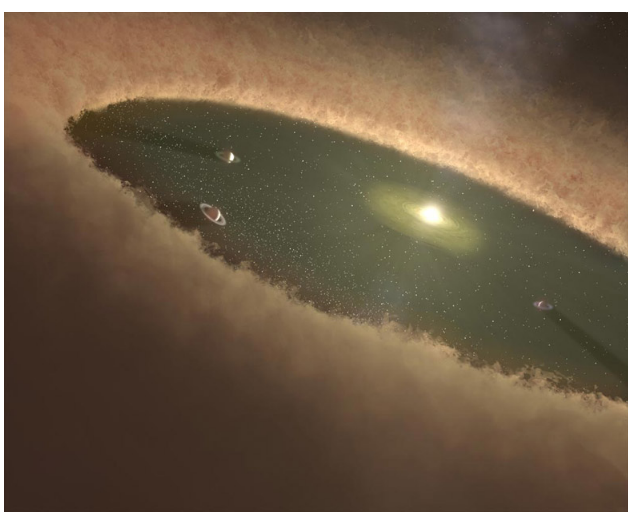

Figure 1: This figure shows many of the features described: the clearing in the dust of the transitional disk, previously measured to be 56 AU. (Thalman et. al. 2014) The authors corroborated this (see Figure 2). The protoplanets are in this cleared area since it is believed that the matter in that zone coalesced into the protoplanet. This drawing also depicts the accretion disks around each protoplanet. (credit: (Reiner 2015))

Partial results of the study are presented in Figure 2 below which shows the LkCa system with its transition disk and protoplanets.

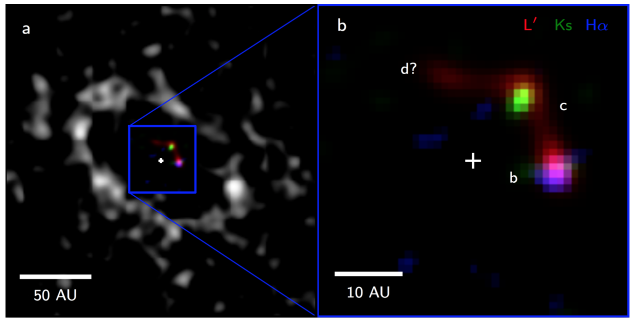

Figure 2: Composite image from the observations. The left panel shows the transition disk with its cleared interior and the developing planets inside the disk. The right hand panel is a magnified image showing the relative locations of the protoplanets. (*credit: (Sallum 2015)*.)

4 Motion of the Protoplanets

The Keplerian motion of the protoplanets was demonstrated by recording the positions of the protoplanets at different times. The planet's locations were previously observed in 2012 and the most recent data is similar but with the protoplanets having moved in a path consistent with independent satellites around LkCa 15.

They applied the principle of the Hill radius to show that these were distinct entities and not gravitationally connected so they are not expected to coalesce into one larger planet. The Hill radius applies to 3 body configurations such as the Earth, its moon and the sun. If the distance between the Earth and the Moon were too great the Moon would be pulled into orbit around the sun rather than staying in orbit around the Earth. In this example, if we let R = the distance from the sun to the earth, r = the distance from the earth to the moon, M = the mass of the sun and m = the mass of the Earth then, since R is much greater than r, the limit simplifies to:[4]
Hill Sphere Equation:

$$r = R \times \sqrt[3]{\frac{m}{(3M)}}$$

Not surprisingly, the mass of the Moon is not involved in the equation since the speed of satellites that are placed in stable orbit around the Earth is dependent on the altitude and not the mass of the satellite. In Figure 3 the left hand panel shows the change in the position angle, PA and separation (inset) for the innermost protoplanet, LkCa 15b. The green and red points correspond to Ks and L' data, respectively. The three left hand points are the previously published data and the right hand points are their current data. The authors used two estimates of statistical error. The colored error bars are from a method they felt underestimates the error, the nonlinear algorithm MPFIT. The black error bars are from what they consider to be a more robust ΔX^2 method. The line is the best fit for the change of position over time with the yellow shading representing one standard deviation of the error from that line. The second panel shows the same data for LkCa 15c.

[4]http://www.jgiesen.de/astro/stars/roche.htm

Solid and dashed lines in the right hand picture show their calculated stable orbits for planets with $0.5M_J$ and $1.0M_J$ orbits, respectively.

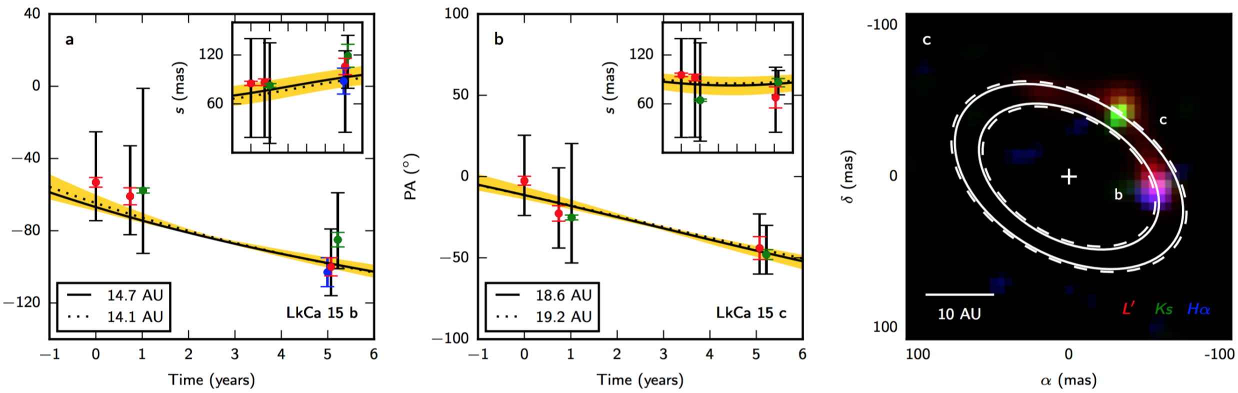

Figure 3: Change in position of the protoplanets over time for LkCa 15a and b in the first two panels and a depiction of the Keplerian orbits in the third panel. (*credit: (Sallum 2015)*.)

5 Calculations

As distant solar systems form from interstellar dust and gas most of the mass comes together and becomes the central star. A small percentage remains first as a disk of particles. In our solar system the Sun has 99.8 percent of the mass compared to the planets.[5] This disk then transitions from a diffuse and broad disk to planets that are fully formed. The article by Sallum et. al. (2015) gives us more detail into this process but it also stimulates one's curiosity, which leads to questions such as: Is the ratio of matter that is partitioned between the star and its planets similar in all solar systems? Is the moment of inertia or angular momentum similar or proportionate in solar systems throughout the universe?

To investigate this, I used the data on the known exoplanets available online in the exoplanet archive.[6] I examined exoplanets for which the mass of its star, period of the planet, mass of the planet and distance of the planet from its star have been measured. I then performed calculations to investigate the above questions. I decided to only include stars with one exoplanet because in our solar system Jupiter accounts for 70 percent of the mass of the solar system that is outside of the sun. It also accounts for the majority of the moment of inertia and angular momentum of the planets so this should still give accurate trends.

5.1 Mass of Star vs. Mass of Exoplanet

Each solar system is believed to coalesce from a cloud of gas and dust. Most of the matter becomes the star, while some eventually forms planets surrounding the star. If the ratio of this matter that is divided between the star and planets in a solar system is constant then a plot of the Mp (planet mass) vs. Ms (star mass) should result in a straight line. The results are graphed below

[5]http://nssdc.gsfc.nasa.gov/planetary/factsheet/
[6]http://exoplanet.eu/catalog/all-fields/

in Figure 4. While not linear, there is a trend toward more massive stars having more massive planets. The red trend line has a positive slope which indicates that larger stars have larger planets. Figure 5 shows the same data but in a 3 dimensional histogram so that denser areas could be seen more clearly. It was also surprising to me that the most common stars in the data set had stars similar to our Sun and planets similar to Jupiter.

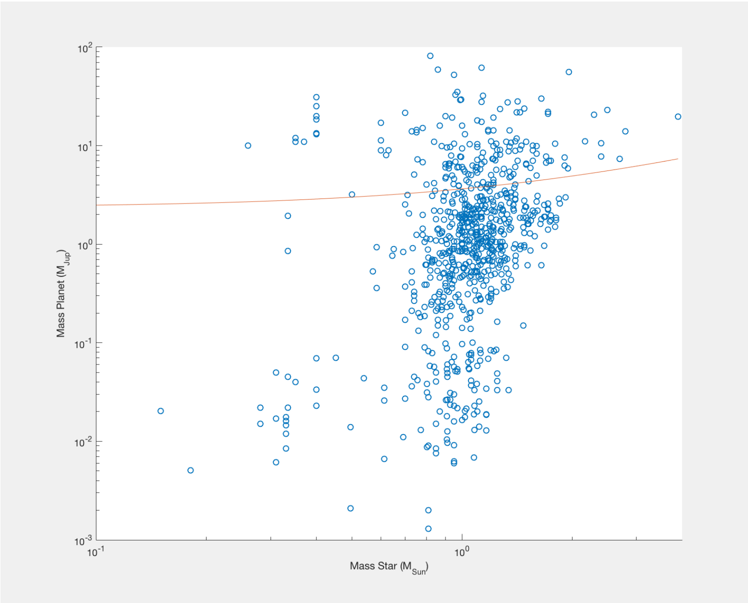

Figure 4: Mass of Star vs. Mass of Exoplanet (*Data credit: exoplanet.eu.*)

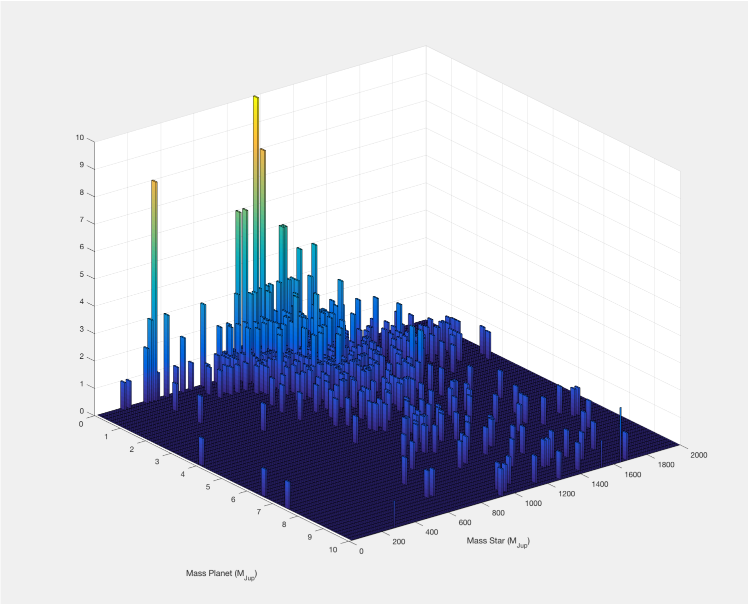

Figure 5: Mass of Star vs. Mass of Exoplanet (*Data credit: exoplanet.eu*)

5.2 Angular Momentum vs. Mass of Star

Angular momentum, $L = m \times v \times r$, can also be calculated for many of the exoplanets discovered using the available data. To see if the angular momentum of exoplanets is proportionate to the mass of its central star, L was plotted vs. Ms. This is demonstrated in Figure 6. This does show a trend but there is significant scatter so, therefore, one cannot conclude that the relationship is linear.

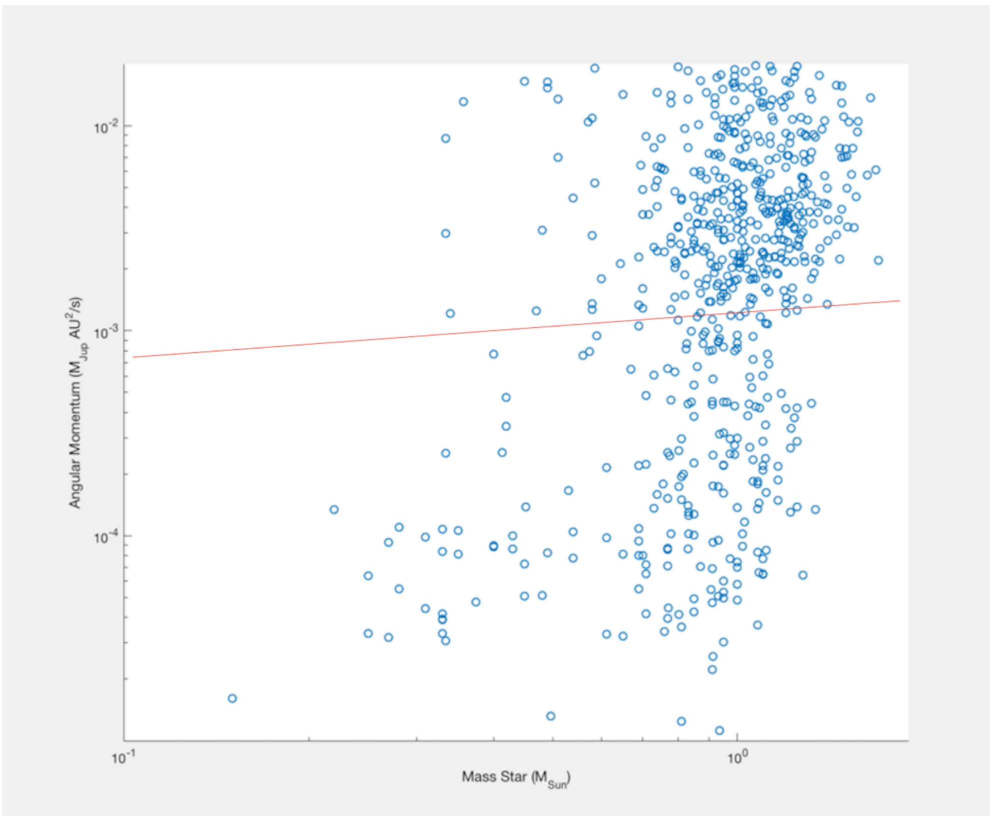

Figure 6: Angular Momentum vs. Mass of Star (*Data credit: exoplanet.eu*)

5.3 Moment of Inertia vs. Mass of Star

Moment of inertia, $I = mr^2$, for the exoplanets studied, when plotted vs. mass of the associated star, did not yield a trend of linearity. As a planet forms over time, it will shift closer to its star and its moment of inertia will change. When the moment of inertia was normalized for the mass of the star, I/Ms, and plotted vs. the age of the star, no significant trend was seen. It is interesting how in both graphs there are two distinct columns. It seems that the inertia of the planets is not greatly affected by the mass of the star or the age. These are demonstrated in Figures 7, 8 and 9 below.

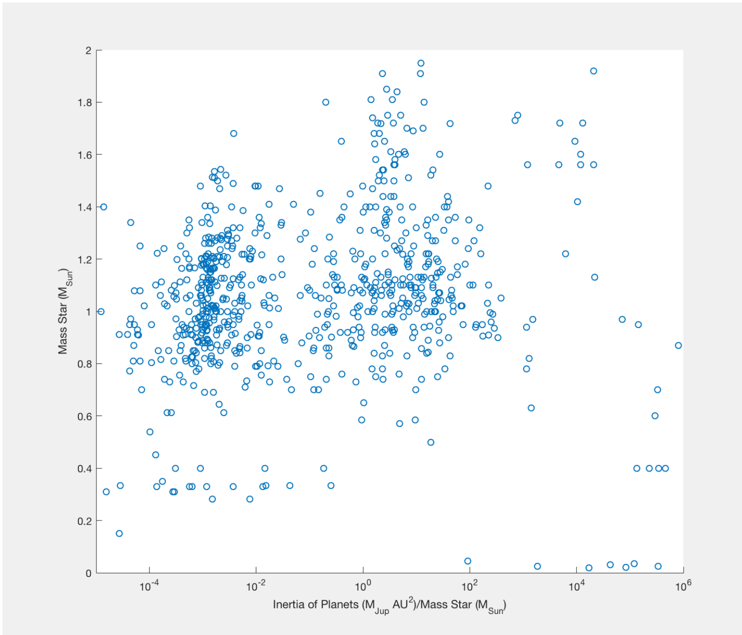

Figure 7: Inertia of Planet vs. Mass of Star (*Data credit: exoplanet.eu*)

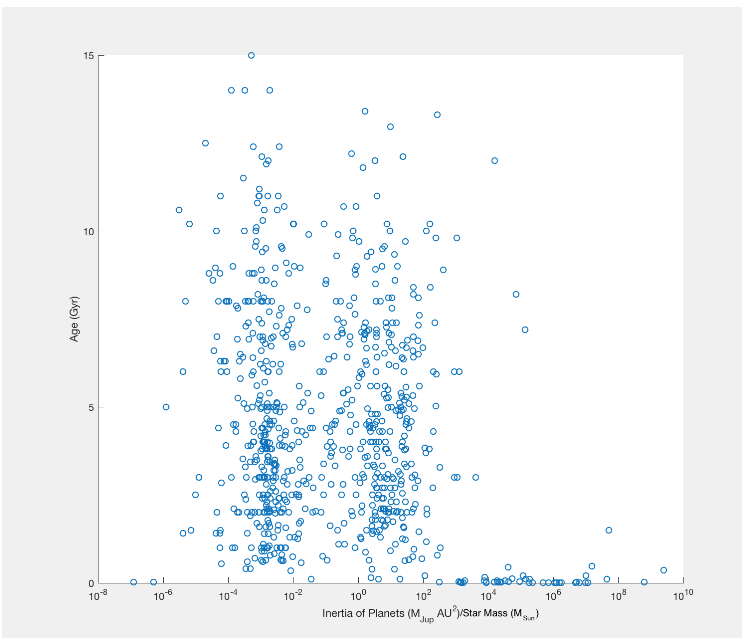

Figure 8: Inertia of Planet vs. Age: There are two vertical dense spots in the data which shows that the y-axis (age) does not greatly affect the data. In the following graph I created a histogram without the age variable. (*Data credit: exoplanet.eu*)

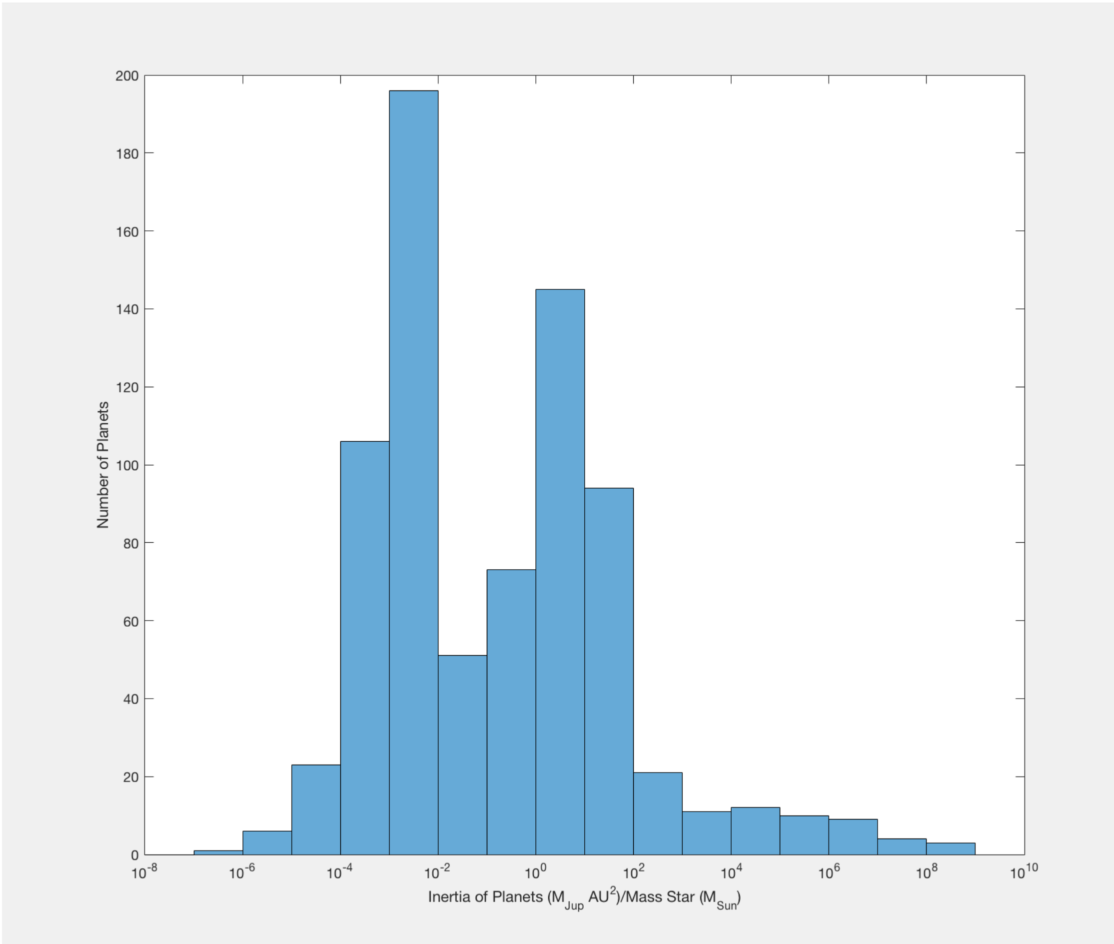

Figure 9: Inertia of Planet normalized for the mass of its star. It is interesting to note there are two peaks in this distribution. The underlying reason for this will require more analysis but this is an unexpected result which could yield interesting results with additional data in the future. (*Data credit: exoplanet.eu*)

6 Discussion and Error Analysis

The first exoplanet was detected on October 6, 1995[7]. While there is some debate about this, we can certainly say that exoplanets have been detected for two decades. This is an amazing achievement considering how distant these planets are and how small they are compared to their solar system's central star. The number of exoplanets discovered now number in the thousands. As we learn more about these distant solar systems we can look for trends to see how "typical" our solar system is. Are there boundaries to the size and proportions of these solar systems?

It is interesting that as a gas cloud condenses into a solar system the final star has angular momentum and the planets, by revolving around the star, have additional angular momentum. Since momentum is conserved, this momentum was either present in the initial cloud or the material ejected from the forming solar system, which had equal but opposite angular momentum. The planets in our solar system have 99 percent of the angular momentum even though the sun has 99

[7] http://earthsky.org/space/this-date-in-science-first-planet-discovered-around-sunlike-star

percent of the solar system's mass.[8] This reference also states that much of the sun's initial angular momentum has been transferred and lost via the solar wind through the interaction of the sun's magnetic field and the solar wind.

That the cloud of gas and dust that formed our solar system was swirling (and therefore had angular momentum) is often stated.[9] As the cloud condensed and became the solar system the overall reduced radius would cause an increase in velocity. The analogy being a figure skater who brings in her arms to increase her rotational speed.

As stated above, the angular momentum of stars is known to decrease as a star ages. This fact is used to date the age of distant stars.[10] By measuring the time it takes for a star to rotate on its axis an estimate as to its age can be made. This process is occurring in our solar system with an effect on the planets. The gravity of the planets have a slight tidal effect on the sun, slowing its rotation on its axis. As the rotation of our sun slows down, that angular momentum is transferred to the earth causing the earth to move faster, and therefore, further from the sun.[11] However, it is estimated that this effect is very small, on the order of 0.1 percent over 10 billion years.[12] This error is so small I did not include it in the presentation of the angular momentum data.

By far, the greatest error in our calculations and therefore graphs, is the margin of error in the data. For example, the age of the stars are given as being $\pm$ 30 percent to 50 percent of the value given in the table. The error reflects the uncertainties due to the faint fluxes and large distances. Another property of the technology is that most of the exoplanets detected are, relative to our solar system, very large planets orbiting very close to their star. As technology advances this configuration is unlikely to make up the majority of distant solar systems. I will not be surprised if repeating this exercise in 20 years yields a more interesting result.

7 Conclusion and future directions

How planets form throughout the Universe is an area of great interest and study. It is important not only to answer the question of how the Earth was formed, but this research will also tell us what we can expect as we learn more and more about our neighboring stars and their planets in the Milky Way Galaxy. This scientific study further refines our ability to learn more about the details of the Universe, specifically in the field of planet formation. The researchers used both infrared and H_α wavelengths to visualize these protoplanets. Their data demonstrates that protoplanets go through a period of high infrared and H_α luminosity during their accretion phase. By establishing a method for detecting forming exoplanets, we can confirm the suspected location of these protoplanets. This will open the door to taking additional measurements of other transition disks to determine if similar emissions are present.

[8] http://abyss.uoregon.edu/ js/ast121/lectures/lec24.html

[9] http://www.as.utexas.edu/astronomy/education/fall04/komatsu/lec-07.pdf

[10] http://www.skyandtelescope.com/astronomy-news/star-spins-show-ages-010820143/

[11] https://www.newscientist.com/article/dn17228-why-is-the-earth-moving-away-from-the-sun/

[12] http://curious.astro.cornell.edu/about-us/41-our-solar-system/the-earth/orbit/83-is-the-distance-from-the-earth-to-the-sun-changing-advanced

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