AST 390 Midterm:
The Hot Jupiter Inflation Problem

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One of the subjects at the forefront of astronomy research today is exoplanets. These extrasolar objects have only recently been known to exist, with the first transiting exoplanet being discovered about twenty years ago. There are many different types of exoplanets that have been discovered, such as super-Earths, mini-Neptunes, and hot Jupiters. Hot Jupiters are one of, if not the most common type of exoplanet that has been found in general. This is mainly due to the fact that most of the exoplanets detected are transits. Transits favor exoplanets that are large compared to their star, and which radiate a lot of energy. Therefore, the closer they are to the host star, the more energy they absorb and then emit, and the more likely they are to be detected. Hot Jupiters fit these descriptions in almost every way.

The first hot Jupiter to be found was around the G star 51 Pegasi, granting it the name "51 Peg b". This planet has a four day period, a mass of approximately .5 Jupiter masses (M_J), an eccentricity of $\approx .03$, and lies .05 AU away from its host star. Normally, gas giants such as 51 Peg b are formed in the outer solar system, as seen in our solar system with Jupiter and Saturn. It was previously thought that gas giants usually formed around 5 AU from their host star (Burrows et al., 1996). It can also be seen that 51 Peg b is nearly 15000 times more luminous than Jupiter, due to it being closer to its host star. This close proximity to the star causes it to have a higher average temperature, in turn producing more radiation. Furthermore, 51 Peg b is within its Roche lobe, meaning that it will not break apart from the high gravity near the star. This stability of gas giants very close to their host star is very prevalent in the Universe, as hot Jupiters are very common.

In order to understand how hot Jupiters came to be, we must first discuss the different theories of planet formation. When stars are very young, they contain a lot of debris rotating around them from when they were formed.

This circumstellar disk is filled with the material that it is made of, meaning namely Hydrogen and Helium. There are two credible theories that predict how gas giants form within this circumstellar disk. The first theory is that particles will begin to coagulate within the disk. (Bodenheimer et al., 2001) After this coagulation, more particles will begin to accrete onto the mass of particles until it grows large enough to be a planet. In this accretion, a could be formed if the density is high enough, though this is not always the case. After this accretion phase, the planet will undergo contraction due to the large gravitational pressure it is experiencing. The planet will eventually reach equilibrium after this contraction, becoming a planet of unchanging size. Another theory for gas giant formation is that which involves gravitational instability (Bodenheimer et al., 2001). Initially, there will be some sort of gravitational instability in the circumstellar disk, causing some of the gaseous debris to become gravitationally attracted to each other. This will then form the gas giant like a star would form, just with much less mass. Seeing as the mass it much less, the core of the planet would not be dense enough to begin fusing Deuterium like a brown dwarf, let alone Helium. Hot Jupiters are not only interesting in their formation, but also in their proximity to the host star.

Hot Jupiters do not form near their host star. Gas giants normally form around 5 AU away from the host star. The theory that explains this discrepancy is one known as planetary migration (Trilling et al., 1999). When being formed, the planet will have a certain angular momentum, usually in the same direction of the circumstellar disk, and therefore the star. However, this angular momentum can be lost in a variety of ways, causing the planet to migrate radially inward or outward. The planet will lose this angular momentum due to the tidal interactions between it and the star. Tides occur when gravity occurs in one direction, but not the other on a stellar object. For instance, the Earth experiences a gravitational pull towards the Sun, but not in the direction of its orbit. This causes the planet to "stretch", losing some of its angular momentum if the tidal force is strong enough. This loss of angular momentum has three different possible outcomes. The first is that the planet migrates inward and does not lose any mass. The second is that the planet migrates inward, loses mass to the star by approaching it too closely, and then migrates away from the star. The third, and most likely option in the case of hot Jupiters, is that the planet migrates inward, loses some mass, and then stabilizes itself near the star. In the case of hot Jupiters, we assume that they migrate during formation, not after they are already formed. This explains how a gas giant could be so close to its host star and be stable.

Many of the hot Jupiters we have discovered all have similar properties: low eccentricity, higher average temperature, small semi-major axis, small period, etc... But one issue all of these planets have is that their measured radii are higher than their calculated radii. When forming, planets will contract until they are in stable, hydrodynamic equilibrium. However, they only stabilize once they reach thermal equilibrium. The planet will cool itself by releasing energy from its interior until it stabilizes. Therefore, the higher the internal temperature of the planet, the longer the period of contraction it undergoes. Seeing as they are close to their host stars, hot Jupiters already have a high average temperature, so their radii should be larger than normal. Though, the measurements made exceed even the calculations based on this temperature. The presence of a core in the planet could also affect this resulting radius, but these calculations cannot account for the measurements either. For example, HD 209458b is a hot Jupiter that is only .05 AU away from its star, so the tidal interactions it experiences are intense. It has a measured radius of 1.35 Jupiter radii (R_J), but a predicted radius of 1.04 R_J (Laughlin et al., 2005). This presents a difference of about 22000 km. In order to account for this larger radius, the temperature inside the planet would need to be unrealistically high. Therefore, however small comparably, this presents a problem unaccounted for by the traditional planetary formation model.

Throughout the last few decades, there have been many proposed solutions to this "inflated radius problem" for hot Jupiters. There are still many solutions being devised to this day, though each one takes data from the last and improves on it. The first few, however, were instrumental in laying the foundation for future works and calling attention to key areas of research. The three theories I will be discussing are tidal dissipation, kinetic winds, and Ohmic dissipation.

Bodenheimer et al. (2001) were the first group of people to combat the inflated radius problem for hot Jupiters. In order to allow this increased radius, there must be a source of energy to raise the internal temperature of the planet, so that contraction does not last as long. The possible sources of energy that were considered were the radiation from the star, the gravitational contraction of the radiative envelope of the planet, and the cooling of the interior of the star. When the planet forms, the outer "layer" will be an envelope that relies on radiative energy transfer, while the interior of the planet relies on convection to transport energy. However, Bodenheimer et al. (2001) considered the effects of tidal interactions, seeing as the planet is so close to the star. Normally, a planet very close to its host star will have a very low eccentricity and rotate synchronously with the star. Though, since hot Jupiters migrate towards the host star, this does not necessarily need to be the case. 51 Peg b has an eccentricity of .03, while HD 209458b has an eccentricity of .014.

The tidal interactions between a planet and its star serve to put the system in equilibrium. Therefore, they make the planet's eccentricity smaller, orbital inclination smaller, and synchronize its rotation with the star's. The tidal forces between the planet and star cause energy to be dissipated in some form. Classical physics presents the results that energy associated with eccentricity and asynchronous rotation are dissipated in the planet. Normally, the eccentricity and asynchronous rotation are too small to have any effect on a forming planet. However, seeing as the tidal interactions on hot Jupiters are very strong, this can impact the radius greatly. Therefore, the energy from the tidal interactions from the star will cause energy to dissipate within the interior of the planet, raising its temperature, causing contraction to take longer, making its radius large. The effect of this tidal heating is directly proportional to its mass, seeing as the mass is related to its binding energy. The lower the binding energy, the less energy input needed to increase its radius. This tidal heating can also be affected by the presence of other planets/stars in the system, as with τ Boo. The tidal forces from the other objects can excite the hot Jupiter even more, causing its eccentricity to become higher, making its radius larger. Finally, the presence of a core can also affect the amount of tidal heating that the planet can receive, as more mass is concentrated in the center (Bodenheimer et al., 2003). All of these factors contribute to the accuracy of this theory and its predictions.

The next significant theory to explain the inflation problem was founded by Guillot and Showman (2002). The paper made by Bodenheimer et al. (2001) gave a solution to the inflated radius problem, but on a timescale of about 10^8 years. The issue with this is that the circumstellar disk, and therefore the formation of gas giants, only lasts approximately 10^6 years. Furthermore, they did not take into account the effects of the atmosphere of the gas giant on planet formation. Therefore, Guillot and Showman (2002) produced a new theory, based on the winds that would form on the planet. During planet formation, a thick radiative envelope is formed on a hot Jupiter, due to the high amount of radiation it receives from its star. The inner planet, as mentioned previously, becomes a convective zone, which mostly determines the radius of the planet. Therefore, increasing the planet's inner temperature would be similar to increasing its radius. Guillot and Showman (2002) assumed that the separation between the interior of the planet and the radiative envelope occurred at a height where the pressure is ~ 10 bars. Due to the strong tides the planet feels, one side of the planet would most likely face the star at all times. However, say this wasn't the case. Say that one side of the planet is just slightly warmer than the other side. This temperature difference would cause a pressure difference on both sides of the planet as well. This pressure difference would cause winds to develop across the planet, much like what happens on Earth. On Earth, a fraction of the heat flux of the planet will be converted to kinetic energy for the wind. This fraction is normally about .01, so it does not have much of an effect on Earth. However, for a hot Jupiter with a high luminosity, the effects can be significant. This kinetic energy then must somehow be dissipated within the planet. Guillot and Showman (2002) predicted that the energy must be dissipated at some height within the planet. The height chosen can drastically affect the outcome of the radius of the hot Jupiter. By only using .08% of the stellar flux as the energy dissipated, and 10 bars as the height, Guillot and Showman (2002) was able to reproduce the radius for HD 209458b. Like with Bodenheimer et al. (2001), increasing the internal energy through some means to counter concentration of the planet left the radius longer. This also happened on a shorter timescale, countering the suggestion of Bodenheimer et al. (2001).

In order to analytically prove which process produced better results, Laughlin et al. (2005) used both methods to try to predict the measured radii of different hot Jupiters. In this data, we can see that HD 209458b is very much an outlier. This hot Jupiter and TrES-1b have almost the exact same masses and temperatures, but the size differs by about .25 R_J. Therefore, HD 209458b is not the best sample hot Jupiter to use for these theories. Laughlin et al. (2005) tried computing the radii of multiple hot Jupiters with kinetic winds and without kinetic winds. The only planet which had a radius that could be predicted by kinetic winds is HD 209458b. Seeing as this planet is very large for its planet-type, the kinetic winds theory does not seem very practical. The tidal heating theory, however, does work for the other hot Jupiters within reasonable uncertainty. For example, TrES-1b's radius was predicted within .05 R_J. It can also be seen that large inflation, like HD 209458b's, can be explained by multiple planets exciting its eccentricity. Therefore, it can be concluded that both of these theories only apply situationally, as neither can be applied to all hot Jupiters, in general.

One of the more recent theories on how to solve the inflation problem was made by Batygin and Stevenson (2010). They proposed a more electromagnetic approach to the problem, using Ohmic dissipation. Seeing as hot Jupiters are very close to their host star, their temperatures are high enough to contain ionized atoms. The interior, being very hot, would be able t contain ionized Hydrogen and Helium. The radiative exterior, having a lower temperature, would only be able to contain ionized alkali metals, such as Sodium or Potassium. Seeing as they are ionized, the interior and exterior of the planet are electrically conductive. The winds produced on the planet will therefore form a current, with current loops in the interior, and a single current developing around the exterior. These current will then produce their own magnetic field, reducing the magnetic flux through the planet in some direction. Therefore, the reduced magnetic flux will cause an emf to be formed opposing the loss of flux. This emf will then drive the current into the interior of the planet, dissipating through Ohmic dissipation. When current flows through a resistance, some of the current will be converted into heat. Accordingly, current going through the interior will dissipate into energy through this Ohmic dissipation, which can then slow the contraction and cooling of the planet, increasing the size of its radius. However, the results of this method vary. When assuming an interior-exterior boundary of $\sim$ 90 bars and a temperature of 1700 K, the predictions match with the results for HD 209458b. However, with another hot Jupiter, HD 189733b, the same assumptions do not produce accurate results. Therefore, another solution to the problem only works in limited cases.

Overall, the problem of inflated hot Jupiters is a puzzling one. Many of the methods that have been tested to prove this inflation only work for certain situations. The method of tidal heating by Bodenheimer et al. (2001) seems the most plausible out of the ones shown, though the timescale it assumes is very long. Therefore, it is evident that this is still an ongoing area of research. As time goes on, more hot Jupiters will be found, making predictions for their inflation easier. However, if there are more outliers such as HD 209458b, the subject may become much more complex. This problem still proves to question our understanding of planet formation, electromagnetic dynamics, and classical atmospheric physics. Research into this topic can only bring extrasolar astronomy to new heights and enhance our knowledge of planetary dynamics.

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