Constraints on the Formation of the Planet Around HD188753A

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ABSTRACT

The recent discovery of a Jupiter-mass planet in the close binary star system HD188753 poses a problem for planet formation theory. A circumstellar disk around the planet’s parent star would be truncated at 1.3 AU, leaving little material available for planet formation. In this paper, we attempt to model a disk around HD188753, exploring a range of parameters constrained by observations of protoplanetary disks. We find that the in situ formation of the planet around HD188753 is extremely unlikely, and that the planet must have formed before the capture of the close stellar companion.

Subject headings: stars: individual (HD 188753) — planetary systems: protoplanetary disks — planetary systems: formation

1. Introduction

A Jupiter-mass planet has been recently discovered orbiting the primary star of the close triple system HD188753 (Konacki 2005). The parameters for this system are listed in Table 1. The primary, HD188753A, hosts the new planet, and the secondary, HD188753B, orbiting at a semi-major axis of 12.3 AU, is actually a spectroscopic binary itself. While the planet is a typical “hot Jupiter,” with a minimum mass of 1.14 $M_J$ and orbital period of 3.35 days, what is exceptional is its existence in a such a close binary system. With an eccentricity of 0.5, at closest approach, the secondary is 6 AU from the primary, which would truncate a protoplanetary disk around the primary at 1.3 AU (Pichardo et al. 2005; Konacki 2005). Given this constraint, could the 1.14 $M_J$ planet around HD188753 have formed in situ, that is, in such a small disk?
Table 1: Orbital Parameters for HD 188753AB

|                  | HD188753A | HD188753B | planet |
|------------------|-----------|-----------|--------|
| mass             | 1.06 M⊙  | 1.63 M⊙* | 1.14 M⊕|
| semi-major axis  | –         | 12.3 AU   | 0.045 AU|
| eccentricity     | –         | 0.50      | 0      |
| orbital period   | –         | 25.7 years| 3.35 days|

*Total mass of the spectroscopic binary HD188753B

Although there is some debate about exactly how planets form, whether by core accretion (e.g. Pollack et al. 1996; Chambers 2004) or gravitational instability (e.g. Boss 1997, 2000, 2001), it is generally accepted that planets form out of disks of circumstellar material leftover from the star formation process. The fact that a disk around HD188753A must be truncated at 1.3 AU puts severe limits on the amount of material that could be available for planet formation. In this paper, we explore the possibilities of planet formation in such a disk.

2. Model Description

The prototypes for protoplanetary disks are pre-main sequence stars known as T Tauri stars. These disks are the remnants of the star formation process and are modelled as accretion disks. It is thought that planet formation occurs in such disks, because they have appropriate ranges of density and temperature. The calculation for the disk models analyzed in this paper is described in detail in Jang-Condell & Sasselov (2004), following the method developed by Calvet et al. (1991) and D’Alessio et al. (1998, 1999). We assume an α-disk model, where the viscosity $\nu$ is given by $\nu = \alpha c_s H$ where $c_s$ is the sound speed and $H$ is the thermal scale height of the disk, and $\alpha$ is a dimensionless parameter (Shakura & Sunyaev 1973; Pringle 1981). The temperature of the disk is set by stellar irradiation at the surface and viscous heating at the midplane. The radial and vertical density and temperature structure of the disk is calculated iteratively to achieve self-consistency.

We adopt stellar parameters of mass $M_*=1\,M_\odot$, temperature $T_* = 4280 \,\text{K}$, and radius $R_*=2.6\,R_\odot$, corresponding to a 1 Myr old star with metallicity $Z=0.02$ (Siess et al. 2000).

The two remaining free parameters for our disk models are the mass accretion rate onto the star, $\dot{M}$, and the viscosity parameter, $\alpha$. Accretion rates of T Tauri stars are calculated by subtracting template spectra from the observed spectra and assuming that the excess
optical and near-ultraviolet continuum flux comes from the accretion shock caused by disk material falling onto the stellar surface (Gullbring et al. 1998). Typical accretion rates are around $\dot{M} \sim 10^{-9} - 10^{-7} \text{M}_\odot \text{yr}^{-1}$. Values for $\alpha$ are calculated by fitting $\alpha$-disk models to dust emission from disks at millimeter wavelengths, with a typical value of $\alpha \sim 0.01$ (Hartmann et al. 1998). The D/H ratio in the outer solar system suggests that the early solar nebula may have experienced accretion rates as large as $10^{-5} \text{M}_\odot \text{yr}^{-1}$ (Hersant et al. 2001). FU Ori objects may accrete as much as $10^{-4} \text{M}_\odot \text{yr}^{-1}$, but these are transient phenomena so that these high accretion rates are not expected to be sustainable in the long run (Calvet et al. 2000).

Given these observational constraints, we calculate a grid of disk models, with $\alpha$ set to 0.001, 0.01 or 0.1, and $\dot{M}$ set to $10^{-9}, 10^{-8}, 10^{-7}, 10^{-6}$ or $10^{-5} \text{M}_\odot \text{yr}^{-1}$. We shall refer to a given disk model by the coordinate pair $(\alpha, \dot{M})$, so that Model (0.01, $10^{-7}$) refers to the run with $\alpha = 0.01$ and $\dot{M} = 10^{-7} \text{M}_\odot \text{yr}^{-1}$.

### 3. Results

#### 3.1. Mass Profiles

The mass profiles of our set of models are shown in Figure 1, with line color identifying the accretion rate, and line texture identifying the value of $\alpha$. The total disk mass is defined as the mass interior to the given radius. Specifically, mass profiles drawn in red, green, blue, cyan, and magenta correspond to mass accretion rates of $10^{-9}, 10^{-8}, 10^{-7}, 10^{-6}, 10^{-5} \text{M}_\odot \text{yr}^{-1}$, respectively, while solid, dotted, and dashed lines correspond to $\alpha = 0.1, 0.01$, and 0.001, respectively. The left vertical axis is in units of $\text{M}_\odot$ and the right vertical axis is in units of $\text{M}_J$, which are related by $\text{M}_J/\text{M}_\odot \approx 0.001$. The disk truncation radius at 1.3 AU, is indicated by the solid vertical line.

The overall mass of the disk increases with increasing accretion rate and decreasing $\alpha$. At the extreme end, we can get disks with masses of several $\text{M}_J$ within 1.3 AU, which may suffice to form a Jupiter-mass planet. It is unlikely that planet formation is 100% efficient, so if we require at least 2 $\text{M}_J$ within 1.3 AU in order to create a Jupiter mass planet, then Models (0.001, $10^{-5}$), (0.001, $10^{-6}$), (0.001, $10^{-7}$), and (0.01, $10^{-5}$) meet this criterion.
Fig. 1.— Enclosed disk mass versus radius for the suite of calculated disk models. Masses are shown in units of both solar masses (left axis) and Jupiter masses (right axis). The accretion rate is indicated by color: $10^{-9}$ (red), $10^{-8}$ (green), $10^{-7}$ (blue), $10^{-6}$ (cyan), and $10^{-5}$ (magenta) $M_\odot$ yr$^{-1}$. Models with $\alpha$ of 0.1, 0.01 and 0.001 are indicated by solid, dotted and dashed lines, respectively.
3.2. Solid Formation

In order to form a planet by core accretion, there must be sufficient mass of solid material to coagulate into a dense core which can then accrete gas. We use the results of Pollack et al. (1994) for sublimation temperatures and mass fractions of olivines, orthopyroxene, iron, water, troilite, refractory organics and volatile organics, which compose the bulk of the dust in the protoplanetary disks. We take into account the dependence on density of the sublimation temperatures for these solids and calculate the total amount of solid material available in the disk as a function of disk size. These results are plotted in Figure 2. The line types correspond to the same models as the line types in Figure 1.

In general, temperatures are hotter in disks with higher accretion rates and lower $\alpha$. Close to the star, viscous heating dominates, so that the more massive disks, those with the higher accretion rates, actually contain fewer solids. At large radii, the temperatures drop low enough so that all condensible materials are frozen out and the amount of solid material is proportional to the total gas mass. At intermediate distances, the trends with changing disk parameters are complicated since temperatures vary both with radius and height in the disk. The temperature profiles determine where various materials freeze out, so the composition of the dust in different regions varies substantially. Nevertheless, Model (0.001, $10^{-7}$) has the most amount of solid material up to 1.3 AU, at around 2 M$_\oplus$. Given that models of core accretion require at least 10 M$_\oplus$ to form a Jupiter-mass planet, this amount of solid material is insufficient for planet formation (Pollack et al. 1996). The disks with the next most amounts of solid mass contain less total gas mass than 1 M$_J$, and the models that do have sufficient total mass have even less solids.

3.3. Disk Lifetimes

Given the high accretion rates of some of the models that might be even remotely feasible, we now address the question of disk lifetimes. In the upper plot in Figure 3, we plot the lifetimes of our disk models, assuming the disk ends at 1.4 AU and is accreted steadily at the given mass accretion rate. Models with $\alpha = 0.1$ get accreted in extremely short timescales, and are likely ruled out. Disks with small accretion rates naturally survive longer, but only around $10^5$ years at best. Of our most massive disks, only Models (0.001, $10^{-6}$) and (0.001, $10^{-7}$) survive longer than 10,000 years. This implies that if planet formation does take place in situ, it must take place very rapidly.
Fig. 2.— Total amount of solid material, in earth masses, available for core formation versus enclosing radius. The lines are labelled in the same way as Figure 1.
Fig. 3.— (upper) Disk lifetimes for the calculated models, assuming that the disk is truncated at 1.4 AU. Times are plotted versus accretion rate, and the relations for an α value of 0.1, 0.01, and 0.001 are indicated by solid, dotted and dashed lines, respectively. (lower) The Toomre Q parameter at 1.4 AU versus accretion rate. Line textures indicate different values of α, as in the upper plot.
3.4. Conditions for Gravitational Instability

Since core accretion generally takes place over million-year timescales (Pollack et al. 1996) whereas gravitational instability can act within a thousand years (e.g. Boss 2001), the extremely short disk lifetimes might be a point in the favor of the gravitational instability model. To address this issue, we consider the Toomre Q parameter, which is a measure of whether or not a gaseous disk is locally stable to axisymmetric perturbations. This parameter is defined as

$$Q = \frac{c_s \kappa}{\pi G \Sigma}$$  \hspace{1cm} (1)

where \(c_s\) is the local midplane sound speed, \(\kappa\) is the epicyclic frequency, \(G\) is the gravitational constant, and \(\Sigma\) is the local gas surface density of disk (Binney & Tremaine 1987). In a disk with approximate Keplerian rotation, \(\kappa \approx \Omega = \sqrt{GM_\star/a^3}\). If \(Q \lesssim 1\), gravitational instability can operate – that is, the disk needs to be sufficiently cold and/or massive in order for gravitationally bound clumps to form.

We plot the value of \(Q\) at 1.4 AU versus accretion rate in the lower plot in Figure 3. The values of \(Q\) for all the disk models are well above the stability threshold, so gravitational instability is unlikely to act. However, the eccentric stellar companion to HD188753 may excite density waves in the disk, increasing the surface density in parts of the disk. Since \(Q\) varies inversely with \(\Sigma\), local enhancements of the surface density may make the disk unstable to clump formation. The most massive disk models also have the smallest values of \(Q\), so planets may be able to form if density waves can create density enhancements by factors of 10 or more without substantial increase in the temperature.

4. Discussion

The most favorable model for in situ planet formation via core accretion around HD188753 postulates a disk with \(\alpha = 0.001\) accreting at \(10^{-7} M_\odot\) yr\(^{-1}\), parameters that are not altogether unreasonable. However, this disk has only 2 \(M_\oplus\) available for core formation, survives only 26,000 years, and contains only 2.6 \(M_J\) total disk mass. Forming a planet via core accretion in these conditions is extremely unlikely.

Things are not much more favorable for forming planets by gravitational instability, either. The value of \(Q\) is well above the stability threshold, even in the most extreme case. So although gravitational instability can get around the problems of timescale and lack of solids in the disk, it is still extremely unlikely. One possible loophole is if density waves can be generated in the disk that sufficiently pump up the local surface density to lower \(Q\) below 1, then gravitationally bound clumps may be able to form and collapse into massive planets.
5. Conclusions

The in situ formation of HD188753’s planet appears to be unlikely according to current models of planet formation. We studied a range of disk parameters that are representative of observed protoplanetary disks and found that even if we can model a disk with sufficient total mass within the disk truncation radius of 1.3 AU, its lifetime is too short, it contains insufficient solids, and it is too hot for planets to form by generally accepted mechanisms.

It is more plausible that the planet formed around HD188753A before its stellar companion assumed its present-day orbit. Perhaps it started out as a system with more than two stars, and ejected all but the two seen today, leaving them as a close pair. Perhaps a close encounter with a third object resulted in the system we see today. At any rate, the binary system must have started out with either a much larger semi-major axis, or much lower eccentricity.

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