Core-Accretion Model Predicts Few Jovian-Mass Planets Orbiting Red Dwarfs

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ABSTRACT

The favored theoretical explanation for giant planet formation – in both our solar system and others – is the core accretion model (although it still has some serious difficulties). In this scenario, planetesimals accumulate to build up planetary cores, which then accrete nebular gas. With current opacity estimates for protoplanetary envelopes, this model predicts the formation of Jupiter-mass planets in $2-3$ Myr at $5$ AU around solar-mass stars, provided that the surface density of solids is enhanced over that of the minimum-mass solar nebula (by a factor of a few). Working within the core-accretion paradigm, this paper presents theoretical calculations which show that the formation of Jupiter-mass planets orbiting M dwarf stars is seriously inhibited at all radial locations (in sharp contrast to solar-type stars). Planet detection programs sensitive to companions of M dwarfs will test this prediction in the near future.

Subject headings: planetary systems: formation — planetary systems: protoplanetary disks — stars: formation

1. Introduction

Over 100 planets have been detected orbiting Sun-like stars and the distributions of extrasolar planetary masses and orbital properties are remarkably diverse (Marcy et al. 2003; Udry, Mayor, & Queloz 2003). The leading mechanism for explaining the origin of both the extrasolar planets and our solar system’s Jovian planets is the core-accretion process, in which collisional accumulation of icy planetesimals builds planetary cores with
mass $M \sim 5 - 15 M_\odot$. These cores then accrete nebular gas and reach Jovian mass. A long-standing difficulty with the core-accretion hypothesis was that the estimated time required for the core to accrete 1 $M_{\text{JUP}}$ of gas exceeded the observed circumstellar disk lifetimes (Pollack et al. 1996). This issue motivated discussion of gravitational instability as an alternative formation process (Boss 2000). However, updated estimates of the opacity in protoplanetary envelopes imply that Jupiter-mass planets readily form via core-accretion in solar-metallicity disks within 2-3 Myr at radii $a \sim 5$AU around solar-mass stars (Hubickyj, Bodenheimer, & Lissauer 2003). This relatively short formation time results if the surface density of solid material in the disk is assumed to be three times greater than that of the minimum-mass solar nebula (MMSN). The resulting core mass was about 16 $M_\oplus$, somewhat larger than the maximum deduced core mass (10 $M_\oplus$) for Jupiter (Wuchterl, Guillot & Lissauer 2000). To explain the low core mass of Jupiter, a cutoff of solid accretion beyond a certain core mass is required, and can be explained by nearby planetary embryos that compete for available solid material. An independent calculation with similar opacities (Inaba & Ikoma 2003; Inaba, Wetherill, & Ikoma 2003) shows that in a disk with eight times the solid surface density of the MMSN, a core of 25 $M_\oplus$ can form in 1 Myr at 5 AU, so that the total formation time is 2–3 Myr. In this model, the fragmentation of planetesimals and the enhancement of the solid accretion rate due to the gaseous envelope (primarily from gas drag) are taken into account, although the main gas accretion phase is not calculated. If the solid surface density is reduced to four times that of the MMSN, an 8 $M_\oplus$ core can still form in 5 Myr. These results imply that somewhat special circumstances are required for the core accretion model to explain the properties of Jupiter. Assuming that the core accretion model can explain the formation of Jovian planets around solar-mass stars, this paper addresses the question of whether or not Jovian planets can form within disks that orbit around M-dwarfs (low mass stars with $M_*=\lesssim 0.4 M_\odot$).

Observational surveys are shifting our view of extrasolar planets from an anecdotal collection of individual systems (e.g., 51 Peg, $\upsilon$ And, or 47 UMa) to a fuller statistical census in which categories and populations of planets can be clearly delineated (e.g., Marcy & Butler 1998; Marcy, Cochran, & Mayor 2000; Udry et al. 2003; Marcy et al. 2003). This emerging statistical view is vital for improving our understanding of the planet formation process, and to see how our own solar system fits into the galactic planetary census. One of the most remarkable statistical results to emerge from planet searches is that stars with observed extrasolar planets tend to have metallicities that are more than twice that of the average Population I star in the immediate galactic neighborhood (Fischer & Valenti 2003; Butler et al. 2000). On the other hand, low metallicity stars are deficient in currently detectable ($P < 8$ yr) Jovian-mass planets (Sozzetti et al. 2004). This connection between planets and host-star metallicity can be interpreted as evidence in favor of the core accretion hypothesis,
although Sigurdsson et al. (2003) argue that it can also be interpreted as evidence in favor of migration. Metal-rich circumstellar disks have a higher surface density of solids and cores can readily reach the $5 - 15M_\oplus$ threshold required for rapid gas accretion. This letter shows that the core-accretion process makes a similar – and readily testable – prediction of the relative frequency of Jovian-mass planets as a function of stellar mass. Compared to disks around solar-mass stars, the circumstellar disks orbiting red dwarfs ($M_\star < 0.5M_\odot$) should be less efficient in producing Jupiter-mass planets.

2. Theoretical Model of Planet Formation

This theoretical treatment assumes that planets form within a circumstellar disk with the following properties. The surface density $\sigma(r) = \sigma_{in}(r_{in}/r)^{3/2}$, where $r_{in}$ and $r_d$ are the inner and outer disk radii, and $\sigma_{in} = (M_d(t)/4\pi r_{in}^2)[(r_d/r_{in})^{1/2} - 1]^{-1}$ is the normalization factor required to obtain a total disk mass $M_d(t)$. We specify the time dependence through a disk depletion factor $f_\sigma(t) = 1/(1 + t/t_0)$ so that $M_d(t) = M_d(0)f_\sigma(t)$. Observations of protostellar disks (e.g., Briceno et al. 2001) suggest that $t_0 = 10^5$ yr and $M_d(0) = 0.05M_\star$ are reasonable fiducial values. The temperature distributions for both viscously evolving accretion disks and flat, passively irradiated disks have nearly the same power-law form, $T_d(r) = T_{d*}(R_*/r)^{3/4}$, where $T_{d*}$ is related to the stellar surface temperature by a geometrical factor ($T_{d*}/T_* \approx [2/3\pi]^{1/4}$ for a flat disk – see Adams & Shu 1986). This model uses disks that are flat and passive, and assumes that the disk is isothermal in the vertical direction. The effective temperature $T_*$ of the star is related to the stellar radius $R_*$ and luminosity $L_*(t, M_*)$ through $T_*(t, M_*) = [L_*(t, M_*)/4\pi R_*^2\sigma]^{1/4}$. We adopt $T_*(t, M_*)$ and $L_*(t, M_*)$ from published pre-main-sequence stellar evolution tracks (D’Antona & Mazzitelli 1994).

We use a Henyey-type code (Henyey, Forbes, & Gould 1964) to compute the contraction and buildup of gaseous envelopes surrounding growing protoplanetary cores embedded in our evolving model disk. Our method (Kornet, Bodenheimer, & Różycki 2002; Pollack et al. 1996) adopts recent models for envelope opacity (Podolak 2003) which includes grain settling (see also Hubickyj et al. 2003). The calculation is simplified (compare with Pollack et al. 1996) in that it uses a core accretion rate of the form $dM_{\text{core}}/dt = C_1\pi\sigma_sR_cR_h\Omega$ (Papaloizou & Terquem 1999), where $\sigma_s$ is the surface density of solid material in the disk, $\Omega$ is the orbital frequency, $R_c$ is the effective capture radius of the protoplanet for accretion of solid particles, $R_h = a[M_p/(3M_\star)]^{1/3}$ is the tidal radius of the protoplanet, and $C_1$ is a constant near unity. An important feature of our present model is that the outer boundary conditions for the planet include the decrease in the background nebular density and temperature with time.
The results of this planet formation calculation are illustrated in Figure 1. The first calculation is for a disk around a 1 \(M_\odot\) star with an initial solid surface density \(\sigma_s = 11.5\ \text{g cm}^{-2}\) at \(a = 5\ \text{AU}\), about four times that of the MMSN. This value is based on an initial gas-to-solid ratio of 70 in the disk; later on, \(\sigma_s\) decreases with time as mass accretes onto the growing planet. A Jupiter-mass planet forms in 3.25 Myr with a core mass of 18 \(M_\oplus\), consistent with the results of Hubickyj et al. (2003). The second calculation is for a disk around an \(M_* = 0.4\ M_\odot\) red dwarf with an initial solid surface density of 4.5 g cm\(^{-2}\) at \(a = 5\ \text{AU}\). Formation of a Jupiter-mass planet does not occur: Planet growth has reached only \(M_P = 14M_\oplus\) at \(t = 10\ \text{Myr}\). At later times, much less than 1 \(M_{\text{JUP}}\) remains in the entire disk. The resulting planet is similar in mass, size, and composition to Uranus and Neptune.

Figure 2 shows that Jovian planet formation around a 0.4\(M_\odot\) star is also thwarted at radii of 1 AU and 10 AU. The lower surface densities (\(\sigma_s\)) and longer orbital timescales (\(\Omega = \sqrt{GM_*/a^3}\)) of M-star disks more than offset the increase in tidal radius \(R_h\) and lead to a greatly reduced capacity for forming Jovian-mass planets within the core-accretion paradigm. Also, the reduced core mass found in the M-star disk results in much longer times for the accretion of the gaseous envelope (Pollack et al. 1996). Figure 2 indicates that although M stars (red dwarfs) have a limited ability to form Jupiter-mass planets, the formation of Neptune-like objects and terrestrial-type planets should be common around these low-mass stars. This finding is the main result of this paper. Furthermore, the final sizes of these objects correlates with the surface density of solids (dust and ice) in the precursor protoplanetary disk and should thus depend on the host star metallicity.

### 3. Potential Tests of the Theory

A number of detection methods can potentially confirm a paucity of Jupiter-mass planets orbiting M-stars, and also detect Neptune-mass objects. Given an adequate time baseline, the Doppler radial velocity method (Marcy & Butler 1998) will readily determine whether Jupiter-mass planets are common around red dwarfs. A Neptune-mass planet in a circular, \(i = 90^\circ\), \(a=3\ \text{AU}\) orbit around a 0.4\(M_\odot\) primary would have a period \(P = 8.2\ \text{yr}\), and would induce a stellar radial velocity half-amplitude \(K = 1.6\ \text{m s}^{-1}\). Such an object would be marginally detectable using current RV precision of 3 m s\(^{-1}\), assuming a high sampling cadence. The California and Carnegie Planet Search radial velocity program has detected one planetary system orbiting the M-dwarf star GJ 876 and \(\sim 100\) other red dwarfs are currently under surveillance.

The GJ876 system (Marcy et al. 2001), with \(M_* \sim 0.3\ M_\odot\), contains two Jovian planets \((M_c \sin i = 0.6M_{\text{JUP}}, \ M_b \sin i = 1.9M_{\text{JUP}})\) with periods \(P_c \sim 30\ \text{d}\) and \(P_b \sim 60\ \text{d}\). The
system displays clear signs of having undergone migration (Lee & Peale 2002), indicating that abundant gas was present in the system when the planets formed. We argue that standard core-accretion theory predicts that systems such as GJ 876 are drawn from the extreme high-mass end of the circumstellar disk mass distribution, and will thus be intrinsically rare. In the alternative formation mechanism (gravitational instabilities; see Boss 2000), the growth rate depends primarily on the ratio of disk mass to star mass and instabilities need not be suppressed in disks surrounding low mass stars (compared to disks around solar-type stars). Systems like GJ 876 may turn out to be examples of giant planet formation via gravitational instability. On the other hand, gravitational fragmentation will not generally produce ice giants (such as Neptune), so the discovery of ice giants in extrasolar systems would be an important confirmation of the core-accretion hypothesis.

Microlensing is another promising method for determining the census of both high and low mass planets orbiting M dwarfs. Recent work (Bond et al. 2004) reports an unusual light-curve for a G-type source star in the direction of the galactic bulge. The observed light curve is consistent with the passage of an optically faint binary lens with mass ratio $\mu = 0.0039^{+11}_{-07}$ for the lensing system. Stellar population models of the galactic disk (Han & Gould 1996) indicate a $\sim 90\%$ a-priori probability that the optically faint lens primary is an M-dwarf (in which case the planet mass is of order $M_P \sim 1.5M_{\text{JUP}}$) and a $\sim 10\%$ probability that the primary is a white dwarf (implying a somewhat higher planet mass). In either case, the projected sky separation of the primary–planet system is $\sim 3$ AU. Our calculations imply that M-dwarfs should rarely harbor Jupiter-mass planets and favor the possibility that the lensing system has a white dwarf primary. This prediction can be tested within $\sim 10$ years as proper motion separates the source star from the lens. We also predict that the mass spectrum of microlensed planets (drawn largely from M-dwarf primaries) should be shifted dramatically toward Neptune-mass objects compared to the mass spectrum of planets found by the ongoing RV and Transit surveys (which draw predominantly from primaries of roughly solar-mass).

Transits provide another method for detecting planets. A Neptune-mass object in central transit around a 0.3 $M_\odot$ M dwarf produces a photometric dip of approximately 1.5%. Such events are easily observed from the ground using telescopes of modest aperture (Henry et al. 2000, Seagroves et al. 2003). The forthcoming Kepler mission (Koch et al. 1998) will monitor $\sim$3600 M dwarf stars with $m_V < 16$ over its 4-year lifetime, and will easily detect transits of objects of Earth size or larger in orbit around M dwarf stars. Assuming that icy core masses of $M \sim 1M_\oplus$ can accrete at $a \sim 1$ AU, the Kepler sample size will be large enough to provide a statistical test of our hypothesis.
4. Conclusion

Within the context of the core-accretion process, this paper argues that M dwarfs face a number of difficulties in producing Jupiter-mass planets. Our principal conclusion is that Jovian planets should be rare in solar systems orbiting red dwarfs, but Neptune-like objects and terrestrial planets should be common around these low-mass stars (see Figures 1 and 2). Since disks orbiting solar-type stars readily produce giant planets (Figure 1), we predict that planet properties should vary with the mass of the central star. This result is straightforward to understand: Giant planet formation must take place before the disk gas is dispersed, and the dynamical time scales in M dwarf systems are longer (the Keplerian orbit time scales like $[M_*/M_\odot]^{-1/2}$). Giant planets form in the outer solar system where ices are frozen onto the rocky building blocks, but the disks around M dwarfs have a much lower surface density in the realm of the nebula beyond the snowline. The mass supply is smaller by a factor of $M_*/M_\odot$, the growth rate for planetesimal formation is smaller by a factor $(M_*/M_\odot)^2$, and the late stages of planetesimal accumulation proceed $M_*/M_\odot$ times slower. All of these effects tend to impede giant planet formation, which must take place before the gas in the nebula is removed.

In addition to the effects calculated herein, planets forming around red dwarfs face additional hurdles. Most stars form in groups and clusters, where external radiation from other nearby stars can efficiently drive mass loss from disks around M stars (Adams et al. 2004). In their youth, M stars are almost as bright as solar type stars, but their gravitational potential wells are less deep; this combination of properties allows the inner disks to be more readily evaporated. For M stars, compared with solar-type stars, photoevaporation due to both external radiation fields and radiation from the central star can be more effective by a factor of $10 – 100$ (depending on the environment), so the gas in the nebula can be much shorter lived. Star forming regions are dynamically disruptive due to passing binary stars and background tidal forces; these influences affect circumstellar disks and planetary systems around M stars more effectively than in systems anchored by larger primaries. Finally, all of these difficulties affect not only planet formation, but also planet migration, indicating that very short-period Jovian-mass planets should be especially rare near M-stars.
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REFERENCES

Briceno, C. et al. 2001, Science, 291, 93
Inaba, S., Wetherill, G. W., & Ikoma, M. 2003, Icarus, 16, 46
Koch, D. G. et al. 1998, SPIE, 3356, 599


Sigurdsson, S., Richer, H. B., Hansen, B. M., Stairs, I. H., & Thorsett, S. E. 2003, Science, 301, 193

Sozzetti, A. et al. 2004, Bull.AAS, 204, abs.#62.01


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Fig. 1.— Growth of the core and envelopes of planets at 5.2 AU in disks orbiting stars of two different masses. The upper curves show the time-dependent core mass (dotted curve) and total mass (solid curve) for a planet forming in a disk surrounding a $1M_\odot$ star. The lower curves show the time dependence of the core mass (dotted curve) and total mass (solid curve) for a planet forming in a disk around a $0.4M_\odot$ star. After 10 Myr, the disk masses become extremely low, which effectively halts further planetary growth. The planet orbiting the M star gains its mass more slowly and stops its growth at a relatively low mass $M \approx 14M_\oplus$. 
Fig. 2.— Growth of the core and envelopes of planets forming in a disk surrounding a 0.4 \( M_\odot \) star. The planetary orbits are circular with radii \( a = 1, 5.2, \) and 10 AU. For each radius, models are shown for times \( t = 0.17 \) Myr, 1.25 Myr, 10.1 Myr, and 100 Myr. At \( t = 100 \) Myr, the disk has dissipated and the planets have undergone Kelvin-Helmholtz contraction to (nearly) reach their final sizes. The figure lists the core mass \( M_c \) and the total mass \( M_t \) (in Earth masses \( M_\oplus \)); the figure also lists the core radius \( R_c \) and the total radius \( R_t \) (in cm). The core sizes and total radii are plotted with an applied scaling proportional to \( r^{1/3} \). Protoplanets orbiting M stars should reach their maximum radius at time \( t \approx 10 \) Myr, corresponding to the time of disk dispersal.