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PLANET FORMATION IS UNLIKELY IN EQUAL-MASS BINARY SYSTEMS WITH $a \sim 50$ AU

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ABSTRACT

We show that planet formation via both gravitational collapse and core accretion is unlikely to occur in equal-mass binary systems with moderate (∼50 AU) semimajor axes. Internal thermal energy generation in the disks is sufficient to heat the gas everywhere so that spiral structures quickly decay rather than grow or fragment. This same heating will inhibit dust coagulation because the temperatures rise above the vaporization temperatures of many volatile materials. We consider other processes not included in the model and conclude that our temperatures are conservatively estimated (low), i.e., planet formation is less likely in real systems than in the model.

Subject headings: planetary systems — stars: formation

1. INTRODUCTION AND THE MODEL SPECIFICATION

Both indirect evidence (Adams, Lada, & Shu 1988; Beckwith et al. 1990) and later direct imaging (Close et al. 1997; McCaughrean & O'Dell 1996) have shown that disks are quite common in young stellar systems. These disks are commonly thought (Beckwith & Sargent 1996) to be sites for planet or brown dwarf formation. A large fraction of stars are formed in binary systems (Mathieu et al. 2000) and in the same star formation regions as single stars. Theory suggests that the most likely mechanisms responsible for forming Jovian-mass planets or low-mass brown dwarfs are either gravitational collapse of large-scale spiral structure or coagulation of small solid grains followed by later accretion of additional gas ("core accretion") in the disks of forming stellar systems. Evaluating the effectiveness of these mechanisms is important for understanding the origin of our own solar system as well as planetary systems in other mature single or multiple systems.

The L1551 IRS 5 system serves as a useful observational test bed for comparison to theoretical modeling because of its relative youth (∼10^5 yr; Bachiller, Tafalla, & Cernicharo 1994) and many previous detailed observations (see, e.g., Men'shchikov & Henning 1997). This system consists of an extended nebulosity some 2400 × 1100 AU in size with an inner core of 220 × 76 AU (Momose et al. 1998). Two bipolar jets flow outward in each direction from the core in the plane perpendicular to its long axis. The core has been resolved into two sources with projected separation of about 50 AU and inferred disk masses of ∼0.05 $M_\odot$, each ∼20–25 AU in diameter (Rodriguez et al. 1998). The total mass in the core has been estimated to contain 0.5–1.0 $M_\odot$ of material (Adams et al. 1988; Momose et al. 1998), which produces ∼30 $L_\odot$ in luminous output (Keene & Masson 1990).

We present a numerical simulation of a binary star/disk + star/disk system using a two-dimensional (x, y) smoothed particle hydrodynamic (SPH) code. The dimensions of the disks and semimajor axis of the binary are chosen to be similar to the inner core region of L1551 IRS 5. In the absence of strong constraints on the constituents of the binary (e.g., the masses of the two stars), we choose to set up a binary system consisting of identical components, obtained by setting up a single system in isolation, then duplicating it exactly. We assume each star and disk have mass $M_* = 0.5\ M_\odot$ and $M_D = 0.05\ M_\odot$, respectively. The disk radius is set to $R_D = 15$ AU which, for a semimajor axis of $a = 50$ AU, is comparable to the largest stable streamline (Paczyński 1977).

The mass and temperature of the disk are distributed according to $r^{-3/2}$ and $r^{-1/2}$ power laws, respectively. The absolute scale of each power law is determined from the disk mass, the radial dimensions of the disk, and the condition that the Toomre stability parameter Q is no smaller than $Q_{\rm min} = 1.5$ over the entire disk. This value ensures that the simulation begins in a state marginally stable against the growth of spiral structure, so that we do not accidently "discover" a collapsed object early in the evolution that in reality is an artifact of our initial condition. Both density and temperature are free to vary in time and space, so the initial condition will not prevent spiral structure growth or fragmentation, if the evolution leads to such. The gas is set up on circular orbits around the star so that pressure and gravitational forces exactly balance centrifugal forces. Radial motion is zero. The magnitudes of the pressure and self-gravitational forces are small compared to the stellar gravity, so the disk is nearly Keplerian in character.

Approximately 60,000 equal-mass particles are set on a series of concentric rings around the star in a single, star/disk system, then duplicated, bringing the total number of particles to ∼120,000. The two stars and disks are offset equal distances in the $+x$ and $-x$ directions. We define the binary semimajor axis to be $a = 50$ AU, similar to L1551 IRS 5. Only weak constraints on eccentricity exist in L1551 IRS 5, primarily consisting of the sizes of the observed disks: eccentricities larger than $e = 0.3$ would lead to rapid Roche lobe overflow. We set $e = 0.3$ to be the initial value in this simulation. The system is at apoapse at time $t = 0$ with the orbital velocities defined by approximating each star + disk system as a point mass, so that the orbit determination reduces to the solution of the two-body problem.

The disks are self-gravitating, and each star is modeled as a point mass free to move in response to gravitational forces from the rest of the system. The stellar gravitational forces are calculated using a Plummer potential with a softening radius of 0.2 AU, which also serves as an accretion radius $r_{\rm acc}$. SPH particles with trajectories that pass closer than $r_{\rm acc}$ to a star are absorbed, and the star's mass and momentum increase accordingly.

The thermodynamic evolution is identical to that described in Nelson, Benz, & Ruzmaikina (2000). Thermal energy is added to the gas due to active hydrodynamic processes using an artificial viscosity scheme, which approximately models shocks and turbulence. This heating is roughly equivalent in magnitude to an alpha model with $\alpha \sim (2–5) \times 10^{-3}$. Thermal energy is removed from the disk gas by radiative cooling due

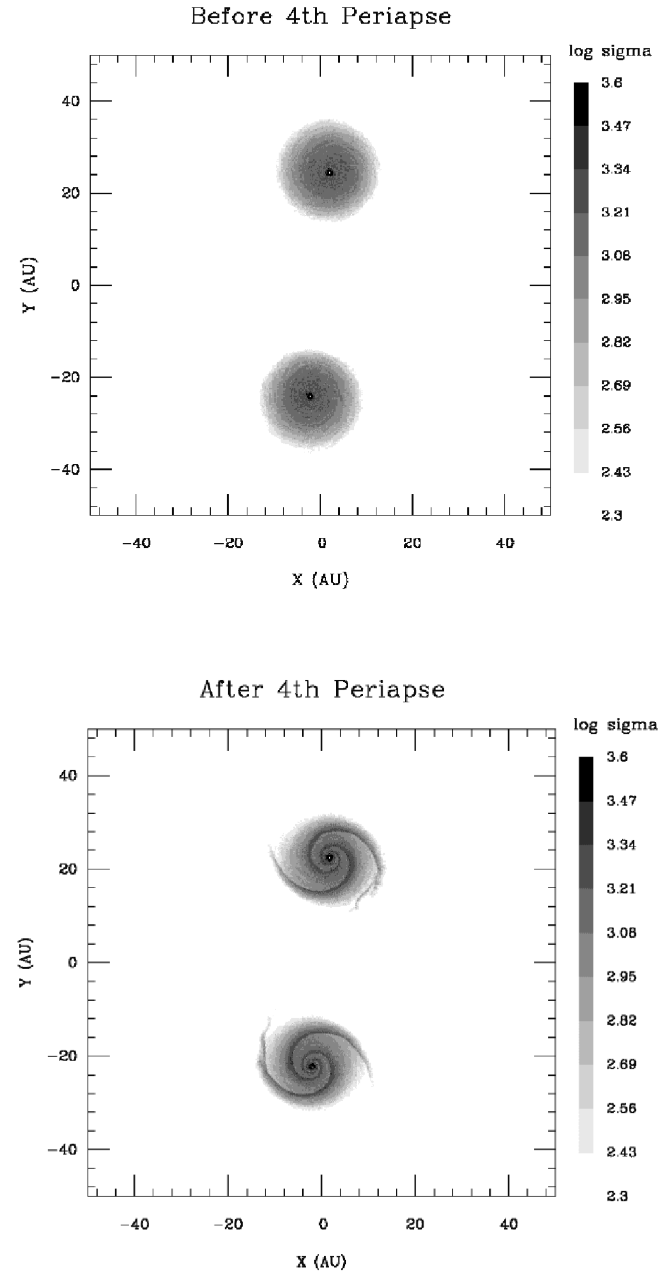

FIG. 1.—Particle distribution of the binary system before (*top*) and after (*bottom*) periapse passage. Mass surface density units are in log (g cm^{-2}). The trajectory of each component is counterclockwise, and periapse occurs when the stars (at each disk center) reach the $y = 0$ axis and are 35 AU apart. No structure is visible in either disk, except that they are no longer exactly round. In the bottom panel, the two components have reversed positions from that shown in the top panel. Tidal torques have caused two-armed spiral structures to develop in the disks. In both images, these torques have also caused mass to be redistributed. The disk edge is no longer sharp and is found near an average radius of ∼12–13 AU rather than the initial 15 AU.

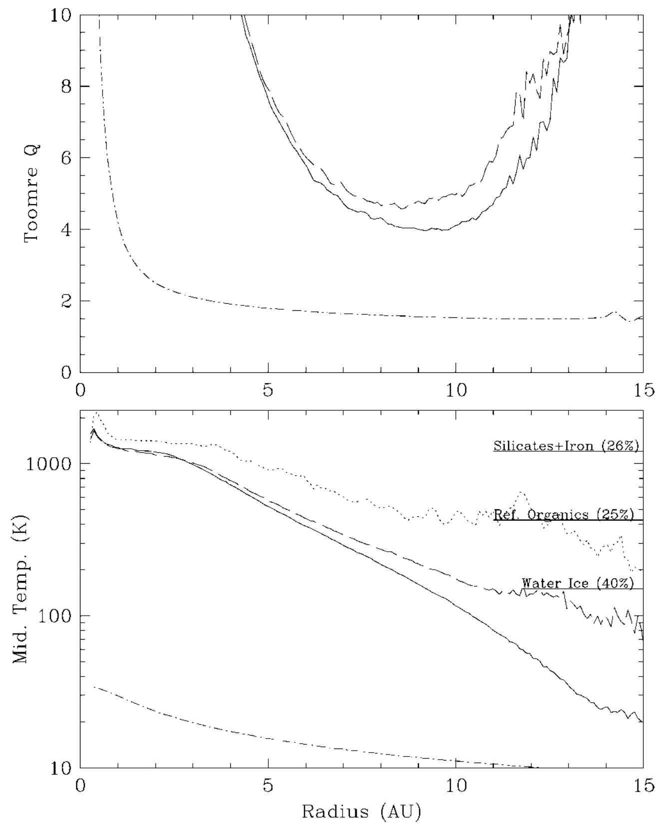

FIG. 2.—Azimuth-averaged Toomre Q (*top*) and temperature (*bottom*) profiles of the disks shown for the same times before (*solid line*) and after (*dashed line*) periapse as in Fig. 1. The initial profiles are shown with dashed dotted lines. Both show large increases over their initial values at all radii. The large increase in Q outside 12 AU is due to the truncation of the disk and relative scarcity of matter remaining there. The dotted curve shows the maximum temperature reached inside the spiral arms at that radius. At the right are vaporization temperatures of the major grain species in the solar nebula and their fraction of the total grain mass, as discussed in Pollack et al. (1994).

to passive blackbody emission from the disk's photosphere surfaces. The blackbody temperature is calculated at each time step and for each SPH particle. This treatment remedies a major shortcoming of previous models (Nelson et al. 1998; Pickett et al. 1998; Boss 1997) which used a "locally isothermal" or "locally adiabatic" approximation to show that relatively low-mass disks can undergo fragmentation and/or collapse, despite earlier claims (Podolak, Hubbard, & Pollack 1993) that a very massive disk is required.

2. RESULTS

The system is evolved for eight binary orbits, or 2700 yr (T_{bin} = 350 yr). Figure 1 shows the system shortly before and after the fourth periapse passage of the two components (measured from the beginning of the simulation). Before each periapse, the two disks are smooth and exhibit no visible spiral structure, although they are no longer perfectly "round." During and after periapse, each disk develops strong, two-armed spiral structures due to the mutual tidal interactions of the binary. The structures decay to a smooth condition like that in the top panel over the next $0.5T_{bin}$. The cycle repeats with little variation as the system again approaches periapse, and we expect that further evolution will be similar.

The spiral structures decay because internal heating in the disk increases the stability of the disks against spiral arm growth, as measured by the Toomre stability (Fig. 2, *top*) of each disk. The minimum value of Q increases from its initial Q_{min} = 1.5 to 4 before periapse and $Q_{min} \sim 5$ afterward. These values are the same before and after each successive periapse passage, and both are well above the $Q \lesssim 3$ values for which spiral structures are expected to grow. Therefore, if we suppose that Jovian planets form via gravitational collapse or fragmentation of spiral structure in disks, their formation will be unlikely in this system.

The high stability is due to an increase in the disk temperature. In fact, the temperatures are high enough to cause some grain species to be vaporized. This is important because the core accretion model for planet formation requires that solid grains can coagulate and are not instead repeatedly returned to the vapor state. Water ice may be particularly important because it composes 40% by mass of the solid material in the disk and is among the most volatile grain species (Pollack et al. 1994), vaporizing at ∼150 K.

The bottom panel of Figure 2 shows the disk midplane temperatures obtained in this simulation. Only in a region with $r \gtrsim 10$ AU does the temperature reach low enough values that water ice can form, even temporarily. However, in this region, the matter is most subject to shocks generated by the spiral structure produced by the binary interaction, which raise its temperature by as much as a factor 3 over the azimuth average. The spiral patterns corotate with the orbit of the binary and the orbital period at 15 AU is ∼82 yr, so material everywhere in the disk will have time to travel through the spiral arms several times before they decay. A simulation run with zero eccentricity also produces spiral structure. In this run, the azimuth-averaged temperatures were similar to Figure 2, but the temperature in the shocked regions are not as extreme. Water ice would still be vaporized everywhere, but more refractory species may not be.

In the outer disk, grains less than ∼1 mm in size which pass through such a shock and which contain water ice will be vaporized on a timescale of $\lesssim 10^4$–10^5 s depending on the temperature (Engel, Lunine, & Lewis 1990; Lenzuni, Gail, & Henning 1995), and the remaining more inert species may disaggregate. In this region, passage through the warmest part of a spiral arm requires ∼1–2 yr, so sufficient time exists to return grains of this size to the gas phase. Grain growth may still occur between the spiral arms and when the spiral arms have decayed, but must begin with gaseous material each time, so growth of solid material into larger entities will be suppressed. Temperatures at high altitudes are lower, but grains that form there will tend to sink to the midplane as they grow larger and also be destroyed. Therefore, Jovian planet formation by the core accretion mechanism will occur much more slowly, if at all in this system.

The weak link remaining in the argument against the core accretion mechanism is the lack of knowledge of the microphysics important for dust coagulation. For example, one could imagine that growth of silicate and iron grains is catalyzed by temporarily enhanced cross sections as mantles of more volatile material form on their surfaces and the gravitational torques produced by the binary interaction enhance mixing throughout the disks. Even if this type of interaction takes place, the eventual formation of planet-sized objects remains in doubt. As the rocky aggregates grow, conditions appropriate for dust coagulation (e.g., "perfect sticking") break down and collisions between particles become increasingly disruptive because of the finite strength of the aggregates.

The disruption of solid bodies depends strongly on the relative velocity of the impactor and target particles, with disruption occurring for velocities $\gtrsim 1$–3 km s^{-1} for planetesimal-sized targets ($\lesssim 1$ km; Benz & Asphaug 1999). On average in an accretion disk, the relative velocity of planetesimals will be proportional to their eccentricities, $v_{\rm rel} \approx e v_{\rm orb}$. For our model, a relative velocity of 1 km s^{-1} corresponds to an eccentricity of $e \sim 0.05$ at 1 AU, or $e \sim 0.15$ at 10 AU.

We have seen that gravitational torques are strong enough to generate large-amplitude spiral structure as they drive the gas onto eccentric orbits. Gas eccentricities are quickly damped due to shock dissipation, but planetesimals are only weakly coupled to the gas and will have time to encounter other objects and collide or to increase their eccentricities still further as the evolution proceeds. If particle eccentricities can grow to $e \sim 0.1$, we expect that the growth of kilometer-sized bodies will be suppressed in binary systems such as the one modeled here. However, a more detailed analysis must be done in order to constrain this possibility.

2.1. *Checks on the Validity of the Conclusions*

The conclusions regarding planet formation will remain valid as long as the temperatures determined from the model are lower limits on the temperatures present in real systems. If the model produces temperatures that are too low, then real systems will be even more stable against spiral structure growth and fragmentation and less likely to produce large, coagulated grains. If they are too high, the model could inaccurately portray the disk as too stable. Are the temperatures produced in the model too low? We can constrain the temperatures in the model by comparing the radiated energy from observed systems (here specifically to L1551 IRS 5) to that produced by the simulation in various wavelength bands. This comparison requires that we relate the luminous output to the temperature.

In regions in which the optical depth is high, as it is in the accretion disks, the radiated emission can be approximated as a blackbody with a temperature of the disk photosphere. The disk's midplane and photosphere temperatures are then related to each other by a given Rosseland opacity and the local vertical density/temperature profile. We determine such a profile as byproduct of the cooling model in this work, under the assumption that the vertical structure is instantaneously adiabatic. Other work (Bell et al. 1997; D'Alessio et al. 1998) has shown that the structure may instead be superadiabatic. If this is the case, then the midplane temperatures will be higher, and our conclusion is stronger.

The opposite case may be true instead: large relative heating can occur at high altitudes, even though the high-altitude heating is small in an absolute sense (Pickett et al. 2000). This means that vertical temperature structure may become distorted and an incorrect midplane temperature could be inferred. High-altitude dynamical heating will play a role similar to high-altitude passive heating from stellar photons. D'Alessio et al. (1998) show that this process produces a temperature inversion high above the photosphere, but this region contributes negligibly to the radiated flux. Therefore, we can rely on the modeled radiated output of the simulation to represent accurately the temperatures at the disk midplane, given the physical processes included in the calculation. Our conclusions about the formation of planets will be confirmed if we find that the energy output from the disks is equal to or less than that observed.

To obtain a valid comparison between the observed and modeled fluxes, we must be certain that the flux from other parts of the system (e.g., the circumbinary disk and envelope) is not a significant contributor to the observed flux used in the comparison. We must also be certain that extinction between the source and the observer has not altered the emitted flux. We therefore require very high spatial resolution photometry at long wavelengths that are not affected by extinction.

In Figure 3, the highest available resolution, long-wavelength observations of L1551 IRS 5 are plotted and compared to the flux densities produced from the simulation. For all wavelengths between 1.3 cm and 870 μm, the observed fluxes exceed those obtained from the simulation by a factor of ∼5. The

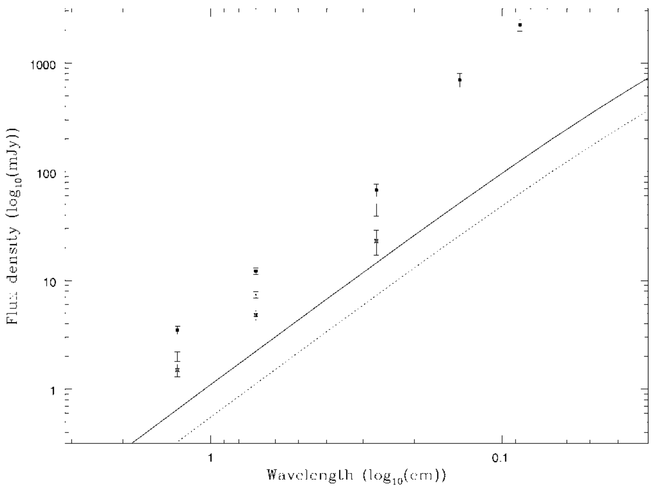

FIG. 3.—Long-wavelength flux densities from L1551 IRS 5: the total from both components of the binary are shown with solid symbols, and the individual components are shown with open symbols. The model is displayed with a solid line for the total from both components, while the value for one component is shown with a dotted line. Each assume a distance of 140 pc to the source. At each wavelength, the model underestimates the flux, indicating that the model temperatures are lower limits. The data are taken from the following literature (at the angular resolution given): D. Koerner (2000, private communication; ∼0″.21 at 1.3 cm), Rodriguez et al. (1998; ∼0″.06 at 7 mm), Looney, Mundy, & Welch (1997; ∼0″.3 at 2.7 mm), Woody et al. (1989; ∼3″ at 1.4 mm) and Lay et al. (1994; ∼0″.8 using single baseline interferometry at 870 μm). For comparison, the binary separation of the L1551 IRS 5 system quoted by Rodriguez et al. (1998) is ∼0″.3.

differences at 1.4 mm and 870 μm are larger, a factor ∼10; however, they do not resolve the binary and may contain some contaminating flux from the circumbinary environment. Given these comparisons, we can conclude that the temperatures in the disk are conservatively estimated by the simulation (too low) and that the disks in L1551 IRS 5 are more stable against spiral arm growth and fragmentation and less likely to allow dust coagulation than in the simulation. Our conclusion that planet formation is unlikely in the L1551 IRS 5 system is secure.

3. REMARKS AND REMAINING QUESTIONS

The inventory of physical processes considered in this calculation is not complete. The total luminosity will include direct contributions at the short-wavelength end of the spectrum from not only the two circumstellar disks, but also the two stars. Accretion of material from the inner disk edge (0.2 AU for this simulation) onto the stellar surface will also add to the total. At longer wavelengths, the circumbinary disk, the infalling envelope, and radio emission from bipolar polar outflows will add to the total. Of these processes, only outflows remove thermal energy from the disks, but such outflows are thought to originate very close to the star. They will not remove energy from the part of the disk important for planet formation. The rest will either add directly to the short-wavelength spectrum or heat the cooler parts of the disk by absorption of short-wavelength radiation, which subsequently reradiates at longer wavelengths (see, e.g., Bell 1999). Including them in the calculation can only raise disk temperatures and strengthen our conclusions. Estimates of the total luminosity (not shown) from all these sources are within a factor of 2 of the observed 30 $L_\odot$ luminosity of L1551 IRS 5. We are encouraged by this agreement and expect that the overall agreement between model and observations would become closer if radiative reprocessing were included.

A number of questions remain: What is the distribution of planetesimal random velocities? Will lower mass disks be more susceptible to planet formation because of increased efficiency of radiative energy losses? What happens for binary systems with different separations or with unequal stellar mass ratios? How distant is distant enough, so that one component of the binary does not strongly influence the other? These questions will be addressed more completely in a follow-up paper.

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