Proximity of Jupiter-Like Planets to Low-Mass Stars

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The sensitivities of astrometric and radial velocity searches for extrasolar planets are strongly dependent on planetary masses and orbits. Because most nearby stars are less massive than the sun, the first detection is likely to be of a Jupiter-mass planet orbiting a low-mass star, with a possible theoretical expectation being that Jupiter-like planets will be found much closer [inside the Earth-sun separation of 1 astronomical unit (AU)] to these low-luminosity stars than Jupiter is to the sun (5.2 AU). However, radiative hydrodynamic models of protoplanetary disks around low-mass stars (of 0.1 to 1 solar mass) show that Jupiter-like planets should form at distances (approximately 4 to 5 AU) that are only weakly dependent on the stellar mass.

Current searches for extrasolar planets are capable of detecting Jupiter-mass companions to a number of nearby low-mass stars (*1*). The sensitivity of any indirect detection method depends strongly on the orbital radius of the putative Jupiter-mass companion, with astrometric measurements of the location of the central star being more sensitive to greater separations, which cause the planetary companion to induce a larger wobble in the orbit of the central star. These searches (*1*) are focused on nearby solar-type stars, but most nearby stars have masses that are substantially less than that of the sun. Because the orbital radius at which ice condenses in free space (*2*) is smaller for stars of lower mass and lower luminosity, nearby Jupiter-like planets might be expected to occur with orbital separations that are much less than is the case in our solar system, making their detection by astrometry more difficult. However, the location of Jupiter-like planets should be determined by the radial temperature profile of the protoplanetary disk in the star's pre–main sequence phase rather than by the present luminosity of the star in its main sequence phase. I report here on detailed calculations of the thermodynamics of protoplanetary disks that extend the results for disks around solar-mass (1 $M_\odot$) protostars (*3*) to protostars of much lower mass (0.1 to 0.5 $M_\odot$).

Planetary-mass objects have been inferred to be in orbit about the millisecond pulsar PSR B1257 + 12 (*4*), and the recent detection of timing variations consistent with mutual gravitational perturbations between the planetary-mass objects appears to confirm this identification (*5*). However, these 'pulsar planets' are almost certainly quite different from the planets in our solar system in terms of their physical and chemical properties, origin, and suitability for evolving and sustaining life. Hence, the search for extrasolar planetary systems similar to our own continues.

In the absence of a more definitive criterion, some prior estimates of the orbital radii of giant planets like Jupiter have been based on the location of the ice condensation point in free space around a star. This estimate involves calculation of the equilibrium temperature of a dust grain that is illuminated by the central star and radiates freely, yielding (*2*)

$$T(r) = \left(\frac{L_s}{16\pi\sigma r^2}\right)^{1/4} \qquad (1)$$

where L_s is the stellar luminosity, σ is the Stefan-Boltzmann constant, and r is the orbital radius of the grain. Given L_s and the ice condensation temperature T_c, Eq. 1 defines the radius r_c inside of which ice grains cannot exist. Because Jupiter and Saturn are thought to have been formed by the hydrodynamic capture of gas envelopes onto planetary cores previously formed by the accumulation of icy planetesimals (*6*), giant planets could not form inside the radius specified by Eq. 1 if the stellar luminosity dominated the thermal environment.

The mass-luminosity relation for main sequence stars can be used to derive a proportionality between the free space r_c and the stellar mass M_s. For solar-type stars, this relation is roughly $L_s \propto M_s^4$ (*7*); this approximate relation also holds for low-mass stars in the range of 0.08 $M_\odot$ to 1.0 $M_\odot$ (*8*). Because $r_c \propto L_s^{1/2}$ (Eq. 1), we find that $r_c \propto M_s^2$. Thus, the free-space luminosity estimate leads to a prediction that the ice condensation radius depends strongly on stellar mass. For the lowest mass stars found in the solar neighborhood (~0.1 $M_\odot$), extrasolar Jupiter-like planets might then be expected to occur within ~0.05 AU of the central star (1 AU is the distance from Earth to the sun: 1.5×10^{13} cm). For an M0 dwarf star ($M_s \approx 0.5\ M_\odot$), extrasolar Jupiter-like planets might be found at ~1 AU. The small separations predicted by the free-space method favor detection by spectroscopy (because Doppler shifts, which measure the velocity wobble induced in the star by the planet, increase in magnitude with smaller separation) or photometry (because shorter-period orbits improve the chances for detection of a transit of the stellar disk by the planet) (*9*). Direct searches are hampered by smaller separations because of the need to distinguish between photons emitted by the planet and those emitted by the star.

However, the free-space estimates are only lower bounds on the orbital radii where icy planetesimals can exist—there is no reason to believe that the free-space temperature profile determines where giant planets actually form. Planetary formation is believed to occur within dense, optically thick protoplanetary disks during the protostellar or pre–main sequence phase of a star's evolution (*10*). Although we do not completely understand the formation of giant planets, it seems safe to say that Jupiter-like planets cannot form inside the ice condensation radius of a protoplanetary disk, because inside this region, icy planetesimals cannot be stable long enough to accumulate into larger bodies. In fact, the ice condensation radius may well be a preferential location for formation of giant planets (*11*). If runaway accretion is required to form the cores of Jupiter-like planets, other constraints can be placed on the planet-forming process as well (*10*), with the ice condensation radius remaining as a lower bound for scenarios involving icy planetesimals.

The thermal structure of a low-mass protoplanetary disk (0.02 $M_\odot$) orbiting a solar-mass protostar and undergoing mass accretion from its precollapse molecular cloud core has been calculated (*3*) and shown to lead to $r_c \approx 5$ AU, which is in good agreement with the location of Jupiter in our solar system. Though it may be fortuitous, this coincidence appears to lend support to the numerical method used and to the assumption of substantial mass accretion during the initial phases of planet formation. These calculations have now been extended to models of the properties of protoplanetary disks surrounding protostars of masses 0.1 and 0.5 $M_\odot$ (*12*).

In the numerical models (*3*), the equations of radiative hydrodynamics are solved in two spatial dimensions (r,θ on a spherical coordinate grid) by means of a spatially second-order accurate hydrodynamics scheme (*13*). Self-gravity of the disk is included, and a full thermodynamic description of the molecular hydrogen gas and dust grains is also included. Radiative transfer is handled in the Eddington approximation by an iterative solution of the mean intensity equation (*13*). Dust grains dominate the opacity at the temperatures of protoplanetary disks

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(*14*), and their condensation and evaporation act as a thermostat leading to temperature plateaus (*3*).

The models seek to find the quasi-equilibrium thermal structure of a realistic protoplanetary disk, starting from an assumed near-equilibrium configuration (*3*). For an arbitrarily thick, self-gravitating, adiabatic disk orbiting a central mass M_s, the vertical density variation is given approximately by

$$\rho(R, Z)^{\gamma-1} = \rho_o(R)^{\gamma-1} - \left(\frac{\gamma-1}{\gamma}\right)\left[\left(\frac{2\pi G\sigma(R)}{K}\right)Z + \frac{GM_s}{K}\left(\frac{1}{R} - \frac{1}{(R^2+Z^2)^{1/2}}\right)\right] \quad (2)$$

where γ is the adiabatic exponent, K is the adiabatic pressure constant ($p = K\rho^\gamma$), $\sigma(R)$ is the surface density as a function of cylindrical radius R, and Z is cylindrical height. The midplane density $\rho_o(R)$ is chosen to be a power law in R with exponent $1/(1-\gamma)$ in order to ensure Keplerian rotation throughout the disk; taking $\gamma = 5/3$ leads to $\rho_o(R) \propto R^{-3/2}$. K is chosen to be 1.7×10^{17} (cgs units), which is consistent with compressional heating becoming significant during protostellar collapse at densities above 10^{-13} g cm^{-3}. Figure 1 shows the disk structure for the two models with $M_s = 1.0\ M_\odot$ and $M_s = 0.1\ M_\odot$.

The midplane density at 1 AU is adjusted so that each disk has a mass of 0.02 $M_\odot$ in the region from 1 AU to 10 AU (the active computational grid); for $M_s = 1.0\ M_\odot$, $\rho_o = 4.0 \times 10^{-10}$ g cm^{-3} at 1 AU. The disks have about the minimum amount of mass necessary to account for the planets in our solar system, a mass estimated to lie in the range of 0.01 to 0.07 $M_\odot$ (*15*), so that the thermal properties of these 0.02 $M_\odot$ disks should be appropriate for the early phases of dust grain agglomeration leading to successful planetesimals. Planetesimals that form out of disks of higher mass may disappear into the star; planetary embryos that form out of disks of lower mass will be unable to accrete the gaseous envelopes characteristic of Jupiter-like planets.

In the absence of other information, it seems appropriate to assume that during the phase of planetesimal formation, protoplanetary disks have masses that are more or less independent of the protostar mass; that is, that the initiation of the planet formation process is more dependent on the properties of the disk than on the mass of the star. A disk mass of 0.02 $M_\odot$ is a small fraction of the total amount of mass transported through the disk to build even a low-mass star; that is, minimum-mass disks are minor remnants of the star formation process. Even without this assumption, however, the conclusions of this report are robust: Similar models (*12*) show that the location of the ice condensation radius is relatively insensitive to disk masses in the range 0.01 to 0.1 $M_\odot$, for fixed stellar mass.

In order to ascertain the equilibrium temperature profile for a given disk and M_s, a number of models are run with varied initial temperature profiles $T(r)$. If the temperature at a given radius initially rises during the calculation, it is assumed that the initial guess was too low; if it falls, vice versa. The results of a number of preliminary models are thus used to derive a final composite temperature profile, as in the previous calculations (*3*). Figure 2 shows the results of this process for the three models with M_s = 1.0, 0.5, and 0.1 $M_\odot$. The ice condensation radius moves inward from ~6 to ~5 to ~4.5 AU during this sequence, which implies a much weaker dependence on protostellar mass than does the $r_c \propto M_s^2$ relation previously derived.

The main source of energy within the disk models is compressional energy associated with vertical and radial compression of the disk, driven by continued mass accretion from the molecular cloud envelope onto the disk (at ~10^{-6} to ~10^{-5}

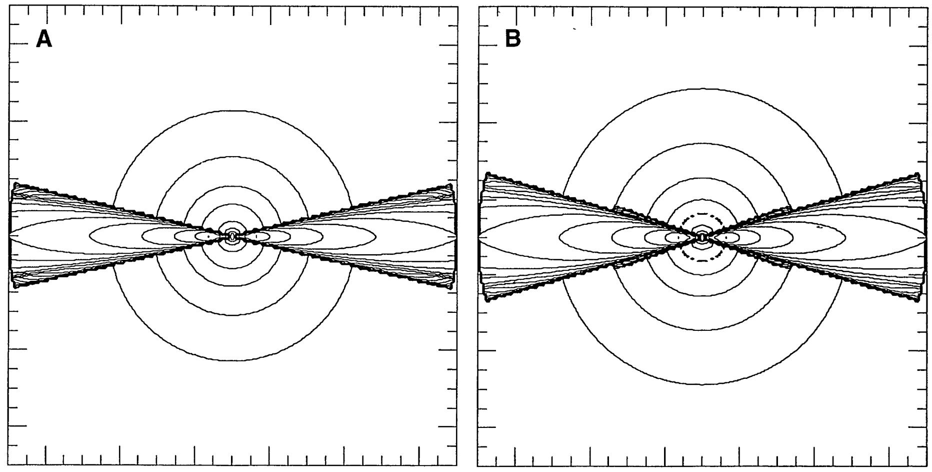

Fig. 1. Cross sections of the protoplanetary disks for two models with central protostar masses M_s = 1 $M_\odot$ (**A**) and M_s = 0.1 $M_\odot$ (**B**). Although the disk is slightly thicker for the protostar of lower mass, these equal-mass (0.02 $M_\odot$) disks are quite similar. Density contours are shown, with each contour representing a change by a factor of 2 in density; the maximum density is 4.0×10^{-10} g cm^{-3} for (A) and 3.2×10^{-10} g cm^{-3} for (B). The region is 10 AU in radius. The protostar lies at the center of each plot; the rotation axis is a vertical line through the central star. Also seen is the infalling spherical halo derived from the molecular cloud core envelope. The jagged surfaces are artifacts of the plotting routine.

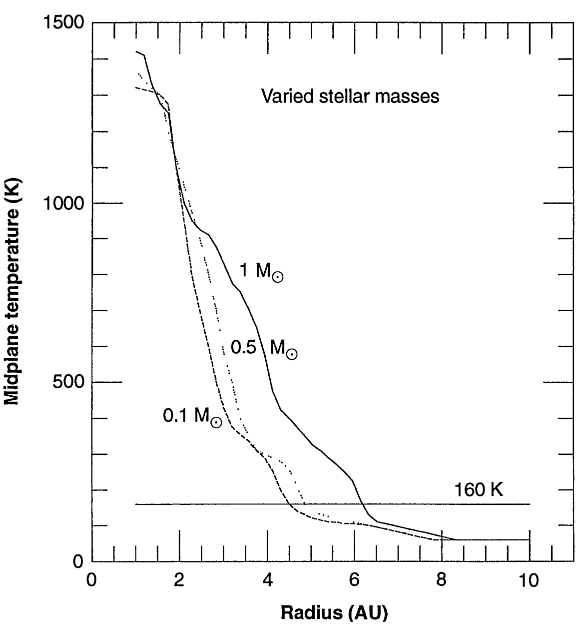

Fig. 2. Midplane temperature as a function of orbital radius for three protoplanetary disk models with varied central protostar masses: M_s = 1.0 $M_\odot$ (solid line); M_s = 0.5 $M_\odot$ (dotted line); and M_s = 0.1 $M_\odot$ (dashed line). The horizontal line is the ice condensation temperature of 160 K at protoplanetary disk densities (~10^{-10} g cm^{-3}). The radius at which the midplane temperature (maximum temperature at a given radius) falls to the ice condensation temperature occurs at progressively smaller radii as the protostar mass is decreased from 1.0 to 0.5 to 0.1 $M_\odot$: ~6 to ~5 to ~4.5 AU.

$M_\odot$ per year) and by the internal adjustment from the assumed initial configuration toward equilibrium. The main energy sink is radiation lost to the cold (10 K) molecular cloud envelope. The thermal profiles are consistent with an independent calculation (*16*) based on plane parallel radiative transfer in a viscous accretion disk undergoing mass accretion at the rates used in these models (*12*). The profiles are also similar to those derived by use of this same numerical technique to model an α accretion disk with $\alpha \sim 0.01$ and the same mass accretion rates (*12*).

These models demonstrate that the ice condensation radius does not move inward very rapidly as the stellar mass is decreased, which is contrary to the result for the free-space temperature profile. This is because the disk temperature profiles in these models are largely determined by the disk properties (disk masses were assumed to be constant) and hence are somewhat decoupled from the stellar masses. Jupiter-like planets are thus likely to be found orbiting low-mass stars at distances not much different (~4 to ~6 AU) than those in our solar system. This result improves the chances that the first extrasolar planet around a low-mass star will be detected by astrometry or direct detection but decreases the likelihood that the first extrasolar planet will be found by Doppler spectroscopy or photometry (*9*).

If extrasolar Jupiter-like planets generally are formed around 5 AU, then their orbital periods will vary with stellar mass as $P \propto M_s^{-1/2}$; that is, the periods will increase with decreasing stellar mass, which again is contrary to previous expectations (*9*). Extrasolar planet searches would then require even longer time intervals than are currently envisioned in order to follow the system for an orbital period. Finally, if extrasolar Jupiter-like planets are found at these distances from low-mass stars, such discoveries would strengthen our confidence in the general theoretical description of protoplanetary disks.

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Synthesis of Linear Acetylenic Carbon: The "*sp*" Carbon Allotrope

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A carbon allotrope based on "*sp*" hybridization containing alternating triple and single bonds (an acetylenic or linear carbon allotrope) has been prepared. Studies of small (8 to 28 carbon atoms) acetylenic carbon model compounds show that such species are quite stable (130° to 140°C) provided that nonreactive terminal groups or end caps (such as tert-butyl or trifluoromethyl) are present to stabilize these molecules against further reactions. In the presence of end capping groups, laser-based synthetic techniques similar to those normally used to generate fullerenes, produce thermally stable acetylenic carbon species capped with trifluoromethyl or nitrile groups with chain lengths in excess of 300 carbon atoms. Under these conditions, only a negligible quantity of fullerenes is produced. Acetylenic carbon compounds are not particularly moisture or oxygen sensitive but are moderately light sensitive.

The known allotropes of carbon are based either on sp^3 hybridization of carbon (diamond) or sp^2 hybridization (graphite, fullerenes, and nanotubes). Although Hoffman (*1*) had predicted in the 1960s that other allotropes of carbon would be synthesized, the generally held view was that the acetylenic carbon allotrope was unstable. In this report, we present evidence for the synthesis of a carbon allotrope based on "*sp*" hybridization that contains alternating triple and single bonds (an acetylenic or linear carbon allotrope) (*2–7*). Studies of acetylenic model compounds (following or modifying reported syntheses and through new synthetic routes) suggested the crucial role of nonreactive terminal groups, or end-caps, for stabilizing these molecules against further reactions. Also, previous work on the gas-phase synthesis of carbon clusters has been reinterpreted and reproduced and we have shown that these methods can produce a substantial fraction of acetylenic carbon gas-phase species. We show that the gas-phase synthetic conditions normally used to generate fullerenes can be used to produce long-chain acetylenic species. When end-capping groups are present, acetylenic carbon is produced at the expense of fullerene synthesis, which depending on conditions is either totally eliminated or substantially suppressed.

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The synthesis of mixtures of long-chain acetylenic carbon species [(α-ω-bis(triethylsilyl)polyynes up to 32 carbon atoms] with alternating single and triple bonds was reported by Walton and co-workers in 1972 (*8*). They had prepared, using copper chloride (Hay coupling), mixtures of acetylenic carbon compounds that contained 2 to 16 acetylene units (Et, ethyl):

$$(Et)_3Si{-}(C{\equiv}C)_n{-}Si(Et)_3$$

$$n = 2 \text{ to } 16$$

Walton proposed that the bulky triethylsilyl groups were useful end groups for stabilizing