

FINAL REPORT ON NASA NCC 2-5418
GIANT MOLECULAR CLOUD STRUCTURE AND EVOLUTION

Principal Investigator: P. H. Bodenheimer
University of California, Santa Cruz

NASA Technical Officer: David Hollenbach
NASA-Ames Research Center

Performance Period: 1 March 01 – 28 Feb 03

Bodenheimer and Burkert extended earlier calculations of cloud core models to study collapse and fragmentation. The initial condition for an SPH collapse calculation is the density distribution of a Bonnor-Ebert sphere, with near balance between turbulent plus thermal energy and gravitational energy. The main parameter is the turbulent Mach number. For each Mach number several runs are made, each with a different random realization of the initial turbulent velocity field. The turbulence decays on a dynamical time scale, leading the cloud into collapse. The collapse proceeds isothermally until the density has increased to about $10^{-13} \text{ g cm}^{-3}$. Then heating is included in the dense regions. The nature of the fragmentation is investigated. About 15 different runs have been performed with Mach numbers ranging from 0.3 to 3.5 (the typical value observed in molecular cloud cores is 0.7). The results show a definite trend of increasing multiplicity with increasing Mach number (M), with the number of fragments approximately proportional to $(1 + M)$. In general, this result agrees with that of Fisher, Klein, and McKee (IAU Symposium No. 200, 2001) who published three cases with an AMR grid code. However our results show that there is a large spread about this curve. For example, for $M=0.3$ one case resulted in no fragmentation while a second produced three fragments. Thus it is not only the value of M but also the details of the superposition of the various velocity modes that play a critical role in the formation of binaries. Also, the simulations produce a wide range of separations (10–1000 AU) for the multiple systems, in rough agreement with observations. These results are discussed in two conference proceedings.

Ralf Klessen has been engaged in numerical studies, in three space dimensions with an SPH code, of the fragmentation of interstellar clouds and the formation of stellar clusters (Klessen and Burkert, ApJ, 549, 386, 2001; Klessen, ApJ, 550, L77, 2001; Klessen, ApJ, 556, 837, 2001). The initial condition is a turbulent velocity and density field, driven by an external energy source, and in balance between energy gain by driving and energy loss by dissipation. The supersonic velocities result in randomly occurring shocked regions, which result in dissipation of energy as well as compression of local regions and formation of dense cores. Some of these cores survive, evolve to high enough densities that they are unstable to collapse, and become protostars. In a typical numerical simulation about 50 of these protostars form. Klessen has analyzed the mass spectrum of molecular clumps (above-average density regions in the overall cloud), as well as that of the protostars, and compared with observations. The high-density protostars are not resolved in the calculations; instead they are represented by sink particles which accrete mass and angular

momentum over time. The evolution of a set of these protostars on much smaller scales than those of the overall simulation is being undertaken by Bodenheimer, with a two-dimensional hydrodynamics code including radiation transfer. The outer boundary condition for this calculation is the accretion rate of mass and angular momentum as a function of time as given by the large-scale code. The evolution of the collapsing protostar is followed until much of the mass has been accreted. Disk formation occurs in most cases, and the question being studied is whether the collapse will result in a binary or a single star plus disk. In one test case spectral energy distributions of the star-disk system have been calculated as a function of time and of viewing angle with respect to the rotation axis.

Recent work on molecular cloud structure has been carried out by Vazquez-Semadeni, Ballesteros-Paredes, and Klessen (ApJ, 585, L131, 2003). They discuss a scenario for turbulent molecular cloud (MC) evolution and control of the star formation efficiency (SFE) and present a first set of numerical tests of it. A compressible cascade with energy loss can generate density fluctuations and further turbulence at small scales from large-scale motions, implying that the turbulence in MCs may originate from the compressions that form them. Below a sonic scale λ_s , turbulence cannot induce any further subfragmentation nor can it be a dominant support agent against gravity. Since progressively smaller density peaks contain progressively smaller fractions of the mass, they show that the SFE decreases with decreasing λ_s , at least when the cloud is globally supported by turbulence. The numerical experiments confirm this prediction. They also find that the collapsed mass fraction in the simulations always saturates below 100% efficiency. This may be due to the decreased mean density of the leftover interclump medium, which in real clouds are not confined to a box and should therefore be more easily dispersed, marking the "death" of the cloud. They identify two different functional dependences ("modes") of the SFE on λ_s , which roughly correspond to globally supported and unsupported cases. Globally supported runs with most of the turbulent energy at the largest scales have similar SFEs to those of unsupported runs, providing numerical evidence of the dual role of turbulence, whereby turbulence, besides providing support, induces collapse at smaller scales through its large-scale modes. They tentatively suggest that these modes may correspond to the clustered and isolated modes of star formation, although here they are seen to form part of a continuum rather than being separate modes. Finally, they compare with previous proposals that the relevant parameter is the energy injection scale.

Bodenheimer, Lin, and Mardling wrote a paper on tidal effects in short-period extrasolar planets (ApJ, 548, 466, 2001). If the planet is within 0.05 AU of the star, the dissipation of the stellar tidal disturbance within the planet provides a significant energy source, which causes the planet to inflate as it adjusts to a thermal equilibrium. They determine the planetary size as a function of the tidal dissipation rate with or without the presence of a core, and apply the results to three systems with short period planets: HD 209458, Ups And, and Tau Boo. The companion of HD 209458 undergoes a transit and its radius has been observationally determined. Models show that a relatively small amount of tidal dissipation is required to explain this radius.

Postdoctoral fellow Pin-Gao Gu, with Lin and Bodenheimer, investigated the possibility of substantial inflation of short-period Jupiter-mass planets, as a result of their internal tidal dissipation associated with the synchronization and circularization of their

orbits. They show that 1) in the low-eccentricity limit, the synchronization of the planets' spin with their mean motion is established before tidal dissipation can significantly modify their internal structure. 2) But, with sufficiently large eccentricities, tidal dissipation of energy during the circularization process can induce planets to inflate in size before their eccentricity is damped. 3) For sufficiently large eccentricities, the planets can become unstable and undergo runaway inflation until their radii exceed the Roche radius. 4) They estimate the mass loss rate, the final planetary masses, and the semimajor axes for planets that overflow the Roche radius, as a function of planetary initial orbital parameters. 5) Based on these results, they suggest that the combined effects of self-regulated mass loss and tidally driven orbital evolution may be responsible for the apparent lack of giant planets with ultra-short periods less than 3 days. A paper has been published by *The Astrophysical Journal* (588, 509, 2003).

Bodenheimer, Laughlin, and Lin made calculations of the evolution of extrasolar planets which range in mass from 0.1 Jupiter masses to 3.0 Jupiter masses, and which range in equilibrium temperature from 113 K to 2000 K. The purpose was to determine the radii at the present time for planets with a range of masses and distances from the star, to compare with radii derived from observations of transiting extrasolar planets. To provide such comparisons, they show that of order 10 transiting planets with orbital periods less than 200 days can be detected around bright main-sequence stars for which accurate well-sampled radial velocity measurements can also be readily accumulated. Through these observations, structural properties of the planets will be derivable, such as the presence or absence of a rocky core, particularly for low-mass, high-temperature planets.

With regard to the transiting planet, HD 209458b, the calculations show, in accordance with other recent calculations, that models without internal heating predict a radius of about 1.1 Jupiter radii, in comparison with the observed radius of 1.4 Jupiter radii. Two resolutions have been proposed for this discrepancy. Guillot and Showman hypothesize that deposition of kinetic wind energy at pressures of tens of bars is responsible for heating the planet and maintaining its large size. Our models confirm that dissipation of this type can indeed produce a large radius for HD 209458b. Bodenheimer, Lin, and Mardling suggest that HD 209458b owes its large size to dissipation of energy arising from ongoing tidal circularization of the planetary orbit. This mechanism requires the presence of an additional planetary companion to continuously force the eccentricity. The authors show that residual scatter in the current radial velocity data set for HD 209458b is consistent with the presence of an as-of-yet undetected second companion, and that further monitoring of the radial velocity of HD 209458 is indicated. A paper has been accepted by *The Astrophysical Journal*.

Bodenheimer, Lin, and Andreas Burkert (Heidelberg, Germany) consider the atmospheric flow on short-period extra solar planets through two-dimensional numerical simulations of hydrodynamics with radiation transfer. The circular orbits of these systems indicate that they are most likely to spin synchronously with their orbits, so that one side of a planet (the day side) is always exposed to the irradiation from the host star whereas the other (the night side) is always in shadow. The temperature of the day side is determined by the equilibrium which the planetary atmosphere establishes with the stellar radiation. For planets around solar-type stars with periods less than 7 days, the flux of

stellar irradiation exceeds that released by the planets' Kelvin Helmholtz contraction by several orders of magnitude. The effect of this energy flux is to modify the temperature distribution in the outer regions of the planet, reduce the contraction rate of the planet, and to result in an increased radius as a function of time, as compared with an isolated planet. The calculations show that the radiation transfer in a planet's atmosphere is a sensitive function of its opacity. If the atmosphere contains grains with an abundance and size distribution comparable to that of the interstellar medium, only shallow heating would occur on the day side whereas the heat flux carried by the circulation would not effectively heat the night side which would cool well below the day side (500 K on the night side compared with 1200 K on the day side for the specific case of the transiting planet HD 209458b). In this case the contraction rate of the planet is not reduced as much as it would be in the case of a uniform surface temperature. But if the grains are depleted, as in the case of Jupiter's atmosphere, stellar radiative flux would penetrate deeply into the atmosphere on the day side, and the atmospheric circulation would carry a large flux of heat over to the night side, so that its temperature difference compared with the day side would be relatively small. The authors also find that the rate of kinetic heating associated with the dissipation of the circulation flow in the outer layers of the atmosphere is unlikely to provide a significant expansion of the planet. A paper is being prepared for *The Astrophysical Journal*.

Bodenheimer and Lin published a review paper in *Annual Review of Earth and Planetary Science* (30, 113, 2002) on "Implications of Extrasolar Planets for Understanding Planet Formation". Bodenheimer (2001) presented a review paper at the IAU Symposium 200: Formation of Binary Stars (published by Astronomical Society of the Pacific).

Postdoctoral fellow Hubert Klahr and Bodenheimer investigated the global baroclinic instability as a mechanism to produce turbulence and outward angular momentum transport in accretion disks. Numerical calculations in two and three space dimensions show that the instability can be induced by a decreasing entropy in the radial direction in a disk. Accretion rates for disks under the influence of this turbulent transport are estimated and are found to be consistent with observed disks. The instability also produces long-lived vortices in the disk. A paper has been published in *The Astrophysical Journal* (582, 869, 2003). Ongoing work involves analytical linearized studies to provide further information on the nature of the instability, as well as calculations on the accretion of solid particles into the vortices which can accelerate the process of planet formation in them.

Mardling and Lin (*ApJ*, 573, 829, 2002) present an efficient method, based on formulations by Heggie and by Eggleton, for calculating self-consistently the tidal, spin, and dynamical evolution of a many-body system, here with particular emphasis on planetary systems. The star and innermost planet (or in general the closest pair of bodies in the system) are endowed with structure while the other bodies are treated as point masses. The evolution of the spin rates and obliquities of the extended bodies are calculated (for arbitrary initial obliquities), as is the tidal evolution of the innermost orbit. In addition, the radius of the innermost planet is evolved according to its ability to efficiently dissipate tidal energy. Relativistic effects are included to post-Newtonian order. For resonant systems such as GJ 876, the evolution equations must be integrated directly to allow for variation of the semimajor axes (other than from tidal damping) and for the possibility

of instability. For systems such as Upsilon Andromedae in which the period ratio of the two inner planets is small, the innermost orbit may be averaged producing (in this case) a 50-fold reduction in the calculation time. In order to illustrate the versatility of the formulation, they consider three hypothetical primitive Earth-Moon-Sun-Jupiter systems. The parameters and initial conditions are identical in the first two models except for the Love number of the Earth, which results in dramatically different evolutionary paths. The third system is one studied by Touma & Wisdom and serves as a test of the numerical formulations by reproducing two secular mean motion resonances (the evection and eviction resonances). The methods may be used for any system of bodies.

Taku Takeuchi and Doug Lin (ApJ, 581, 1344, 2002) studied the radial migration of dust particles in accreting protostellar disks analogous to the primordial solar nebula. Their main objective was to determine the retention efficiency of dust particles, which are the building blocks of the much larger planetesimals. This study takes account of the two-dimensional (radial and normal) structure of the disk gas, including the effects of the variation in the gas velocity as a function of distance from the midplane. It is shown that the dust component of disks accretes slower than the gas component. At high altitude from the disk midplane (higher than a few disk scale heights), the gas rotates faster than the particles because of the inward pressure gradient force, and its drag force causes particles to move outward in the radial direction. Viscous torque induces the gas within a scale height from the disk midplane to flow outward, carrying small (size $< 100\mu\text{m}$ at 10 AU) particles with it. Only particles at intermediate altitude or with sufficiently large sizes ($> 1\text{ mm}$ at 10 AU) move inward. When the particles' radial velocities are averaged over the entire vertical direction, the particles have a net inward flux. The magnitude of their radial motion depends on their distance from the central star. At large distances, particles migrate inward with a velocity much faster than the gas accretion velocity. However, their inward velocity is reduced below that of the gas in the inner regions of the disk. The rate of velocity decrease is a function of the particles' size. While larger particles retain fast accretion velocity until they approach closer to the star, $10\mu\text{m}$ particles have slower velocity than the gas in the majority of the disk ($r < 100\text{ AU}$). This differential migration of particles causes size fractionation. Dust disks composed mostly of small particles (size $< 10\mu\text{m}$) accrete slower than gas disks, resulting in an increase in the dust-gas ratio during the gas accretion phase. If the gas disk has a steep radial density gradient or if dust particles sediment effectively to the disk midplane, the net vertically averaged flux of particles can be outward. In this case, the accretion of the dust component is prevented, leading to the formation of residual dust disks after their gas component is severely depleted.

Recent mm continuum observations of protostellar disks indicate that the total mass of heavy elements in these disks is about 1 % that contained in the central star. This ratio is comparable to the ratio of the total mass of heavy elements contained in all the planets and comets in the the solar system to that in the Sun. Postdoctoral fellow T. Takeuchi and D. Lin (ApJ, submitted) inferred, on the assumption that all the mass contained in stars was accreted onto them via protostellar disks, that a self regulation may lead to the observed heavy element content in most protostellar disks. By examining the effects of radiation pressure and hydrodynamic drag on the dust as well as the structure of gaseous

protostellar disks, they showed that small grains are well coupled to the gas whereas cm-size grains are affected by the meridional circulation of the disk and have a slower mass accretion rate through the disk onto the central star than the gas. Hydrodynamic drag is more important than for larger particles so they undergo orbital decay. Nevertheless, as the surface density of the cm-size grains increases relative to that of the gas, large particles would coagulate rapidly and their orbital decay would be stalled. This result resolves the growth barrier from grains to planetesimals. Takeuchi and Lin further showed that particle collisions also lead to angular momentum transport which leads to an upper limit on the surface density of the heavy elements locked up in particles.

Takeuchi and Lin, in a study accepted by *The Astrophysical Journal* (2003), considered the outflow of dust particles on the surface layers of optically thick disks around young stars. Small dust particles (less than 10 microns) experience support from stellar radiation pressure and orbit more slowly than the surrounding gas. The resulting tail wind imparts energy and angular momentum to the particles, moving them outward. This outflow occurs in the thin surface layer of the disk that is exposed to starlight, and the outward mass flux is carried primarily by particles of size 0.1 micron. Beneath the irradiated surface layer, dust particles experience a head wind, which drives them inward. For the specific case of a minimum mass solar nebula, less than a thousandth of the dust experiences outward flow. If the stellar luminosity is 15 times that of the Sun, or if the gas disk mass is less than $100 M_{\oplus}$ then the surface outflow can dominate the inward flux in certain radial ranges, leading to the formation of rings or gaps in the dust disks.

Debris disks have been observed around luminous young stellar objects. Around HR 4796, a ring with relative sharp edges and around HD141569, two rings with gaps between them have been observed. Postdoctoral fellow Hubert Klahr and Lin showed (*ApJ*, 554, 1095, 2001) that the combined effect of stellar radiation pressure and hydrodynamic drag can cause dust particles to accumulate into rings. They also examined the conductive heating of the gas by rings of dusty particles and showed that such a feedback process may lead to substructures such as gaps within the rings. These results are particularly important for the interpretation of observed gaps in the dusty rings. They may also be relevant for the formation of cometary clouds at large distances from some Herbig Ae/Be stars.

Nagasawa, Lin, and Ida (*ApJ*, 586, 1374, 2003) have studied the eccentricity evolution of extrasolar multiple planetary systems as a result of the depletion of protostellar disks. Most extrasolar planets are observed to have eccentricities much larger than those in the solar system. Some of these planets have sibling planets, with comparable masses, orbiting around the same host stars. In these multiple planetary systems, eccentricity is modulated by the planets' mutual secular interaction as a consequence of angular momentum exchange between them. For mature planets, the eigenfrequencies of this modulation are determined by their mass and semimajor axis ratios. However, prior to the disk depletion, self-gravity of the planets' nascent disks dominates the precession eigenfrequencies. They examine the initial evolution of young planets' eccentricity due to the apsidal libration or circulation induced by both the secular interaction between them and the self-gravity of their nascent disks. They show that as the latter effect declines adiabatically with disk depletion, the modulation amplitude of the planets' relative phase of periapsis is approx-

imately invariant despite the time-asymmetrical exchange of angular momentum between planets. However, as the young planets' orbits pass through a state of secular resonance, their mean eccentricities undergo systematic quantitative changes. For applications, they analyze the eccentricity evolution of planets around ν Andromedae and HD 168443 during the epoch of protostellar disk depletion. They find that the disk depletion can change the planets' eccentricity ratio. However, the relatively large amplitude of the planets' eccentricity cannot be excited if all the planets had small initial eccentricities.