Stars, brown dwarfs and planets

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ABSTRACT

There is both observational and theoretical evidence for the occurrence of an embedded stage in the evolution of a stellar cluster during which the density of normal stars can be as high as a few times 10^4 stars pc^{-3}, although usually somewhat lower than this. During this final stage of cluster development, when the gas density is higher and the Jeans mass limit is lower, lower-mass normal stars and brown dwarf formation takes place. In such an environment interactions between Sun-like stars and diffuse proto-bodies of lower mass will be common. It is shown by smoothed-particle-hydrodynamics (SPH) modelling that such interactions can lead to planet formation. The SPH program used for these simulations contains a novel algorithm for radiation transfer, an important component if misleading results are not to be obtained. An estimate of the proportion of Sun-like stars having planetary companions obtained from the model agrees reasonably well with deductions from observations. The model also explains the existence of large numbers of 'free-floating planets' recently discovered in the Orion nebula. The ability of the model to explain observations is compared with that of the standard model, the Solar Nebula Theory (SNT), and also that of a model involving disk-disk or star-disk interactions between young stars. It is concluded that the SNT still has important outstanding problems but that the other two mechanisms are equally plausible and may be complementary.

1. STAR FORMATION – EARLY SCENARIO

Observations of young stellar clusters, in which stars are still evolving towards the main sequence, indicate that the first stars produced are of mass around 1.35 $M_{\odot}$ and that, later, stars of both progressively decreasing mass and increasing mass are formed (Williams & Cremin, 1969). This is well explained by a model for the evolution of a turbulent dense cool cloud (DCC) developed by Woolfson (1979), a paper later referred to as W79. The collisions of turbulent elements in the DCC give rise to heated denser regions that cool on a much shorter timescale than they physically re-expand. If a number of conditions are satisfied then a cooled denser region can collapse to form a star. The stream of stars of lessening mass with time is explained by the increase of density as the DCC collapses and the consequent decreasing turbulence scale-length and decreasing Jeans critical mass. The stream of stars of increasing mass with time is due to accretion by earlier-formed stars that happen to move through a denser region of the DCC.

At any particular time the forming stars cover a range of masses since the cloud will not be homogeneous but the general trend of average mass with time will be as indicated above. The initial mass distribution, as deduced from the model, is $f(M) \propto M^{\alpha}$ where the mass index, α, is 2.5; the value from observation is about 2.35 (the Salpeter index). Another outcome of the model is that it gives late-type stars like the Sun spinning slowly, a result that most other theories have difficulty in reproducing. Additionally the model indicated that more massive stars, those produced by accretion, would rotate more rapidly and, in particular the predicted relationship between mass and angular momentum agreed well with that inferred from observation. One deficiency of the model is that binary systems were not produced directly and it is known that binary systems are at least as common as single stars.

Golanski & Woolfson (2000) have described a plausible model for the formation of DCCs. They showed that injection of coolant material into the interstellar medium by a supernova gives, within the affected region, a number of dense cloudlets, of masses from tens to hundreds of solar masses, which collide with each other at supersonic speeds. This agreed with the scenario adopted by Bhattal *et al.* (1998) who showed by smoothed-particle-hydrodynamics (SPH) modelling that in such collisions binary and other multiple systems could be produced. Some composite of the Woolfson and Bhattal *et al.* models might possibly give both the good agreement with observed individual stellar characteristics of the former model and also the frequency of binary systems offered by the latter one.

W79 followed the evolution of DCCs with various initial parameters down to the formation of stars with mass ~ 0.075 $M_{\odot}$, the lower limit of the main sequence. At this stage the density of the cloud was about 10^{-14} kg m^{-3}, its radius about 0.12 pc and 400 stars had been produced. This corresponds to a stellar density of ~ 50 000 stars pc^{-3}, which was neither noticed nor noted at the time. Recently such large stellar densities in star-forming regions have been confirmed by observation. Densities in the range $10^4 – 10^5$ stars pc^{-3} have been observed in the core of the Trapezium cluster although such densities are unusually high; densities of 10^2 - 10^4 stars pc^{-3} are probably more typical. Various authors (e.g. Lada& Lada, 1991; Gaidos, 1995) have referred to this high-density stage of cluster development as the *embedded stage*. The stars in the embedded stage are bound into a quasi-stable system by the remains of the molecular gas from which they formed. As this gas is dispersed, particularly by radiation from luminous O and B stars, so the cluster will expand, lose some members, and eventually end up as a galactic cluster. The total process of gas dispersion is estimated to last about 5×10^6 years. The velocity dispersion in the embedded stage is in the range 0.5 – 2 km s^{-1} (Gaidos, *loc. cit.*).

2 BROWN DWARFS

By whatever process stars are formed, even if not as suggested above, there can be no reason for nature to terminate the process at the main-sequence lower mass limit. Less massive objects, brown dwarfs (BDs), should also be expected as a product of any process of star formation. The difference in nature between stars and brown dwarfs is only apparent after they have reached a dense state. Brown dwarfs, of mass less than 0.075 $M_{\odot}$, will initiate only deuterium-based nuclear reactions while main-sequence stars will manifest other nuclear reactions, both requiring and giving higher temperatures. At the other end of the brown-dwarf mass range, at about 0.013 $M_{\odot}$, not even deuterium reactions take place and this mass is conventionally taken as the boundary between brown dwarfs and planets. Cole (2000) has given a more detailed discussion of the distinction between planets and brown dwarfs.

If the Salpeter mass index persisted to the lower end of the BD mass range then BD numbers would be very large, exceeding the number of main-sequence stars by a factor of ten. Much current interest in BDs is concerned with estimating their contribution to the missing mass in the universe. In general, if the mass index is greater than two then the total mass of all the bodies will increase significantly with the lower mass limit – otherwise it is very little dependent on the lower mass limit. Observations of BDs suggest that the appropriate mass index is less than two so they make very little contribution to the total mass but, nevertheless, they can greatly outnumber main-sequence stars. Binney (1999) indicates that a mass index of 1.8 for masses between 2 $M_{\odot}$ and 0.01 $M_{\odot}$ is allowed by observations and this would give four times as many BDs as normal stars. On the other hand Reid *et al.* (1999) suggest that there may be only twice as many. Recent observations of more than 100 BDs in the Orion nebula by Lucas & Roche (2000) gives general support to the idea of the presence of large numbers of such bodies. A best estimate in the light of present knowledge is to assume that there are three times as many BDs as normal stars.

3 THE CAPTURE-THEORY MECHANISM

The Capture Theory (CT) for planet formation involves a tidal interaction between a condensed star and a diffuse protostar (Woolfson, 1964). Theory by Jeans (1928) shows that a filament of matter drawn out of the protostar could be gravitationally unstable and break up into a string of blobs. If individual blobs have greater than a Jeans critical mass and are not unduly disturbed by external influences, such as tidal effects, then they could produce planetary-mass condensations. Computational modelling by point-mass models of ever-increasing complexity (e.g. Woolfson, 1964; Dormand & Woolfson, 1971; Dormand & Woolfson, 1988) have indicated that the planetary condensations, if they formed, could be captured by the condensed star – hence the name of the theory. However, while these previous calculations confirmed the plausibility of the general CT concept they were not detailed enough to show the break up of a filament and the subsequent behaviour of the condensations.

One motivation of W79 was to estimate the proportion of Sun-like stars that would have planetary companions. The basic assumption at that time was that only normal stars were formed and that conditions were similar to those in observed evolved clusters. It was also assumed that in order to get the range of orbital radii seen in the solar system the periastron distance of the star-protostar orbit would need to be a few tens of AU. The co-existence of diffuse lower-mass protostars with earlier produced condensed late-type stars was supported both by observation and theory so the basic conditions for CT interactions were present.

The estimate made in W79 was that the probability of a Sun-like star having a planetary companion was about 10^{-5}. In the light of recent observations of extra-solar planets this estimate is quite untenable. Current estimates of the proportion of Sun-like stars having planets are somewhere in the range 3 – 6% and any plausible theory should give something of this order.

The combination of the embedded state of clusters and confirmation of the existence of large numbers of BDs clearly makes the previous W79 estimate completely invalid. The number of bodies potentially able to act as protostars (we shall refer to them as such even if they are of BD mass) is much greater than was originally postulated. Of even greater importance is the realization of the embedded stage during which stars are closer together, so increasing the likelihood of interactions, and also during which smaller-mass normal stars and BDs will be produced in large numbers.

4 FROM PROTOSTARS TO CONDENSED STARS

It is often assumed in theoretical work that an isolated static uniform sphere of gas equal to or greater than a Jeans critical mass will completely collapse, while if it has less than that mass it will completely disperse. This is a misunderstanding of what would actually occur. The usual equation for the Jeans critical mass is

$$M_J = \left(\frac{375k^3T^3}{4\pi G^3\mu^3\rho}\right)^{½} = \frac{5kTR}{G\mu} \qquad (1)$$

where T and R are the temperature and radius of a sphere of material for which the mean molecular mass is μ. This form is derived from an application of the Virial theorem

$$2K + \Omega = 0 \qquad (2)$$

where K is the translational kinetic energy of the gas, in this case due to thermal motion, and Ω is the potential energy. Actually the theorem is a special case of the more general

$$2K + \Omega = ½\frac{d^2I}{dt^2} \qquad \text{(Poincaré's theorem)} \quad . \qquad (3)$$

The quantity I is the geometric moment of inertia given for a distribution of N masses by

$$I = \sum_{j=1}^{N} m_j r_j^2 \qquad (4)$$

where m_j is the mass of the j^{th} particle and r_j its distance from the centre of mass of the system. Clearly if the right-hand side of (3) is zero then the mass-averaged value of r^2 does not change with time but this does not mean that the distribution of masses is static. What happens in practice is that the central material starts moving inwards since, with a uniform density and temperature, there are no pressure-gradient forces acting, only gravity, while outside material moves outwards. If this did not happen then the Virial theorem would indicate that a Jeans critical mass could not collapse at all. The final outcome will depend on the way that energy is dissipated as heat radiation but it could become a condensed body containing less than the original Jeans critical mass, as indicated by (1) for the original state of the material. The same pattern occurs with a body somewhat less than, or somewhat more than, a Jeans critical mass. This form of behaviour has been described by Ruskol (1955) and by Woolfson (1964). In Figure 1 we show the results from SPH simulations of the collapse of gas spheres of radius 1 000 AU, temperature 15 K and with $\mu = 4 \times 10^{-27}$ kg. The Jeans critical mass is 5.82×10^{29} kg ($\sim 0.3\ M_{\odot}$) and the figure shows the relationship of the final collapsed mass to the initial mass. It will be seen that there are some slight losses of material for initial masses at and above the Jeans critical mass and that below 4.4×10^{29} kg ($0.76\ M_{\mathrm{Jeans}}$) no final condensation is formed.

This numerical experiment was carried out with constant initial radius and temperature but with variable mass to sweep through the Jeans mass. Alternatively it could have been done by changing either the radius or the temperature while keeping the other two parameters fixed. Since a realistic radiation transport term is included in the calculations the results are not scalable. For an initial mass any particular fraction of a Jeans mass, a hotter configuration will collapse more freely, since it will be able to radiate energy away more efficiently during the calculation.

The main point being made here is that brown dwarfs and lower-mass normal stars may be, and probably are, derived from the collapse of proto-bodies of greater initial mass. Actually the above simple theory indicates that there is no finite lower limit to the masses of the final bodies. While additional physical limitations will prevent gaseous bodies forming of very small mass, mainly-gaseous bodies with the mass of Jupiter, and somewhat below, are clearly possible since they actually exist. However, final bodies of planetary mass correspond to a very narrow range of initial proto-body masses for the material we have considered here (Figure 1) and it is not suggested that large numbers of planetary-mass bodies, or even any, would form in this way.

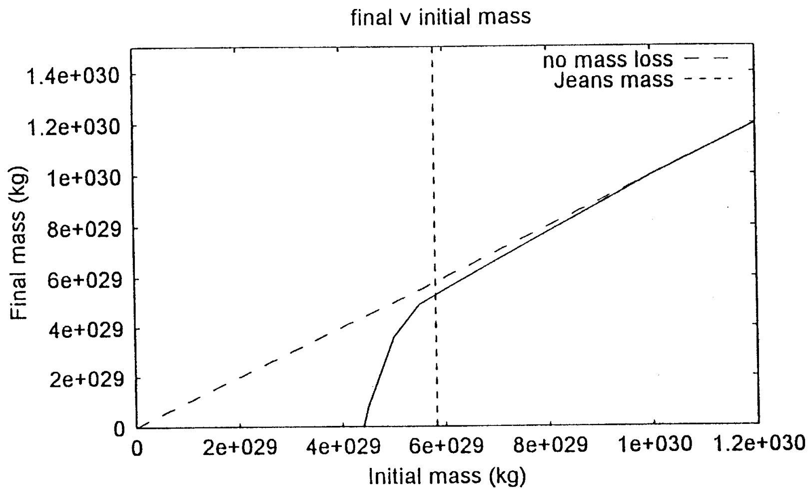


Figure 1 The relationship of initial mass to final condensation mass for an initially static gaseous mass of radius 1 000 AU, temperature 15 K for which the mean molecular mass is $4{\times}10^{-27}$ kg.

5 RECENT MODELLING OF CAPTURE THEORY INTERACTIONS

In previous models of CT interactions the diffuse protostar had a mass in the range 0.15 – 0.25 $M_{\odot}$. These models, of limited resolution, showed that a tidal filament was formed but that the bulk of the protostar remained intact and moved away in a depleted state. The models indicated that some of the filament material was captured but, due to lack of resolution, its subsequent evolution could not be followed within the same calculation that produced the filament. Assuming that blobs of matter *were* formed in the filament, calculations by Dormand & Woolfson (1971, 1988) and by Schofield & Woolfson (1982a, b) supported the idea that planetary condensations would form.

Some of the later CT modelling was carried out with SPH, developed by Gingold & Monoghan (1977) and also described by Lucy (1977). Astrophysical bodies are represented by distributions of particles, each particle being associated with a particular equation of state and possessing mass and internal energy. Differential equations involving gravitational, pressure and viscosity forces are solved numerically to follow the motions of particles and to update the internal energy associated with them. From the positions, masses and internal energies of the SPH particles subsidiary quantities such as temperature and density can be estimated at any point within the domain of the simulation. There have been many excellent and convincing simulations carried out with SPH – e.g. Bhattal *et al.* (*loc. cit.*) – and the technique is particularly appropriate to non-symmetric problems.

Radiation transport has not previously been modelled in a general way. There have been treatments of transparent regimes, where a compressed region will quickly cool to the same temperature as its surroundings, and of opaque regimes where energy changes due to radiation can be ignored compared to those due to dynamic processes. However, in considering the large range of densities and sizes of bodies we wished to deal with – from large diffuse protostars to comparatively dense and small protoplanets - we concluded that some detailed scheme for radiation transfer was necessary. Therefore we have developed a novel and realistic model of radiation transfer, incorporated within our general SPH package, that is applicable for all opacities, all optical depths and all distributions of material. The algorithm for this is described in detail by Oxley (1999). It is based on a Barnes-Hut tree structure (Barnes & Hut, 1986) and uses a Monte-Carlo approach for transporting energy through the tree. The properties of the SPH particles are interpolated onto the tree, energy is then transported through the tree by a novel random-walk sampling scheme and finally energy is returned to the SPH particles. The algorithm has been tested in a number of idealized trial situations – luminosity of an isolated sphere, radiation from a point source, equilibrium temperature of isolated bodies and the rate of energy transport in an opaque body – and in all cases the results are close to expectation.

In our present SPH modelling the equation of state used for the protostar was that for a 70:30 mixture of H:He, not taking account of a 1-2% dust component that would have little effect on its dynamical behaviour. The equation of state must include the variation of specific heat with temperature and also variations of the temperature and mean molecular mass with internal energy. The dissociation of molecular hydrogen is both pressure and temperature dependent and, under the conditions of our material, results extrapolated to zero pressure are appropriate. The values used in these calculations, the details of which are given by Oxley (*loc. cit.*), are a compilation from numerous published works, weighted according to their reliability, as given by Touloukian & Ho (1970).

The first situation we examined with the tested program used the parameters suggested by Woolfson (1964) in the paper that first proposed the CT. A protostar of mass 0.15 $M_\odot$ and radius R = 14.7 AU, in quasi-static equilibrium, interacted with the Sun in a parabolic orbit with perihelion, $q = 3R$. The protostar was represented by 11 119 SPH points and its appearance at 50 year intervals is shown in Figure 2. It is clear that the main body of the protostar remains intact and that a stream of matter drawn from it is captured by the Sun but it is also obvious that no protoplanets are forming. The density of the lost material is such that it is always well within the Roche limit and hence is never able to form condensations.

The next application of the SPH algorithm, described by Oxley (*loc. cit.*) was begun before details of extra-solar planets orbits were available and where the aim was to reproduce something with the distance scale of the solar system. Also at that time we were still in the mindset that, to do this, it was necessary to have the protostar perihelion a few tens of AU. This application involved an encounter between a BD of mass 0.05 $M_\odot$ and a star similar to the Sun both in mass and luminosity. The initial radius of the BD was 100 AU and its temperature, 25 K, was such that it just satisfied the Jeans mass criterion. The encounter was parabolic (e = 1) with a periastron distance, q = 60 AU. At the beginning of the simulation the star-BD distance was 450 AU.

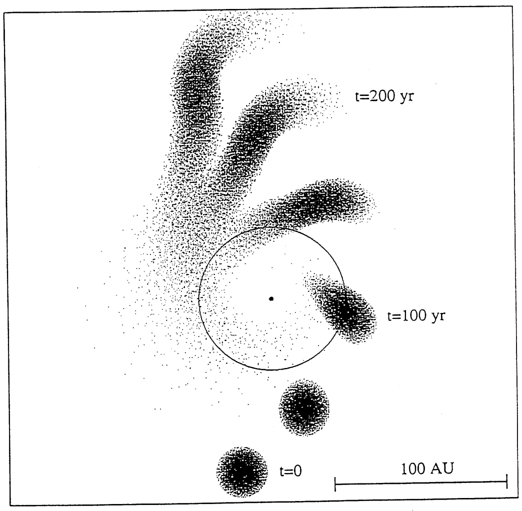


Figure 2 An SPH simulation of a Capture Theory scenario with the parameters given by Woolfson (1964)

Figure 3 shows the disrupting BD, represented by 11 119 particles, at intervals of 400 years. The whole dwarf is stretched out into a filament with a condensation forming at each end. The outer condensation escapes from the star but the inner one is captured. The appearance of the latter body, at 100 year intervals between 3 000 and 4 000 years after the beginning of the simulation, is given in Figure 4. At 4 000 years it consists of a condensing compact core, of mass about 5 M_J, with a surrounding diffuse disk. The orbit of the captured protoplanet is given by (a, e) = (252.3 AU, 0.860), corresponding to a periastron distance of 35.4 AU. Much of the BD material ends up in a diffuse form around the star and will act as a resisting medium within which the newly formed protoplanet will move.

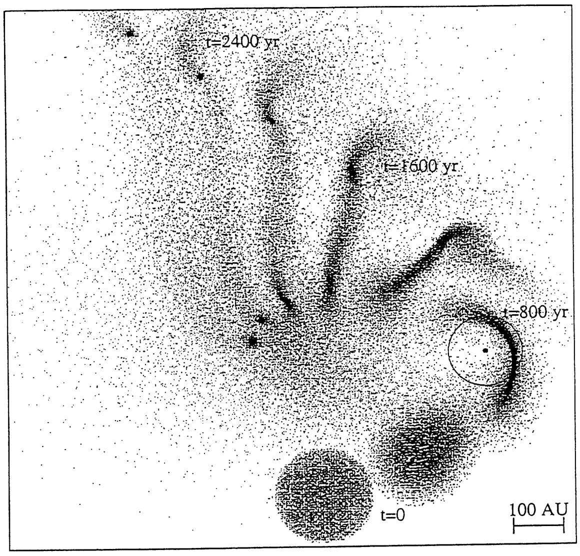


Figure 3 An encounter between a star with solar characteristics and a protostar of brown-dwarf mass. The protostar is represented by 11 119 SPH particles and its configuration is shown

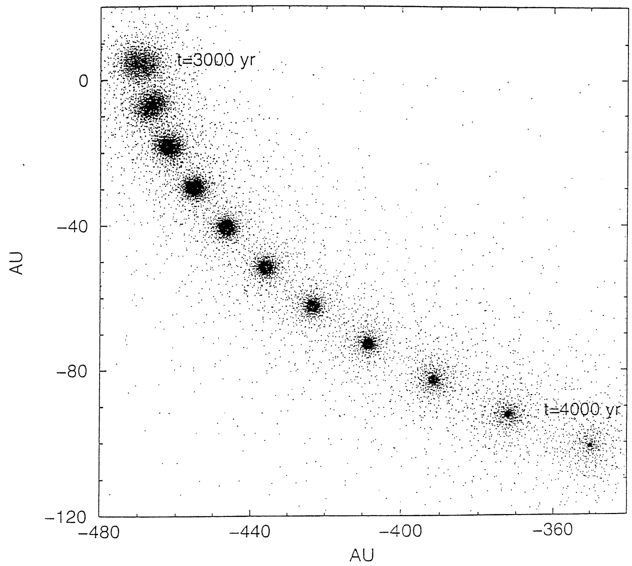


Figure 4 The collapse of the captured protoplanet shown in Figure 3. The configuration is shown at 100 year intervals between 3 000 and 4 000 years from the beginning of the simulation

It is self-evident that the inclusion of radiation transfer assists in the formation of protoplanets since they are able to radiate away the thermal energy generated during their collapse. On the other hand, radiation due to stellar luminosity heats the filament and will work in the other direction to inhibit planetary formation. If the model leading to Figures 3 and 4 are repeated with just the change that stellar luminosity is removed then several planetary condensations are produced, three of which are captured (Figure 5).

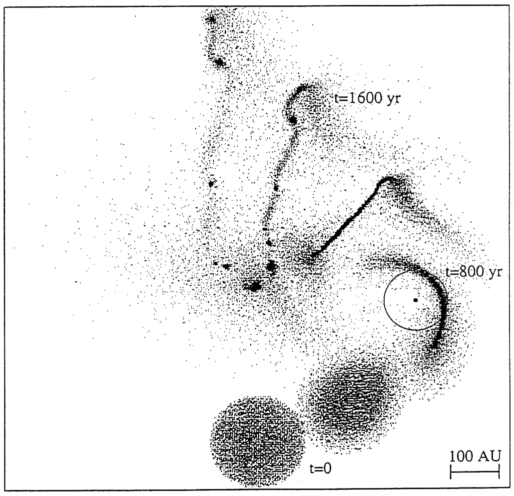


Figure 5 The encounter shown in Figure 3 repeated with the stellar luminosity made equal to zero. Several condensations are formed, three of which are captured.

The discovery of planets around stars with almost circular orbits of radius down to about 0.04 AU led to a rethink of the appropriate parameters that would give such an outcome. The idea that the protostar orbit should have a periastron distance of the same order as the radius of the protoplanet orbit was completely untenable and, in any case, such a condition would lead to very small probabilities of CT interactions leading to planet formation. In fact, even the parameters leading to the outcome shown in Figures 3 and 4 would lead to probabilities that were too small in the light of current knowledge. The conclusion from this reassessment was to consider CT interactions with much more diffuse protostars than hitherto and to look more carefully at the process of orbit evolution, the result of which is described in §6.

For an embedded stage of a cluster with, say, 10^3 normal stars pc^{-3} the average density provided by the stars corresponds to 290 $M_\odot$ pc^{-3}, assuming the Salpeter index. The W79 model gives the mass of formed stars at the end of the star-forming process as about one-eighth of the total mass; accepting this factor for the embedded state the gas would have a density of 1.4×10^{-16} kg m^{-3}. This agrees with the density at which stars with mass below 0.25 $M_\odot$ are produced in W79. A protostar is formed when a body of density higher than that of the surrounding medium is stable and is able to begin the slow process of contraction. It is not too clear what the criterion for stability should be. Obviously it must be able to produce a condensation in isolation so that it has to satisfy the criteria suggested by the results displayed in Figure 1.

However, in addition to this it must be able to withstand any disturbance, including buffeting, from the external medium. We suggest here that this would require that the pressure within the protostar should be greater than the ram pressure of turbulent streams of matter from the external medium. The ram pressure is given by

$$P_r = \rho(z\mathrm{c})^2 = \rho z^2 \frac{3kT}{\mu} \qquad (5)$$

where c is the speed of sound in the medium and z is the Mach number of the turbulence within it. If the density of the material of the protostar is n times that of the medium, but with the same temperature, then the pressure in the protostar is

$$P_p = \frac{n\rho kT}{\mu} \quad . \qquad (6)$$

The condition that $P_p > P_r$ gives

$$n > 3z^2 \quad . \qquad (7)$$

The W79 model suggests that an appropriate value for z is 10 and this gives a density for the protostar of 4×10^{-14} kg m^{-3}. At a temperature of 15 K the Jeans mass is then 5.9×10^{29} kg (~ 0.3 $M_\odot$) and the radius is 1 010 AU. It should be pointed out that we had these results in mind when carrying out the calculations leading to Figure 1. While this analysis depends on many approximations and assumptions it indicates that it is reasonable to consider protostars of about this radius. This estimate is also consistent in order of magnitude with the usually accepted initial size of a protostar when it begins its free-fall stage (e.g. Shklovskii, 1978).

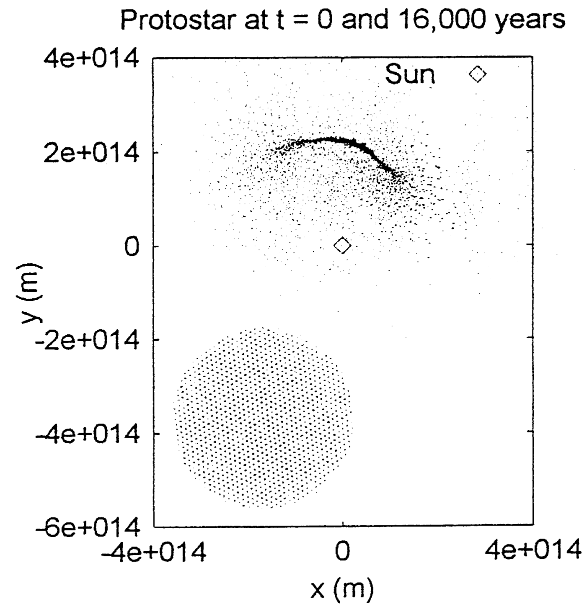
Further investigation of CT simulations using our SPH program has shown that planet formation can occur at any scale of interaction and occurs very readily with protostars of radius 1 000 AU or so. To illustrate this we now show the results from three simulations using protostars of radius 800 – 1 300 AU with different masses and temperatures and in orbits with a range of periastron distances and eccentricities. In all cases the star has the mass and luminosity of the Sun. The radiation transfer algorithm in these simulations is slightly modified from that given by Oxley (1999) in that energy transfer may be in any direction rather than being restricted to the principal directions defined by the tree structure.

Simulation A

protostar mass, radius and temperature	1.3×10^{30} kg, 1 300 AU, 15 K.
number of SPH particles	5 946
orbit periastron and eccentricity	700 AU, 1.1
Initial star-protostar distance	2 700 AU

The appearance of the protostar after 16 000 years is shown in Figure 6a. The protostar has been stretched out into a filament that has fragmented into six condensations (Figure 6b). Starting from the left the first three condensations are captured with the following properties:

condensation 1	mass 8.85 M_J ,	orbital (a, e) = (2 566 AU, 0.712)
condensation 2	mass 5.6 M_J,	orbital (a, e) = (2 496 AU, 0.622)
condensation 3	mass 10.7 M_J	orbital (a, e) = (3 661 AU, 0.902)

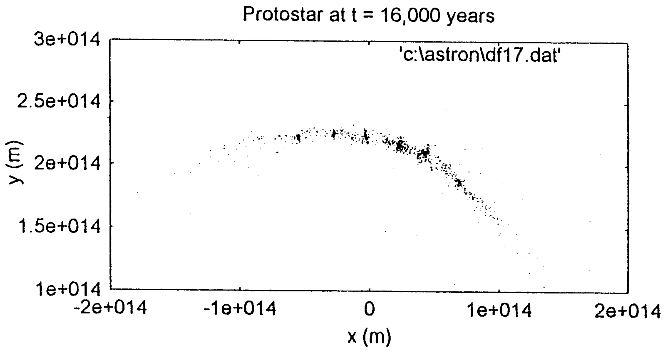


(a)

Figure 6 Simulation A

(a) An encounter between a star with solar characteristics and a protostar with mass 1.3×10^{30} kg, radius 1 300 AU and temperature 15K. The protostar configuration is shown at t = 0 and t = 16 000 years.

(b) The filament after 16 000 years has broken up into six condensations of which the first three on the left are captured.



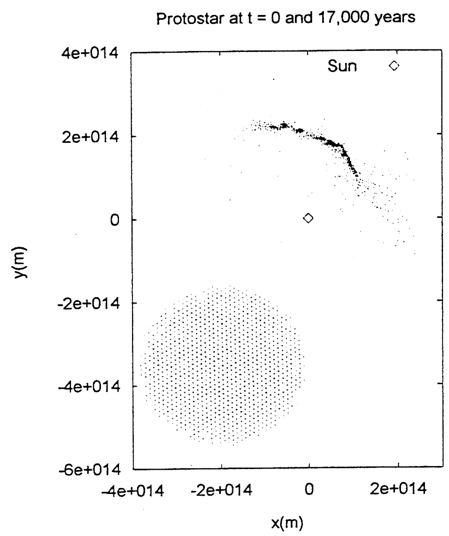
(b)

Simulation B

protostar mass, radius and temperature	1.0×10^{30} kg, 1 000 AU, 30 K.
number of SPH particles	5 946
orbit periastron and eccentricity	800 AU, 0.9
Initial star-protostar distance	2 700 AU

The appearance of the protostar after 17 000 years is shown in Figure 7a. The protostar has been stretched out into a filament that has fragmented into a number of condensations including some that are rather nebulous. The three clear condensations, indicated with arrows in Figure 7b, are captured with the following properties:

condensation 1	mass 6.45 M_J , orbital (a, e) = (6 757 AU, 0.881)
condensation 2	mass 23.3 M_J, orbital (a, e) = (980AU, 0.766)
condensation 3	mass 15.2 M_J orbital (a, e) = (1 385 AU, 0.429)

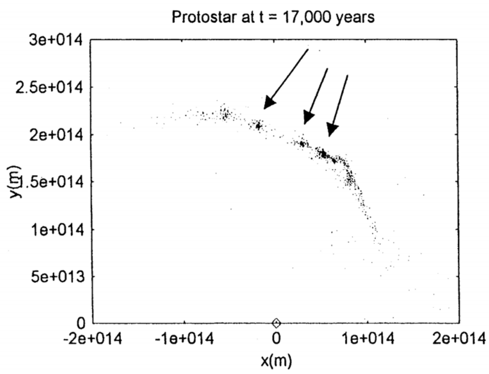


(a)

Figure 7 Simulation B

(a) An encounter between a star with solar characteristics and a protostar with mass 1.0×10^{30} kg, radius 1 000 AU and temperature 30 K. The protostar configuration is shown at t = 0 and t = 17 000 years.

(b) The filament after 17 000 years has broken up into a number of condensations of which the three indicated are captured.



(b)

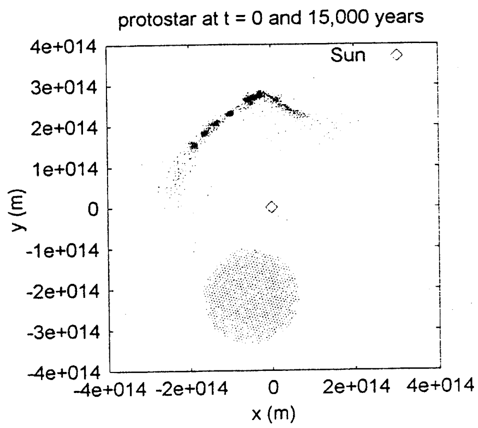
As might be expected from an elliptical protostar orbit, more material is captured than in simulation A and the orbits are generally of lower eccentricity. Condensations 2 and 3 have masses indicative of BDs but it is not certain that BDs would be the final outcome. These simulations have not been taken as far as those illustrated in Figures 3 and 4 and it is possible that eventually a lower-mass core surrounded by a disk would form.

Simulation C

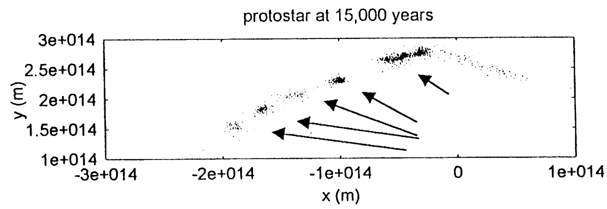
protostar mass, radius and temperature	7×10^{29} kg, 800 AU, 20 K.
number of SPH particles	5 946
orbit periastron and eccentricity	600 AU, 0.95
Initial star-protostar distance	1 600 AU

The appearance of the protostar after 15 000 years is shown in Figure 8a and in greater detail in Figure 8b. The protostar has been stretched out into a filament that has fragmented into several condensations although some are rather diffuse. The condensations marked with arrows, numbered from the left, are captured with the following properties:

condensation 1	mass 4.7 M_J ,	orbital (a, e) = (1, 247 AU, 0.835)
condensation 2	mass 7.0 M_J,	orbital (a, e) = (1 885 AU, 0.772)
condensation 3	mass 4.8 M_J	orbital (a, e) = (1 509 AU, 0.765)
condensation 4	mass 6.5 M_J,	orbital (a, e) = (1 325 AU, 0.726)
condensation 5	mass 20.5 M_J	orbital (a, e) = (2 686 AU, 0.902)



(a)



(b)

Figure 8 Simulation C

(a) An encounter between a star with solar characteristics and a protostar with mass 7×10^{29} kg, radius 800 AU and temperature 20 K.

(b) The filament after 15 000 years has broken up into a number of condensations of which five are captured.

This elliptical protostar orbit gives many condensations, some with modest eccentricities. The condensation with the BD mass has a rather complex form and has a satellite condensation. It may end up as a BD-planet binary in orbit around the star.

The four examples of CT simulations given here illustrate that the mechanism is robust, operates on a large range of distance scales and is not dependent on the fine tuning of parameters. Indeed, present experience indicates that *any* passage of a still-diffuse protostar with a periastron distance less than the radius of the protostar and with an orbit that is elliptical, or even just hyperbolic (e.g. $e = 1.1$), will give rise to a capture event. Even if that turns out to be not strictly true at least it can be stated on the basis of experience that most such interactions will lead to capture.

In these simulations all the captured bodies have initial masses of order ten times that of Jupiter. These masses are the maximum final mass of any planets subsequently formed. Preliminary investigations show that as the captured bodies collapse, material is initially left behind in a cocoon, and later on in a disk. It is therefore possible, and indeed likely in some scenarios, that the final masses of the planets will be an order of magnitude smaller than that contained in the initial condensations.

6 FREQUENCY OF POTENTIAL CAPTURE-THEORY INTERACTIONS

Both observations of young stellar clusters and W79 give the total period for the formation of normal stars somewhere in the range 5 – 8 × 10^6 years. The earliest stars collapse to fairly compact objects, not necessarily on the main sequence, in 10^5 to 10^6 years and are thereafter candidates as stars in a CT process. The earlier a star is produced, the more later-produced protostars will be available with which to interact. Hence we might suppose that the first stars produced, of solar mass and somewhat above, have the greatest likelihood of acquiring planetary companions. Stars and BDs produced later, and of smaller mass, will begin their existence as protostar candidates able to contribute planets to other stars. Later, when they condense, they too can play the role of a star in a CT interaction although with smaller probabilities. Another time-varying parameter is the density of stars as the cloud collapses to the embedded stage.

To evaluate the probability that a star would acquire one or more planetary companions as a consequence of being a part of this constantly changing environment is clearly a difficult exercise, especially as there is a wide range of possible parameters. Instead we shall take an idealized situation in which a number of condensed stars have been formed and protostars are being formed within the cloud by the collision of turbulent streams of matter, as described in W79. If the star density and other properties of the cloud are taken as fixed, then the probability that a particular star acquires a planetary companion or companions depends only on the total number of protostars subsequently produced and not on the rate of, or total period of, formation.

We consider a region where the density of condensed stars is n_s and the velocity dispersion is v_s. The mean distance between stars is

$$d = \left(\frac{1}{n_s}\right)^{1/3} \tag{8}$$

and, on average, the volume within which a particular star will be the nearest star will be d^3. We now consider the probability that a protostar will form, moving at less than the escape velocity from the nearest condensed star.

For simplicity we take the protostar as forming somewhere within a cubical box of side d with the star at the centre. With the star as origin the probability that the protostar will be in a box of volume dx dy dz centred on point (x, y, z) is dx dy dz / d^3. The protostar will be at distance

$$r = \sqrt{x^2 + y^2 + z^2} \tag{9}$$

from the star and the escape speed at that distance is

$$v_{esc} = \sqrt{\frac{2GM_c}{r}} \tag{10}$$

where M_c is the combined mass of the star and protostar. Using a Maxwell distribution of velocities with rms value v_s, the probability that a particular protostar is formed in a captured state with respect to the nearest star is

$$p_{pc} = \frac{4\pi}{d^3}\left(\frac{3}{2\pi}\right)^{\frac{3}{2}} \frac{1}{v_s^3} \int_{-\frac{1}{2}d}^{\frac{1}{2}d}\int_{-\frac{1}{2}d}^{\frac{1}{2}d}\int_{-\frac{1}{2}d}^{\frac{1}{2}d} \left\{ \int_0^{v_{esc}} v^2 \exp\left(-\frac{3v^2}{2v_s^2}\right) dv \right\} dxdydz \quad . \tag{11}$$

If the protostar is formed in a captured state then, regardless of any other condition, if it is not subsequently perturbed in some way the star will acquire a companion of some sort – a binary companion if a CT interaction does not take place. For a CT interaction to take place we impose two extra conditions:

(a) The protostar must get to the vicinity of the star as a diffuse object – our simulations suggest to within a distance R_{ps}, the radius of the protostar.

(b) The periastron distance must be less than the radius of the protostar. This condition is suggested by the numerical simulations reported in §5. In all cases tried so far this condition gives a captured body when the initial orbit is elliptical or parabolic. Actually, one or more captured planets are often formed, even when the star-protostar orbit is hyperbolic with eccentricity close to unity (simulation A).

If the radius of the protostar is R_{ps} and its mass M_{ps} then the free-fall collapse time is

$$t_{ff} = \sqrt{\frac{\pi^2 R_{ps}^3}{8GM_{ps}}} \quad . \tag{12}$$

If the protostar is moving towards the star with an initial speed v then it will accelerate and the time taken to get within a distance R_{ps} of the star would depend on the geometry of the interaction and the periastron distance but would be of order $(r-R_{ps})/v$. If this time is to be less than t_{ff} then we may place a lower limit on the speed of the protostar at the time of its formation

$$v_{\min} = \frac{r - R_{ps}}{t_{ff}} \quad . \tag{13}$$

Coupled with this condition we impose an extra restriction that the protostar cannot be formed closer than $2R_{ps}$ from the star – a reasonable condition since radiation from the star will inhibit protostar formation at very close distances.

For condition (b) it is necessary that the orbit of the protostar should take it to within a distance R_{ps} of the star. In Figure 9 we show the motion of the protostar relative to the star such that it just satisfies the distance condition. The interaction parameter

$$D = \left\{ R_{ps}\left(R_{ps} + \frac{2GM}{v^2} \right) \right\}^{\frac{1}{2}} \quad , \tag{14}$$

and the probability that it moves in a direction satisfying (b) is

$$P_b = \tfrac{1}{2}(1 - \cos\alpha) \tag{15}$$

where $\alpha = \sin^{-1}(D/r)$.

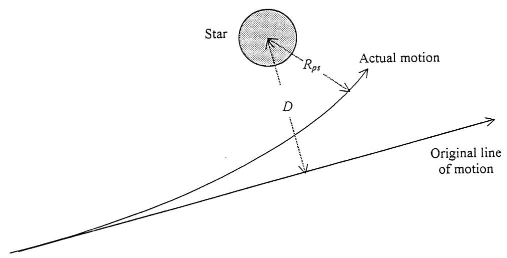


Figure 9 The impact parameter D for a closest approach R_{ps}.

Incorporating these extra conditions, the probability that a particular protostar is formed moving with less than the escape speed from the nearest star on an orbit that will take it to within its own radius from the star while it is still in a diffuse state is

$$p_p = \frac{4\pi}{d^3}\left(\frac{2}{\pi}\right)^{\frac{3}{2}} \frac{1}{v_s^3} \int_{-\frac{1}{2}d}^{\frac{1}{2}d} \int_{-\frac{1}{2}d}^{\frac{1}{2}d} \int_{-\frac{1}{2}d}^{\frac{1}{2}d} \left\{ \int_{v_{\min}}^{v_{esc}} v^2 \exp\left(-\frac{3v^2}{2v_s^2}\right) P_b dv \right\} dxdydz \qquad (16)$$

If the ratio of the number of protostars (formed after the star) to condensed stars is ϕ then the average number of captured protostars per star is $p_s = \phi p_p$; while p_p by its nature is a probability, and is hence less than unity, p_s can, in principle, be greater than unity.

The value of p_s depends on ϕ, v_s, n_s, R_{ps} and M_{ps} and these would vary in time as cluster formation proceeds. The value of v_s is taken as 1 km s^{-1}, the geometric mean of the range given by Gaidos (*loc. cit.*). We shall take $\phi = 3$, the proposed ratio of BDs to normal stars. The quantities n_s, R_{ps} and M_{ps} have been taken with various values in the evaluation of p_s. Values of n_s found in embedded states from 10^2 stars pc^{-3} to 1.28×10^4 stars pc^{-3} have been considered. A sample of results is shown in Figure 10 together with the 3-6% probability band estimated from observations. It will be seen that much of the parameter space explored is in agreement with observation. There are many approximations made in this analysis, some of which reduce the probability estimates. Other parameters can be found, that would appear to be reasonable and could be defended, that yield probabilities both lower and higher than those given here. For this reason not too much is being claimed from the results shown in Figure 10. While it cannot be argued that these probability predictions positively support the model they do, at the very least, indicate that the model cannot be discounted on grounds of probability.

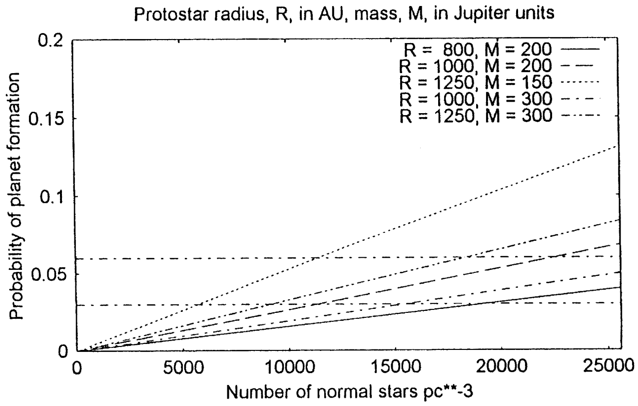


Figure 10 The probability of a planetary companion of a Sun-like star for different densities of normal stars, protostar radius and protostar mass with all other parameters kept constant. The range of estimates from observations, 3 – 6%, is indicated

7 ORBITAL EVOLUTION

A sample of extra-solar planets, listed in order of the magnitude of their semi-major axes together is given in Table 1.

Star	**Minimum planet mass (M_J)**	**Period (days)**	**Semi-major axis (AU)**	**Eccentricity**
HD	0.52	3.097	0.042	0.03±0.03
τ-Bootis	3.87	3.313	0.0462	0.018
ν-Andromedae	0.71	4.62	0.059	0.034
55Cnc	0.84	14.65	0.11	0.051
HD19501	3.43	18.3	0.14	0.05
Gliese	2.1	60.85	0.21	0.27±0.03
HD16844	5.04	57.9	0.277	0.54
70 Virginis	6.6	116.6	0.43	0.4
16 Cygni B	1.5	804	1.70	0.67
Lalande 21185	0.91	2118	2.5	0
14 Herculis	3.3	1619	2.5	0.354

Table 1 The characteristics of a sample of extra-solar planets.

This sample illustrates the general characteristics of the complete set of extra-solar planets presently known. Many of them orbit the parent star very closely indeed and in nearly circular orbits; for comparison the closest planet to the Sun is Mercury with a = 0.387 AU. Those that are in wider orbits often have large eccentricities, much larger than those for planets in the solar system. Disregarding Pluto, that is not a normal planet, the largest eccentricity for a planet is 0.2056, again for Mercury. The results given in §5 show that, characteristically, the CT model gives planets on orbits with semi-major axes of order 10^3 AU and eccentricities in the approximate range 0.6 to 0.9. It must be shown that these initial orbits could evolve to what is observed today.

From the simulations shown in Figures 4 and 6 - 9 it is evident that some material from the protostar is captured in a diffuse state by the star and this constitutes a resisting medium within which the newly formed protoplanet will move. The same situation was inferred from early CT simulations and Dormand & Woolfson (1974, 1977) showed that such a medium would round off an initially-eccentric orbit. The scenario they considered was similar to that of the original Woolfson (1964) CT model and the orbits characteristically had semi-major axes from 10 – 50 AU and eccentricities from 0.7 – 0.9. In their 1977 work, Dormand and Woolfson used for the resistance of the medium

$$D = 2\pi\rho(r)\frac{G^2M}{W^2}\ln\left(1+\frac{s^2W^4}{G^2M^2}\right) \quad , \qquad (17)$$

Dodd & McCrea(1952), where W is the relative speed of the protoplanet with respect to the medium, M_p is the protoplanet mass and

$$s = r\left(\frac{M}{2M_{\odot}}\right)^{1/3} \qquad (18)$$

is the radius of the sphere of influence of the planet at a distance r from the Sun. There are other contributions to medium resistance involving the accretion of material but Dormand & Woolfson (1977) found that these could be neglected since rounding time was shortened by only a small amount.

In their computational work Dormand & Woolfson (1974, 1977) assumed that the medium was rotating at Keplerian speed. At perihelion, the protoplanet was moving faster than the medium and was slowed down. The effect of this was to reduce the eccentricity and also reduce the aphelion distance. Conversely, at aphelion the protoplanet was moving more slowly than the medium and speeded up. This increased the perihelion distance and, again, reduced the eccentricity. The final effect was to round off the orbit to circular form with a final radius somewhere between the original perihelion and aphelion – usually close to the original semi-latus rectum. With the characteristics of initial orbits from the original CT models this gave a range of final orbital radii matching those in the present solar system. Our present model is giving initial orbits with semi-major axes typically 2-3 000 AU and eccentricities 0.9 or less, so the same kind of rounding would give final circular orbits with radii some hundreds of AU. Such values are consistent neither with orbits in the solar system nor those for observed extra-solar planets.

In reconsidering the rounding-off process we have taken account of several factors:

The distribution of the medium

In the Dormand & Woolfson (1974, 1977) work the medium was taken with spherical symmetry around the Sun and with either an exponential fall-off in density or with a Gaussian distribution with a peak at 10^{12} m. The results in terms of the final outcome and the times for round-off were very similar for both distributions. We have taken a different model in two respects. The first is that the distribution is more disk-like although the disk thickness increases with distance from the star. For a constant-temperature disk with much less mass than the star the density profile perpendicular to the disk will be

$$\rho(z) = \rho(0)\exp\left(-\frac{z^2}{h^2}\right) \tag{19}$$

where $h = \pi c/2\Omega$, c is the speed of sound in the gas and Ω is the local Keplerian angular velocity. In view of the overall approximations in our analysis we have taken the disk to have a thickness h and a uniform density along z. For the areal density of the disk we have taken

$$\rho(r) = \rho(0)r^2 \exp(-\alpha r) \quad , \tag{20}$$

which has something of the quality of both the distributions used by Dormand & Woolfson (*loc. cit.*).

Solar-wind effects

The stars with which we are dealing are very young stars and are much more active than mature main-sequence stars. Observation and modelling suggest that the total duration of the star-forming process in a cluster is somewhat less than 10^7 years, which may be compared with the time for the Kelvin-Helmholtz contraction of a solar-mass star on to the main sequence, about 5×10^7 years. T-Tauri stars, that generate high solar winds, are in this pre-main sequence stage and mass losses as high as 10^{-7} $M_\odot$ year^{-1} maintained for 10^6 years have been inferred. It has been pointed out by those working on solar nebula ideas that such a strong solar wind would completely sweep away the residual nebula after planets had formed. It is easily shown that such winds acting on small grains within the nebula gas and coupled to it would easily overcome the gravitational attraction of the central star.

Such strong solar winds are probably the exception rather than the rule and loss rates of 10^{-8} to 10^{-9} $M_\odot$ per year are more typical. Even these loss rates can have an appreciable effect on a resisting medium. If the solar wind material, with rate of mass loss m, has a mean speed v then the momentum flux at distance r from the star is

$$Q = \frac{mv}{4\pi r^2} \quad . \tag{21}$$

The total force on an absorbing spherical grain of radius a will then be

$$f_a = \frac{mva^2}{4r^2} \quad . \tag{22}$$

The corresponding gravitational force on the particle, of density ρ, will be

$$f_g = \frac{4\pi G M_\odot \rho a^3}{3r^2} \tag{23}$$

and the ratio

$$\frac{f_a}{f_g} = \frac{3mv}{16\pi G M_\odot \rho a} \quad . \tag{24}$$

Inserting $m = 6.34 \times 10^{13}$ kg s^{-1} (10^{-9} $M_\odot$ year^{-1}), $v = 500$ km s^{-1}, $\rho = 3 \times 10^3$ kg m^{-3} and $a = 1$ μm gives $f_a / f_g = 4.7$. If 1% of the medium was dust tightly coupled to the gas then the solar wind would reduce the effective gravitational field by 0.047 of its value – which is not a great deal. However, given that the rate of mass loss could easily be an order of magnitude greater and that absorption and reddening of starlight by the interstellar medium indicates that sub-micron dust particles are present, then substantial effective reduction of the gravitational field is possible. In our work we have just expressed this effect as a quantity S ($0 < S \leqslant 1$) which is the factor by which the Keplerian speed is modified. Although the medium is not rotating with Keplerian speed we have still used the Keplerian speed in the expression for h in (19).

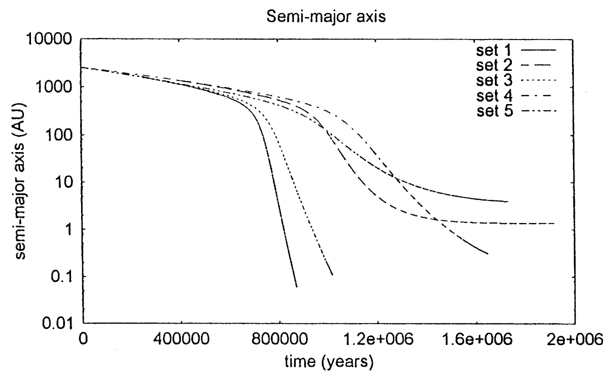
Time-dependent effects

The lifetime of diffuse material around stars is limited and affected by various factors. Radiation and a strong solar wind could drive material outwards but there is also evaporation at the boundaries of the cloud. Observations of disks around young stars suggest a lifetime of a few million years and this timescale is probably appropriate here. Thus we have put into our modelling an exponential decline in both the density of the disk and also in the solar wind, the latter expressed as a exponential decline with time of the quantity $1 - S$. The characteristic times of decline of the density and solar-wind effect (i.e. the time to decline to 1/e times the initial value) are not necessarily the same since they relate to different physical phenomena.

Figure 11 shows the evolution of (a) semi-major axis and (b) eccentricity for a number of different resisting medium characteristics. In each case the protoplanet had a mass 5 M_J and the initial orbit had a = 2 500 AU and e = 0.9. The medium had an areal density given by (20) with α = 200 AU^{-1} and the initial value of S was always taken as 0.5. The values of the other parameters that made the runs different are given in Table 2.

Set	**Mass of medium (M_J)**	**Characteristic time for solar wind (years)**	**Characteristic time for medium (years)**
1	45	1×10^6	1×10^6
2	40	1×10^6	1×10^6
3	50	2×10^6	1×10^6
4	40	2×10^6	1×10^6
5	50	2×10^6	7.75×10^5

Table 2 Parameters for the orbital-decay calculations



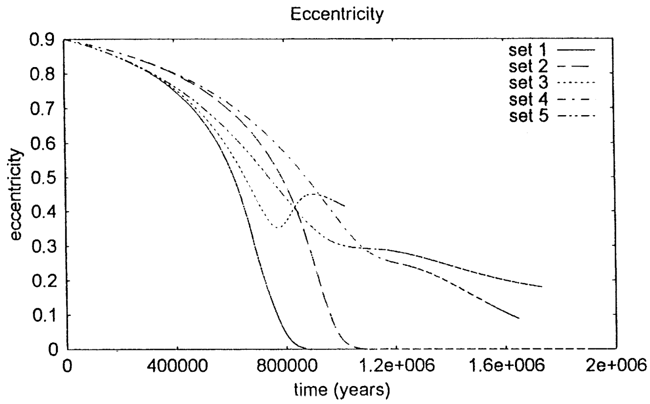


Figure 11 The changes of (a) semi-major axis and (b) eccentricity for various resisting medium and solar wind conditions for a protostar of mass 5 M_J and with an initial orbit with (a, e) = (2500 AU, 0.9).

These results are typical of many that have been done that include variations of all the other parameters not varied here. We notice a number of features in the Figure 11 results that may be compared with observations.

Set 1

This set goes to a very small semi-major axis (0.089 AU) and eccentricity (4.7×10^{-6}). With further computational time a would have become even smaller. This is similar to the first three entries in Table 1.

Set 2

The final semi-major axis (1.37 AU) and eccentricity ($\sim 10^{-6}$) corresponds to something like a planet in the terrestrial region of the solar system. The closest example in Table 1 is the protoplanet around Lalande 21185, a star with a second planet in a circular orbit even further out.

Set 3

This gave a fairly small semi-major axis (0.11 AU) but a large eccentricity (0.41). The closest correspondences in Table 1 are Gliese and HD16844.

Set 4

The combination (a, e) = (0.30 AU, 0.088) is most closely represented by HD19501 in Table 1.

Set 5

The combination (a, e) = (4.0 AU, 0.18) is most closely represented by 14 Herculis in Table 1.

With so many adjustable parameters it is possible to mimic almost any observed combination of semi-major axis and eccentricity. What is important here is that it has been shown that initial orbits of high eccentricity and large semi-major axes of several thousand AU may evolve to what is seen today on a timescale of one or two million years, corresponding well with the expected lifetime of a surrounding disk. This decay mechanism could be applied to any other theory producing planets on initial orbits similar to those suggested by the latest CT models.

7 RELEVANCE TO THE SOLAR SYSTEM

No extra-solar planetary systems observed thus far resembles the solar system. The upsilon Andromadae system has three planets with (a, e) = (0.53 AU, 0.04), (0.74 AU, 0.23), (2.2 AU, 0.36) and with minimum masses 0.72, 1.98, 4.12 M_J respectively. It is unreasonable to have expected to have found a system resembling the solar system, even assuming that such systems exist, since planets of terrestrial mass are impossible to detect at present and massive planets in close orbits are most easily detected.

Some aspects of the solar system can be explained just in terms of the basic CT process. Dormand & Woolfson (1989) pointed out that solid grains within the captured medium, drawn towards the Sun by the Poynting Robertson effect, will gradually pull the spin angular momentum vector of the Sun towards the normal of the interaction plane. It only requires ¼ M_J of absorbed material to contribute the same magnitude of angular momentum as the Sun now possesses and something of this order of mass of solids could be provided by 25 M_J of medium. The solar spin axis is at 7^o to the normal to the mean plane of the system: it is a natural outcome of the CT model that there should be a small, but non-zero, angle of tilt.

During the development of the CT over many years it has been shown that virtually all the major features of the solar system can be explained in terms of an initial system of six major protoplanets in elliptical orbits within a resisting medium. Non-central forces due to the extended medium cause differential precession of the slightly inclined planetary orbits so that occasionally they intersect. This leads to a high probability of strong interactions between protoplanets and the outcomes of close tidal interactions and of an actual planetary collision have been widely investigated. A causally-related sequence of events gives explanations of the terrestrial planets (Dormand & Woolfson, 1989; Connell & Woolfson, 1983; Woolfson, 2000), the regular satellite systems of Jupiter, Saturn and Uranus (Williams & Woolfson, 1983), the Moon and its features (Dormand & Woolfson, 1989; Stock & Woolfson, 1983), asteroids and comets (Woolfson, 2000), the tilts of planetary spin axes (Woolfson, 2000), isotopic anomalies in meteorites (Holden & Woolfson, 1995) and the Neptune-Triton-Pluto relationship (Woolfson, 1999). The present modelling does bring out one new feature that impinges on previous work. For the formation of regular satellites Williams & Woolfson (*loc. cit.*) considered interactions between the Sun and quite diffuse, originally spherical, protoplanets. With the original parameters the initial orbits had a much shorter period such that the protoplanets had not appreciably collapsed at their first perihelion passage. On the other hand, the present modelling suggests that the protoplanets themselves might be quite compact at perihelion passage and would never approach the Roche limit corresponding to their mean density. However, the modelling leading to Figure 4, which has been taken further in terms of protoplanet development than any of the others, shows that the compact core is surrounded by an extensive disk and this could certainly be affected at or near periastron. On a larger scale Whitworth *et al.* (1998) have made simulations of interactions between a star and a disk around a second star in which bound planets are formed. It seems possible that a similar, but smaller-scale version of such interactions would lead to regular satellites in the present case. Another possibility is that satellites could form directly by the accretion of solid material within the disk.

There remains the question of how the initial system of six protoplanets is formed - from which everything else follows. So far in our simulations we have produced up to five captured bodies, all of initial mass greater than a Jupiter mass although not all that mass may end up in the final condensed planet. There seems to be no reason in principle why six captured bodies should not be an outcome, particularly with a star-protostar orbit of lower eccentricity than any we have considered here. It is also worth remarking that, although we now know that many stars have planetary companions, at present we have no reason to believe that systems with many planets and with satellites accompanying most of the planets are common.

If it can lead to an initial system of six protoplanets then *the CT mechanism, and what precedes and follows it, will provide a complete picture of solar system formation and evolution from the interstellar medium through to the solar system in much its present state.*

8 CONCLUSIONS

The CT has been steadily developed for more than thirty-five years but has been largely overlooked in favour of the current paradigm, the Solar Nebula Theory (SNT). Since about 1970 work in the field of cosmogony has been mostly concentrated on the SNT and it is the standard model in terms of which astronomers interpret their observations. It is also the one presented by science journalists to other scientists and to the general public.

Another theory of more recent origin that bears close scrutiny is that described by Whitworth *et al.* (*loc. cit.*), referred to previously in relation to satellite formation. These workers consider the early environment of a cluster where forming stars have associated protostellar disks. These disks can be up to 1 000 AU in radius and may contain an appreciable fraction of the mass of the forming star. SPH calculations have been carried out for different scenarios. One is where the two protostars both have disks very close to the orbital plane. The disks collide to form a shocked filament that is gravitationally unstable and within which planetary-mass objects condense. Some of these objects remain bound to their parent protostars. When the disks and orbit are not closely parallel then a star-disk interaction is more appropriate and tidal effects acting on the disk produce a filament within which the planets form.

In the simulation for this case it is not the tidal filament between the star and disk that produces planets but rather a tidal filament from the disk that forms in a direction pointing away from the star. There is a family resemblance between the star-disk interaction and the CT model in that tidal interaction between two stars is producing a filament, although the detailed behaviour is quite different. However, in the CT there is nothing equivalent to the direct collision of disks. An argument in favour of interactions involving disks is that they are rotationally supported and hence long-lived – with lifetimes of several million years according to observation. Consequently this increases the likelihood of interactions and would thus lead to planetary companions being as common as observations suggest.

As new observations are made, so these offer new constraints against which to test theories. In the last few years there have been many new observations made that are relevant to planetary formation. It may therefore now be timely to review such theories to see how well they are able to accommodate the new knowledge.

There are two basic and longstanding problems that SNT theorists have been working on over many years. The first of these is that of angular momentum transfer within an evolving nebula between the core and the surrounding disk in order that the Sun, with 99.86% of the mass of the system should end up with only 0.5% of the angular momentum. At present there is no straightforward solution to this problem. The other is that of the time required for forming planets. The original Safronov (1972) theory gave the time for formation of Jupiter as 250 million years and for Neptune several times 10^9 years or even greater. The generally accepted time limit, imposed by observations of disks around young stars is 10^7 years. A 'runaway growth' model put forward by Stewart & Wetherill (1988) improves matters but not sufficiently for the outer major planets. In a BBC series, *The Planets*, one SNT theorist stated that "…according to our theories Uranus and Neptune do not exist".

Although planetesimal accretion has been the main problem in planet formation for the SNT, an earlier stage in planet formation within a nebula is the formation of a dust disk in the mean plane. It has been argued that micron–sized particles would take too long to settle and the perfectly reasonable solution has been suggested of cold welding whereby the particles would stick together forming larger bodies that would settle more quickly (Weidenschilling *et al.*, 1989). The recent CODAG (Cosmic Dust Aggregation Experiment) experiment on the space shuttle has shown that micron-sized dust particles tend to stick together in a linear fashion rather than in a more-compact form so that the whole process of particle accumulation needs to be reconsidered (Blum *et al,* 2000). Whether or not this leads to any additional major difficulty for planet formation in a nebula is uncertain at present.

The early work on planet formation by the SNT required that there should be little turbulence in the nebula so that planetesimals could approach each other with a small hyperbolic excess and so combine. This led to the idea of planets forming on more-or-less circular orbits close to their final positions. Observations of extra-solar planets very close to their parent stars disturbed this picture since it is not possible for a protoplanet to *form* so close to a star although it is perfectly possible for a mature condensed planet to *exist* in such proximity. These observations, coupled with the Uranus-Neptune time-of-formation problem has led recently to the idea of planet migration so that planets may form within a reasonable time at a comfortable distance from a star and then migrate inwards, to explain close planets, or outwards, to explain the outer solar-system planets. In view of the results given in §7 there should be no difficulty with inwards migration but to explain outward migration is more challenging. The ways considered of moving a body outward involve coupling it to another body so that it gains energy at the expense of the other body, which moves inwards. One direct way that this can happen is to have a close gravitational encounter between the two bodies. A less-direct way involves the generation of spiral waves in the nebula by Jupiter that causes it to move inwards while the energy in the spiral wave is transmitted to the outer planet causing it to move outwards. Another indirect process is through the scattering of planetesimals by Jupiter; the energy that they gain from Jupiter being transmitted to Uranus and Neptune when they later interact with these bodies (Malhotra, 1999).

Placement problems do not occur in either the CT or Whitworth models. These latter are both dualistic theories, with stars produced in a different process from that producing the planets. Again, they both produce planets through the gravitational instability of a filament, with no difficulties with formation times, and inward migration by orbital decay to explain close-in planets is a perfectly straightforward process.

Another recent observation, that of free-floating planets in the Orion nebula (Lucas & Roche, 2000), has also been cited as a possible problem for the SNT since they have been interpreted as planets formed in space isolated from any star. This is not really a separate problem for the SNT. It can be linked to the problem of migration of the outer major planets of the solar system if the solution to the migration process also allows complete escape of the migrating body. Both the CT and Whitworth models can give bodies of planetary mass that escape from the star and so become free-floating planets.

The impression is growing that the SNT is rarely able to explain new observations in a natural way that fits in with previous expectations. This is even true for older observations; an obvious outcome for the SNT is that the solar spin axis should be normal to the mean plane of the system but the 7^{o} tilt is too large just to ignore. The idea that after the planets formed their plane was modified by the gravitational effects of a passing star (Tremaine, 1991) cannot be ruled out – although it too has difficulties. It is the constant need to find band-aid solutions as each new observation comes along that erodes the credibility of the SNT.

Both the CT and the Whitworth mechanisms have been modelled by SPH in a very convincing way to the extent that it might be said that if the conditions they postulate are met then some planets ought almost certainly to come about in the way they propose. In both these scenarios the existence of an embedded stage of a cluster makes the interactions likely to occur. There is no law of nature that rules out the possibility that two separate mechanisms operate within the same general environment – one when the protostar is a very young and nebulous object and the other when it is more compact with an accompanying disk. Certainly it is better to have two plausible theories than none.

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