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FREE-FLOATING PLANETS: THEIR ORIGIN AND DISTRIBUTION.

Author: Martyn J. Fogg.

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Supervisor: Richard P. Nelson.

ABSTRACT.

Evidence for the existence of planetary mass objects, unattached to any star and free-floating in interstellar space, has recently emerged. In this paper, this evidence and the history of the concept of free-floating planets is reviewed and a classification is proposed, based on mode of origin. It is suggested that free-floating planets can originate in two settings: 1) interstellar space, where the object forms in the manner of a star; 2) circumstellar space, where the object forms in the manner of a conventional planet and is subsequently lost to interstellar space. We designate the former type of object a *planetar* and the latter an *unbound planet*. Three possible scenarios of planetar formation and four scenarios of unbound planet origin are explored and discussed. Estimates of the abundance of these objects suggest that planetars in the mass range of 1 – 13 $M_{♃}$ may be about as common as stars and brown dwarfs. The number of unbound planets however may exceed the number of stars by two orders of magnitude, although most of them should be low-mass rock/ice planetary embryos ejected from planetary systems in formation. It seems likely therefore that advances in observational techniques, such as infrared astronomy and microlensing, will lead to the discovery of many more free-floating planets in the future, securing their recognition as genuine astrophysical objects.

PRAETERIA CUM MATERIES EST MULTA PARATA,
CUM LOCUS EST PRAESTO NEC RES NEC CAUSA MORATUR
ULLA, GERI DEBENT NIMIRUM ET CONFIERI RES.

LUCRETIUS, DE RERUM NATURA, **2**, 1067 (C. 60 B.C.)

"*Consider the true picture. Think of myriads of tiny bubbles, very sparsely scattered, rising through a vast black sea. We rule some of the bubbles. Of the waters we know nothing…*"

Larry Niven & Jerry Pournelle, *The Mote in God's Eye*, 1975.

TABLE OF CONTENTS.

1. INTRODUCTION.

When considering the range of astronomical objects from stars to planets, it used to be thought likely that a gap existed within the mass spectrum between low-mass stars ($\gtrsim 0.1\ M_{\odot}$) and high-mass planets ($\lesssim 10^{-3} M_{\odot} \approx 1\ M_{♃}$). One of two explanations seemed likely: the “gap” was either false and merely a reflection of inadequate observing power, or it was real and hence concrete evidence of stars and planets being distinct objects.

From the theoretical point of view, there seemed good reason to believe the gap was real. Although studies of the theoretical minimum stellar mass that could condense from a molecular cloud indicated it to be $\sim 0.01\ M_{\odot}$, this required special initial conditions. Adding detail to the analysis, such as the effects of rotation and magnetic fields, just seemed to augment the minimum mass to $\gtrsim 0.1\ M_{\odot}$ (Silk, 1977). Similarly, studies of gas giant accretion suggested that a growing planet would open up a gap within the disc from which it was forming once it attained roughly $1\ M_{♃}$ (Lin & Papaloizou, 1980). The mass of Jupiter was therefore explained as having reached an upper threshold beyond which significant further growth was self-limited.

However, since 1995 there have been detections of over 50 possible planetary companions about solar-type stars (Marcy *et al.,* 2000) with minimum masses ranging from $\sim 0.25 - 15\ M_{♃}$. A decade’s worth of theoretical speculation (e.g. Kafatos *et al.*, 1985) concerning brown dwarf stars (objects below the hydrogen-burning mass limit of $\sim 0.08\ M_{\odot}$, but still capable of fusing deuterium) has also been rewarded by ample discoveries, both in the field and in young star clusters where they are easier to detect (Basri, 2000). Free-floating objects of planetary mass (below the deuterium-burning limit of $\lesssim 0.012\ M_{\odot} \approx 13\ M_{♃}$) have also been spotted in these same star forming regions (Lucas & Roche, 2000; Zapatero Osorio *et al.*, 2000) with estimated masses as low as $\sim 5\ M_{♃}$.

Thus the “mass gap” has now disappeared and has been replaced by a continuum of objects all the way from massive stars down to planetesimals. However, the discovery of free-floating planets raises the question of their origin. Do they form like a star, directly from the collapse of a molecular cloud fragment? Or do they form like a planet, in a disc surrounding a star, from which they are subsequently ejected to interstellar space? Might both processes operate?

This paper aims to examine the question of the existence of interstellar planets over its widest possible range. If we define a body of planetary mass to be one incapable of nuclear fusion and where gravitational forces dominate over elastic forces, then the mass range is ~ $10^{-2} – 10^{-11}$ $M_{\odot}$. The young and luminous free-floating planets so far discovered lie close to the top of this range. But is it possible that planets, large and small, could be invisibly littered through interstellar space? By marrying theory with imagination, how many different formation processes can we envisage? And lastly, is it possible to make a reasonable estimate of their abundance and form?

2. HISTORY.

2.1 *Early Conjectures*.

Some astronomers have long suspected that interstellar space is host to a much more diverse population of compact baryonic objects than the luminous stars and stellar remnants we can see. Until recently however, such speculations only surfaced in the literature about once or twice every decade. Shapley (1958, 1962) raised the issue of “stray planets”, including their possibilities for favourable life conditions, whilst Öpik (1964) confidently wrote: “*There must be numbers of runaway planets in interstellar space, joining a host of independent dark little suns and planets which were never bound to any star. If planets can have originated in the vicinity of a sun, there is no valid reason why these small bodies could not have originated also independently, without being gravitationally attached to a large body*.” In this statement, Öpik clearly hints that free-floating planets might originate either around a star or in solitary fashion, implying that a number of formation processes might operate.

Lawton (1974) was inspired by Russian observations of the star forming region of W49 (Strelnitsky & Sunjaev, 1972) to propose that “stray planets” might result from the expulsion of uncondensed protoplanets from the vicinity of young blue supergiant stars by the action of a stellar wind or radiation pressure and estimated a number density ratio of such objects as high as ten times that of stars (n_{FFP} / n ≈ 10). This model however turns out to be unrealistic once its overoptimistic assumptions have been accounted for. Fogg (1988) modelled the loss of "unbound planets" from mature planetary systems, as a function of radial distance from the galactic centre, either via supernova explosion of the primary or through rare close encounters with passing stars. He concluded that whilst such objects undoubtedly exist, they are expected to be uncommon within the solar neighbourhood ($n_{FFP} / n \approx 6\times10^{-3}$).

The first general assessment of the possible existence and variety of interstellar planets was published by Fogg (1990) and a more recent review has been given by Taylor (2001). Fogg's discussion divided these objects into two types: "Singular Planets" that are formed in solitary fashion and "Unbound Planets" that are formed within and subsequently ejected from a planetary system. This latter category was subdivided into "Late-Type" and "Early-Type" unbound planets depending on whether ejection takes place from a mature solar system, or one still in formation. Six modes of origin emerged along with abundance estimates, namely:

(1) Singular Planets.
    (a) Formation of sub-brown dwarf bodies in star forming regions, assuming a Salpeter stellar mass function extending below 0.01 $M_\odot$ ($n_{FFP} / n \approx 100$).
    (b) Formation of giant comets up to lunar size within molecular clouds ($n_{FFP} / n < 10^9$).
(2) Unbound Planets (Late Type).
    (a) Ejection from a star system after supernova of the central star ($n_{FFP} / n \approx 10^{-2}$).
    (b) Gravitational scattering and ejection from a planetary system following a close encounter with a foreign star ($n_{FFP} / n \approx 10^{-4} – 0.1$).
(3) Unbound Planets (Early Type).
    (a) Gravitational scattering and ejection of massive planetesimals during the terminal stages of planetary accumulation ($n_{FFP} / n \approx 1 – 100$).
    (b) Ejection of giant gaseous protoplanets from the vicinity of O,B class stars by stellar wind or radiation pressure ($n_{FFP} / n \approx 10^{-2}$).

Fogg (1990) did not regard all of these options as being equally likely. The existence of singular planets seemed at the time to require unconventional cosmogonic hypotheses, especially category 1b, and category 3b is unworkable. This led Fogg to conclude, "*The existence of singular planets is problematic, their existence requiring that the most favoured models for star and comet formation to be incorrect. However, it would appear that unbound planets will be created automatically by the processes of circumstellar planetary accumulation, stellar evolution and close encounters.*"

Theoretical advances and modern evidence have partially challenged this view. Not only have new formation possibilities emerged, but evidence for free-floating planetary mass objects is now at hand and their nature appears to fit best into Fogg's category of a high-mass singular planet (1a), the class about which he expressed the most reservation. The above formation-based classification of interstellar planets is therefore obsolete and an alternative proposed in this paper.

2.2 *Modern Discoveries*.

Star formation regions are a good place to search for sub-stellar objects since, when young, they are freshly radiating their heat of formation and can be 1000 times more luminous at an age of a few million years than they would be at a billion years. The younger such an object is, the brighter it will be and the lower will be the mass threshold at which it can be detected. If the distance to the star formation region and its age can be estimated, and a reliable apparent magnitude of a source measured, then its absolute magnitude and hence its luminosity can be determined. Comparing these data with theoretical evolutionary models for sub-stellar objects (e.g. Burrows *et al*., 1997) permits the mass to be estimated.

Early in 2000, Lucas and Roche (2000) reported the results of their deep infrared imaging survey of the Trapezium in Orion, a star cluster $\lesssim 3\times10^6$ years old, ~ 470 pc distant. A rich population of possible sub-stellar objects were detected: 32% of the 515 point sources being brown dwarf candidates and 13 of these appearing to have masses at or below the deuterium-burning threshold of $\lesssim 0.012\ M_\odot$. Assuming an age of 1 Myr, the faintest of these objects, Orion 023-115, has an estimated mass of ~ 8 $\mathrm{M}_{♃}$. These objects are not bound to any star, are freely floating through the outer regions of the cluster, and are likely to have formed through cloud core fragmentation like stars and brown dwarfs. Lucas and Roche (2000) also stated that there is some evidence of a cut off in the abundance of these objects below several Jupiter masses and they speculated that this either represents a genuine lower limit to the stellar initial mass function or is the result of the pre-emption of lower mass condensations (which take longer to form) through the dispersal of molecular gas by the luminous O,B stars at the cluster's heart.

Soon after these initial discoveries Zapotero Osorio *et al*. (2000) presented their results of an optical and near-infrared imaging survey of a red and faint population of objects in the σ Orionis star cluster (1 – 5 Myr old, ~ 352 pc distant). Again, numerous sources were detected including 18 possible isolated planetary mass objects: the least massive cluster member so far identified being S Ori 60, with a mass estimated to between 5 – 10 $\mathrm{M}_{♃}$. In contrast to the Trapezium case, there appears to be no evidence of a downturn in the cluster mass function near the detection limit, implying that isolated planetary mass objects can form commonly and could form a significant invisible population within the galactic disc as a whole. Whilst their data seems quite robust, the authors noted that, "*Whether objects with just a few* $M_{♃}$ *or less can form in isolation from stars remains an open issue. Theoretical models describing the fragmentation of collapsing clouds are uncertain regarding the lower mass limit for this process. However, recent observations … suggest that isolated planetary mass objects could also form.*"

Discoveries of free floating planets continue to be made at an accelerating rate. In 2001, a press release by Subaru Telescope (2001) announced preliminary results of deep infrared observations of the nebulous star forming region S106. At a distance of ~ 610 pc, S106 is centred on a massive ~ 20 $\mathrm{M}_{\odot}$ star, IRS4, that is only ~ 10^5 years old. Hundreds of faint young objects were spotted throughout the surrounding nebula which the astronomer team identified as both brown dwarfs and isolated planetary mass objects. Estimates of the mass if these objects is not yet available, but if they are not much older than IRS4 it is possible that free floating planets of even lower mass than those of Lucas and Roche (2000) and Zapotero Osorio *et al.* (2000) have been detected.

Further studies of the Trapezium and σ Orionis sources (Lucas *et al.*, 2001; Martín *et al.*, 2001; Barrado *et al.*, 2001) have added to the weight of argument supporting the isolated planetary-mass object interpretation. Cluster membership of many of the sources has been confirmed and their spectra indicate relatively cool (~ 2000 K) dusty atmospheres. However, not all such discoveries have survived a second look. In mid 2001, Sahu *et al.*, (2001a) announced the results of a microlensing survey of the globular cluster M22 against the rich stellar backdrop of the galactic bulge. A classical microlensing event was observed, attributed to a ~ 0.13 $M_{\odot}$ star in the cluster and six others so brief as to be unresolved in time. These events, if real, indicated a lens mass weighing in at only ~ 0.25 $M_{♃}$. The implication seemed to be that the outskirts of M22 were rich with interstellar planets of roughly the mass of Saturn, with ~ 100 of these objects present per visible star! A discovery as extraordinary as this, especially in a metal-poor cluster such as M22, really did seem to signify the need for radical revision of cosmogonic theory. However, the M22 free-floating planets were not to last: by the end of 2001, further analysis of the six short term brightenings concluded that they were due to coincident cosmic ray hits on the HST's detector and hence were not genuine (Sahu *et al.*, 2002).

The probable discovery of free floating planets has lead to a growing interest in their classification, origin and significance. All three of these items are discussed in the following Sections.

3. DEFINITIONS AND NOMENCLATURE.

A number of different terms have been applied to the objects under discussion and have been used interchangeably above; but not all necessarily apply to or reflect their potential diversity. Thus, for the sake of precision in the following theoretical sections, a classification and nomenclature is defined here.

Terms often used in the literature include: “free-floating planets”, “isolated planetary mass objects”, “unbound planets” and, less commonly, “interstellar planets”, “stray planets”, “runaway planets”, “sub-brown dwarf stars”, “grey dwarfs”, “planetars” and “singular planets”. Some of these seem general, whilst others allude to a mode of formation; some contain the word “planet”, whilst others avoid it. As well as perhaps being the most popular, “free-floating planets” would seem one of the most general terms, being free of an implied formation mechanism. But are all these objects planets – or merely of “planetary mass” and should we worry about the distinction?

There is actually no official definition of a planet. The requirement for this seemed less obvious before the ambiguities raised by the discovery of exoplanets, free-floating planets and Kuiper Belt mini-worlds such as 28978 Ixion. Here, we adopt the conclusion of Stern and Levison (2002). Their definition of a planetary body is one that at no time can sustain a fusion reaction and that lies between more massive bodies such as stars and stellar remnants and less massive ones such as planetesimals, asteroids and comets. Thus the pre-requisite of a planetary body is a mass below the deuterium fusion limit, $\lesssim 0.012\ M_\odot$ and, for its shape to be dominated by gravity (Cole, 1984), the mass must be above $\gtrsim 10^{-11}\ M_\odot$. Stern and Levison (2002) rejected mode of origin as a pre-requisite as this can sometimes be poorly determinable. Here, we shall be calling all the objects in question “planets” but speculating over various formation possibilities divided into two main categories: 1) isolated formation within a collapsing molecular cloud and 2) formation within and subsequent ejection from a circumstellar planetary system.

The full classification is illustrated in Figure 1. “Free floating planets” is chosen as a general term for all isolated objects of planetary mass. “Unbound planets” is a good, self-explanatory, term for those free-floaters ejected and hence unbound from a primary star. “Planetars” is the word used for those free-floaters than are born in the manner of a star. This pleasingly concise and descriptive term has only recently been invented[1], being a collapse of the words “planet” and “star”, quite like its predecessor constructs “pulsar” and “quasar” that were also coined to describe a new category of celestial object.

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[1] “Planetar” was apparently coined independently in the USA by Paul D. Rust III and in the UK by Paul Lucas.

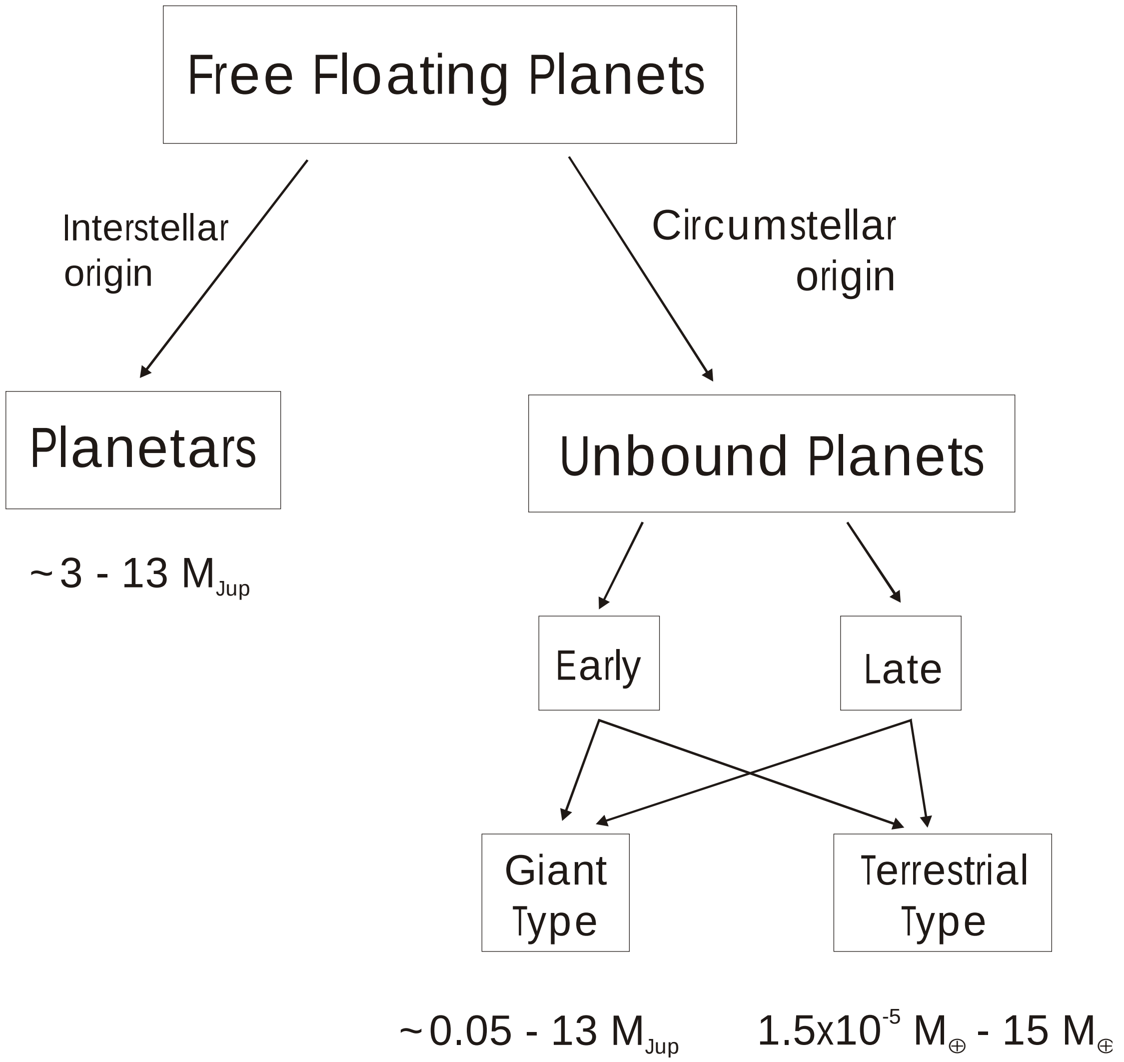

Figure 1: Classification of free-floating planets adopted for this paper.

4. THEORETICAL MODES OF ORIGIN.

Seven modes of origin are considered in this section, their categorisation being shown in Figure 2.

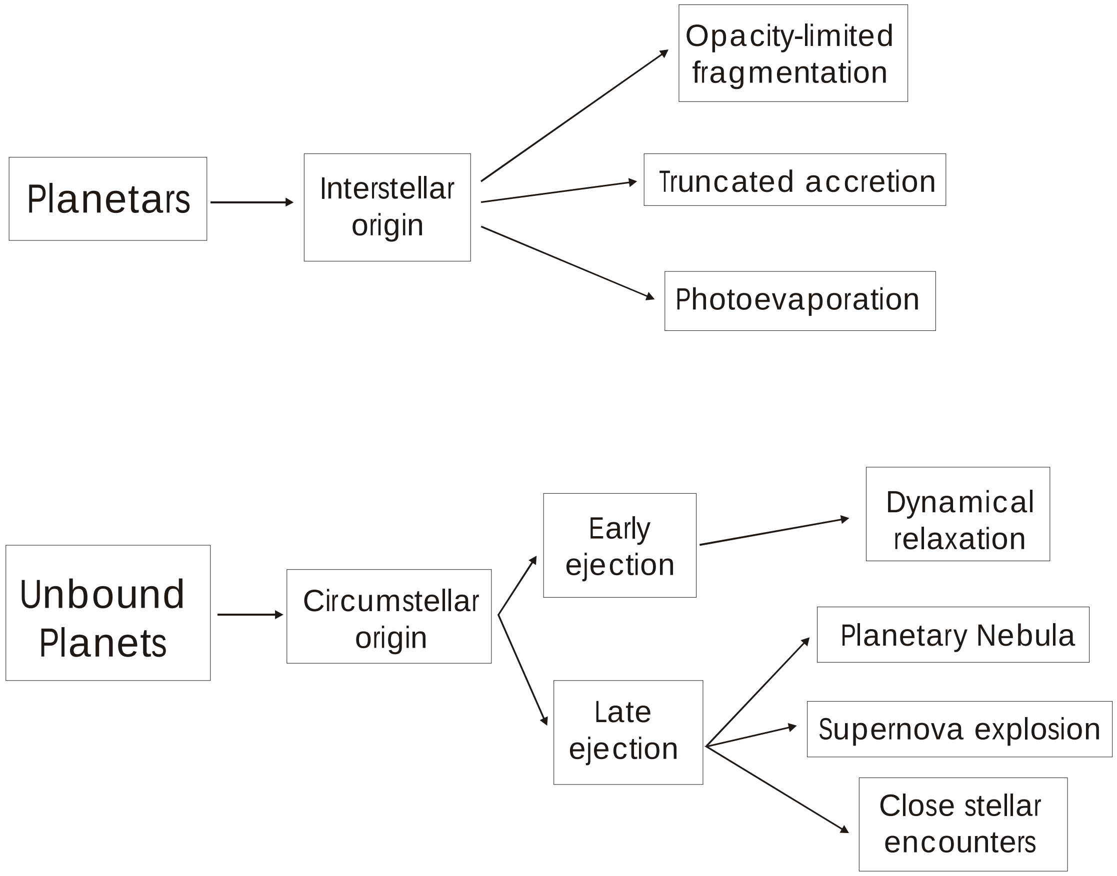

Figure 2: Modes of origin for both planetars and unbound planets to be discussed in this section.

4.1 *Planetars*.

4.1.1 *Opacity Limited Fragmentation*.

Firstly we consider planetars as an extension of the stellar Initial Mass Function (IMF) beyond stars and brown dwarfs to lower masses. If it is reasonable to argue for a minimum stellar mass of $\lesssim 0.01$ $M_{\odot}$, then planetars might be regarded as “sub-brown dwarfs” just as brown dwarfs are seen as “sub-stars”.

In forming a population of proto-stars from a collapsing interstellar gas cloud, an important process is thought to be the fragmentation of the cloud into sub-masses which undergo independent collapse. These sub-masses may in turn fragment and several iterations of this process might result in the diverse stellar mass spectrum observed (Hoyle, 1953). Past attempts to determine the minimum stellar mass limit M_F have involved analytical or computer models of opacity-limited hierarchical fragmentation (Low & Lynden Bell, 1976; Rees, 1976; Silk, 1977; Boss, 1988). Here, we illustrate the physics with a simple derivation of M_F (which leaves out detailed radiation processes) and then compare our estimate with more sophisticated treatments.

Jeans' criterion for gravitational stability indicates that a spherical, homogenous, cloud is unstable to density perturbations if its size R exceeds the Jeans Radius:

$$R > R_J = \frac{1}{2}\left(\frac{\pi a^2}{G\rho}\right), \tag{1}$$

where a is the isothermal sound speed and ρ is the density.

The critical Jeans mass is that within a Jeans Radius:

$$M_J = \frac{4}{3}\pi R_J^3 \rho = \frac{\pi}{6}\left(\frac{\pi a^2}{G}\right)^{\frac{3}{2}} \rho^{-\frac{1}{2}} \quad . \tag{2}$$

Taking the isothermal sound speed as:

$$a = \sqrt{\frac{\Re T}{\mu}} \ , \tag{3}$$

where $\Re$ is the gas constant (k/m_H), T is temperature and μ is mean molecular weight, then the expression for the Jeans mass becomes:

$$M_J = \frac{\pi^{\frac{5}{2}}}{6}\left(\frac{\Re}{G}\right)^{\frac{3}{2}}\left(\frac{T}{\mu}\right)^{\frac{3}{2}}\rho^{-\frac{1}{2}} \approx 6.4\times10^4 M_{Sun}\left(\frac{T}{100K}\right)^{\frac{3}{2}}\left(\frac{\rho}{10^{-21}kgm^{-3}}\right)^{-\frac{1}{2}}\mu^{-\frac{3}{2}}. \quad (4)$$

Larger masses will tend to break up into masses of this size. The growth of instabilities is roughly the free fall time:

$$\tau_{ff} = \left(\frac{3\pi}{32G\rho}\right)^{\frac{1}{2}}, \quad (5)$$

which measures typically, at the beginning of the process, on the order of 10^6 years but falling as collapse and densification proceeds.

The efficiency with which the cloud can lose the potential energy released during contraction is crucial to the progress of fragmentation. The thermal adjustment time can be estimated by dividing the internal energy per unit mass by the rate of losses due to radiation:

$$\tau_{adj} \approx \frac{c_v T}{\Lambda}, \quad (6)$$

where for hydrogen, $c_v \approx 10^4$ J kg^{-1} K^{-1} and the energy loss rate for typical clouds is $\Lambda \approx 10^{-4}$ J kg^{-1} s^{-1}. The typical value for the thermal adjustment time is centuries and hence $\tau_{adj} \ll \tau_{ff}$. This implies that the collapse at first is very near isothermal.

If collapse is proceeding at constant temperature, we see that R_J, $M_J \propto \rho^{-1/2}$. This means that as density increases, the Jeans radius and mass shrink allowing for sub-condensations to appear in the original cloud. Further collapse might encourage further fragmentation and so on.

Eventually however a cloud can become opaque enough to trap its own radiation and start to warm up: τ_{adj} becomes comparable to τ_{ff} and continuing collapse will tend to be adiabatic. In this regime, pressure $P \propto \rho^{\Gamma}$ and the adiabatic sound speed $c^2 \propto \rho^{\Gamma-1}$.

If the adiabatic exponent $\Gamma = 5/3$, then $M_J \propto \rho^{1/2}$. The Jeans mass no longer falls as collapse proceeds and fragmentation halts. Thus the Jeans mass must have a minimum at the transition between isothermal and adiabatic regimes and it is this minimum mass fragment that may constrain the minimum stellar mass.

The rate *A* at which energy must be radiated away to maintain the same temperature is:

$$A \approx \frac{GM^2}{R\tau_{ff}} = \frac{\sqrt{8}}{\pi} G^{\frac{3}{2}} \left(\frac{M}{R} \right)^{\frac{5}{2}} . \tag{7}$$

However, the fragment cannot radiate more than a black body of the same temperature which would lose radiation at the rate:

$$B = 4\pi R^2 \sigma T^4 f \ , \tag{8}$$

where $0 < f < 1$ is a factor representing the fact that the fragment will radiate less efficiently than a black body. For isothermal collapse, $A \ll B$, whereas at the transition to adiabatic collapse $A \approx B$. Setting $A = B$, we find:

$$M^5 = 2\pi^4 \frac{\sigma^2 T^8 f^2 R^9}{G^3} \ . \tag{9}$$

Assuming fragmentation has reached its limit, then $M = M_J = M_F$ and:

$$R = \left(\frac{3}{4\pi} \right)^{\frac{1}{3}} \frac{M_J^{\frac{1}{3}}}{\rho^{\frac{1}{3}}} \ , \tag{10}$$

then:

$$M_J^2 = \frac{27\pi}{32} \frac{\sigma^2 f^2 T^8}{G^3} \rho^{-3} \ . \tag{11}$$

From the Jeans mass formula we get:

$$\rho^{-3} = M_J^6 \frac{6^6}{\pi^{15}} \left(\frac{G}{\Re} \right)^9 \left(\frac{\mu}{T} \right)^9 \ . \qquad (12)$$

So substituting for ρ^{-3} and evaluating all factors and constants gives the mass of the final fragment:

$$M_F = M_J = 0.01 \frac{T^{\frac{1}{4}}}{\mu^{\frac{9}{4}} f^{\frac{1}{2}}} M_{Sun} \ . \qquad (13)$$

Given $\mu = 2.46$ for typical molecular cloud material and T = 10 – 60 K, then if f = 0.1, $M_F = 0.007 – 0.01\ M_\odot$, and for f = 0.5, $M_F = 0.003 – 0.005\ M_\odot$. Minimum fragment masses within the planetar range are predicted.

Minimum Jeans masses arrived at in previous studies, which incorporate more detailed physics are listed in Table 1 below.

Table 1.

Study	Minimum Jeans Mass
Low & Lynden-Bell (1976)	~ 0.007 $M_\odot$
Rees (1976)	~ 0.004 – 0.01 $M_\odot$ *
Silk (1977)	~ 0.01 $M_\odot$
Boss (1988)	~ 0.01 $M_\odot$

* Calculated from a given formula, assuming T = 10 – 60 K, f = 0.1 – 0.5.

Their results are similar to each other as well as to the basic analysis presented above, all in the region of $\lesssim 0.01\ M_\odot$, just below the deuterium-burning threshold in the planetar range.

It should be emphasised however that these estimates result from the assumption that homogeneous, spherical, Jeans-style collapse is realistic and not too much of an oversimplification. Gas clouds actually seem to collapse into filaments and sheets and are characterised by non-uniform density, temperature and velocity fields – a very different and more turbulent environment for proto-stellar origin (Larson, 1985). Even if the Jeans collapse picture retains some relevance, when rotation and magnetic fields are included in the model, the minimum fragment mass may be increased, perhaps as high as $\gtrsim 0.1\ M_\odot$ (Silk, 1977). Moreover, after the minimum mass protostellar core is formed, it can grow by accretion of surrounding gas, or by coalescence with other fragments, processes which could substantially increase the final mass of the star.

Thus, whilst one can argue for the origin of planetars as solitary condensations with molecular clouds, the argument would seem to require either unusual initial conditions or requires validation through more inclusive and detailed modelling, taking into account not just the collapse and fragmentation of the pre-stellar cloud, but subsequent growth and interactions of the protostellar fragments.

4.1.2 *Truncated Accretion.*

The minimum mass fragmentation model only barely arrives at the masses we seek to explain and then from idealised, static, initial conditions and simplified physics. Fortunately, the increasing availability of powerful computers has permitted much more detailed modelling of star formation that takes into account more complex initial conditions and dynamical processes.

Three studies have recently been published that explain the origin of brown dwarfs and planetars not so much in terms of being ultra-low-mass stars but as being “failed stars” instead. Whilst details vary between the models, they have in common that formation is envisaged by fragmentation of dense molecular gas into an unstable multiple system of stellar embryos; one or more of these objects are then ejected from the ensemble via dynamical interactions and are therefore removed from the infalling envelope of gas from which they were growing. Thus, accretion is truncated and an ejected fragment fails to grow to a stellar mass (see Figure 3).

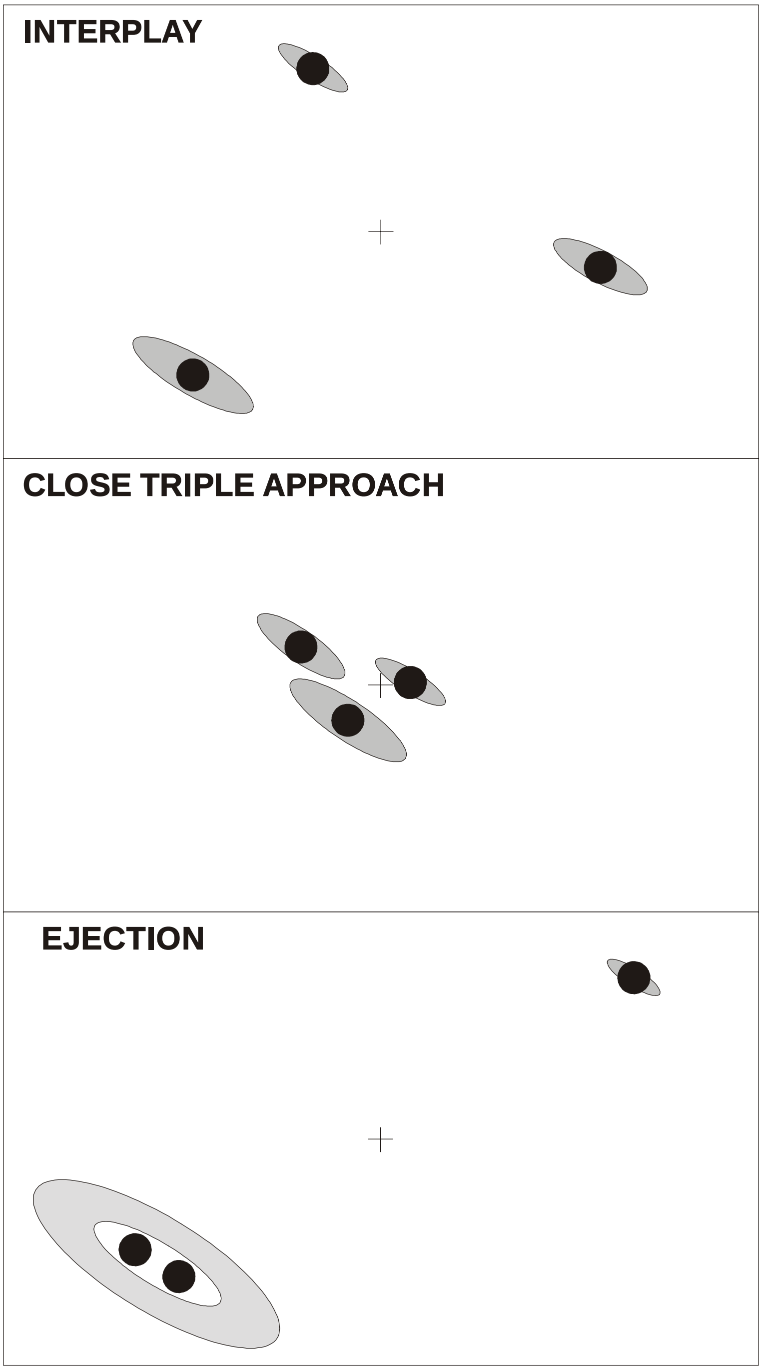

Figure 3: Three stages in the evolution of a non-hierarchical triple star system. The end result is the formation of a stable binary and the ejection of (typically) the least massive of the trio (after Reipurth, 2000).

Boss (2001) has run a computerised hydrodynamical model of gravitational collapse of a dense molecular cloud which includes approximate simulation of magnetic field effects. The most important new feature observed in the output, when compared to non-magnetic calculations, is a central rebound caused by the magnetic field which leads to an off-centre density maximum of ~ 10^{-7} kg m^{-3} and a decompressional cooling down to ~31 K. This brings about renewed fragmentation within a radius of ~ 3 AU, the cloud first breaking into two and then four clumps of ~ 0.3 – 0.5 $M_{♃}$ each. (Non-magnetic calculations without this decompressional cooling give a temperature of ~ 200 K at this stage which would result in a Jeans mass sixteen times greater.) A quadruple protostar system is therefore formed and, whilst Boss' simulation did not extend to determining its subsequent evolution, he did discuss possible fragment mergers and growth from accretion of infalling gas. However, due to the non-hierarchical nature of the quadruple system, the chances of its disintegration due to a three body encounter and the ejection of one or more fragments appears quite probable. Moreover, if one fragment is ejected before further significant growth, its accretion would be prematurely terminated and its mass could remain well below the stellar threshold.

Reipurth & Clarke (2001) published a more broad brush study that considered both mechanism and observational evidence. They summarised their scenario with the words, "*Brown Dwarfs are stellar embryos that have been ejected as part of close dynamical interactions between small unstable groups of nascent stellar seeds, i.e., brown dwarfs differ from hydrogen-burning stars only in that dynamical interactions deprive them from gaining further mass by prematurely cutting them off from their infalling gas reservoirs*."

They went on to illustrate their idea in a simple "toy model" format, noting that:

- A specific requirement of the model is that the timescale for ejection of a fragment should be significantly less than the time taken to accrete a stellar mass. The bulk of this mass would be accreted in the ~ 10^5 year free fall timescale of the core.
- The decay of non-hierarchical multiple systems is random, but within 100 crossing times, ~ 95% of systems will have decayed, resulting typically in ejection of the lightest member (Sterzik & Durisen, 1998).

The crossing time is the time taken by an object to travel from one side of a cluster to the other and Reipurth & Clarke used the approximate formula:

$$t_c \approx 0.17\left(\frac{R^3}{M}\right)^{\frac{1}{2}}, \qquad (14)$$

where R is the length scale of the system in AU and M is the total system mass in $M_\odot$.

These two time scales are roughly equal for a configuration of stellar embryos within a diameter of 200 AU. The “toy model” that Reipurth & Clarke (2001) chose to present was that of three equal mass embryos occupying a volume of a diameter 200 AU, their totalled masses rising during growth from 0.06 – 0.24 $M_\odot$, and crossing times falling from ~ 2000 – 1000 years. The time when dynamical interactions became relevant was arbitrarily set at 3×10^4 years and growth rate was chosen such that an embryo reaches the stellar mass threshold of 0.08 $M_\odot$ at 6×10^4 years. During this time window they showed that ~ 30% of such systems would decay, releasing a brown dwarf of mass 0.04 – 0.08 $M_\odot$. Later decays resulted in the ejection of a low mass star.

This illustration appears quite conservative when one considers also:

a) Embryos may have non-equal access to infalling matter, hence they may grow at different rates.
b) Lowest mass objects are ejected preferentially.
c) Stellar embryos may be formed over a period of time with late-forming ones being more rapidly ejected than their heavier siblings.
d) If embryos are born in a more compact configuration, the crossing time decreases, leading to an enhanced probability of rapid ejection.

The latter point can easily be appreciated by noting that if embryo growth is approximately linear then $M \propto t$ (where t is time) and the ejection timescale $\propto t_c \propto R^{3/2}M^{-1/2}$. Hence the relation between the characteristic mass of an ejected fragment and the size of the multiple system is $M \propto R$. A tighter 20 AU configuration for example might result in the ejection of planetars of ~ 4 $\mathrm{M}_{♃}$ and upwards. The even more compact ~ 3 AU-sized system arrived at by Boss (2001) with its ~ 0.5 $\mathrm{M}_{♃}$ fragments seems also to fit this relation.

In conclusion, Reipurth & Clarke (2001) noted that this interpretation of brown dwarf origin naturally explains the lack of wide brown dwarf binaries, the rarity of brown dwarfs as companions to normal stars and the flattening of the low-mass end of the IMF.

Although Reipurth & Clarke's paper consists of empirical arguments and "back of envelope" calculations, their work has received support from an impressive simulation of star formation recently performed by Bate *et al.* (2002). Using a smoothed particle hydrodynamics code running on the SGI Origin 3800 (a 128-processor supercomputer) at the UK Astrophysical Fluids Facility, they simulated the collapse of a molecular cloud to form a cluster of stars. The calculation was one of the most sophisticated and ambitious yet undertaken, using 3.5×10^{6} mass points, a resolution of 10 AU and requiring ~ 95000 processor hours (~ 1 month) to complete the ~ 10^{16} arithmetic operations needed.

Initial conditions involved a cloud of 50 $\mathrm{M}_{\odot}$, 0.375 pc across, at a temperature of 10 K, on which a turbulent velocity field had been imposed. The free fall time of the cloud was 1.9×10^{5} years and simulation was run for 2.66×10^{5} years. According to their parameterisation of opacity-limited fragmentation, the minimum Jeans mass occurred at a density of 10^{-10} kg m^{-3} during the isothermal collapse phase and was ~ 0.0011 $\mathrm{M}_{\odot}$ (1.1 $\mathrm{M}_{♃}$).

23 stars and 18 brown dwarfs were produced and 9 more objects were still accreting when the calculation terminated, leading the authors to claim, "*Brown dwarfs occur as a natural and frequent product of the collapse and fragmentation of a turbulent molecular cloud*."

All brown dwarfs began as opacity-limited fragments of just a few Jupiter masses in unstable multiple systems but were then ejected from their natal cloud before they could accrete enough gas to become stars. In no case did they find a solitary core collapse to completion producing either a single or binary brown dwarf. Looking at the process in more detail, they found that ~ 25% of the brown dwarfs originated in exactly the manner envisaged by Reipurth & Clarke (2001): stellar embryos formed in collapsing gas filaments, fell into a multiple system and are then ejected from the dense gas. The other ~ 75% originated in gravitationally unstable circumstellar discs: fragments interacted mutually, or with the central star, and were thrown back into interstellar space.

The general conclusions of Bate *et al.* (2002) were:

1) The number of stars ≈ the number of brown dwarfs.
2) < 5% of brown dwarfs occur in binaries.
3) Brown dwarf binaries that do exist must be close: $\lesssim$ 10 AU.
4) Many circumstellar discs are truncated by close encounters to within $\lesssim$ 10 AU.
5) Brown dwarfs are “failed stars”, rather than “low mass stars.”

Although Bate *et al*. (2002) only mention brown dwarfs, the formation of planetars is also implied in their results. At least one of the objects in their simulation only reached ~0.007 $M_\odot$ before ceasing growth.

4.1.3 *Photoevaporation*.

The dramatic effects of O,B-class stars ($\gtrsim$ 10 $M_\odot$) on the star forming regions where they are born has long been appreciated: their enormous output of ultraviolet radiation heats local gas which is eventually driven off, leaving behind a naked star cluster. Extreme ultraviolet photons (EUV: $h\nu$ > 13.6 eV) raise gas temperatures to ~ 10,000 K, and cause ionization and the formation of an HII region. Far ultraviolet photons (FUV: 6 eV < $h\nu$ < 13.6 eV) heat molecular gas to ~ 1000 K, dissociate it and create a photodissociation region beyond the HII region. As well as driving off the residual gas remaining after formation of a star cluster, smaller scale observations have shown this UV flux driving photoevaporative flows from dense clumps of gas in which protostars might be embedded. Such photoevaporation of gas has also been noted eroding protoplanetary discs (so-called “proplyds”, O’Dell *et al.*, 1993) around more evolved protostars.

The high slope of the stellar mass-luminosity function means that a handful of the most massive, and hence luminous, stars in a given star formation region dominate its radiation environment and hence may play a role in regulating star formation. Once O,B-class stars “switch on”, their effects might be relevant to the minimum condensation mass in a number of, not necessarily exclusive, ways:

- O,B-class stars could halt all further gas cloud fragmentation and star formation in their vicinity, possibly effecting the minimum fragment mass.
- Photoevaporation erodes clumps and discs from their outer regions inwards, possibly reducing the mass available for accretion and hence the final mass of the central condensation. Objects emerging from partially photoevaporated clouds would be less massive than otherwise.
- Intense and sustained photoevaporation could cause the complete dispersal of a pre-stellar clump so that no condensation forms. If this only occurs to clumps below a certain mass, this mass would be the smallest capable of forming a condensed object.

A number of analytical studies of photoevaporation of gas clumps and circumstellar discs have been published (Bertoldi & McKee, 1990; Johnstone et al., 1998; Störzer & Hollenbach, 1999; Scally & Clarke, 2001; Gorti & Hollenbach, 2002). Photoevaporation rates of ~ 10^{-7} $M_\odot$ yr^{-1} have been derived giving an expected mass loss of ~ 0.01 $M_\odot$ over 10^5 years: figures that are in accord with measurements made by Henney & O’Dell (1999) who found mass loss rates of this order from proplyds close to θ^1C Ori, the most luminous star in the Trapezium cluster. However, generalising from these models to propose a systematic effect on star formation, or a minimum condensate mass mediated by photoevaporation, is perhaps unrealistic. The relevant physics is not yet fully understood and the models have many variables and incorporate random and dynamic processes. For example, the extent and duration of photoevaporation is significantly dependent on such contingencies as the proximity of the UV sources (determined in part by the mass and density of the star forming region and the random formation of the rare high-mass stars responsible for the radiation field), the stage of evolution of stellar embryos when subjected to the radiation field, their movement through and duration spent within the cluster, shadowing by interposed gas clouds and the "rocket effect", which can propel a photoevaporating clump away from the radiation source.

Here, it suffices to briefly consider some simple scaling relationships from the models to illustrate the relative impact of photoevaporation on young protostars of varying masses. The photoevaporation timescale for clumps exposed to FUV radiation derived by Gorti & Hollenbach (2002) is:

$$t_{PE} \approx 10^4 \left(\frac{n}{10^{11} m^{-3}}\right)^{\frac{2}{3}} \left(\frac{R}{0.01 pc}\right)^{\frac{5}{3}} \left(\frac{0.3 kms^{-1}}{a_c}\right)^{\frac{2}{3}} \left(\frac{3 kms^{-1}}{a_{PDR}}\right)^{\frac{1}{3}} \text{ years,} \qquad (15)$$

where n is the number density of particles within the clump, R is its radius, a_c is the sound speed of the interior, cool, cloud material and a_{PDR} is the sound speed in the heated outflow.

Photoevaporation can only occur outside a critical radius r_{min} within which the gravitational potential of a central object can confine the gas. This radius is approximately:

$$r_{\min} \approx \frac{GM}{2a_{PDR}^2} \quad . \qquad (16)$$

If we assume that, for a cloud fragment that has completed its isothermal collapse stage, the onset of adiabatic collapse occurs at a constant mean density then, if photoevaporation begins at this point, $R \propto M^{1/3}$ and $t_{PE} \propto M^{5/9}$. Since such objects rapidly develop a density gradient towards the centre, the denser central regions collapse much faster than the exterior so it is interesting to consider $(r_{min} / R)^3$, the ratio of the "protected" volume within r_{min} to the overall volume of the clump. We note in this case that $(r_{min} / R)^3 \propto M^2$. Thus we can deduce that lower mass clumps are evaporated faster and a greater fraction of their mass has the potential to be lost.

Lucas and Roche (2000) speculated that their evidence for a minimum planetar mass of ~ 8 $M_{♃}$ in the Trapezium, as opposed to no apparent lower limit in σ Orionis (Zapotero Osorio *et al.*, 2000), may be due to the fiercer UV environment there preventing cloud cores below a certain mass from condensing. Given the uncertainties in this scenario, it is possible to say that whilst photoevaporation undoubtedly has some influence on star formation, its relevance to the existence of planetars cannot yet be estimated with confidence.

4.2 *Unbound Planets.*

4.2.1 *Early Ejection: Dynamical Relaxation.*

A potentially rich and probably inevitable source of free-floating planets are planetary systems in formation. Although cosmogony is not fully understood, all of the theories of planetary accumulation invoke the likelihood of a stage of chaotic interaction whereby unstable systems of planetary embryos dynamically evolve into more stable and lasting configurations via mergers and ejections (Lissauer, 1995).

Planet formation is envisaged as commencing in two, not necessarily exclusive, ways. Planets could form in a “bottom-up” fashion via the accretion of numerous planetesimals within a circumstellar disc (Safronov, 1969), followed by gas accumulation onto massive cores in the case of giant planets (Pollack *et al.*, 1996). Alternatively, a “top-down” mode of formation could involve the gravitational instability of a massive circumstellar disc followed by its fragmentation into a number of giant gaseous protoplanets (Cameron, 1978). Neither of these “planetesimal” or “protoplanet” theories currently describe planetary formation as a placid process with perfect mass conservation. The planets remaining within a stable planetary system are those that have avoided being eaten by larger siblings, swallowed by the central star, or becoming unbound entirely and ejected into interstellar space.

Within the context of the planetesimal hypothesis, planetary formation is thought to proceed as follows. Dust in the plane of a circumstellar disc coagulates into a swarm of kilometre-sized planetesimals. The largest of these then undergo runaway accretion by rapidly sweeping up smaller planetesimals in their feeding zones. This continues until a given planetesimal isolates itself from the swarm by having accreted all objects within its gravitational reach. The result is the formation of a substantial number of planetary embryos in near-circular orbits each of roughly the so-called "isolation mass" (Lissauer, 1987):

$$m_p = \frac{\left(4\pi BR^2\Sigma\right)^{\frac{3}{2}}}{\sqrt{3M_{Sun}}} \quad , \qquad (17)$$

where B ≈ 4 (being the width of the cleared lane within the disc in Hill Radii), R is the orbital radius and Σ is the disc surface density.

Theoretical isolation masses for a range of orbital radii are given in Table 2, assuming $\Sigma \propto R^{-3/2}$, $\Sigma(1\ \text{AU}) = 100\ \text{kg m}^{-2}$ and $\Sigma(\geq 3\ \text{AU}) = \Sigma \times 4$ to reflect the formation of water ice augmenting the mass of solids at these distances.

Table 2.

Distance (AU)	Isolation Mass ($M_\oplus$)
0.4	0.04
0.8	0.07
1.0	0.08
1.5	0.11
2.0	0.14
3.0	1.48
5.0	2.18
10.0	3.66
20.0	6.16

Planetary embryos with a mass spectrum of the order of that in Table 2 then proceed to interact via accrued long-range gravitational perturbations: crossing orbits result in either further embryo growth from collisions or scattering due to close encounters. The terminal phase of accretion therefore is seen as an era of wayward worlds in collision, of giant impacts that may have left clues on the solar planets that can still be discerned today. In the case of the solar system, once Jupiter has formed it would have acted as a very efficient ejector of material crossing its orbit, the probability of ejection per encounter being 2-3 orders of magnitude higher than collision (Weidenschilling, 1975).

Since the 1970's, numerous papers have appeared modelling portions of this ~ 10^7 – 10^8 year terminal accretion phase. A recent example is the 3-D N-body computer simulation of Chambers & Wetherill (1998) which calculates the evolution of a disc of up to 56 planetary embryos, ranging in initial mass between 0.02 – 0.1 $M_\oplus$ and encompassing the region of the terrestrial planets and asteroid belt. They found that ~ 85% of the mass originally in the terrestrial zone was accreted into surviving planets, whereas the asteroidal zone was efficiently cleared by scattering of planetary embryos into resonances where they are lost via encounters with Jupiter or collisions with the Sun. In the process of forming a stable system of terrestrial planets, such a model therefore predicts the release of a substantial handful of lunar to Mars-mass unbound planets.

Much more massive planetesimals could have come into existence in the outer solar system and would have been scattered far and wide by Jupiter and Saturn. This has been proposed by Lissauer (1987) as a solution to the problem of forming the giant planets fast enough (within 10^6 years) so that they can accumulate gas from the solar nebula before it is dispersed by the newborn Sun's T-Tauri stellar wind. Lissauer has proposed that if the surface density of solids in Jupiter's zone was 5 – 10 times that needed to account for the Jovian core then the planet could have grown sufficiently rapidly to its full size of 318 $M_\oplus$, whereupon it would have dominated a large region of the solar system through gravitational perturbations. The excess solids ($\gtrsim$ 50 $M_\oplus$) would then have been ejected from the solar system. The bulk of this material may have consisted of comets (as evidenced by the Sun's lingering Oort cloud) but some of it was probably slung out in planet-sized packages.

Although this unstable excess of planet-sized bodies is a theoretical prediction of the planetesimal hypothesis, there is indirect evidence that such a population existed. The hypothesis that best explains the properties of the Earth-Moon system involves the early Earth being struck a glancing blow by a Mars-sized impactor; the Moon then accretes from a disc of orbiting debris left in the aftermath (Hartmann, 1986). Even more suggestive are the variations in obliquity and rotation of the planets which are too great to be the result of average accumulation of small particles. Hartmann & Vail (1986) have investigated the largest size of impacting planetesimals required to explain these properties. Their optimum model involves the planets of the inner solar system being hit by a population of impactors associated with each planet, ranging up to a few percent of the planet's mass. The outer solar system is dominated by a scattered swarm of Jovian planetesimals with masses up to 2% that of Jupiter (~ 6 $M_\oplus$). Such a model explains the low obliquity of Jupiter and the high obliquity of Uranus as they are struck by giant planetesimals of the lowest and highest relative mass, respectively. In the context of such a scenario, one would expect a similar mass spectrum of massive planetesimals to be thrown out of the solar system to become unbound planets.

The concept of gravitational scattering of planet-sized objects into hyperbolic escape orbits appears likely in the context of solar system formation and may be bolstered by the evidence of giant planets in highly elliptical or very close orbits around some nearby stars. The existence of these "Eccentric Jupiters" and "Hot Jupiters" could perhaps represent the aftermath of a particularly extreme terminal phase of dynamical interaction between full-sized planets. More recent modelling of the formation of giant planet systems by Levison *et al.* (1998), succeeded in producing arrangements of planets that were reminiscent of the solar system and others that were more compact or much sparser, with planets in highly eccentric orbits. In all cases, much of the initial mass was lost to interstellar space, often in the form of unbound planets of several earth masses. Mazari and Weidenschilling (2002) have simulated unstable systems of 3 Jupiter mass planets and noted that the most common endpoint of evolution was ejection of one planet, with one of the survivors moved closer to the star (where tidal circularisation of the orbit could occur) and the other left in a distant orbit. It is not inconceivable therefore to suggest that fully-formed gas giants could end up unbound from the star about which they formed, especially in view of the fact that some of the discovered exoplanetary systems have planets of several Jupiter masses, in eccentric orbits, that could be interpreted as the “survivor” in a close encounter that resulted in the ejection of a junior sibling.

The unexpected characteristics of many of the discovered exoplanetary systems have prompted new examination of the possibilities of forming giant planets through gravitational instability in the cool and optically thin outer regions of a protostellar disc (e.g. Li, 2002). In order to see to what extent similar systems can be reproduced, Papaloizou & Terquem (2001) conducted a series of N-body simulations of the orbital evolution of between 5 – 100 gaseous protoplanets, with masses in the giant planet range, assumed to form rapidly by using up the gas in a protostellar disc. They found in all their runs that most protoplanets were ejected and that, at most, 3 planets remained in highly eccentric orbits. One of their conclusions therefore was particularly relevant to the discussion here: *“The objects expelled as a result of the type of relaxation process we consider may produce a population of freely floating planets which is several times larger than that of the giant planets close to the central star. This population would be expected to be typically at least 10 times larger than the population of massive planets orbiting around the star and depends on the initial number of planets in the distribution.”*

Thus, whilst cosmogonic hypotheses are not advanced enough to derive a firm mean number density and mass range of early-type unbound planets, they do inspire some confidence that a wide variety of these objects exists and they may be substantially more abundant than stars.

4.2.2 *Late Ejection: Planetary Nebulae.*

Once a stable planetary system is formed, there are a number of ways one could conceive of it becoming unstable and shedding planets to interstellar space. One way this could happen is through mass loss from the central star occurring as part of its post-main sequence evolution. This could happen either gradually when a star casts out a planetary nebula (losing $\gtrsim$ half its mass) whilst evolving into a white dwarf, or suddenly following a supernova explosion. The former of these possibilities is considered in this section.

Studies of planetary system stability often express the separation of planets in terms of their "mutual Hill radius":

$$R_H = \left(\frac{m_1 + m_2}{3M} \right)^{\frac{1}{3}} \left(\frac{R_1 + R_2}{2} \right) , \qquad (18)$$

where M is the mass of the central star, m and R are planetary masses and semi-major axes and subscripts 1 and 2 denote inner and out planets respectively.

If we take the separation between two planets to be $\Delta = R_2 - R_1$, then for stability we require:

$$\Delta \geq \Delta_{cr} R_H \ , \qquad (19)$$

where Δ_{cr} is a critical separation value for stability.

Gladman (1993) has shown that for a system of two low mass planets in circular orbits, $\Delta_{cr} \approx 2\sqrt{3}$. However, for systems of three planets or greater (especially when non-circular orbits are accounted for), numerical integration experiments (e.g. Chambers *et al.*, 1996) have cast doubt on any such thing as permanent stability. The time elapsing before a disruptive close encounter scales as $\log t \propto \Delta / R_H$ and for ~ billion year stability we require $\Delta_{cr} \gtrsim 8 - 10$.

When mass loss from the central star is gradual, occurring over a timescale greater than the orbital period of its planets, angular momentum is conserved and planets will widen their orbits in proportion to the mass lost. Since orbits widen by the same factor, the relative separation of the planets (R_2 / R_1) remains unchanged. However, Debes and Sigurdsson (2002) have pointed out that since $R_H \propto M^{-1/3}$, the Hill radius increases with mass loss and the stability criterion (as expressed in eq.19) is less likely to be satisfied (e.g. see Figure 4). In other words, *"Orbits that are initially marginally unstable, or close to being unstable, will become unstable to close planet-planet approaches as a consequence of mass loss from the central star."*

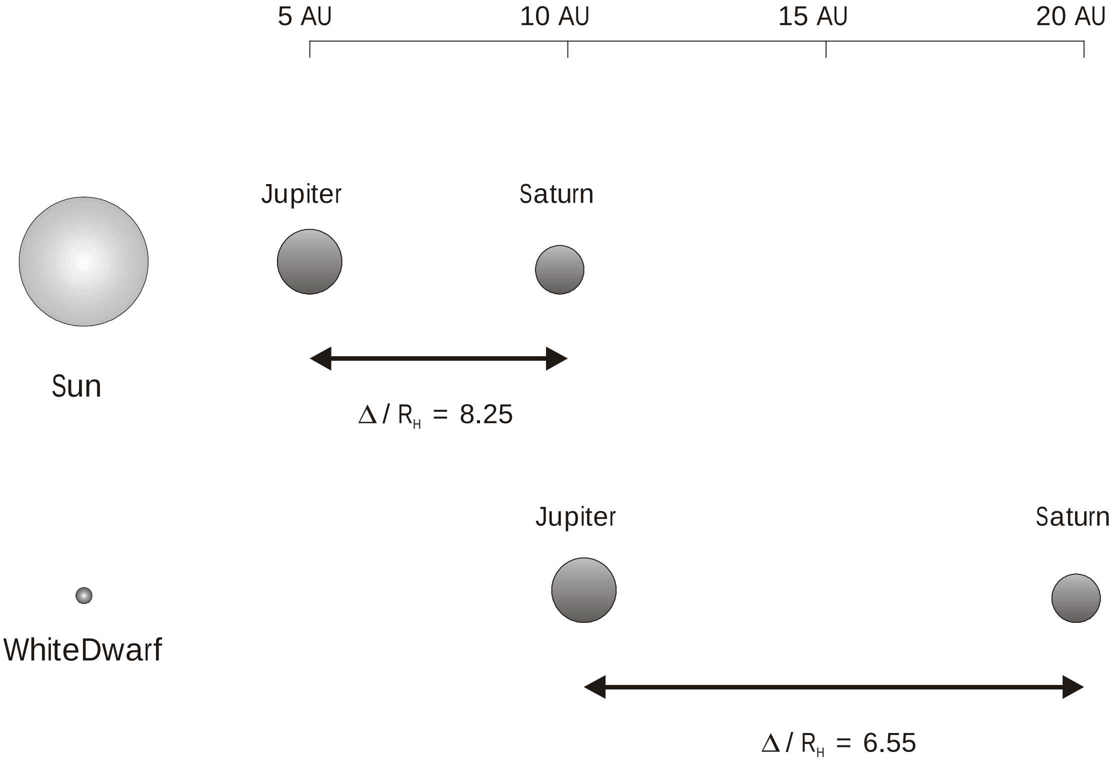

Figure 4: If the Sun were to lose half its mass when becoming a white dwarf, the orbits of Jupiter and Saturn would double in extent but their separation in mutual Hill radii would fall. Orbital instability over a timescale of ~ 10^6 years could result.

Debes and Sigurdsson (2002) tested this hypothesis with several numerical simulations of multi-planet systems orbiting a central star losing mass over a period of 1000 orbits. Timescales to close planetary encounters were found to shorten by roughly two orders of magnitude and the effect was shown to increase in severity the greater the initial mass of the star since a greater fractional mass reduction is undergone in arriving at the final white dwarf remnant. Thus, planets with orbits that were formerly stable on $10^9 - 10^{10}$ year intervals are predicted to become unstable in ~ $10^7 - 10^8$ years after their primary has evolved into a white dwarf. Such instability will typically result in orbital rearrangements, collisions and ejections, allowing for a modest population of unbound planets to be liberated from the systems of dying stars.

4.2.3 *Late Ejection: Supernovae.*

When a star explodes as a supernova it ejects a large quantity of mass at high velocity on a timescale much shorter than that of a planetary orbit. If a supernova progenitor “instantaneously” loses more than half its mass, orbiting planets will find themselves moving at greater than escape velocity and the entire planetary system will become unbound (Hills, 1970).

Type II supernovae are thought to occur following the core collapse of rare massive stars of $\gtrsim 8\ M_{\odot}$; the envelope of the star is blown off, leaving behind a neutron star remnant of $\lesssim 3\ M_{\odot}$. Even given the likelihood of previous gradual mass loss during preceding post-main sequence stages of evolution, most scenarios ending in supernova explosion support the conclusion that orbiting planets would be lost. Planets that have been discovered orbiting pulsars are thought probably to have formed from debris left behind after the cataclysm.

But would planets form about such massive stars in the first place? The main sequence lifetime of stars is roughly $t_{MS} \approx 10^{10}(M/\ M_{\odot})^{-2.3}$, so stars of $\lesssim 20\ M_{\odot}$ last for longer than $\sim 10^{7}$ years, the approximate time required for planet formation as indicated by current theories. However, the high binary frequency of such stars might well preclude planetary formation in some cases and more generally their fierce radiation environment might well prevent giant planets from forming at all (Armitage, 2000). Nevertheless, it remains possible that some such stars may be accompanied by primitive planetary systems which would be scattered into interstellar space when they succumb to supernova explosion.

4.2.4 *Late Ejection: Close Stellar Encounters*.

Between the time of the formation of a stable planetary system and possible instability caused by the evolution of the central star lies the great majority of a star's main sequence lifetime, a lengthy period of usually billions of years. The principal cause of planet loss and unbound planet creation from main sequence stars is expected to be random encounters with passing stars that pass sufficiently close to destabilise planetary orbits. The probability of such an encounter depends on such parameters as the stellar number density and mass spectrum, their relative velocity, the extent of planetary orbits and the age of the system. These can vary significantly between stellar populations. Field stars in the solar neighbourhood, for example, inhabit a low density environment ($n \approx 0.1$ pc^{-3}) with a high relative velocity ($v \approx 40$ km s^{-1}) that is up to $t \approx 10^{10}$ years old. Stars in open clusters are much more crowded ($n \approx 10^1 - 10^4$ pc^{-3}), but their relative velocities and ages are usually much less ($v \approx 1 - 2$ km s^{-1}, $t \lesssim 10^9$ years). Globular cluster stars can be even more tightly packed and can exceed the age of the galactic disc.

Whilst limited aspects of this problem can be approached analytically (e.g. Fogg, 1988), modelling the typical outcome of the intrusion of a foreign star into a planetary system, with its plethora of independent variables, is best approached statistically using the results of computer simulations. An early example of such work is that of Hills (1984) and more recently studies by Laughlin & Adams (1998, 2000), Bonnell *et al*. (2001), Smith & Bonnell (2001), Davies & Sigurdsson (2001) and Hurley and Shara (2002). The approaches of these authors differs and only a crude comparison of their results can be made. Their conclusions relevant to the unbinding of planets are listed below in Table 3.

Table 3.

Study	Environment	Relevant Finding.
Laughlin & Adams, 1998	Open clusters	~ 13% of systems have disruptive encounter. ~ 5% of Jupiter-analogue planets ejected.
Laughlin & Adams, 2000	Galactic disk field	Ejections rare
Bonnell et al., 2001	Globular clusters	~ 47% of systems “ionized”
Smith & Bonnell, 2001	Open clusters Young open clusters	~ 27% of systems “ionized” ~ 8% of systems “ionized”
Davies & Sig…, 2001	Globular clusters	Planets with R $\gtrsim$ 0.3 AU likely to be lost.
Hurley & Shara, 2002	Open clusters	5 – 10% of planets unbound.

Except within ancient globular clusters, only a minority of planetary systems are expected to have suffered disruption due to a close stellar encounter. Field stars are the least at risk with only one system in a few thousand likely to have been affected. A larger minority of planetary systems in open clusters are susceptible to disruption.

In order to appreciate these processes more clearly, without going into the differing details of the papers cited above, a simple analysis of unbound planet creation is offered here.

The time it takes for a star to randomly encounter another star is:

$$\tau = \frac{1}{\sigma v n} \ , \qquad (20)$$

where σ is the cross section for stars to pass within a distance R_{min}, v is the relative stellar velocity, and n is the stellar number density.

The cross-section, including the influence of gravitational focussing is:

$$\sigma = \pi R_{\min}^2 \left(1 + \frac{2G(M_1 + M_2)}{R_{\min} v^2}\right) , \tag{21}$$

where M_1 and M_2 are the masses of the target and intruder stars.

In *high-v environments* (e.g. the galactic disk) the second term in brackets is usually small so:

$$\sigma \approx \pi R_{\min}^2 \ . \tag{22}$$

If, for ejection to occur, $R_{\min} \leq R$, where R is the semi-major axis of the planet in question, then the ejection timescale is:

$$\tau_{ej} \approx \frac{1}{\pi R^2 v n} = 1.33\times 10^{16}\, yr \left(\frac{AU}{R}\right)^2 \left(\frac{kms^{-1}}{v}\right)\left(\frac{pc^{-3}}{n}\right) . \tag{23}$$

In *low-v environments* (e.g. young and open clusters) the gravitational focussing term in Eq.21 is dominant so the encounter cross section becomes:

$$\sigma \approx \frac{2\pi G R_{\min} (M_1 + M_2)}{v^2} \ . \tag{24}$$

Again, if for ejection we need $R_{\min} \leq R$, then the ejection timescale becomes:

$$\tau_{ej} \approx \frac{v}{2\pi G R n (M_1 + M_2)} = 7.46\times 10^{12}\, yr \left(\frac{AU}{R}\right)\left(\frac{pc^{-3}}{n}\right)\left(\frac{M_{Sun}}{M_1 + M_2}\right)\left(\frac{v}{kms^{-1}}\right) . \tag{25}$$

The probability of ejection, for planets ≥ R, over a time t would be:

$$P_{ej}(\geq R) \approx \frac{t}{\tau_{ej}} \quad . \qquad (26)$$

Most stars are thought to be born in clusters, in comparatively densely-packed conditions, before being lost to the field star population as the cluster disperses over $10^8 – 10^9$ years. First of all therefore, let us consider an open cluster environment with $v = 1$ km s^{-1}, $n = 1000$ pc^{-3}, $M_1 + M_2 = 2$ $M_\odot$ and $t = 10^8$ years. To unbind a Neptune-analogue, R = 30 AU, so Eq.25 gives $\tau_{ej} = 1.24\times10^8$ years and $P_{ej} \approx 0.81$. This is quite likely, supporting the view of Bonnell *et al.* (2001) that the Sun may have been born in a fairly low-density cluster, or escaped at an early stage. To unbind a Jupiter-analogue, R = 5.2 AU, giving $\tau_{ej} = 7.2\times10^8$ years and $P_{ej} \approx 0.13$, identical to the estimate of Laughlin and Adams (1998) for disruptive encounters in a similar environment (not all of which actually unbind the planet).

For field stars in the solar neighbourhood, we take $v = 40$ km s^{-1}, $n = 0.1$ pc^{-3} and $t = 4.6\times10^9$ years. The ejection of a Neptune-analogue now takes (from Eq.23) $\tau_{ej} \approx 3.7\times10^{12}$ years and $P_{ej} \approx 1.25\times10^{-3}$, a value similar to that found in Fogg (1988) when other factors in his model are accounted for, but somewhat higher than that found by Laughlin & Adams (2000) who model the varied outcomes of scattering processes more realistically.

The creation of unbound planets by close stellar encounters over most of the main sequence lifetime of the star is therefore a rare process. The disruption and scattering of a planet system, if it occurs, is likely to happen at early times within the birth cluster. Globular cluster stars, on the other hand, due to both high stellar number density and great age, are likely to have had all but their closest planets stripped away. These old stars however are a small minority of those in the galaxy as a whole.

Not taken into account here are those close encounters that stir up the planetary system but which do not lead to ejection. These instead will drive eccentricity into the planetary system, possibly leading to future close encounters between planets and ejections reminiscent of those processes described in § 4.2.1 and 4.2.2. Thus we might speculate that a number of “delayed action” unbound planets might eventually join those lost to interstellar space in a single pass of a foreign star.

5. ESTIMATES OF THE ABUNDANCE OF FREE-FLOATING PLANETS.

Despite the uncertainties remaining over the physical processes discussed above, an attempt is made here to constrain their inherent possibilities and hence arrive at reasonable estimates of the abundance of the various classes of free-floating planet.

5.1 *Planetars.*

Three possible modes of planetar formation were discussed in § 4.1.1. – 4.1.3. However, since their relative significance is not known, it is difficult to derive direct numerical estimates of planetar abundance in each case. The formidable and detailed star formation simulation of Bate *et al.* (2002) generated roughly one brown dwarf (planetars included) per star; but this result is from just one run of the program and it remains to be seen if this conclusion stands the test of time.

Since planetars are thought to form in a manner similar or identical to that of low mass stars, one way to arrive at an abundance estimate is to use the stellar initial mass function (IMF). The number of stars born in the mass range (M, M + dM) can be modelled as:

$$dn = \Phi(M)dM \quad . \tag{27}$$

The form of the IMF was originally derived by Salpeter (1955) who found:

$$\Phi(M) \propto M^{-\alpha} \quad , \tag{28}$$

where $\alpha \approx 2.35$.

The stellar number density within a given mass range can thus be calculated:

$$n = \beta \int_{\min}^{\max} \Phi(M)\, dM \quad , \tag{29}$$

with the total mass in the range being:

$$M_{tot} = \beta \int_{\min}^{\max} M\Phi(M)\, dM \quad , \tag{30}$$

where β is a normalization constant. For n = 0.1 pc^{-3}, α = 2.35, between the limits *min* = 0.1 $M_{\odot}$ and *max* = 50 $M_{\odot}$, β = 0.006.

Before brown dwarfs had been discovered, it used to be thought possible that a large population of such dim sub-stellar objects might account for the ~ 0.1 $M_{\odot}$ pc^{-3} of the mass in the solar neighbourhood that is “missing,” or unseen according to dynamical studies (e.g. Kumar, 1972). D’Antona and Mazzitelli (1986) showed that integrating the Salpeter IMF down to 3 $M_{♃}$ accounts for the discrepancy and predicts a total of ~ 11 brown dwarfs and planetars pc^{-3}. However, if planetar masses go as low as 1 $M_{♃}$, with an IMF slope as steep as α = 2.35, ~ 50 planetars pc^{-3} are predicted, leading to an “excess mass” discrepancy (see Table 4).

Table 4: Integration of Salpeter IMF into sub-stellar range.

Object	Mass Range ($M_{\odot}$)		n	Ratio to	M_{tot}
	Max	Min	pc^{-3}	stars	$M_{\odot}$ pc^{-3}
Stars	50	0.08	0.13	1	0.04
Brown Dwarfs	0.08	0.012	1.6	12	0.04
Planetars	0.012	0.003 / 0.001	9.6 / 48	74 / 369	0.05 / 0.11

Today, more capable observations can start to constrain theory and it is becoming clear that the slope of the mass function flattens at lower masses and that brown dwarfs and planetars are unlikely to be numerous enough to account for the missing mass.

A more realistic IMF that better fits the data gleaned since Salpeter's time is that of Kroupa *et al.* (1993) which has the form of a broken power law:

$$\Phi(M) = \begin{array}{lcl} 0.035M^{-1.3} & : & 0.08 \le M \le 0.5 \\ 0.019M^{-2.2} & : & 0.5 \le M \le 1.0 \\ 0.019M^{-2.7} & : & 1.0 \le M \le \infty \end{array} , \qquad (31)$$

where, as before, M is in units of $M_\odot$.

Values of the IMF exponent α are now being derived for lower masses ($\lesssim 0.1\ M_\odot$) from sensitive modern observations, particularly in young clusters where these objects are more luminous. Reid *et al.* (1999) estimated $\alpha \approx 1.3$ for field stars; Hillenbrand & Carpenter (2000) estimated $\alpha \approx 0.43$ for the Trapezium cluster; Najita *et al.* (2000) arrived at $\alpha \approx 0.5$ in the young cluster IC 348; and Béjar *et al.* (2001) fitted an IMF with $\alpha \approx 0.8$ to their discovered population of brown dwarfs and planetars in σ Orionis. Here, we fit these sub-stellar IMF segments ($\le 0.08\ M_\odot$) to the Kroupa mass function as follows:

Reid *et al.* (1999):	$\Phi(M) = 0.035\ M^{-1.3}$
Hillenbrand & Carpenter (2000):	$\Phi(M) = 0.315\ M^{-0.43}$
Najita *et al.* (2000):	$\Phi(M) = 0.264\ M^{-0.5}$
Béjar *et al.* (2001):	$\Phi(M) = 0.124\ M^{-0.8}$. (32)

Results of integrating these flatter mass functions down to 1 $M_♃$ are shown in Table 5 and are a sharp contrast to those in Table 4.

Table5: Integration of Modern Sub-Stellar IMFs.

Study	Object	Mass Range ($M_\odot$)		n	Ratio to stars	M_{tot}
		Max	Min	pc^{-3}		$M_\odot$ pc^{-3}
Kroupa *et al.* 1993	High mass stars	50	8	3.11×10^{-4}	2.27×10^{-3}	4.53×10^{-3}
	Medium mass stars	8	1	0.011	0.079	0.021
	"Sunlike" stars	1	0.5	0.021	0.150	0.014
	Red dwarfs	0.5	0.08	0.105	0.770	0.022
			Total:	0.137	1.0	0.062
Reid *et al.* 1999	Brown dwarfs	0.08	0.012	0.191	1.394	6.27×10^{-3}
	Planetars	0.012	0.001	0.487	3.557	1.86×10^{-3}
H & C 2000	Brown dwarfs	0.08	0.012	0.087	0.633	3.61×10^{-3}
	Planetars	0.012	0.001	0.034	0.246	1.90×10^{-4}
Najita *et al.* 2000	Brown dwarfs	0.08	0.012	0.092	0.668	3.75×10^{-3}
	Planetars	0.012	0.001	0.041	0.300	2.26×10^{-4}
Béjar *et al.* (2001)	Brown dwarfs	0.08	0.012	0.118	0.863	4.48×10^{-3}
	Planetars	0.012	0.001	0.100	0.733	4.86×10^{-4}

Brown dwarfs and planetars are now no longer predicted to be much more abundant than stars. In fact, if we take the Béjar *et al.* (2001) IMF, the only one to actually extend observationally into the planetar range, we see that brown dwarfs and planetars are about as common as stars: i.e. $n_{BD} / n \approx 1$ and $n_{Pl} / n \approx 1$. The mass range of free-floating planets of this type is expected to be limited to 1 – 13 $M_{♃}$.

5.2 *Early-Type Unbound Planets.*

In contrast to the case of planetars, there is no direct evidence of the existence of unbound planets. Predictions as to the abundance of unbound planets therefore can only be model-dependent and hence poorly constrained.

Both the planetesimal and protoplanet theories of planetary system formation predict the freeing of early-type unbound planets as young planetary systems dynamically relax into a stable configuration, ejecting some excess solids into interstellar space. This process is an inevitable outcome of Newton's laws and, unless the core concepts of modern cosmogony are wrong, early-type unbound planets must exist in large numbers. Past dynamical interactions between massive planets may be indicated by the eccentric exoplanets recently discovered and perhaps these systems constitute indirect evidence for planetary ejection.

Free-floating planets over the entire planetary mass range ($\sim 10^{-2} - 10^{-11}$ $M_{\odot}$) could potentially be liberated. However, since an ejected planet has to have encountered a significantly heavier planet to eject it, there would be expected to be a bias for forming planetary systems to eject its lighter members in each size class. According to planetesimal models, systems would be expected to eject planetary embryos of masses between the lower limit and roughly the mass of the Earth (see Table 2). Later stages in the formation of outer systems could result in the loss of several ~ 20 $M_{\oplus}$ Neptune-analogue "ice giants" (Levison *et al*., 1998), given larger Jovian-mass planets to eject them. In time, even the most massive planets could be lost if formed in a marginally unstable binary star system.

Current cosmogonic models, with the recent exception of Papaloizou & Terquem (2001), do not commonly highlight their capacity to shed unbound planets. Perhaps as good a guess as any gleaned from scanning the literature is that $\gtrsim 100$ unbound planets are generated per young planetary system, $n_{UBP} / n \approx 100$ and that the great majority of these will be of low mass.

5.3 *Late-Type Unbound Planets: Planetary Nebulae.*

In order to estimate the frequency of unbound planet liberation following planetary nebula ejection and white dwarf formation, we can refer directly to Debes and Sigurdsson (2002) where the issue is discussed. The authors quote Ford et al. (2001) who determined, for a system of two dynamically unstable giant planets, end-point probabilities of 8% for collision, 35% for ejection and 57% for orbital rearrangement. They then argue for probabilities of ~ 50% of stars having planetary systems in the first place, and ~ 50% of these being only marginally stable before mass loss from the central star.

The number of ejections per white dwarf star would therefore be $\sim 0.5 \times 0.5 \times 0.35 = 0.0875$. To calculate the ratio of unbound planets of this origin to all stars we need to know the present ratio of white dwarfs to all stars formed. Over the age of the galaxy ($\sim 10^{10}$ years) only stars of $\gtrsim 1\ M_\odot$ will have had time to complete their evolution. Since the lifetime of stars is roughly $\propto M^{-2.3}$, the *present day* stellar mass function for main sequence stars of $\gtrsim 1\ M_\odot$ is $\propto M^{-2.7}M^{-2.3} \propto M^{-5}$. The fraction of all stars born $> 1\ M_\odot$ is ~ 0.082 (see Table 5), but the fraction surviving today (using $\Phi(M) \propto M^{-5}$) is $\sim 9.025\times 10^{-5}$. This is very small, so the ratio of white dwarfs to stars is nearly the same as the fraction of stars born $\gtrsim 1\ M_\odot$. Thus, the prediction as to the abundance of unbound planets formed in this way is a modest $n_{UBP} / n \approx 7\times10^{-3}$.

5.4 *Late-Type Unbound Planets: Supernovae.*

A straightforward estimate can be made of the number of unbound planets released following supernova of the central star. Type II supernova progenitor stars weigh in at $\gtrsim 8\ M_\odot$ and the fraction of stars born of this mass is $\sim 2.3\times10^{-3}$ (Table 5). All surviving planets, over their entire mass spectrum, would be ejected. If we take an average of 10 planets per star we obtain $n_{UBP} / n \approx 0.02$.

5.5 *Late-Type Unbound Planets: Close Stellar Encounters.*

Previous papers that looked at the destabilisation of planetary systems due to close stellar encounters have been vague about the actual average number of ejected planets resulting from their particular model. Some model simplified single planet systems whilst others abstract the process by referring to the number of “ionized” systems, as opposed to the number of unbound planets released (see Table 3).

To address this issue here, we extend the simple analytic model presented in §4.2.4. Given $P_{ej}(\geq R)$, the probability of an encounter capable of ejecting planets exterior to R (Eq.26), the average number of unbound planets ejected per star would be:

$$\frac{n_{UBP}}{n} \approx \int_{R_{in}}^{R_{out}} n_p(R) dP_{ej} \ , \tag{33}$$

where $n_p(R)$ is the average number of planets ejected by an encounter at R and the integration limits are the outer and inner boundaries of the planetary system.

The following equation was chosen for $n_p(R)$, using a Bode's law arrangement of planets of 40 AU ≥ R ≥ 0.7 AU and assuming all the planets exterior to R are ejected:

$$n_p(R) = 8 - 1.44 \ln\left(\frac{10}{3} R - \frac{4}{3}\right) , \tag{34}$$

with R in units of AU. The fact that this equation is a continuous, rather than a step function, does not matter as mean values are being sought.

For ejection in a field star environment we obtain:

$$\frac{n_{UBP}}{n} \approx 2\pi (AU)^2 vnt \int_{0.7}^{40} \left[8R - 1.44 R \ln\left(\frac{10}{3} R - \frac{4}{3}\right)\right] dR \ , \tag{35}$$

which simplifies to:

$$\frac{n_{UBP}}{n} \approx 2.05 \times 10^{-5} \left(\frac{v}{kms^{1}}\right)\left(\frac{n}{pc^{-3}}\right)\left(\frac{t}{10^{8}\,yr}\right) . \tag{36}$$

For ejection in clustered environments the relative abundance is:

$$\frac{n_{UBP}}{n} \approx \frac{2\pi G(AU)(M_1 + M_2)nt}{v} \int_{0.7}^{40} \left[8 - 1.44 \ln\left(\frac{10}{3} R - \frac{4}{3} \right) \right] dR \ , \quad (37)$$

which simplifies to:

$$\frac{n_{UBP}}{n} \approx 1.14 \times 10^{-3} \left(\frac{M_1 + M_2}{M_{Sun}} \right) \left(\frac{n}{pc^{-3}} \right) \left(\frac{t}{10^8 yr} \right) \left(\frac{kms^{-1}}{v} \right) . \quad (38)$$

Evaluating Eq.38 for the cluster case, with v = 1 km s^{-1}, n = 1000 pc^{-3}, $M_1 + M_2$ = 1.29 $M_\odot$ (M_2 = 0.29 $M_\odot$ being the average stellar mass from the Kroupa IMF) and t = 10^8 years gives n_{UBP} / n ≈ 1.5.

Evaluating Eq.36 for the field star case, with v = 40 km s^{-1}, n = 0.1 pc^{-3} and t = 4.6×10^9 years gives n_{UBP} / n ≈ 1.3×10^{-3}. This ratio would increase gradually with decreasing radial distances within the galactic disc, being over an order of magnitude higher within the more crowded galactic bulge (Fogg, 1988).

These values blend quite well with those of more detailed studies, especially when taking into account the possibility of multiple ejections, star systems lacking planets etc. More realistically, the odds on ejection would be < 1 for planets at ≥ R, but delayed ejections could still occur millions of years later due to instability having been driven into the system at the time of the original stellar encounter. Most ejections would take place early in a system’s history within the birth cluster. For Population I stars therefore we expect close stellar encounters to produce similar numbers of unbound planets to stars: n_{UBP} / n ≈ 1. In globular clusters this ratio may be higher by a factor of ~ 10. Outer, and hence possibly massive, planets are preferentially ejected by this process.

A summary of the abundance estimates of the different types of free-floating planets derived in this section and a qualitative impression of their potential mass range are illustrated in Figure 5.

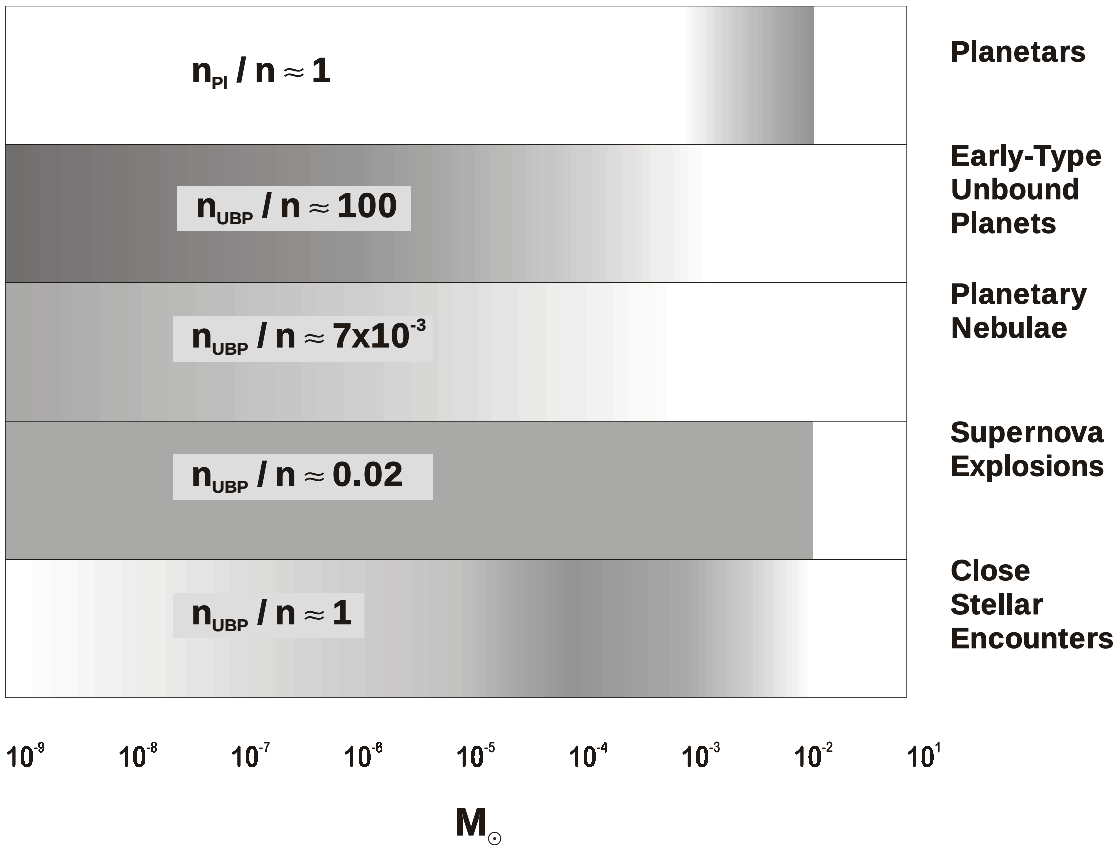

Figure 5: Summary of results: relative number densities and mass ranges of various categories of free-floating planet.

6. DETECTION OF FREE-FLOATING PLANETS.

Free-floating planets can only be detected via optical astronomy if they are massive and young and hence still relatively hot and luminous. It is for this reason that all the free-floating planets discovered so far are in young star forming regions. As these objects age, they become cooler and fainter, their emission moving further into the infrared. For example, according to the models of Burrows *et al*. (1997) a 1 $M_{♃}$ planet at 10^6 years has an effective temperature of 840 K and luminosity of 1.4×10^{-5} $L_{\odot}$; by the time it is 10^9 years old, the temperature has fallen to 160 K and luminosity to 8.3×10^{-9} $L_{\odot}$. Nevertheless, Burrows *et al*. (1997) expect ultra-sensitive next-generation infrared cameras to be able to detect isolated Jupiter-mass objects out to a distance of 100 pc, so significant discoveries may be in store over the next couple of decades. Smaller and fainter free-floating planets however will be much harder to find by detecting their infrared flux. If we were to place the Earth in interstellar space, its ~

0.08 W m^{-2} discharge of radiogenic heat would suffice to give it an effective temperature of a mere 34 K and a luminosity of ~ 10^{-13} $L_{\odot}$.

Another possible detection method, that has the advantage of being sensitive only to mass, not flux, is gravitational microlensing against a dense stellar background, such as the galactic bulge. Whilst no planets have yet been discovered by this method, given an assumed number density of free-floating planets, it is possible to estimate the magnitude of the observing effort required for a discovery (Zinnecker, 2001).

To do this here, we defer to the discussion in §5 and assume relative number densities of n_{FFP} / n = 1 for Jupiter-mass objects; n_{FFP} / n = 10 for Neptune-mass objects; and n_{FFP} / n = 100 for Earth-mass objects (most of the objects in these latter two categories would be early-type unbound planets). The variation of disk star number density in the galactic plane at a distance r from the galactic centre is approximately given by:

$$n \approx 0.1 \exp\left[-\left(r - r_0\right)/h\right] \ \mathrm{pc}^{-3} , \qquad (39)$$

(Bahcall & Soniera, 1980), where r_0 is the distance of the Earth from the galactic centre ($r_0 \approx 8.5$ kpc) and h is the scale length (h ≈ 3.5 kpc). We take the rim of the galactic bulge to be ~ 0.7 kpc from the centre. The average of this distribution between 0.7 – 8.5 kpc is n ≈ 0.37 pc^{-3}. Over an observational column depth of 7.8 kpc we therefore find surface number densities of $N_{FFP} \approx 3\times10^{3}$ pc^{-2} for “Jupiters”, $N_{FFP} \approx 3\times10^{4}$ pc^{-2} for “Neptunes”, and $N_{FFP} \approx 3\times10^{5}$ pc^{-2} for “Earths”.

The probability of a microlensing event (also known as the microlensing optical depth) is:

$$P_{ML} = \pi R_E^2 N_{FFP} \ , \qquad (40)$$

where R_E is the Einstein Radius:

$$R_E = \sqrt{\frac{4GM_{FFP} D_S x(1-x)}{c^2}} \ , \qquad (41)$$

and M_{FFP} is the mass of the free-floating planet, D_S is the distance to the source (~ 7.8 kpc) and $x = D_L / D_S$, the ratio of the distance to the lens to the distance of the source (here we take $x = 0.5$).

Putting in the numbers we find for the three cases:

Jupiter-mass free-floating planets: $P_{ML} \approx 3.4\times10^{-9}$
Neptune-mass free-floating planets: $P_{ML} \approx 1.8\times10^{-9}$
Earth-mass free-floating planets: $P_{ML} \approx 1.1\times10^{-9}$

These add to a total of $P_{ML} \approx 6\times10^{-9}$ so we would need to simultaneously observe a sample of $\gtrsim 1.6\times10^{8}$ galactic bulge stars in order to get a good chance of detection. Given that the timescale for Einstein ring crossing is R_E / v (where the relative velocity $v \approx 200$ km s^{-1}), the observation period must be $\gtrsim 1$ day with a time resolution of ~ 1 hour. Whilst such a task is challenging, it will apparently be possible with state of the art equipment in the near future (Zinnecker, 2001).

7. CONCLUSIONS.

It is argued in this paper that free-floating planets exist in profusion over the entire theoretical planetary size and mass range (summarised results are in Figure 5). Seven modes of origin have been discussed and organised into a classification based on whether formation originally occurs in interstellar space (in the manner of a star) or circumstellar space (in the manner of a conventional planet). How should we classify the massive $\gtrsim 5\ M_{♃}$ free-floating planets found in young clusters such as the Trapezium and σ Orionis? They appear to be of planetary mass (albeit near the upper limit) but, from the point of view of origin, are they planetars or unbound planets?

This is controversial. The Trapezium free-floating planets preferentially inhabit the outskirts of the cluster which is what would be expected if they formed like stars. This is because gravitational interactions between cluster members leads to an equipartition of energy: the heavier stars become more tightly bound and sink to the core of the cluster whilst the lighter members drift outwards. The computer simulations of Smith and Bonnell (2001), which looked at unbound planet generation in young clusters, indicated that free-floating planets originating via ejection from young planetary systems retain "*a memory of their original Keplerian orbital velocity*" and hence would be travelling well above the cluster escape velocity. Hence they would be lost from the cluster over a timescale of just 1 – 10% of its age and we would not expect to see so many of them at the present time. This conclusion however is disputed by Hurley and Shara (2002) whose own computer modelling suggests that a non-negligible fraction of unbound planets can be retained by the cluster.

Even so, the masses of these objects are more suggestive of their being "failed stars" rather than expelled planets that have completed their growth; although in this high-mass range, the distinction between the truncated accretion scenario for the origin of planetars (§4.1.2) and the dynamical relaxation scenario for the origin of unbound planets (§4.2.1) is blurred. In both cases, objects of this mass would probably need an encounter with a small star in order to liberate them. The simulation of Bate *et al*. (2002) actually shows both generation processes in action: brown dwarfs and planetars being released from both non-hierarchical protostellar systems and fragmented protostellar discs. Thus, it is concluded here that planetars exist and have been discovered. Observations to date suggest they have a similar abundance to stars and brown dwarfs, so whilst there may exist hundreds of billions of them in the galaxy as a whole, planetars are unlikely to provide the answer to the persistent missing mass question.

Unless our theories of planetary system formation are seriously in error, the existence of a plentitude of unbound planets of all sizes appears inevitable, although the majority of them should be invisible ice/rock objects rather than massive and briefly luminous giants. One can be as convinced of this as one can be about anything that is unseen but which emerges repeatedly from sound, physically-based, argument. Imaging such dark and frigid bodies may be impossible for some time but indirect confirmation of their existence by a technique such as microlensing may happen within the next decade. Thus, the controversy over whether planets really do wander interstellar space will eventually fade and these objects will take their proper place within the catalogue of astrophysical objects.

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