Interstellar Planets

The presence of unseen mass in the solar neighborhood has prompted modelling of, and searches for, a population of cool, low mass stars to make up the deficit. Such brown dwarfs are thought to exist within a mass range of $0.01\ M_\odot < M < 0.08\ M_\odot$. In this paper, the possibility of the existence of *interstellar planets* (ISPs), of mass range $5 \times 10^{-9}\ M_\odot < M < 0.01\ M_\odot$, is examined. Six potential modes of formation of ISPs are identified, although some are mutually exclusive, depending on different cosmogonic hypotheses. ISPs are of two basic types: those formed solitary within molecular clouds and those formed within, and subsequently unbound from, planetary systems. While the existence of the former is uncertain, interstellar planets of the unbound variety almost definitely exist, although not in sufficient quantity to account for the unseen mass. The number density of unbound planets in the solar neighborhood may be of a similar, or greater, order of magnitude to that of stars, the majority of them being massive planetesimals ejected from planetary systems in formation. The nearest extra-solar planet may thus be closer to the solar system than the nearest star.

Key Words: *planets*, *cosmogony*, *dark matter*

1. INTRODUCTION

Do all planets exist within systems, orbiting a primary star, or is it possible that some planets are solitary, wandering unaccompanied the depths of interstellar space? Considering the fact that there is not yet convincing evidence for the existence of any planetary system other than our own, this question may seem premature. However, it has become apparent from studies of stellar kinematics that about half the mass in the solar neighborhood is

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unaccounted for, or "missing".[1] It is not obvious what type of characteristic body this unseen mass is made from. The main constraint for an object to have escaped observation up to the present time is that it should have a low, substellar luminosity, and thus the unseen mass could in theory be accounted for by large numbers of planet-mass interstellar bodies. Speculation concerning the existence of *interstellar planets* (ISPs) has appeared sporadically in the literature over many years. In 1963, Öpik[2] 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 larger body."* The number density of ISPs in the solar neighborhood is unknown; in this paper a number of processes that might give rise to ISPs are discussed in an attempt to provide constraints as to their abundance.

To contain such speculation to within reasonable limits, it is necessary to set upper and lower boundaries within which an object can be considered "planetary." The most favored candidate body to account for the unseen mass in the solar neighborhood is the brown dwarf,[3] a body normally considered to be more massive than a planet, but below the hydrogen burning minimum mass limit ($\sim 0.08\ M_\odot$) that would give it the luminosity characteristic of a main sequence star. Such objects would derive their luminosity through gravitational contraction and the fusion of light elements and are expected to fade to near invisibility on a timescale of ~ 1 Gyr after formation. At the present time, no nearby solitary brown dwarfs have been detected, although there are a number of candidates in binary star systems, such as VB8B[4] and the recently discovered companion to the star HD114762.[5]

Should a brown dwarf be properly classified as a planet or a star? Black[6] has defined a brown dwarf as *"any sub-stellar mass body formed by the same process that forms stars."* Thus, according to this, an isolated brown dwarf, forming from a fragment of a contracting gas cloud, without any significant dissipation or chemical fractionation, is clearly a "failed star" rather than an oversized jovian planet. However, it would not do to call an interstellar condensation of, say, Earth mass a star rather than a planet, and thus the need to draw an upper mass limit below which an object ceases being called a brown dwarf star and is instead designated as a planet despite the mode of formation.

Is it possible, as hinted at by Öpik, that the brown dwarf mass function extends down to masses characteristic of planets in the solar system giving rise to numerous ISPs? It is as yet unknown whether the stellar mass function increases below 0.1 $M_\odot$ into the brown dwarf range and the brown dwarf mass function itself can only be guessed at. On the assumption that the mass function for low mass stars can be extrapolated below 0.08 $M_\odot$, D'Antona and Mazzitelli[3] calculated that the missing mass could be accounted for by a population of brown dwarfs with a minimum mass of $\sim 0.003\ M_\odot$ and a number density of $\sim 11\ \mathrm{pc}^{-3}$. However, theoretical studies of brown dwarf formation have identified a lower limit to their mass of ~ 0.01–$0.02\ M_\odot$ as gas cloud fragmentation terminates when individual fragments become opaque.[7,8] In the light of this, Probst[9] has modelled a brown dwarf population of number density $\sim 1.6\ \mathrm{pc}^{-3}$, minimum mass 0.01 $M_\odot$ and total mass density of half the observed density, for comparison with observational results. Thus, although there is no universally accepted value for the minimum mass of a brown dwarf, it does appear that, if they exist at all, the brown dwarf mass function truncates at a value well in excess of the masses of the solar planets. The smallest brown dwarf is likely to mass 3–20 Jupiters.

Thus, here we set the upper planetary mass limit as 0.01 $M_\odot$. In setting this limit, brown dwarfs and ISPs are thus recognized as distinct objects. Cole[10] has suggested a lower limit to a planetary mass on physical grounds at which elastic forces within the planetary body begin to dominate over gravitational forces. He calculates this to be for a body of $\sim 10^{19}$ kg, with a diameter of ~ 300 km. However, adoption of this threshold would mean that a number of asteroids, the comet Chiron and many medium-sized planetary satellites would be defined as planetary. Thus, for the purposes of this study of ISPs, the lower planetary mass limit is arbitrarily set at 10^{22} kg ($\sim 5 \times 10^{-9}\ M_\odot$), diameter ~ 2500 km: thus including all the solar system planets and their major satellites. The mass domain assumed for this study of ISPs is illustrated in Fig. 1.

As recognized by Öpik, interstellar planets might originate in

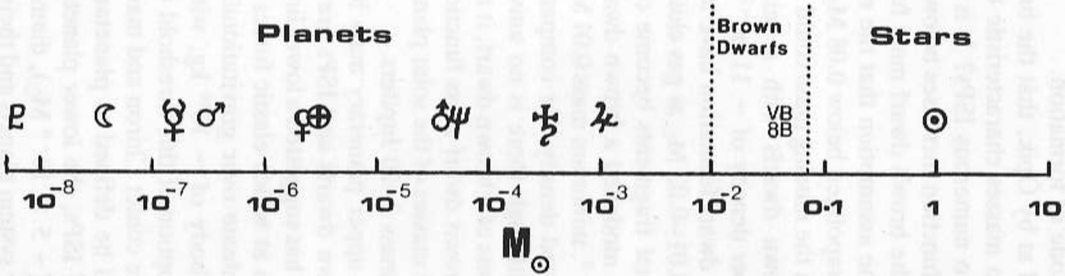

FIGURE 1 The mass range of stars, brown dwarfs and planets assumed for the study.

two distinct situations. They might either form as a solitary aggregate in a similar fashion to that of a star, or they may originate within a planetary system and be later ejected. This dichotomy can be used as the basis for a classification of ISPs. In this paper, therefore, we choose to label ISPs of the former type *singular planets* (SPs), and the latter as *unbound planets* (UBPs). The hypothesized ISPs of each type are discussed below.

2. SINGULAR PLANETS

The choice of the term *singular* is a deliberate double entendre. If star forming regions also give birth to isolated objects of planetary mass, then such planets would not just be solitary, but would also differ radically in mode of formation from planets originating within a solar system. As mentioned above, the most highly regarded theory of star formation, that of bulk hydrodynamic collapse and fragmentation of gas clouds, seems to preclude the formation of isolated bodies of $< 0.01\ M_{\odot}$. If star and planet formation occur the way most astronomers think, then singular planets do not exist. However, cosmogeny is a subject that as yet defies a full understanding and which still permits the existence of alternative hypotheses. In this section, two such hypotheses are briefly outlined which have particular relevance to SP formation.

In a theory where stars are formed by being built up from numerous smaller bodies, the case for the existence of SPs is much stronger. McCrea[11] has put forward an explanation of the angular momenta of the Sun and planets by proposing that the Sun was formed by the collision and aggregation of $\sim 10^5$ "floccules," transient and isolated regions of high density within a cloud of interstellar matter that is going to form a star cluster. Some floccule aggregates that failed to be incorporated into the Sun went into orbit around it to become protoplanets. McCrea's prime concern was to explain the formation of the solar system and he did not elaborate on the minimum stellar mass predicted by his theory. However, where stars are being formed from a swarm of smaller objects, it would not be surprising if the minimum mass turned out to be considerably less than that predicted by the standard theory. With the average floccule mass being $\sim 2 \times 10^{25}$ kg, with a temperature of $\sim$ 50 K and a density of $\sim 10^{-6}$ kg m^{-3}, the Jeans mass for floccule material would be about 48 floccules. Thus, the smallest aggregate that might be stable enough to collapse would be of half the mass of Jupiter, well within the range adopted as being planetary. The realization that the floccules might be too short-lived to fulfill their purpose and that the Sun and planetary system probably possessed about ten times the angular momentum than at present has recently caused McCrea to revise his theory.[12] The system now has to be assembled from parts that are 100 times fewer, but with the mass of each being a hundred times greater. Consequently floccules are replaced by bodies of protoplanetary mass, which are stable once formed. If such objects could form within dense interstellar gas clouds, then those that do not become incorporated into visible stars could in principle make up a population of "Jupiters" that might account for the unseen mass. It is interesting to note that the brown dwarf population modelled by D'Antona and Mazzitelli has a number density of ~ 9 pc^{-3} between 0.003–0.01 $M_{\odot}$. Such a population is thought unlikely to exist in the standard picture of star formation.

Singular planets may also exist at the bottom end of the mass range as "plomets"—giant comets of planetary size. The provenance of comets remains uncertain,[13] even though the majority of current opinion favors a solar system origin. Clube and Napier have been prominent in advocating an interstellar origin of comets.[14,15] They envisage comets being formed in molecular clouds, either by sedimentation of dust,[16] or by differential radiation pressure,[17] and thus provide an explanation for the heavy element depletion observed in molecular clouds. They estimate a comet number density of 10^{-1} AU^{-3} within the cloud and 10^{-4} AU^{-3} within the galactic disk as a whole, consistent with the failure to observe comets on hyperbolic trajectories entering the solar system.[18] This is linked to a theory of terrestrial catastrophism where comets are captured by the Sun as it passes through galactic spiral arms. They propose that episodic climate changes, mass extinctions and geological changes, such as magnetic field reversals, are evidence for the arrival and break-up of giant comets in the inner solar system. Thus, if giant comets exist and originate within molecular clouds, the largest of them may qualify as SPs.

Napier and Humphries[19] have provided a model where comets grow in the star forming regions of interstellar clouds by the coagulation of grains driven by a photo-desorption mechanism within a UV radiation field. In such an environment they estimate a collapse time of 10^3–10^5 yr with comets forming of dimensions up to lunar size in particularly quiescent regions. This proposed *"population of interstellar comets and moons"* is of interest to this study of ISPs as the most massive of them, $\sim 10^{22}$ kg, is within the range adopted. The uncertainties are so great, however, that it is not possible to derive a number density of such objects in interstellar space. An upper limit can be estimated from two constraints, the lack of such bodies passing through the solar system in recorded history and the metal depletion of the galaxy. According to Napier[20] if bodies of mean mass $\overline{m}$ kg and number density n AU^{-3} are produced in giant molecular clouds with lifetimes L yr, then over 10^{10} yr the metal content locked up in such bodies is:

$$\delta z = 0.03\,\frac{(\overline{m}/10^{21})(n/10^{-7})}{(L/4 \times 10^7)}. \qquad (1)$$

Galactic chemistry requires $\delta z < 0.1$, so the number density of "plomets" could be as high as $\sim 10^{-8}$ AU^{-3} ($\sim 10^8$ pc^{-3}) without violating any obvious constraints. In reality, however, since the cometary mass distribution probably tails off at masses above $\sim 10^{20}$ kg, the number density of truly planetary sized comets, should a population of interstellar comets exist at all, is likely to be far less.

The above analysis of the prospect for the existence of singular planets would fill few astronomers with optimism. It seems that SP formation requires the most favored cosmogonic hypotheses to be wrong. This is quite possible, in which case singular planets might be very abundant. However, if the general thrust of the majority of current research is in the right direction, interstellar planets must be stray bodies, unbound and lost from their original planetary systems.

3. UNBOUND PLANETS

For the purposes of this study, UBPs are classified into two groups designated *late type* and *early type*. Late type UBPs are defined as planets ejected from systems where the process of planetary formation is complete and early type are protoplanets or planetesimals of planetary mass ejected from systems in formation.

3.1. Production of Late Type Unbound Planets

Fogg[21] has identified two planetary unbinding mechanisms that might serve to produce UBPs, namely a supernova of the central star and close stellar encounters.

3.1.1. Supernovae

When a star explodes as a supernova (SN), it ejects a substantial amount of its mass in a blast wave at high velocity. From the point of view of an orbiting planet this loss is effectively instantaneous and if the star expels more than half its mass in the explosion, the planets will become unbound.

There are no theoretical considerations that totally rule out the formation of planets about Type II SN progenitor stars. The main constraint would be that planets must have the time to form during the Main Sequence lifetime of the primary. The lower limit for the mass of a Type II SN progenitor is not known due to uncertainties regarding the evolution of intermediate mass stars of 2.3–8 $M_\odot$. It appears that stars of > 8 $M_\odot$ undergo a core collapse SN,[22] leaving a neutron star remnant of < 2 $M_\odot$ and stars of < 4 $M_\odot$ become white dwarfs. Stars between 4–8 $M_\odot$ either evolve to the white dwarf stage[23] or undergo degenerate carbon ignition, producing a carbon deflagration SN, which disrupts the entire star, leaving no remnant at all. Unless the SN progenitor suffers extensive mass loss, reducing it to < 4 $M_\odot$ before the explosion, then the unbinding of any planetary system is inevitable.

The main sequence lifetime of a star is roughly $T_{\text{MS}} \simeq 10^{10}$ $(M/M_\odot)^{-2.5}$ yr. Thus, 4 $M_\odot$ stars endure for $\sim 3 \times 10^8$ yr and 8 $M_\odot$ stars for $\sim 6 \times 10^7$ yr. The timescale for planetary formation varies with competing models from $\sim 10^4$ yr according to the gaseous protoplanet hypothesis[24] to $\sim 10^7$–10^8 yr by the accretion of planetesimals.[25] Either way, it seems that planets could reach an advanced stage of formation around supernova progenitor stars. The number density of UBPs produced by the supernova mechanism is expected to be:

$$n_{\text{UBP}} \simeq n_* f_{\text{SN}} f_s n_p \text{ pc}^{-3}, \tag{2}$$

where n_* is the stellar number density; f_{SN} is the fraction of stars that undergo SN explosion; f_s is the fraction of single stars, those assumed to have planetary systems,[26] and n_p is the average number of planets surrounding such a star. Here we take $f_s = 0.3$ (Apt[27]), $n_* \sim 0.1$ pc^{-3} and $n_p = 10$ (on the assumption that satellites do not become unbound from planets and that no population of "plomets" exist within any circumstellar cometary cloud).

The fraction f_{SN} can be estimated from the initial stellar mass spectrum derived by Scalo[28]:

$$dN/dM \propto M^{-\gamma}, \tag{3}$$

where M is the stellar mass and $\gamma = 1.94 + 0.94 \log(M)$. If supernovae occur for stars of > 4 M$_\odot$, then $f_{\mathrm{SN}} \sim 0.01$ and $n_{\mathrm{UBP}} \sim 3 \times 10^{-3}$ pc^{-3}. If, as seems more likely, only stars of > 8 M$_\odot$ explode, then $f_{\mathrm{SN}} \sim 0.002$ and $n_{\mathrm{UBP}} \sim 6 \times 10^{-4}$ pc^{-3}. It is apparent that the supernova unbinding mechanism does not give rise to abundant numbers of unbound planets relative to stars.

3.1.2. Close Stellar Encounters

Gravitational perturbation into an escape orbit by a passing star is another mechanism that might serve to unbind planets and distribute them into interstellar space.

Hills[29] has simulated the scenario of a close encounter between a 1 M$_\odot$ star/planet system with an intruding star of 1 M$_\odot$. He found that if the closest approach of the intruder is 2–3 times the semimajor axis of the orbit or less, then the encounter tended to increase the semimajor axis of the S/P system or to dissociate it altogether. The probability of the solar system planets having been disturbed over the lifetime of the Sun can give some indication as to the prevalence of UBPs produced by close stellar encounters.

Over a time t, the most probable impact parameter in AU of any stellar intruder relative to another star is:

$$P_0 = 210 \left[\left(\frac{\mathrm{pc}^{-3}}{n_*} \right) \left(\frac{10^{10}\ \mathrm{yr}}{t} \right) \left(\frac{30\ \mathrm{kms}^{-1}}{v} \right) \right]^{1/2} \mathrm{AU}, \tag{4}$$

where v is the average relative stellar velocity. For the Sun we have $t = 4.6 \times 10^9$ yr and $v = 30$ km s^{-1}; thus $P_0 = 980$ AU.

According to Hills, an encounter at an impact parameter of $P =$ 40 AU or less would have left its mark on the solar planets, the probability of this being $\sim (P/P_0)^2 \sim 0.0017$. This low probability indicates that the stellar encounter mechanism for unbinding planets is very inefficient in our comparatively uncrowded suburb of the Milky Way.

The number density of UBPs produced in this way can be estimated from the following equation:

$$n_{\mathrm{UBP}} \approx 2n_* f_s P_0^{-2} \int P n_{ej}(P)\, dP \ \mathrm{pc}^{-3} \tag{5}$$

where P is the impact parameter of the stellar intruder and $n_{ej}(P)$ is a function determining the number of planets ejected by the encounter.

The following equation was derived to represent the ejection function, using a Bode's Law arrangement of planets of semimajor axes $a > 0.7$ AU and assuming that half the planets with $a > P$ are ejected:

$$n_{ej}(P) = 4 - 0.72 \ln\left(\frac{10}{3} P \sim \frac{4}{3}\right). \tag{6}$$

Thus, so long as $P_0 >> P$ and assuming the average extent of a typical planetary system is similar to the solar system, Eq. (4) becomes:

$$n_{\mathrm{UBP}} \approx 2n_* f_s P_0^{-2} \int_{0.7}^{40} \left\{ 4P - 0.72P \ln\left(\frac{10}{3}P - \frac{4}{3}\right)\right\} dP \ \mathrm{pc}^{-3}. \tag{7}$$

Solving Eq. (6) with input parameters appropriate to the solar neighborhood gives the value $n_{\mathrm{UBP}} \sim 4.2 \times 10^{-5}\ \mathrm{pc}^{-3}$.

However, the choice of a stellar number density of $n_* \sim 0.1$ pc^{-3} (case (i)) represents only visible stars. If the unseen matter in the solar neighborhood is taken into account, estimates for the number density of UBPs of this type can be substantially increased.

Three alternative values of n_* are considered here. Case (ii): the unseen mass is comprised of stellar remnants such as dim white dwarfs, giving $n_* \sim 0.2$ pc^{-3}. Case (iii): a population of brown dwarfs exists, similar to that modelled by Probst,[9] giving $n_* \sim 1.7$ pc^{-3}. Case (iv): a population of brown dwarfs exists, similar to that modelled by D'Antona and Mazzitelli,[3] giving $n_* \sim 11$ pc^{-3}. All these models satisfy Hill's criterion that the probability of a stellar encounter of $P < 40$ AU over the lifetime of the solar system is $<< 1$.

Table I summarizes the results for late type UBPs, in terms of number density, for the solar neighborhood. Estimates are divided into three columns depending on the rate of supernova produced UBPs. Case (a): supernova progenitor stars do not possess planets; case (b): stars of > 8 $M_\odot$ eject planets by the SN mechanism; and case (c): stars of > 4 $M_\odot$ eject planets by the SN mechanism. These data show that reasonable estimates of n_{UBP} vary by 4 orders of magnitude due to uncertainties of factors such as the stellar number density and the nature of the local unseen mass. The value of n_{UBP} for case (iv), however, must be considered as an over-estimate as the majority of encounters would be with objects of < 0.01 $M_\odot$ which would be less likely to cause serious gravitational disturbance. The planetary systems of such "stars" might also be more compact than considered above, reducing the impact parameter required for unbinding to occur. Moreover, since brown dwarfs of

TABLE I

	n_{UBP} pc^{-3}		
	No Planets Around SN Progenitors (a)	SN for Stars > 8 $M_\odot$ (b)	SN for Stars > 4 $M_\odot$ (c)
Unseen matter not in stars (i)	4.2×10^{-5}	6.4×10^{-4}	3.0×10^{-3}
Unseen matter in WDs (ii)	1.7×10^{-4}	7.6×10^{-4}	3.2×10^{-3}
Probst BD model (iii)	1.2×10^{-2}	1.3×10^{-2}	1.5×10^{-2}
D and M BD model (iv)	5.1×10^{-1}	5.1×10^{-1}	5.1×10^{-1}

$< 0.01\ M_\odot$ may never form in the first place, a value of n_{UBP} of between 4.2×10^{-5} and 1.5×10^{-2} seems more plausible.

Unless a massive population of brown dwarfs, accompanied by their own planets, exists, then it is apparent that the relative scarcity of stars and the rarity of stellar encounters is not conducive to frequent disruption and unbinding of fully formed planetary systems. Late type UBPs are rare and will be in any environment where the stellar number density is not exceptionally high. However, in contrast to the case of singular planets, it is at least possible to state with a reasonable degree of confidence that unbound planets exist. Fogg[21] has investigated the radial abundance gradients of such UBPs in the galactic plane. For case (ib), the stellar encounter production mechanism dominates over the SN mechanism only at distances of < 0.9 kpc from the galactic center. Only in exotic localities, such as within the heart of a galaxy or globular cluster, would n_{UBP} approach the limiting value of $n{\cdot}f_s n_p$.

3.2. Production of Early Type Unbound Planets

A potentially rich source of UBPs are planetary systems in formation. Recent research suggests that gravitational scattering of massive planetesimals into hyperbolic orbits during the accumulation process is likely, the details depending on the cosmogony. A large number of papers have been published on the subject of planetary formation, particularly in the last decade; the review below is a very limited attempt to assess the relevance of modern cosmogeny to the production of unbound planets.

The most highly regarded models of the solar nebula divide into two types: a massive nebula of $\sim 1\ M_\odot$ where giant gaseous protoplanets form by gravitational instability[24] and a low mass nebula of $\sim 0.02\ M_\odot$ where the terrestrial planets and the cores of the giant planets form by the accumulation of planetesimals.[25] The latter model, being currently the most fashionable, is considered first.

The accretion process within a heliocentric swarm of planetesimals is thought to proceed as follows. Once an embryo planet reaches a certain mass, it undergoes a runaway accretion, rapidly sweeping up the remaining planetesimals in its feeding zone. It is probable that the number of planetary embryos formed initially was considerably greater than the final number of planets. The giant planets, particularly Jupiter and Saturn, then grow further by gravitational accretion of nebular gas. In the latter stages, the dominant process changes from accumulation to ejection as the random velocities of the planetesimals are increased by encounters with larger bodies. Once Jupiter had formed, it would have acted as a very efficient ejector of material, the probability of ejection per encounter being 2–3 orders of magnitude higher than that of collision.[30] Fernandez and Ip[31] have modelled the formation of the Oort Cloud by the scattering of icy planetesimals by the giant planets. The percentage of ejecta *escaping* the solar system as opposed to winding up in the Oort Cloud was for each planet: Jupiter, 97%; Saturn, 86%; Uranus, 43% and Neptune, 28%. Thus, while Neptune and Uranus may have been the primary contributors to the Oort Cloud, Jupiter and Saturn would have been most responsible for unbinding material and launching it into interstellar space.

A planetesimal would count as a planet (i) when it reaches a characteristic mass and (ii) when it ceases significant growth. Thus, for early type UBPs to be abundant, massive planetesimals must come into existence during planetary system formation and some must be ejected rather than colliding with a future planet. Much interest has been shown recently in a population of such massive planetesimals with respect to the impact origin of the Moon[32] and to explain the spin and orbital properties of the planets.[33]

Wetherill[34] has simulated the formation of the terrestrial planets from a swarm of planetesimals and has found that the accumulation of large planetesimals that fail to become planets may be a normal phenomenon. Midway through the growth of the swarm, ~ 100 bodies of lunar mass, ~ 10 bodies of mercurian mass and several of the mass of Mars are in existence. By the end of the accretion process, typically ~ 5% of the mass of the swarm has been perturbed into Jupiter crossing orbits and is assumed to be ejected from the solar system. This mass loss is preferentially in $< 10^{23}$ kg bodies, implying that ~ 8 Moon-sized UBPs could have been produced as a byproduct of terrestrial planet accretion. The creation of UBPs of up to Mars size within this scenario is not implausible.

Much more massive planetesimals could have come into existence in the outer solar system. If the nebular density falls off as

$1/a$, then the limiting mass of a runaway planetary embryo is proportional to $a^{1.5}$. This is indeed suggested by the variation in obliquity and rotation of the planets which is too great to be the result of average accumulation of small particles. Hartmann and Vail[33] have investigated the largest size of impacting planetesimals required to explain these properties. Their most promising model involves the planets in the inner solar system being hit by a population of impactors associated with each planet, ranging up to a few percent of each planet's mass. The outer solar system is dominated by a scattered swarm of Jupiter planetesimals with masses of up to 2% the mass of Jupiter. Such a model predicts 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. The presence of Jupiter-scattered planetesimals has also been invoked to explain the high relative velocities of the asteroids and the dearth of mass in the asteroidal region. In a recent investigation, Wetherill[35] has simulated the simultaneous orbital evolution of 500 4×10^{21} kg asteroids interacting with 100 4×10^{24} kg (2/3 Earth mass) Jupiter-scattered planetesimals. After 700 Myr, 94% of the mass in the asteroidal region had been lost and almost all of the Jupiter planetesimals were found to be ejected. Similar calculations with smaller Jupiter-zone bodies showed that these objects had to be $> 1.8 \times 10^{24}$ kg to be effectual in accelerating most of the asteroids to high velocities. Thus, a substantial population of massive outer solar system planetesimals can be invoked to resolve a number of problems. The conservation of mass during the accumulation process in this region would have been much less efficient than that in the terrestrial zone because of the greater distance from the Sun and the presence of more massive planets, especially Jupiter. This provides the strong possibility of the ejection of such planetesimals from the solar system and the production of early type UBPs of up to several Earth masses.

One of the problems with the planetary accretion hypothesis is that the cores of the giant planets must grow rapidly in $< 10^6$ yr so that they can accrete their gaseous envelopes before the protoplanetary disk is dispersed by the Sun's T-Tauri stellar wind. Minimum mass models of the solar nebula give accretion timescales of $\sim 10^8$ yr for Jupiter to longer than the age of the solar system for Neptune. Lissauer[36] has proposed that accretion timescales can be greatly reduced if the minimum mass disk assumption is relaxed. If the surface density of solids in the Jupiter zone was 5–10 times that required to account for the Jovian core (10–25 $M_\oplus$), then it could have grown rapidly in $\sim 8 \times 10^5$ yr. It would then have rapidly accreted gas to grow to 318 $M_\oplus$ whereupon it would have dominated a large region of the solar system through gravitational perturbations. Lissauer's model implies that if Jupiter's zone contained 5–10 times the amount of solids contained within its core, then > 50 $M_\oplus$ must have been ejected from the solar system. It might have been that a significant fraction of this mass was contained within bodies of planetary dimension.

If the protoplanet hypothesis[24] is the correct cosmogonic theory, then it is likely that, in the terminal stages of planetary formation, ejection of excess solids into interstellar space would occur in a similar manner to that outlined above. However, Lawton[37] has outlined a possible mechanism where uncondensed protoplanets of roughly 10 Earth masses, in orbit about O,B class stars, might be propelled to escape velocity by a strong stellar wind or radiation pressure. This idea was based on observations of HII maser concentrations in W49 that were tentatively interpreted as an aggregate of protoplanetary formations in the vicinity of a massive protostar.[38] Further observations[39] of the radial velocity dispersions of these sources suggested that some of them are approaching the escape velocity of the system. On the assumption that ten such protoplanets are ejected per O,B class star and they can condense in free space, Lawton estimated a number density for these UBPs of ~ 1 pc^{-3}. However, this value is unrealistically high by 2–3 orders of magnitude as Lawton greatly underestimated the lifetimes of the parent stars and thus overestimates their past abundance. In fact, since these stars are the type that ultimately suffer supernova explosion, the number density of UBPs produced by the Lawton model should be similar in magnitude to that given by the SN model, i.e., $n_{\mathrm{UBP}} \sim 10^{-3}$ pc^{-3}.

It therefore appears that the formation of early type UBPs is quite probable, the details depending on (i) which cosmogonic theory is correct and (ii) the mass distribution of planetesimals. It is not possible, however, to make any firm predictions as to the number density of such objects in interstellar space. In a qualitative study of some of the runs of his computer simulation, Ip[40] has estimated that the ejection of 5 Mars-sized bodies is possible in some circumstances, giving $n_{\mathrm{UBP}} \sim 5f_s n_*\ \mathrm{pc}^{-3}$ or 0.15 pc^{-3} using the number density of visible stars only. This may represent a low estimate if Lissauer's cosmogonic model is correct; the ejection of 100 "Jupiter-zone bodies" per star would give $n_{\mathrm{UBP}} \sim 3\ \mathrm{pc}^{-3}$.

4. CONCLUSIONS

A classification of interstellar planets has been proposed and six potential mechanisms for their formation have been reviewed, namely:

(1) Singular Planets

(a) Formation of isolated sub-brown dwarf mass bodies in star forming regions, if stellar mass function extends below 0.01 $M_\odot$ ($n_{\mathrm{UBP}} \sim 10\ \mathrm{pc}^{-3}$).

(b) Formation of giant comets of up to lunar size within molecular clouds ($n_{\mathrm{UBP}} < 10^8\ \mathrm{pc}^{-3}$).

(2) Unbound Planets (Late Type)

(a) Ejection from a star system after supernova of the central star ($n_{\mathrm{UBP}} \sim 10^{-3}\ \mathrm{pc}^{-3}$).

(b) Gravitational scattering and ejection from a planetary system following a close encounter with a foreign star ($n_{\mathrm{UBP}} \sim 10^{-5}$–$10^{-2}\ \mathrm{pc}^{-3}$).

(3) Unbound Planets (Early Type)

(a) Gravitational scattering and ejection of massive planetesimals during the terminal stages of planetary accumulation ($n_{\mathrm{UBP}} \sim 0.1$–$10\ \mathrm{pc}^{-3}$).

(b) Ejection of giant gaseous protoplanets from the vicinity of O,B class stars by stellar wind or radiation pressure ($n_{\mathrm{UBP}} \sim 10^{-3}\ \mathrm{pc}^{-3}$).

Figure 2 shows the most likely mass range for ISPs in each category.

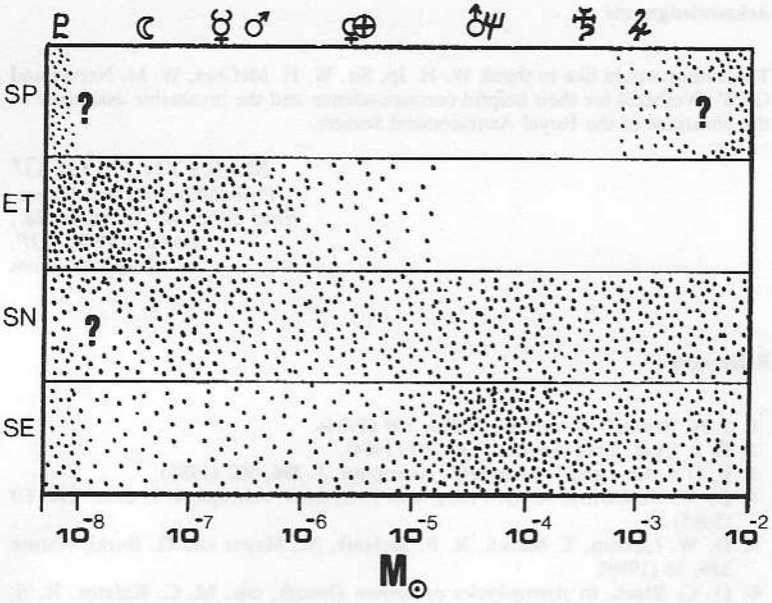

FIGURE 2 The likely mass ranges of four types of ISP. Bars represent, in order of top to bottom, (i) singular planets, (ii) early type UBPs, (iii) suprnova produced UBPs and (iv) UBPs produced by close stellar encounters. Question marks indicate areas of particular uncertainty. SPs have difficulties outlined in Section 2 and planets of very low mass may not survive a SN explosion that ejects them.

The existence of singular planets is problematic, their existence requiring that the most favored models for star and comet formation 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. A better understanding of these processes will enable more rigorous estimates to be made as to their importance. Perhaps the best guess that can be made for the number density of ISPs in the solar neighborhood is $n_{\mathrm{ISP}} > 0.1\ \mathrm{pc}^{-3}$. Over ninety percent of these would be early type UBPs (unbound massive planetesimals), the rest varieties of late type. The contribution of such a population of ISPs to the unseen mass would be negligible, possibly little more than a millionth of that required. It is interesting, however, that with a values of $n_{\mathrm{ISP}}/n_* > 1$, the nearest extra-solar planet may be considerably closer to the solar system than the nearest star.

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