UNBOUND PLANETS

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Abstract. Current protostellar theory has determined a lower limit to the mass of a pre-stellar gas cloud fragment of $\sim 0.01\ M_\odot$. This suggests that isolated interstellar bodies in the mass range $\sim 10^{-7}$–$10^{-2}\ M_\odot$ must have originated within a planetary system. Two possible mechanisms whereby planets are lost from their parental systems to interstellar space are discussed and the abundance and distribution of such 'unbound planets' within the Galaxy is examined. It is found that, except within the central regions of the Galaxy, unbound planets are expected to be scarce. In the solar neighbourhood for instance, the number density ratio of unbound planets to stars is estimated to range between extremes of $\sim 4 \times 10^{-4}$–3×10^{-2} with a most probable value of $\sim 6 \times 10^{-3}$. The faint possibility that the hypothetical 'Planet X' might be of extra-solar origin is also discussed.

1. Introduction

It has been inferred from studying the distribution of stars that about half of the mass in the solar neighbourhood is unseen or 'missing' (Bahcall, 1984). The most likely explanation for the local 'missing mass' (which may be distinct from the missing mass in the galactic halo) is considered to be the presence of numerous substellar objects too faint to be observable with present techniques. Stars of less than $0.08\ M_\odot$ cannot sustain hydrogen burning in the core, and after a brief phase of deuterium burning, they slowly contract to become cool, faint, Jupiter sized bodies (D'Antona and Mazzitelli, 1985). It is not known if enough of these 'brown dwarfs' have formed to account for the local mass density. No solitary brown dwarf has been definitely detected and it is as yet unknown whether the stellar mass function increases for $M < 0.1\ M_\odot$.

Should a brown dwarf be properly classed as a star or as a planet? Black (quoted from Trimble, 1986) has drawn a sharp line between the two, based upon their mode of formation: stars form by fragmentation of a gas cloud without significant dissipation or chemical fractionation; planets result when dissipation produces a disk around a single proto-star. Solitary brown dwarfs thus would clearly be 'failed stars'. Studies of star formation have identified a minimum stellar mass limit of $\sim 0.01\ M_\odot$, as gas cloud fragmentation terminates when individual fragments become opaque (Silk, 1978). Thus brown dwarfs, as the smallest solitary objects to form from a gas cloud are expected to have a minimum possible mass; an ever increasing mass function extrapolated down to lower masses does not seem likely. True interstellar planets therefore are likely to be stray bodies, unbound and lost from their original planetary systems and ranging in mass from $\sim 10^{-7}\ M_\odot < M < 10^{-2}\ M_\odot$ (see Figure 1).

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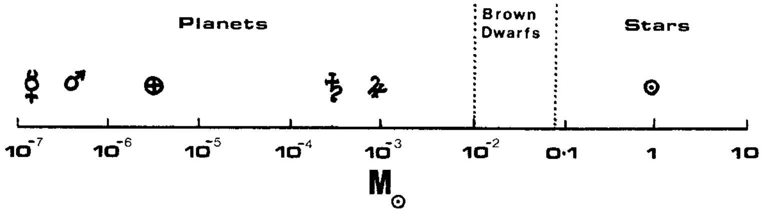

Fig. 1. The masses of stars and planets, classified as such according to mode of formation.

Lawton (1974) has considered the ejection of protoplanets from the vicinity of O,B class stars and has estimated the number density of stray planets produced to be $\sim 1 pc^{-3}$. As will be shown, this is probably much too high – mainly because Lawton greatly underestimates the Main Sequence lifetime of the parent stars and thus overestimates their past abundance.

In this paper, interstellar planets are henceforth called *unbound planets* (UBPs), a term that is more specific as to their origin. The possible formation of UBPs, their abundance and their relevance to the Planet X question are examined.

2. Possible Mechanisms of UBP Production

2.1. SUPERNOVAE

When a star explodes as a supernova it ejects a substantial quantity of mass in a blast wave at a very high velocity. From the point of view of an orbiting planet, this mass loss is effectively instantaneous. An orbiting planet finds itself travelling above the planetary system's escape velocity when a supernova progenitor ejects more than half its mass during the explosion (Hills, 1970).

Only stars of high mass end their lives in a supernova explosion (SNE). Could planets be associated with such stars? It used to be thought that the slow rotation of stars later than F5 was due to the transfer of their rotational angular momentum to a planetary system and thus only relatively low mass stars possessed planets. However, there is now evidence that stars spin down progressively with age so that the observed fast rotation of massive stars may be merely due to the fact that these stars have such short lifetimes, not because they lack planetary systems (Harrington, 1982).

The lower mass limit for the progenitor of a Type II SNE is not known due to uncertainties concerning the evolution of intermediate mass stars of 2.3–8 $M_\odot$. It appears that stars of $\gtrsim 8\ M_\odot$ undergo a core collapse SNE, leaving a neutron star remnant of $\lesssim 3\ M_\odot$ or a black hole (Nomoto, 1984) and stars of $\lesssim 4\ M_\odot$ evolve to become white dwarf stars. Stars of $4\ M_\odot \lesssim M \lesssim 8\ M_\odot$ either evolve to the white dwarf stage (Iben, 1985) or undergo degenerate carbon ignition, producing a carbon deflagration SNE, which disrupts the entire star leaving no remnant at all (Arnett, 1969). In all these cases of SNE, insufficient mass is retained in a central body to prevent the unbinding of a planetary system.

The main sequence lifetime of a star is roughly $T_{MS} \simeq 10^{10}(\mathrm{M}/\mathrm{M}_\odot)^{-2.3}$ yr. Thus 4 $\mathrm{M}_\odot$ stars last for $\sim 4 \times 10^8$ yr and 8 $\mathrm{M}_\odot$ stars for $\sim 8 \times 10^7$ yr. The time-scale for planet formation varies between competing models from $\sim 10^4$ yr according the the protoplanet hypothesis (Cameron, 1978) to $\sim 10^7$–10^8 yr by the accretion of planetesimals (Wetherill, 1978). Either way, it seems that planets would have sufficient time to form around supernova progenitor stars.

It is quite possible therefore that stars of a much greater mass than the Sun could be accompanied by planets in a fairly primitive state. These planets might become unbound following a SNE. The type of star producing UBPs by this mechanism is the same that Lawton (1974) proposes might shed protoplanets early on in its lifetime. The ultimate effects on UBP production would thus be similar, irrespective at which stellar evolutionary stage the planetary system was shed. Lawton is in error, however, to assume that the typical lifetime of such a star to be only about 10^6 yr and thus his estimate for UBP abundance is at least two orders of magnitude too high.

2.2. CLOSE STELLAR ENCOUNTERS

Hills (1984) has studied the effects of a close encounter between a 1 $\mathrm{M}_\odot$ star/planet system with a stellar intruder of 1 $\mathrm{M}_\odot$ 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 semi-major axis of the S/P system or even to dissociate it. This mechanism therefore would also serve to unbind planets and to distribute them into interstellar space.

Hills also looked at the probability of a close stellar encounter having disturbed the Solar System. Over a time t, the most probable smallest impact parameter in AU of any stellar intruder relative to the S/P system is

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

where n is the stellar number density and V is their average velocity relative to the S/P system. For the Solar System, $n = 0.1\,pc^{-3}$, $t = 4.6 \times 10^9$ yr and $V = 30$ km s^{-1}; thus $P_0 = 980$ AU. Hills assumed that an encounter with impact parameter $P = 40$ AU or less would have left its mark on the orbits of the solar planets. The probability of this $\simeq (P/P_0)^2 = 0.17\%$.

This low probability of the Solar System having been disturbed tells us that, in our region of the Galaxy, UBPs released by close stellar encounters would not be abundant. However as stellar density increases with decreasing distance from the galactic center so would the effectiveness of UBP production by the Hills mechanism.

3. Modelling the Production of UBPs

In view of the considerable magnitude of uncertainty involved in the processes of planetary formation and the loss of planets to interstellar space, a simple model for the production of UBPs is justified. A method of estimating the abundance of UBPs in different locations in the galactic plane is outlined below.

The variation of disk star number density in the galactic plane at a distance r from the galactic center is approximately given by

$$\rho_d \approx 0.1 \exp[-(r - r_0)/h]\, pc^{-3} \tag{2}$$

(Bahcall and Soneira, 1980), where r_0 is the distance of the Sun from the galactic center ($r_0 \simeq 8.5\ kpc$) and h is the scale-length ($h = 3.5\ kpc$).

The spheroidal star population is well fit by an $r^{-3.5}$ power law (Mould, 1986) and the number density of these stars in the solar neighbourhood is only about 1/800 of the value for the disk. Thus, the following equation for spheroidal star number density has been adopted:

$$\rho_{sph} \approx 1.25 \times 10^{-4}\left(\frac{r}{r_0}\right)^{-3.5} pc^{-3}. \tag{3}$$

The overall stellar number density, therefore, is $n = \rho_d + \rho_{sph}\, pc^{-3}$. The number density of UBPs is expected to be

$$n_{UBP} \approx n(L_{SN} + L_H)\, pc^{-3}, \tag{4}$$

where the term in brackets represent the average number of UBPs produced per star by the SNE mechanism and the Hills mechanism, respectively.

The SNE mechanism coefficient is given by

$$L_{SN} \approx f_{SN}\, n_p\, f_s \tag{5}$$

where f_{SN} is the fraction of stars that explode as supernovae, n_p is the average number of planets surrounding such a star and f_s is the fraction of single stars, those assumed to possess planetary systems (Heppenheimer, 1978). Here we take $n_p = 10$ and $f_s = 0.3$ (Apt, 1978).

The quantity f_{SN} can be estimated from the stellar mass spectrum estimated by Scalo (1978) as

$$dN/dM \propto M^{-\gamma} \tag{6}$$

where M is the stellar mass and $\gamma = 1.94 + 0.94\log(\mathrm{M})$. If SNE occur for stars $>4\ \mathrm{M}_\odot$ then $f_{SN} \simeq 1\%$; if only stars $>8\ \mathrm{M}_\odot$ explode then $f_{SN} \simeq 0.2\%$.

UBP production by the Hills mechanism is modelled by

$$L_H \approx f_s \int 2P\, P_0^{-2}\, n_{ej}(P)\, \mathrm{d}P \tag{7}$$

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

The following equation was chosen for the ejection function, using a Bode's law arrangement of planets of semimajor axes $a \geqslant 0.7$ AU and assuming that half of the planets with a $\geqslant P$ are ejected,

$$n_{ej}(P) = 4 - 0.72 \ln\left(\frac{10}{3}P - \frac{4}{3}\right). \tag{8}$$

Thus, so long as $P_0 \gg P$ and assuming the average extent of a typical planetary system is similar to the solar system, Equation (7) becomes

$$L_H \approx 2 f_s P_0^{-2} \int_{0.7}^{40} \left\{ 4P - 0.72P \ln\left(\frac{10}{3} P - \frac{4}{3} \right) \right\} \mathrm{d}P. \tag{9}$$

4. Estimates of UBP Abundance

4.1. PARAMETERS

Three choices of parameters are chosen to estimate the possible range of UBP abundance:

(1) $L_{SN} = 0$; planets are not formed around high mass stars and thus only the Hill's mechanism can produce UBPs.

(2) $L_{SN} = 0.006$; only stars $\geqslant 8\ \mathrm{M}_\odot$ eject UBPs by the SNE mechanism ($f_{SN} \simeq 0.002$). This parameter set may represent the most reasonable estimate of L_{SN}.

(3) $L_{SN} = 0.03$; stars of $\geqslant 4\ \mathrm{M}_\odot$ eject UBPs by the SNE mechanism ($f_{SN} \simeq 0.01$).

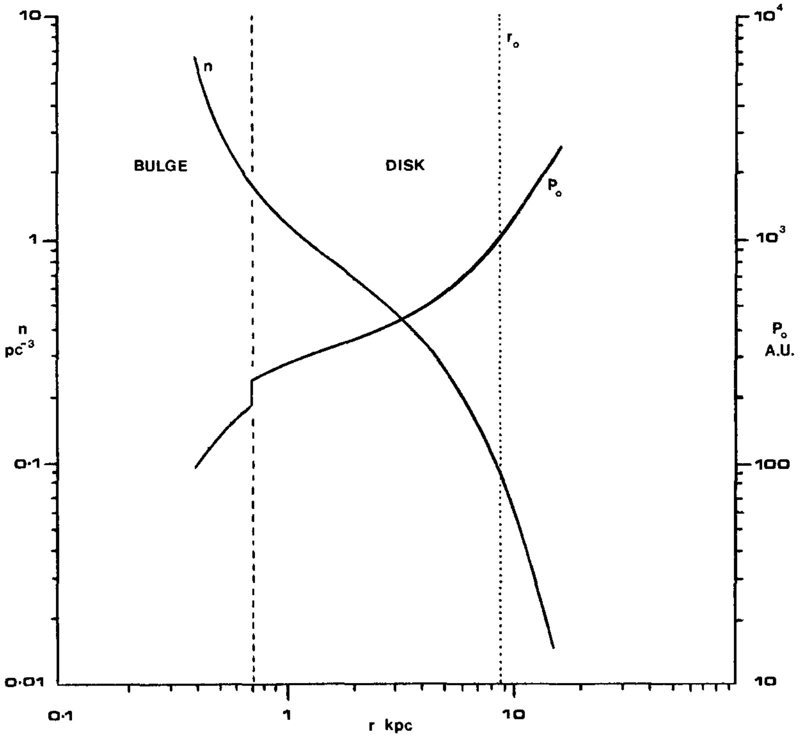

Fig. 2. Stellar number density n pc^{-3} and most probable impact parameter P_0 AU, plotted against distance along the galactic plane r kpc. The line marked r_0 represents the distance of the Sun from the galactic centre.

Other parameters are set as follows. Relative stellar velocity is assumed fixed at $V = 30\ \mathrm{km\ s^{-1}}$. For $r > 0.7$ kpc, $t = 5 \times 10^9$ yr; for $r \leqslant 0.7$ kpc (the interior of the galactic bulge) $t = 7.5 \times 10^9$ yr. Equation 9 becomes unreliable at low values of r, so calculations are terminated at $r = 0.4$ kpc.

Figure 2 shows stellar number density n and most probable smallest impact parameter P_0 plotted against radial distance along the galactic plane r from the galactic center. These are the parameters relevant to UBP production by the Hills mechanism.

4.2. RESULTS

For each parameter set, the ratio of UBPs to local stars, n_{UBP}/n, is plotted against radial distance along the galactic plane r in Figure 3. The location of the Sun is indicated by the line marked r_0. Values for n_{UBP}/n and estimates of the average spatial separation of UBPs at r_0 are given in Table I.

It can be seen that the UBP abundance in the solar neighbourhood is expected to be very low. The results indicate that 1 UBP is expected for between ~30–2400

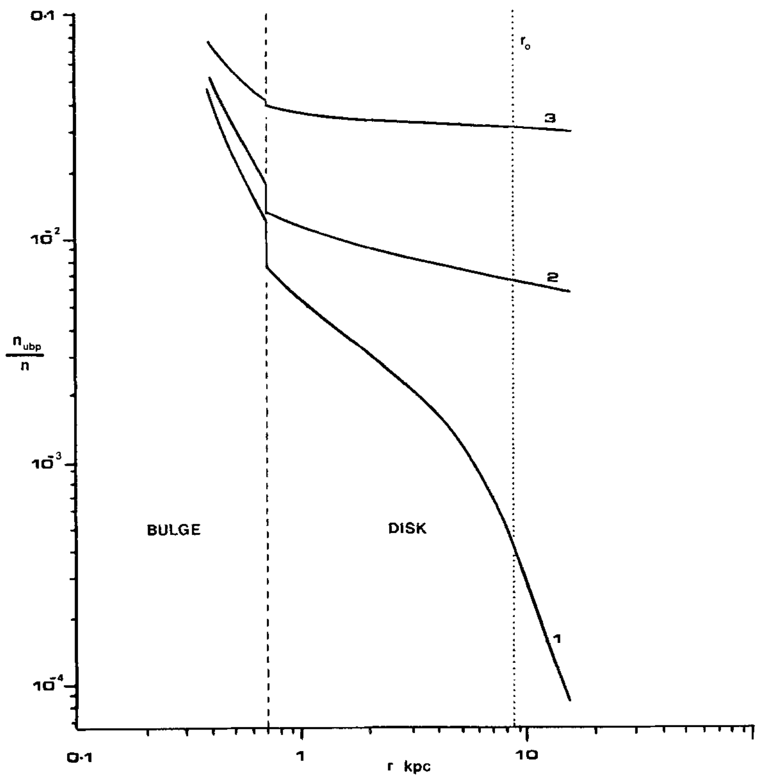

Fig. 3. The ratio of UBP number density n_{UBP} to stellar number density n, for the three parameter sets, plotted against r. The step in each curve at $r = 0.7$ kpc is due to the higher average age assumed for bulge stars.

TABLE I

Results for UBPs in the solar neighbourhood

Set	1	2	3
n_{UBP}/n ~	4.2×10^{-4}	6.4×10^{-3}	3.0×10^{-2}
av. sep (pc) ~	17.8	7.2	4.3

stars, these objects having an average separation of ~4–18 pc. The nearest UBP to the Solar System probably lies no nearer than 2 pc. In no case do we obtain a value close to $n_{UBP}/n \sim 10$, as estimated by Lawton (1974).

Ejection of planets by supernovae is the dominant mechanism of UBP production for all values of r investigated in Set 3. In Set 2 L_H becomes larger than L_{SN} at $r < 0.9$ kpc. Thus only within the inner disk or galactic bulge would substantial quantities of UBPs be expected as the Hills mechanism becomes more efficient. Deep within the core of the Galaxy (not modelled here) unbound planets would wander crowded interstellar space; n_{UBP}/n would approach the limiting value of $f_s \cdot n_p$.

5. Conclusions

It is concluded here that, whilst it is likely that interstellar planets exist, they are relatively rare. The search for unseen bodies to account for the missing mass properly concentrates on the detection of brown dwarfs.

However, should current theories of star formation be incorrect in predicting a minimum gas cloud fragment mass of $\sim 0.01\ M_\odot$, then one might still speculate that numerous bodies, both of planetary mass and dimensions, litter interstellar space. All that can then be concluded from the above calculations is that the fraction of these bodies that are in reality unbound planets is low.

6. An Afterthought: Could Planet X Be a UBP?

A hypothetical tenth planet, the so-called 'Planet X', has been invoked on a number of occasions to account for diverse astronomical phenomena.

Harrington and Van Flandern (1979) have proposed that Pluto might have originally been a satellite of Neptune and was ejected into its present eccentric orbit by a close encounter between Neptune and Planet X. Might this Planet X have been a UBP on a flyby through the Solar System, with impact parameter $P \sim 30$ AU?

Matese and Whitmire (1986) have presumed the existence of Planet X in order to drive a comet shower mechanism that might account for the supposed ~26 Myr periodicity in biological mass extinctions on the Earth (Raup and Sepkoski, 1984). In their model, Planet X parameters are as follows: mass $m \simeq 5\ m_\oplus$; semi-major axis $a \simeq 100$ AU; eccentricity $e \simeq 0.3$ and inclination to the ecliptic $i \simeq 45°$. Current theories of planet formation would have difficulty explaining the formation of a planet in such an eccentric and inclined orbit. Could Planet X therefore be of extra-solar origin?

Taking the Set 2 parameter results, the number density of UBPs in the solar neighbourhood is $n_{UBP} \simeq 6 \times 10^{-4}$ pc^{-3}. The most probable smallest impact parameter for UBPs encountering the Solar System is, therefore, about 12640 AU. In our former case $P \simeq 30$ AU, so the chance of such an encounter occurring over the lifetime of the Solar System $\simeq (30/12640)^2 \simeq 6 \times 10^{-6}$. Similarly, for the latter case, the probability of an encounter with a UBP at $P \simeq 100$ AU $\simeq 6 \times 10^{-5}$. Both these encounter probabilities are very low and the hypothesis of an extra-solar origin of Planet X is rendered even more improbable if capture into a solar orbit is required.

Thus Planet X, should it exist at all, is unlikely to be a captured extra-solar planet. It may instead have originated in the Solar System and have had its orbit perturbed by a star passing at $P \sim 200$ AU. The probability of this is ~ 0.04, much greater than the chance of encountering UBPs.

However, should a tenth planet be discovered and is found to exhibit evidence of a past episode of violent heating and ablation, such as might be expected close to a SNE, then this could well point strongly to the planet's extra-solar origin.

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References

Apt, H. A.: 1978, in T. Gehrels (ed.), *Protostars and Planets*, University of Arizona Press, p. 323.
Arnett, W. D.: 1969, *Astrophys. Space Sci.* **5**, 180.
Bahcall, J. N.: 1984, *Astrophys. J.* **276**, 169.
Bahcall, J. N. and Soneira, R. M.: 1980, *Astrophys. J. Suppl.* **44**, 73.
Cameron, A. G. W.: 1978, in T. Gehrels (ed.), *Protostars and Planets*, University of Arizona Press, p. 453.
D'Antona, F. and Mazzitelli, I.: 1985, *Astrophys. J.* **296**, 502.
Harrington, J. P.: 1982, in Hart, M. H. and Zuckerman, B. (eds.), *Extraterrestrials: Where Are They*? Pergamon Press, Oxford, p. 142.
Harrington, R. A. and Van Flandern, T. C.: 1979, *Icarus* **39**, 131.
Heppenheimer, T. A.: 1978, *Astron. Astrophys.* **65**, 421.
Hills, J. G.: 1970, Nature **226**, 730.
Hills, J. G.: 1984, *Astron. J.* **89**, 1559.
Iben, I.: 1985, *Quart J. R. Astr. Soc.* **26**, 1.
Lawton, A. T.: 1974, *Spaceflight* **16**, 188.
Matese, J. J. and Whitmire, D. P.: 1986, *Icarus* **65**, 37.
Mould, J.: 1986, in Norman, C. A., Renzini, R. and Tosi, M. (eds.), *Stellar Populations*, Cambridge University Press, p. 9.
Nomoto, K.: 1984, in Chiosi, C. and Renzini, D. (eds.), *Stellar Nucleosynthesis*, Reidel, Dordrecht, Holland, p. 239.
Raup, D. M. and Sepkoski, J. J.: 1984, *Proc. Natl. Acad. Sci. U.S.A.* **81**, 801.
Scalo, J. M.: 1978, in Gehrels, T. (ed.), *Protostars and Planets*, University of Arizona Press, p. 265.
Silk, J.: 1978, in Gehrels, T. (ed.), *Protostars and Planets*, University of Arizona Press, p. 172.
Trimble, V.: 1986, *Nature* **320**, 311.
Wetherill, G. W.: 1978, in Gehrels, T. (ed.), *Protostars and Planets*, University of Arizona Press, p. 565.