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Possibility of Life-Sustaining Planets in Interstellar Space

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During planet formation, rock and ice embryos of order Earth's mass may be formed and some of these may be ejected from the solar system as they gravitationally scatter from proto-giant planets. These bodies can retain molecular hydrogen-rich atmospheres which, upon cooling, have basal pressures of 10^2 -10^4 bars. Pressure-induced far IR opacity of H_2 prevents such a body from eliminating its internal radioactive heat except by developing an extensive adiabatic-convective atmosphere, so that although the effective temperature of the body is of order 30K, its surface temperature can exceed the melting point of water. These bodies may thus have water oceans whose surface pressure and temperature differ little from the conditions at the base of Earth's oceans. These possible abodes for life and interstellar way stations will be difficult to detect.

Planet formation is imperfectly understood, but many models involve the accumulation of solid bodies up to ~ several Earth masses while the hydrogen-rich solar nebula is still present[1]. These bodies form a gravitationally bound envelope of nebula gas. In the outer solar system, they may continue to accrete gas, so that some of them become the giant planets, while those closer to the Sun lose their gaseous envelope because of the high UV output of the Sun as it evolves onto the main sequence. In one development of these ideas[2], many embryos form quickly by runaway accretion; some of these embryos may merge but others may be scattered into escape trajectories by protoJupiter or protoSaturn. This is relatively easy since the escape velocity from Jupiter is large compared to orbital velocities at Jupiter's distance from the Sun. Planet formation may be quite inefficient in the sense that more solid material is ejected than retained. However, the extent to which this occurs depends on many poorly understood parameters, including the spatial extent of the gaseous envelopes, which may cause close encounters to become mergings rather than ejections[3]. Excessive scattering may prevent terrestrial planet formation and there are alternative views of giant planet formation[4,5] but there is also the likelihood of diverse solar system formations, so the possibility of ~Earth mass bodies in interstellar space should be taken seriously.

The amount of nebular gas accumulated and retained varies greatly according to model details , but the following general principles apply. For a solid planetary embryo of mass M immersed in a nebula of density ρ_n , the optically thin portion of its bound atmosphere has a density at distance r from the embryo center that is given by the equation of hydrostatic equilibrium and the ideal gas law:

$$\rho(r) = \rho_n \exp\left[\int_r^{\infty} \frac{R_G\,dx}{x^2 h(x/R_o)}\right] / h(r/R_o)$$
$$R_G \equiv \frac{GM}{c_n^{\,2}}; \qquad h(\xi) = [1+\xi^{-2}]^{1/4}; \quad R_o \equiv \left(\frac{L}{4\pi\sigma T_n^{\,4}}\right)^{1/2} \qquad (1)$$

where G is Newton's gravitational constant, c_n is the isothermal sound speed in the nebula, L is the luminosity of the planetary embryo, σ is Stefan-Boltzman's constant and T_n is the nebula temperature. The upper limit of the integral can be taken as infinite because the Hill sphere radius of the embryo (determining the domain in which planetary gravity dominates) is much larger than other lengthscales of interest. For T_n =150K, one finds that R_G = 8.5 x

10^{10} χ cm, where the planet mass is χM and 1M = one Earth mass ≈ 6 x 10^{27}g. The surface radius of a body of density 3 g/cm is R_s = 7.8 x 10^8 $\chi^{1/3}$ cm. For R_o small (h ~1), the surface enhancement of gas begins to occur for bodies of lunar mass (χ ~ 0.01) and becomes enormous for Mars mass bodies (χ ~ 0.1) because $R_G >> R_s$. Even for bodies eliminating their energy of formation rapidly (i.e., L ~ $GM^2/R_s\tau$ with τ ~ 10^6 years), large gas density enhancement occurs at χ ~ 0.1. For ρ_n ~ 10^{-11} g/cm^3 and sufficiently massive bodies, equation (1) ceases to be valid below a photosphere (r= R_{ph}, T = T_{ph}) when the gas becomes optically thick (roughly where $\rho(R_{ph})\kappa R_{ph}{}^2/R_G > 1$ where κ is the opacity). For an adiabatic convective atmosphere at greater depths,

$$\rho(r) = \rho(R_{ph})[1 + \frac{(\gamma - 1)R_G T_n}{\gamma T_{ph}}\left(\frac{1}{r} - \frac{1}{R_{ph}}\right)]^{1/(\gamma-1)} \qquad (2)$$

where γ is the ratio of specific heats. All these equations assume that the atmosphere has negligible mass f≡M_{atm}/M <<1. The nature of the opacity and the magnitude of the luminosity is important. One finds , for example, that an Earth mass body eliminating its energy of formation in a million years and with only pressure induced opacity due to hydrogen[6] develops an atmosphere with f ~ 0.01. These bodies have R_{ph} ~ 3 R_s. More opaque models[7] still yield atmospheric masses with f ~ 0.001 at χ ~ 1, and this agrees with detailed models[1].

The retention of a major part of this atmosphere is difficult at 1AU but increasingly likely at greater distances, and especially once the atmosphere cools (so that the photosphere is no longer large compared with the solid body). Suppose that an incident energy flux of UV photons L_{UV} is completely available to promote escape of hydrogen, then $L_{UV}.\pi R_{ph}^{2} \sim fGM^2/R_{ph}\tau_e$, where τ_e is the escape time for the atmospheric mass . One finds that

$$\tau_e \approx (5\times10^{13}\,yr).\left(\frac{R_s}{R_{ph}}\right)^2.\left(\frac{1\ erg.cm^{-2}.\sec^{-1}}{L_{UV}}\right).\chi f \qquad (3)$$

This can be as short as a million years at 1AU early in the solar system[1], but longer than the age of the solar system in the interstellar medium where a plausible value[8] for $L_{UV} \sim 10^{-2}$ $erg.cm^{-2}.s^{-1}$ in HI regions. Cosmic rays are equally unimportant .

At the present epoch (assumed to be ~4.6 Ga after formation) an interstellar planet would have a luminosity L derived from long-lived radionuclides of around $4 \times 10^{20}\chi$ erg/s if it is like Earth[9] and perhaps $2 \times 10^{20}\chi$ erg/s if it is 50/50 mixture of water ice and rock (like Ganymede, only much more massive). Assuming a thin atmosphere, the effective temperature T_e of this planet is given by $L = 4\pi R_s^2\sigma T_e^4$. Accordingly, $T_e \approx 26\chi^{1/12}$ K (rock/ice body with mean density of 3 g/cm^3) or $34\chi^{1/12}$ K (rock dominated body with mean density of 5.5 g/cm^3).

Suppose now that this planet has a dense yet thin atmosphere dominated by molecular hydrogen. From hydrostatic equilibrium, it follows that $f\chi M \approx 4\pi R_s^2 P_s/g$ where P_s is the surface pressure and g is the gravitational acceleration. One finds that P_s (in bars) $\approx$ (0.7 to 1.1) f x 10^6 bars, where the lower and higher estimates correspond to ice/rock and rock dominated bodies respectively. At 26K, the liquefaction pressure of pure H_2 is about 4 bars. For comparison, the critical pressure and temperature of H_2 are 12.8 bars and 33K respectively. However, optical depth unity at relevant IR wavelengths (~100μ or so) is achieved in such an atmosphere at a pressure of around 1 bar[6,10]. This pressure $P_e \approx g/\kappa$ where g is the gravitational acceleration and κ is the opacity, arising in this case from rotational-translational collision-induced absorption. For comparison, Uranus ($T_e \approx$ 55K and similar gravitational acceleration to Earth) achieves optical depth unity for outgoing IR at 0.3 to 0.6 bars[10] in the relevant frequency range of 50-200 cm^{-1} . The slightly higher 1 bar estimate adopted here accounts for the freezing out of rotational excitations at these very low temperatures and is fortuitously highly insensitive to χ.

A convective adiabat must form at all greater depths, even when the heat flow is very low. At the temperatures of interest, the adiabat is not a simple power law because the rotational degrees of freedom of H_2 are imperfectly excited and the discreteness of these levels must be taken into account[11]. Ortho and para populations might also be in disequilibrium[10,11]. However, an adequate estimate for our purpose assumes an adiabatic relationship $T \quad P^{0.36}$. The exponent assumes a cosmic mixture of hydrogen and helium (73% and 27% by mass respectively) and would take the value of 0.4 for a monatomic gas (or rotational degrees of freedom completely frozen) and 0.31 for this mixture when the rotational degrees of freedom are fully excited. It follows that the surface temperature T_s is given by

$$T_s \approx (275 \text{ to } 425).\ \chi^{1/12}.(f/0.001)^{0.36}\ \mathrm{K} \qquad (4)$$

where the lower (higher) value corresponds to the rock/ice (rock dominated) body respectively. The thickness of atmosphere from surface to photosphere is only of order $250\chi^{--1/3}$ km (for $T_s \approx$ 300K), and the downward corrections of estimated temperatures are typically only a few percent, justifying our thin atmosphere assumption. The melting point of water is typically exceeded for basal pressures of order one kilobar. The atmosphere will have several cloud layers (cf. Uranus) but this negligibly influences the temperature estimates. For sufficiently low masses, an alternative (collapsed atmosphere) solution exists with a molecular hydrogen ocean overlain by a thin vapor pressure-equilibrium atmosphere.

We thus see that bodies with water oceans are possible in interstellar space. The "just right" conditions are plausibly at an earth mass or slightly less, fortuitously similar to the expected masses of ejected embryos during giant planet formation. For a 50/50 ice-rock body, the ocean is very deep and may be underlain by high pressure phases of water ice with a rock core at still greater depths, but bodies with earthlike water reservoirs may have an ocean underlain with a rock core. Either way, these bodies are expected to have volcanism in the rocky component and a dynamo-generated magnetic field leading to a well-developed (very large) magnetosphere. Despite thermal radiation at microwave frequencies that corresponds to the temperatures deep within their atmospheres (analogous to Uranus[10]) and despite the possibility of non-thermal radio emission , they will be very difficult to detect. If, as many have suggested[12], life can develop and be sustained without sunlight (but with other energy sources, plausibly volcanism or lightning in this instance) then these bodies may provide a long-lived stable environment for that life (albeit one where the temperatures slowly decline on a billion year timescale). It is even conceivable that these are the most common sites of life in the Universe.

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