mismatching of spectral peaks and resolution[1,4,5], but we believe that our analysis of a complete and high-resolution record using a powerful spectral technique provides strong evidence of 33-Myr periodicity.

It is not yet clear what drives this periodicity and there is no simple relationship with mass extinction or impact cratering. However, the existence of remarkable spectral power stability and the statistical reliability of our results support the authenticity of this cycle and provide a stimulus for further research into the coupling of bio-geochemical cycles.

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Life-sustaining planets in interstellar space?

During planet formation, rock and ice embryos of the order of Earth's mass may be formed, some of which may be ejected from the Solar System as they scatter gravitationally from proto-giant planets. These bodies can retain atmospheres rich in molecular hydrogen which, upon cooling, can have basal pressures of 10^2 to 10^4 bars. Pressure-induced far-infrared opacity of H_2 may prevent these bodies from eliminating internal radioactive heat except by developing an extensive adiabatic (with no loss or gain of heat) convective atmosphere. This means that, although the effective temperature of the body is around 30 K, its surface temperature can exceed the melting point of water. Such bodies may therefore have water oceans whose surface pressure and temperature are like those found at the base of Earth's oceans. Such potential homes for life will be difficult to detect.

Planet formation is imperfectly understood, but many models involve the accumulation of solid bodies of up to several Earth masses while the hydrogen-rich solar nebula is still present[1]. These bodies form an envelope of nebula gas bound together by gravity. In the outer Solar System, they may continue to accrete gas, forming the giant planets, while the high ultraviolet output of the early Sun causes those bodies closer to it to lose their gaseous envelope. In one development of these ideas[2], runaway accretion causes many embryos to form quickly, some of which may merge, while others may be scattered into escape trajectories by proto-Jupiter or proto-Saturn. The formation of planets may be quite inefficient in the sense that more solid material is ejected than retained. There are uncertainties and alternatives[3–5] but, because solar systems may have been formed in diverse ways, the possibility of bodies of roughly Earth mass in interstellar space should be taken seriously.

The amount of nebular gas accumulated and retained depends strongly on planet mass, nebula temperature, opacity assumptions and accretion timescale. An Earth-mass body eliminating its energy of formation in a million years and with only pressure-induced opacity of hydrogen[6] develops an atmosphere with $M_{atm}/M \approx 0.01$, where M is planet mass and M_{atm} is atmospheric mass. More opaque models[7] yield atmospheric masses with $M_{atm}/M \approx 0.001$, in agreement with detailed models[1].

The retention of a major part of this atmosphere is difficult at Earth orbit once most of the nebula has cleared, but becomes increasingly likely at greater distances, especially once the atmosphere has cooled (so that the photosphere is no longer large compared with the solid body). The atmospheric escape time can be as short as a million years at one astronomical unit early in the Solar System[1], but longer than the age of the Solar System in the interstellar medium. Sputtering (collision with interstellar molecular or atomic hydrogen at tens to hundreds of kilometres per second) can be important if denser interstellar regions are encountered, but the column density of hydrogen in the case of $M_{atm}/M \approx 0.001$ to 0.01 is so large that removing such an atmosphere would correspond to much more mass being sputtered per unit area than the total mass per unit area of a comet in the Oort cloud.

At the present epoch (assumed to be around 4.6 Gyr after formation), an interstellar planet would have a luminosity derived from long-lived radionuclides of around $4 \times 10^{20}\ \chi$ erg s^{-1} if it is like Earth[8], where χ is the planet mass in units of Earth masses. Assuming a thin atmosphere and an Earth-like density, the effective temperature T_e of the planet is given by $T_e \approx 34\ \chi^{1/12}$ K. From hydrostatic equilibrium, the surface pressure $P_s \approx 10^6 \times M_{atm}/M$ bars. However, optical-depth unity at relevant infrared wavelengths (about 100 μm) is achieved in such an atmosphere at a pressure of around 1 bar (refs 6,9) and liquefaction at this pressure occurs at a temperature of around 22 K, below the actual atmospheric temperature. A convective gas adiabat must form at all greater depths (at a pressure between 1 bar and P_s), even when the heat flow is very low. An adequate estimate for this adiabat turns out to be $T \propto P^{0.36}$, which does not intercept the condensation curve for hydrogen. It follows that the surface temperature is given by $T_s \approx 425\chi^{1/12}((M_{atm}/M)/0.001)^{0.36}$ K.

The melting point of water is typically exceeded for basal pressures of the order of one kilobar. The atmosphere will have several cloud layers (methane, ammonia and perhaps water, like Uranus), but this has little influence on the temperature estimate.

It seems, then, that bodies with water oceans are possible in interstellar space. The ideal conditions are plausibly at an Earth mass or slightly less, similar to the expected masses of embryos ejected during the formation of giant planets. Bodies with Earth-like 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[9]), and despite the possibility of non-thermal radio emission, they will be very difficult to detect.

If life can develop and be sustained without sunlight (but with other energy sources, plausibly volcanism or lightning in this instance), these bodies may provide a long-lived, stable environment for life (albeit one where the temperatures slowly decline on a billion-year timescale). The complexity and biomass may be low because the energy source will be small, but it is conceivable that these are the most common sites of life in the Universe. Details of the above results are available from the author.

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