the amount of cellular iron, or as oceanographers like to express it, the Fe:C ratio. This ratio is critical in understanding how iron affects carbon cycling, the biological pump and the role of oceanic biota in global climate.

The Fe:C ratios found by Tortell *et al.* will be a surprise to many. In iron-deficient cultures and in the subarctic Pacific, Fe:C ratios in heterotrophic bacteria are twice those in eukaryotic phytoplankton, a difference that is not predictable even after reviewing the biochemistry of aerobic heterotrophy and photosynthesis. Cell size probably has something to do with the difference, as does the energetic cost of heterotrophic bacteria living in organic-poor waters such as the open oceans (more on this later). Further work on Fe:C ratios in cyanobacteria and in heterotrophic eukaryotic protozoa may help sort out whether being a prokaryote or a heterotroph is more decisive in determining the high iron content of heterotrophic bacteria.

Although it is unclear why Fe:C ratios in bacteria and phytoplankton differ, the data clearly indicate that in the subarctic Pacific the heterotrophic bacterial assemblage contains more iron than either eukaryotic phytoplankton or cyanobacterial communities. That observation may not surprise microbial ecologists familiar with work showing that the standing stocks of bacteria and phytoplankton are roughly equal in the open oceans[3]. In spite of their known ecological importance, however, bacteria have been completely ignored in discussions of how iron controls phytoplankton growth; the main battle has been over the role of grazing by zooplankton.

Tortell *et al.* now decisively add bacteria to the fray. What may be more important than the amount of iron is the rate at which heterotrophic bacteria take it up. These rates are much more difficult to come by, but fortunately several different methods turn up roughly the same answer. The take-home message is that heterotrophic bacteria account for 20–45 per cent of total iron uptake in the subarctic Pacific, suggesting that bacteria are competing with phytoplankton for this potentially limiting micronutrient.

As well as having a higher surface-area-to-volume ratio, bacteria can excrete ligands (siderophores) in order to complex and ultimately assimilate dissolved iron, an uptake mechanism unknown to eukaryotic phytoplankton. It may be more than coincidental that the binding constants of these bacterial siderophores are similar to those of dissolved iron complexes in seawater[4].

Completing the microbial ferrous wheel is iron regeneration, the input of iron back to the dissolved pool by grazing and viral lysis. Like the nitrogen cycle, iron regeneration supports much primary production in many parts of the world's oceans[5] (see figure). Unlike nitrogen and other plant nutrients, the form of released iron may differ greatly depending on the prey (bacteria or phytoplankton) and the mode of regeneration (viral lysis or grazing by protists and multicellular organisms). The end result is that this microbial ferrous wheel — the uptake, storage and ultimate release of iron from heterotrophic bacteria — may greatly affect iron availability and thus primary production in waters such as the subarctic Pacific.

Might heterotrophic bacteria be limited by iron like some phytoplankton? A recent report[6] says so, but most microbial ecologists think that bacterial growth rates are limited by organic carbon in open oceans. Tortell *et al.* suggest a more subtle limitation, involving both carbon and iron deficiency. They observed that the growth efficiency of several bacterial strains was lower under iron limitation, probably because of deleterious effects on the iron-rich electron-transport system. If so, to maintain growth rates bacteria would require more organic material as iron concentrations decrease. As a result, bacterioplankton could exhibit both carbon and iron deficiencies. The potential effect of iron on the bacterial growth efficiency is quite important; this efficiency indicates whether carbon flows through bacteria either to CO_2 or to higher trophic levels via bacteriovores.

A model that incorporates both grazing and iron limitation for understanding what controls primary production is really not much more complicated than the iron-ruled ocean first proposed by Martin and colleagues. A microbial ferrous wheel, however, complicates our simple models, and we will need further work before we see how everything meshes together. An important opportunity may be part of the Southern Ocean programme of the US Joint Global Ocean Flux Study, which went to sea a few weeks ago. The story of iron limitation began in the subarctic Pacific and an epiphany was realized with work in the equatorial Pacific[7], but its climax may be in the Southern Ocean. All three areas have relatively low phytoplankton growth in spite of high concentrations of major plant nutrients. But it is the vast Southern Ocean that matters most for the biological pump and its role in global climate[8]. □

David L. Kirchman is in the Graduate College of Marine Studies, University of Delaware, Lewes, Delaware 19958, USA.

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DAEDALUS

Astromagnetics

How did the first stars form? The accepted theory is that a large volume of very dilute hydrogen gas slowly collapsed into stars by gravitational contraction. But such masses would warm up as they grew denser, generating pressure which would oppose the contraction. Only by radiating their heat away could the protostars contract further. Yet hydrogen is almost perfectly transparent, and therefore hardly radiates at all. Daedalus has been musing on the problem.

The early Universe, he says, had a magnetic field. One theory even claims that the fields of the stars are 'fossil' remnants of it, trapped and concentrated in the stars as they condensed. Now, materials with unpaired electrons are paramagnetic, and are attracted into a magnetic field. Interstellar hydrogen is an extreme case: it consists of single atoms with one electron each, so *all* its electrons are unpaired. Daedalus calculates that a field of 80 T could by itself pump cold monatomic hydrogen at one atom per cubic metre right up to the billions of atmospheres of a stellar interior. So in forming the first stars, he says, magnetism came to the aid of gravity.

Magnetic fields have tricks unknown to mere gravitational ones. They are always multipolar, for a start, and can be dragged around by moving magnetic material. The Sun heats its corona much hotter than its surface by exporting energy as hydromagnetic waves. Daedalus reckons the early stars did the same thing. The turbulence and spin of their contraction allowed them to radiate energy, not thermally, but magnetically.

These deductions have practical uses. One planned satellite will carry a huge neodymium–boron magnet, to look for anti-matter cosmic rays by their opposite deflection in its field. Daedalus expects it to concentrate interplanetary monatomic hydrogen as well. It could then form the basis of a deep-space rocket motor which would attract this gas as fuel. It would catalyse its conversion to dihydrogen — the most energetic chemical reaction known. The resulting hot exhaust would develop both thermal and magnetic thrust. Dihydrogen is diamagnetic, and would be repelled away from the motor.

Daedalus has even been dreaming of a satellite so intensely magnetized that it could hold an atmosphere of molecular oxygen, also a paramagnetic gas. It would thus form a tiny planet for astronauts to walk on, needing no space-suits but wearing iron-soled boots for adhesion. The oxygen atmosphere would even give them a faintly blue sky. Sadly, the field required exceeds the capacity of modern magnets.

David Jones