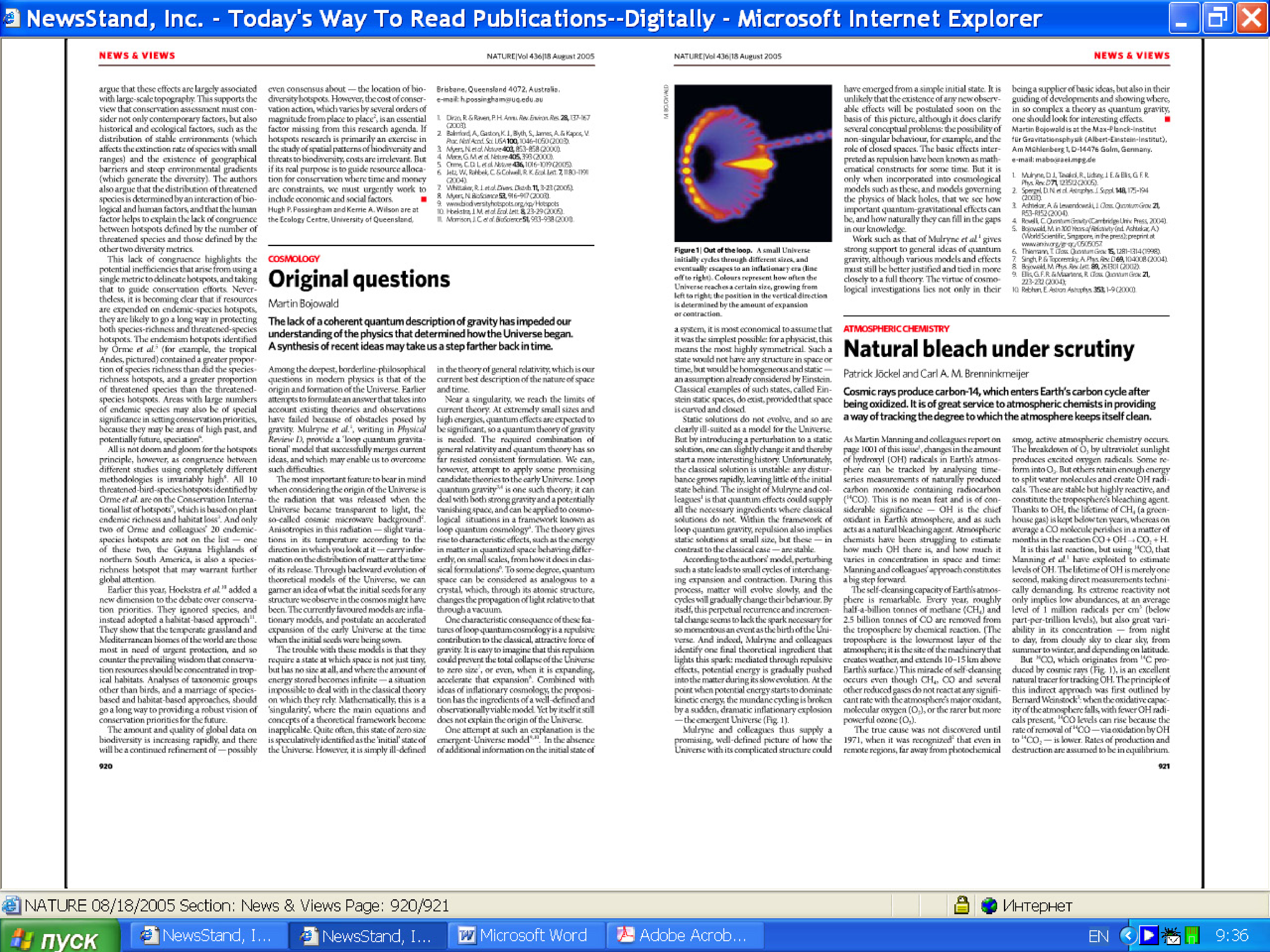

argue that these effects are largely associated with large-scale topography. This supports the view that conservation assessment must consider not only contemporary factors, but also historical and ecological factors, such as the distribution of stable environments (which affects the extinction rate of species with small ranges) and the existence of geographical barriers and steep environmental gradients (which generate the diversity). The authors also argue that the distribution of threatened species is determined by an interaction of biological and human factors, and that the human factor helps to explain the lack of congruence between hotspots defined by the number of threatened species and those defined by the other two diversity metrics.

This lack of congruence highlights the potential inefficiencies that arise from using a single metric to delineate hotspots, and taking that to guide conservation efforts. Nevertheless, it is becoming clear that if resources are expended on endemic-species hotspots, they are likely to go a long way in protecting both species-richness and threatened-species hotspots. The endemism hotspots identified by Orme *et al.*[5] (for example, the tropical Andes, pictured) contained a greater proportion of species richness than did the species-richness hotspots, and a greater proportion of threatened species than the threatened-species hotspots. Areas with large numbers of endemic species may also be of special significance in setting conservation priorities, because they may be areas of high past, and potentially future, speciation[6].

All is not doom and gloom for the hotspots principle, however, as congruence between different studies using completely different methodologies is invariably high[8]. All 10 threatened-bird-species hotspots identified by Orme *et al.* are on the Conservation International list of hotspots[9], which is based on plant endemic richness and habitat loss[3]. And only two of Orme and colleagues' 20 endemic-species hotspots are not on the list — one of these two, the Guyana Highlands of northern South America, is also a species-richness hotspot that may warrant further global attention.

Earlier this year, Hoekstra *et al.*[10] added a new dimension to the debate over conservation priorities. They ignored species, and instead adopted a habitat-based approach[11]. They show that the temperate grassland and Mediterranean biomes of the world are those most in need of urgent protection, and so counter the prevailing wisdom that conservation resources should be concentrated in tropical habitats. Analyses of taxonomic groups other than birds, and a marriage of species-based and habitat-based approaches, should go a long way to providing a robust vision of conservation priorities for the future.

The amount and quality of global data on biodiversity is increasing rapidly, and there will be a continued refinement of — possibly even consensus about — the location of biodiversity hotspots. However, the cost of conservation action, which varies by several orders of magnitude from place to place[2], is an essential factor missing from this research agenda. If hotspots research is primarily an exercise in the study of spatial patterns of biodiversity and threats to biodiversity, costs are irrelevant. But if its real purpose is to guide resource allocation for conservation where time and money are constraints, we must urgently work to include economic and social factors.

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1. Dirzo, R. & Raven, P. H. *Annu. Rev. Environ. Res.* **28**, 137–167 (2003).
2. Balmford, A., Gaston, K. J., Blyth, S., James, A. & Kapos, V. *Proc. Natl Acad. Sci. USA* **100**, 1046–1050 (2003).
3. Myers, N. *et al. Nature* **403**, 853–858 (2000).
4. Mace, G. M. *et al. Nature* **405**, 393 (2000).
5. Orme, C. D. L. *et al. Nature* **436**, 1016–1019 (2005).
6. Jetz, W., Rahbek, C. & Colwell, R. K. *Ecol. Lett.* **7**, 1180–1191 (2004).
7. Whittaker, R. J. *et al. Divers. Distrib.* **11**, 3–23 (2005).
8. Myers, N. *BioScience* **53**, 916–917 (2003).
9. www.biodiversityhotspots.org/xp/Hotspots
10. Hoekstra, J. M. *et al. Ecol. Lett.* **8**, 23–29 (2005).
11. Morrison, J. C. *et al. BioScience* **51**, 933–938 (2001).

COSMOLOGY

Original questions

Martin Bojowald

The lack of a coherent quantum description of gravity has impeded our understanding of the physics that determined how the Universe began. A synthesis of recent ideas may take us a step farther back in time.

Among the deepest, borderline-philosophical questions in modern physics is that of the origin and formation of the Universe. Earlier attempts to formulate an answer that takes into account existing theories and observations have failed because of obstacles posed by gravity. Mulryne *et al.*[1], writing in *Physical Review D*, provide a 'loop quantum gravitational' model that successfully merges current ideas, and which may enable us to overcome such difficulties.

The most important feature to bear in mind when considering the origin of the Universe is the radiation that was released when the Universe became transparent to light, the so-called cosmic microwave background[2]. Anisotropies in this radiation — slight variations in its temperature according to the direction in which you look at it — carry information on the distribution of matter at the time of its release. Through backward evolution of theoretical models of the Universe, we can garner an idea of what the initial seeds for any structure we observe in the cosmos might have been. The currently favoured models are inflationary models, and postulate an accelerated expansion of the early Universe at the time when the initial seeds were being sown.

The trouble with these models is that they require a state at which space is not just tiny, but has no size at all, and where the amount of energy stored becomes infinite — a situation impossible to deal with in the classical theory on which they rely. Mathematically, this is a 'singularity', where the main equations and concepts of a theoretical framework become inapplicable. Quite often, this state of zero size is speculatively identified as the 'initial' state of the Universe. However, it is simply ill-defined in the theory of general relativity, which is our current best description of the nature of space and time.

Near a singularity, we reach the limits of current theory. At extremely small sizes and high energies, quantum effects are expected to be significant, so a quantum theory of gravity is needed. The required combination of general relativity and quantum theory has so far resisted consistent formulation. We can, however, attempt to apply some promising candidate theories to the early Universe. Loop quantum gravity[3,4] is one such theory; it can deal with both strong gravity and a potentially vanishing space, and can be applied to cosmological situations in a framework known as loop quantum cosmology[5]. The theory gives rise to characteristic effects, such as the energy in matter in quantized space behaving differently, on small scales, from how it does in classical formulations[6]. To some degree, quantum space can be considered as analogous to a crystal, which, through its atomic structure, changes the propagation of light relative to that through a vacuum.

One characteristic consequence of these features of loop quantum cosmology is a repulsive contribution to the classical, attractive force of gravity. It is easy to imagine that this repulsion could prevent the total collapse of the Universe to zero size[7], or even, when it is expanding, accelerate that expansion[8]. Combined with ideas of inflationary cosmology, the proposition has the ingredients of a well-defined and observationally viable model. Yet by itself it still does not explain the origin of the Universe.

One attempt at such an explanation is the emergent-Universe model[9,10]. In the absence of additional information on the initial state of a system, it is most economical to assume that it was the simplest possible: for a physicist, this means the most highly symmetrical. Such a state would not have any structure in space or time, but would be homogeneous and static — an assumption already considered by Einstein. Classical examples of such states, called Einstein static spaces, do exist, provided that space is curved and closed.

Static solutions do not evolve, and so are clearly ill-suited as a model for the Universe. But by introducing a perturbation to a static solution, one can slightly change it and thereby start a more interesting history. Unfortunately, the classical solution is unstable: any disturbance grows rapidly, leaving little of the initial state behind. The insight of Mulryne and colleagues[1] is that quantum effects could supply all the necessary ingredients where classical solutions do not. Within the framework of loop quantum gravity, repulsion also implies static solutions at small size, but these — in contrast to the classical case — are stable.

According to the authors' model, perturbing such a state leads to small cycles of interchanging expansion and contraction. During this process, matter will evolve slowly, and the cycles will gradually change their behaviour. By itself, this perpetual recurrence and incremental change seems to lack the spark necessary for so momentous an event as the birth of the Universe. And indeed, Mulryne and colleagues identify one final theoretical ingredient that lights this spark: mediated through repulsive effects, potential energy is gradually pushed into the matter during its slow evolution. At the point when potential energy starts to dominate kinetic energy, the mundane cycling is broken by a sudden, dramatic inflationary explosion — the emergent Universe (Fig. 1).

Mulryne and colleagues thus supply a promising, well-defined picture of how the Universe with its complicated structure could have emerged from a simple initial state. It is unlikely that the existence of any new observable effects will be postulated soon on the basis of this picture, although it does clarify several conceptual problems: the possibility of non-singular behaviour, for example, and the role of closed spaces. The basic effects interpreted as repulsion have been known as mathematical constructs for some time. But it is only when incorporated into cosmological models such as these, and models governing the physics of black holes, that we see how important quantum-gravitational effects can be, and how naturally they can fill in the gaps in our knowledge.

Work such as that of Mulryne *et al.*[1] gives strong support to general ideas of quantum gravity, although various models and effects must still be better justified and tied in more closely to a full theory. The virtue of cosmological investigations lies not only in their being a supplier of basic ideas, but also in their guiding of developments and showing where, in so complex a theory as quantum gravity, one should look for interesting effects.

M. BOJOWALD

Figure 1 | Out of the loop. A small Universe initially cycles through different sizes, and eventually escapes to an inflationary era (line off to right). Colours represent how often the Universe reaches a certain size, growing from left to right; the position in the vertical direction is determined by the amount of expansion or contraction.

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1. Mulryne, D. J., Tavakol, R., Lidsey, J. E. & Ellis, G. F. R. *Phys. Rev. D* **71**, 123512 (2005).
2. Spergel, D. N. *et al. Astrophys. J. Suppl.* **148**, 175–194 (2003).
3. Ashtekar, A. & Lewandowski, J. *Class. Quantum Grav.* **21**, R53–R152 (2004).
4. Rovelli, C. *Quantum Gravity* (Cambridge Univ. Press, 2004).
5. Bojowald, M. in *100 Years of Relativity* (ed. Ashtekar, A.) (World Scientific, Singapore, in the press); preprint at www.arxiv.org/gr-qc/0505057
6. Thiemann, T. *Class. Quantum Grav.* **15**, 1281–1314 (1998).
7. Singh, P. & Toporensky, A. *Phys. Rev. D* **69**, 104008 (2004).
8. Bojowald, M. *Phys. Rev. Lett.* **89**, 261301 (2002).
9. Ellis, G. F. R. & Maartens, R. *Class. Quantum Grav.* **21**, 223–232 (2004);
10. Rebhan, E. *Astron. Astrophys.* **353**, 1–9 (2000).

ATMOSPHERIC CHEMISTRY

Natural bleach under scrutiny

Patrick Jöckel and Carl A. M. Brenninkmeijer

Cosmic rays produce carbon-14, which enters Earth's carbon cycle after being oxidized. It is of great service to atmospheric chemists in providing a way of tracking the degree to which the atmosphere keeps itself clean.

As Martin Manning and colleagues report on page 1001 of this issue[1], changes in the amount of hydroxyl (OH) radicals in Earth's atmosphere can be tracked by analysing time-series measurements of naturally produced carbon monoxide containing radiocarbon (^{14}CO). This is no mean feat and is of considerable significance — OH is the chief oxidant in Earth's atmosphere, and as such acts as a natural bleaching agent. Atmospheric chemists have been struggling to estimate how much OH there is, and how much it varies in concentration in space and time: Manning and colleagues' approach constitutes a big step forward.

The self-cleansing capacity of Earth's atmosphere is remarkable. Every year, roughly half-a-billion tonnes of methane (CH_4) and 2.5 billion tonnes of CO are removed from the troposphere by chemical reaction. (The troposphere is the lowermost layer of the atmosphere; it is the site of the machinery that creates weather, and extends 10–15 km above Earth's surface.) This miracle of self-cleansing occurs even though CH_4, CO and several other reduced gases do not react at any significant rate with the atmosphere's major oxidant, molecular oxygen (O_2), or the rarer but more powerful ozone (O_3).

The true cause was not discovered until 1971, when it was recognized[2] that even in remote regions, far away from photochemical smog, active atmospheric chemistry occurs. The breakdown of O_3 by ultraviolet sunlight produces excited oxygen radicals. Some reform into O_2. But others retain enough energy to split water molecules and create OH radicals. These are stable but highly reactive, and constitute the troposphere's bleaching agent. Thanks to OH, the lifetime of CH_4 (a greenhouse gas) is kept below ten years, whereas on average a CO molecule perishes in a matter of months in the reaction $CO + OH \rightarrow CO_2 + H$.

It is this last reaction, but using ^{14}CO, that Manning *et al.*[1] have exploited to estimate levels of OH. The lifetime of OH is merely one second, making direct measurements technically demanding. Its extreme reactivity not only implies low abundances, at an average level of 1 million radicals per cm^3 (below part-per-trillion levels), but also great variability in its concentration — from night to day, from cloudy sky to clear sky, from summer to winter, and depending on latitude.

But ^{14}CO, which originates from ^{14}C produced by cosmic rays (Fig. 1), is an excellent natural tracer for tracking OH. The principle of this indirect approach was first outlined by Bernard Weinstock[3]: when the oxidative capacity of the atmosphere falls, with fewer OH radicals present, ^{14}CO levels can rise because the rate of removal of ^{14}CO — via oxidation by OH to $^{14}CO_2$ — is lower. Rates of production and destruction are assumed to be in equilibrium.