GEOSCIENCE

Driving Earth's surface motions

Rinus Wortel and Rob Govers

Density variations within Earth's mantle may be a significant driver of both horizontal and vertical surface movements. The fingerprints of such mantle processes have been found in the Mediterranean region.

Horizontal and vertical motions near Earth's surface are typically stately in pace — some 0.1 to 10 centimetres per year. But their net effects over long periods can be major. After decades to centuries, velocity differences across faults in Earth's crust produce slip deficits of up to a few tens of metres, which are resolved during large earthquakes. On timescales of millions of years, surface movements result in mountain building, in the opening of ocean basins and in the separation of continents. Faccenna and Becker (page 602 of this issue)[1] show that convective action in Earth's mantle, at depths extending from about 100 to 2,900 kilometres, is partly responsible for surface dynamics in one of the most complex tectonic areas in the world — the Mediterranean region.

Almost all scientists now accept that the motion of tectonic plates is part of a sluggish convection system in the mantle that is slowly cooling Earth's interior. But it has been difficult to predict such surface motions as the mechanical part of this heat engine, because we have had only a sketchy knowledge of the distribution and magnitude of density anomalies that drive convective flow.

From studies of the propagation of seismic waves, it has long been known that Earth has largely the same (spherical) structure as an onion. The outer spherical layer is the crust, the layers beneath it being the upper and lower mantle above the spherical core. But knowing this was not enough to understand the dynamics. Convection is driven by relatively small density anomalies within the mantle and core layers, and imaging these anomalies was much more of a challenge. Since the 1980s, the creation of a worldwide network of high-quality seismometers and the development of tomographic mapping techniques have changed this situation drastically[2]. Anomalies that could be tied to upwellings and downwellings were first imaged in the upper mantle, and later in the lower mantle[3].

Another line of investigation — geodynamic flow models[4] — developed in concert with the seismological findings. Historically, three-dimensional information was restricted to crustal levels, and explanations for the three-dimensional crustal structure were sought at crustal levels too. But as tomographic information for the upper mantle became available, complications in plate-tectonic processes were identified, for example in the Mediterranean region[5]. Faccenna and Becker[1] now include the anomalies and flow of the entire mantle in their next-generation geodynamic model.

The idea that flow in the lower mantle contributes to the deformation of Earth's surface is not new. A study[6] of uplift of southern Africa above a wide lower-mantle upwelling convincingly demonstrated such an effect. But not only do Faccenna and Becker bring planetary-scale mantle flow into the picture, they also show that flow driven by smaller-scale anomalies is needed to understand a plate-boundary zone such as the Mediterranean.

The tectonic structure of the Mediterranean is complicated, and especially interesting for that reason. Overall, two major plates, the African and Eurasian, are converging here. This convergence is not simply accommodated in a single subduction zone where one plate is being thrust below the other, however; the region has a number of smaller subduction zones and (micro)plates, the behaviour of which seems to be independent of the convergence dynamics of their larger fellows. From models of mantle flow, Faccenna and Becker demonstrate that smaller-scale convection in the mantle can account for much of that behaviour. Intriguingly, they find that flow beneath the Mediterranean region is significantly affected by the northward inflow of mantle material from beneath the Arabian continent.

We are not yet at the stage at which we have a full appreciation of a plate-boundary region such as the Mediterranean. This work[1] is just one step towards the development of a fully dynamic model that accurately reflects all the observed movement and deformation of tectonic plates, including microplates. Model representations of the connection of surface plates to mantle downwellings need to be improved. Flexing and deforming plates need to become integral parts of flow models to reliably predict dynamic topography. Only then will it be possible to convert the eighteenth-century geologist James Hutton's principle of uniformitarianism, "The present is the key to the past", to "The present is the key to the future" — that is, only then will it become possible to predict the future behaviour of Earth's surface. ■

Rinus Wortel and Rob Govers are in the Department of Earth Sciences, Utrecht University, PO Box 80.021, 3508TA Utrecht, the Netherlands.
e-mail: wortel@geo.uu.nl

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ASTROPHYSICS

Young stars in young galaxies

Robert C. Kennicutt Jr

A fine marriage between galaxy data and theoretical simulations offers an explanation for two apparently conflicting sets of observations on the rate at which stars formed at early cosmic times.

Thanks to a recent surge of multi-wavelength observations and theoretical simulations, an ever clearer picture of the build-up of stars and galaxies in the Universe is beginning to emerge. Writing in *The Astrophysical Journal*, Gnedin and Kravtsov[1] take a significant step in unifying these observations and simulations, and provide a prime illustration of the recent progress in the subject as a whole.

Numerical simulations of galaxy formation and evolution have progressed immensely over the past decade. Remarkably, the same cold dark matter theory that can reproduce the large-scale structure of the Universe also reproduces in broad outline the forms and life histories of the galaxies we observe today. Many of the details within this outline remain unresolved, however, including the structure and build-up of stars, which dominate the visible contents of galaxies. These limitations arise because the evolution of a galaxy is driven not only by gravity, which is readily modelled in what is called an *N*-body simulation, but by a suite of more complicated 'gastrophysical' processes as well: the cooling and accretion of gas, the conversion of the gas into stars, and the 'feedback' of energy and momentum from the stars back into the gas. These latter processes are poorly understood and are far too complex to simulate from scratch. Instead, analytical approximations or physical recipes are melded into the simulations.

Fortunately, nature has provided strong clues to some of these physical recipes, through observed patterns and scaling laws in the properties of galaxies. One of the most powerful of these has become known as the Kennicutt–Schmidt law (KS relation), which relates the concentration (surface density) of star formation in galaxies to the concentration of cold gas[2,3]. The relation, consisting of a nonlinear power law at high gas densities with a turnover or threshold at low densities[4], applies across virtually all galaxies today, from relatively quiescent systems such as our Milky Way to the most active 'starburst' galaxies. For the galaxy modeller, it provides a one-step means of predicting the amount of star formation from the distribution of cold gas, and this law or close variants of it are incorporated into nearly all models of galaxy formation and evolution.

The question posed by Gnedin and Kravtsov[1] is whether this star-formation law, which applies to present-day galaxies, is invariant over cosmic time. For simplicity, most models incorporate a time-invariant law, but observations of distant (early-epoch) galaxies present a mixed picture. For example, quasar-absorption-line galaxies — distant galaxies identified through their gas absorption of light from background quasars (extremely bright galactic nuclei) — show far lower rates of star formation (by more than an order of magnitude) than would be expected if they followed the present-day KS law[5,6]. This is consistent with a strong evolution in at least the threshold in the KS law when the Universe was 15–50% of its current age. On the other hand, luminous starburst galaxies at similar cosmic epochs show no such suppression of star formation relative to the local KS law[7]. Indeed, a wide range of observations show that early-epoch galaxies overall were forming stars much more rapidly than they are today.

Gnedin and Kravtsov offer a tentative solution to this paradox. They do so by using numerical simulations as a virtual laboratory to explore how changes in the properties of galaxies and the Universe at early cosmic epochs might change the star-formation law. The simulations use a theoretically motivated star-formation prescription in which the formation rate per unit volume scales as the ratio of the molecular-gas density to the gravitational free-fall time (the time taken for a gas cloud to collapse freely to its centre), multiplied by star-formation efficiency per free-fall time. Their prescription comes out of recent theoretical work[8,9], and is broadly consistent with the observed properties of local, present-day star-forming galaxies and the phenomenological basis of the KS law[2,8]. However, when Gnedin and Kravtsov examined the properties of the high-redshift galaxies in their simulation (in this case $z = 3$, or 16% of the present age of the Universe), they found that star formation was suppressed at much higher gas surface densities than is found today, in a regime where present-day galaxies readily form stars.

Dissecting the simulations revealed the physical explanation for such suppression. Young galaxies tend to be strongly depleted in heavy elements and interstellar dust (which build up gradually over multiple generations of stars and stellar explosions called supernovae), and this depletion acts together with the more-intense ultraviolet radiation in the early Universe to suppress the formation of molecular hydrogen, a necessary ingredient for forming stars. This would suppress star formation over wide swathes of a young galaxy, without inhibiting it in unusually dense regions, where sufficient shielding remains to form molecular gas. In this way, the models can account for the lack of star formation in the quasar-absorption-line galaxies while preserving the efficient star formation in the bright starburst galaxies.

Apart from offering an elegant explanation for a seemingly contradictory set of observations, Gnedin and Kravtsov's study[1] has broader implications. It demonstrates that local scaling relations such as the KS law may themselves evolve over cosmic time, complicating the task of the galaxy modeller. The robustness of this result rests heavily on the validity of the star-formation prescription used in the calculations, but studies by many other groups[9] support it. Viewed more broadly, this renaissance of theoretical interest in the physics of star formation in the Universe is sure to lead to new insight into the formation of galaxies and stars alike. ■

Robert C. Kennicutt Jr is at the Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK.
e-mail: robk@ast.cam.ac.uk

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ORGANIC CHEMISTRY

Symmetrizing the unsymmetrical

Scott A. Snyder

You might think that the partial symmetry of the molecule complanadine A makes it easy to prepare, but the reverse is true. Two syntheses of this compound offer insight into how to make partly symmetrical molecules.

When the molecular structures of naturally occurring organic compounds are symmetrical, it is relatively easy for synthetic chemists to come up with a blueprint to make them in the laboratory. But if that symmetry is broken just a little — say, by the presence of a single bond in the 'wrong' place, or by the insertion of an atom into one of the two otherwise equivalent parts of the molecule — then all bets are off. Two recent syntheses[1,2] of the non-symmetrical molecule (+)-complanadine A, reported in the *Journal of the American Chemical Society*, provide insight into how to access such non-symmetrical structures. Ironically, the key to success involves symmetry.

Nature weaves together carbon, nitrogen, oxygen, hydrogen and a few other select atoms into millions of different organic molecules of varying size and complexity. The diversity of architectures produced from just these few components is truly stunning[3]. Equally striking is that these structures include what is arguably a disproportionate number of symmetrical molecules — compounds that are easily broken into two identical halves that are usually natural products in their own right.

The fact that such dimeric structures are formed — and that there are so many of them — is probably born of the need to make the most efficient use of energy. The biosynthesis of any small molecule requires a lot of energy-carrying ATP molecules, not to mention highly evolved enzymatic machinery. It therefore seems logical for the organism producing it to form a second compound from that molecule if the second product can be accessed for 'free' or at a modest additional energetic cost. After all, the new molecule might confer an added evolutionary advantage on the organism in the form of different and/or improved biological activity.

Usually, nature will make such a dimer through the easiest and most energetically economical reaction available, producing molecules that are fully symmetrical and that chemists can typically make using available synthetic tools. But every once in a while, nature abandons this low-cost approach and becomes more extravagant, joining together monomers in a manner that is not only less obvious to chemists, but that also creates dissymmetry. Although the monomer in these compounds is still clear, finding the means to unite two of them often proves highly challenging — if not impossible — to achieve in a laboratory flask, because the union requires each monomer to behave in a chemically very different way. Complanadine A (Fig. 1) is one example of this relatively rare phenomenon[4].