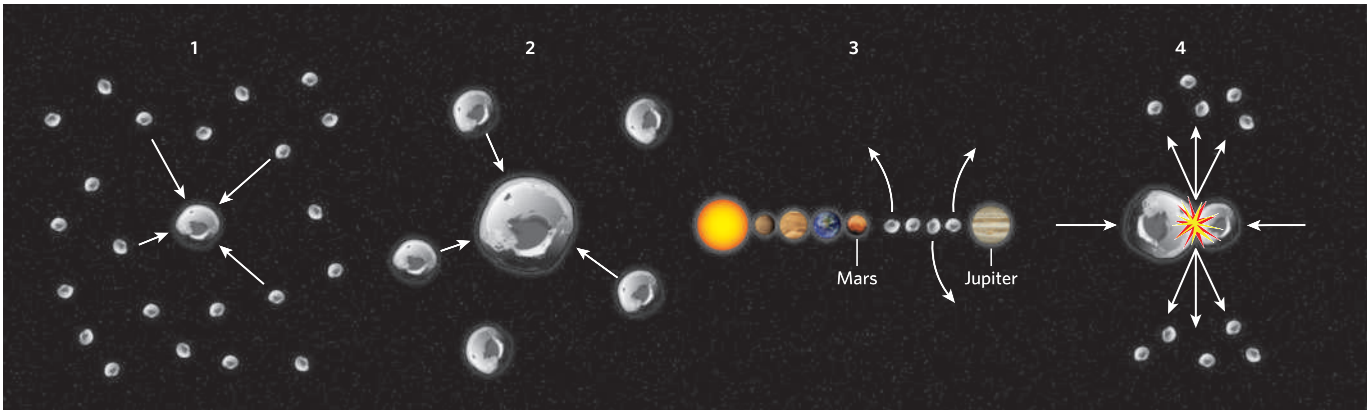

Figure 1 | Evolutionary stages of the main asteroid belt. 1, Dust grains coalesced into planetesimals, objects of 1–1,000 km in diameter, through an unknown process; **2,** planetesimals merged to form Moon-to-Mars-sized planetary embryos; **3,** the vast majority of planetesimals and all embryos were dynamically removed from the asteroid belt; **4,** the surviving planetesimals underwent occasional high-speed collisions with one another, leading to catastrophic break-up and the formation of many small objects. By studying stages **2**–**4**, and comparing the outcome with the size distribution of present-day asteroids in the main asteroid belt, Morbidelli *et al.*[1] have determined the sizes of planetesimals at the end of stage **1**, placing strong constraints on models of how planetesimals form.

belt existed in bodies larger than 100 km in diameter, and that smaller bodies were relatively rare. Because the dynamic depletion of stage 3 was independent of size, bodies larger than 100 km in diameter also dominated the asteroid belt at the end of stage 2.

Morbidelli and colleagues' contribution[1] is to provide a detailed model of stage 2 (planetesimals to planetary embryos). They consider a wide variety of possible planetesimal size distributions, on the basis that we don't know enough to say how big planetesimals were when they formed. Combining the results of this model with the size-independent depletion of stage 3, the authors find that the current size distribution of the asteroid belt can be reproduced only if most planetesimals were at least 100 km in size at the end of stage 1, with a size distribution extending up to 1,000 km (the size of the belt's largest object, Ceres), and possibly beyond. This is precisely the size range predicted by the new models[5,6] for planetesimal formation. Furthermore, the new study[1] suggests that planetesimals formed with a size distribution that is essentially identical to that seen in the asteroid belt today for diameters larger than 100 km.

The rarity of planetesimals smaller than 100 km in diameter at the end of stage 1 seems to rule out the possibility that dust aggregates somehow made it across the metre-size barrier by gradually sweeping up material from their surroundings. Instead, objects must have grown very rapidly from sub-metre-sized pebbles into 100-km-sized bodies, possibly in a single leap.

Morbidelli and colleagues' model is not the last word on the subject of planet formation. In particular, the authors considered the evolution of the asteroid belt in isolation, neglecting processes that may have exchanged material between the asteroid belt and other parts of the Solar System. However, by showing that the size distribution of the asteroids preserves information about the earliest history of the Solar System, the authors have opened a new window on the least-understood aspect of planet formation. This gives us hope that we may yet understand how Earth and its cousins came to be. ■

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ASTROPHYSICS

Gravity ripples chased

Marc Kamionkowski

Discovering gravitational waves would not only validate Einstein's theory of gravitation but also reveal aspects of the Universe's earliest moments. The hunt for these elusive ripples is now well under way.

For several decades, physicists have been racing to detect gravitational waves — tiny disturbances in space-time that propagate at the speed of light. But the experiments are challenging. They require detection of minute changes — a mere fraction of the size of an atomic nucleus — in kilometre-scale separations between free-floating masses. Although gravitational waves have yet to be detected, on page 990 of this issue the LIGO Scientific Collaboration and the Virgo Collaboration report a milestone in this quest[1]. The authors improve on a long-standing upper limit to the number of gravitational waves generated in the early Universe.

The immediate triumph of Einstein's theory of general relativity was an explanation for the apparently anomalous advance of Mercury's perihelion (its closest orbital point to the Sun) with each orbit. But his theory of gravitation made several other predictions, including the ideas that light from a distant object is deflected by the Sun (confirmed by Arthur Eddington in 1919) and that clocks tick at different rates in different gravitational fields (confirmed by Robert Pound and Glen Rebka in 1959).

Gravitational waves are yet another prediction. They are the gravitational analogues of electromagnetic waves: just as accelerated charges generate electromagnetic waves, accelerated masses produce gravitational waves. Strong, albeit indirect, evidence for the existence of gravitational waves is provided by observations of the Hulse–Taylor binary pulsar, a pair of neutron stars, one of which is a pulsar, revolving around their common centre of mass. The pair's orbital energy loss agrees precisely with that expected in general relativity from the emission of gravitational-wave radiation as the stars draw closer together.

However, it is important to detect gravitational waves directly. That would test whether

The LIGO site in Livingston, Louisiana.

LIGO LAB

they propagate at the speed of light and whether their polarization states agree with those predicted by general relativity. Moreover, because gravitational waves carry information about the sources that produce them and can propagate through regions of the Universe that are opaque to electromagnetic radiation, they offer an otherwise unattainable view of the Universe. For example, whereas the Universe was opaque to electromagnetic radiation during its first 380,000 years, gravitational waves have been able to propagate freely throughout the history of the Universe. The most important pay-off of gravitational-wave experiments will probably be an improved understanding of black holes. The efficiency of gravitational-wave production, relative to that of electromagnetic waves, increases markedly as the sources become denser. Gravitational waves would thus provide much more telling clues about the physics of black holes (the densest objects in the Universe) than do electromagnetic waves.

The investigation undertaken by the LIGO and Virgo collaborations is about a stochastic background signal — originating from all directions in space — of gravitational waves that may have arisen from a large number of unresolved sources and a variety of mechanisms in the early Universe. Such mechanisms include: inflation, a period of exponential space-time expansion that may have occurred as early as 10^{-38} seconds after the Big Bang; early-epoch phase transitions such as that which occurred when electroweak interactions were first broken into distinct electromagnetic and weak interactions about 10^{-11} seconds after the Big Bang; a network of cosmic strings (or other topological defects), a remnant of a phase transition that may have happened before the electroweak one; the 'compactification' of extra spatial dimensions; or some mechanisms associated with string-theory-inspired hypotheses for the origin of the cosmic expansion.

Just as electromagnetic waves are detected through the motions they induce in test charges (free-floating electric charges), gravitational waves can be detected by the motions they induce in test masses. The 'strain' (amplitude) of a gravitational wave determines the fractional change that it induces in the separation between two test masses. However, these motions are expected to be incredibly small. The current generation of experiments is targeting dimensionless strains no larger than 10^{-22}, meaning that measurements must be made of changes that are just a tiny fraction of the size of an atomic nucleus in kilometre-scale distances between objects.

Suppose some mechanism produced gravitational waves before the time of Big-Bang nucleosynthesis (BBN) when protons and neutrons first assembled into helium — a few seconds to minutes after the Big Bang. The energy density of such gravitational waves would have increased the cosmic expansion rate, leaving less time for neutrons to decay, and so more neutrons available to produce helium. The observed abundance of helium constrains the fractional gravitational-wave contribution, $\Omega_{\rm GW}$, to the total energy budget of the Universe to less than 1.1×10^{-5} in the frequency band (about 100 Hz) accessible to the LIGO (Laser Interferometer Gravitational-wave Observatory) detector[2,3]. A similar, more recent, bound was obtained from measurements of the cosmic microwave background (CMB) radiation (relic radiation from the hot Big Bang), which can be used to determine the expansion rate of the Universe 380,000 years after the Big Bang[4].

Through an experimental tour de force, the LIGO and Virgo collaborations find that the gravitational-wave background contributes no more than a fraction, $\Omega_{\rm GW} < 7 \times 10^{-6}$, at frequencies near 100 Hz, an order-of-magnitude improvement on their previous result and the aforementioned BBN and CMB bounds. To make these measurements, LIGO uses laser interferometry to determine the distances between test masses (mirror-covered 11-kilogram chunks of fused silica) separated by a distance of 4 km. These measurements constrain the root-mean-square values of the motion of their test masses to be less than a few times 10^{-17}, corresponding to a dimensionless strain of less than 4×10^{-23} over the frequency range 40–170 Hz (see the green curve in Fig. 1 on page 990).

Although the new constraint[1] does not controvert any dearly held theoretical predictions, it represents a watershed event in gravitational-wave astrophysics; terrestrial detectors can now dig into gravitational-wave amplitudes not yet limited by the existing BBN and CMB constraints. And whereas the 'Initial LIGO' detector and Virgo were pursued largely as engineering projects (there were no really promising gravitational-wave sources accessible to Initial LIGO and Virgo), the next generation of detectors, Advanced LIGO[5] (due to begin observing in 2014) and Advanced Virgo[6] are almost guaranteed to see a signal from compact binary-star systems.

But there are other, albeit indirect, gravitational-wave detectors that offer competition to LIGO and Virgo. Pulsar-timing arrays[7], which measure tiny gravitational-wave-induced shifts in the arrival times of radio pulses from a collection of pulsars, are racing to achieve indirect detection of gravitational waves from merging supermassive black holes. Experiments that measure the CMB, such as the recently launched Planck satellite[8], will seek to detect ultralow-frequency gravitational waves from inflation through their imprint on the polarization of CMB radiation.

By exploiting the effect of higher-frequency gravitational waves on the temperature of CMB radiation[4], CMB experiments can also improve current sensitivity to such waves by an order of magnitude. These indirect measurements may come in before Advanced LIGO/Virgo start operation. But dedicated gravitational-wave observatories, which may later include the spaced-based Laser Interferometer Space Antenna (LISA)[9], will be required to capitalize fully on the new observational window that gravitational waves will ultimately provide. LISA will operate at the lower frequencies at which the signals from compact stellar binaries and supermassive black holes are expected to be even clearer than in the LIGO/Virgo frequency band. ■

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