PERSPECTIVES: SOLAR SYSTEM

How Asteroids Come to Earth

Richard Greenberg

When 18th century scientists came to believe reports of rocks falling from the sky, they considered them to be meteorological phenomena and named them meteorites. Late in that century, Chladni argued correctly that meteorites were extraterrestrial, perhaps fragments of celestial bodies. Soon after, numerous asteroids were discovered in orbits between those of Mars and Jupiter, providing a likely source. Every meteorite was a tiny near-Earth asteroid (NEA) up until a few minutes before it hit the ground, so the story of how meteorites get here is part of the story of how all NEAs arrived on orbits that threaten to impact our planet. In this issue on page 2022, Migliorini *et al.* (*1*) demonstrate a type of orbital evolution that gets material to Earth, and that supports a classical hypothesis.

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In the late 19th century, Kirkwood identified gaps in the distribution of asteroids at distances from the sun at which orbital periods would be commensurable with Jupiter's period (forming ratios of small whole numbers). It was already known that such orbits would be resonant, with enhanced perturbations by the giant planet. A plausible hypothesis was that resonances had ejected asteroids, creating the gaps and sending some material onto orbits that intersected Earth's. However, the viability of this model of meteorite and near-Earth asteroid delivery remained in question through much of the 20th century.

A quantitative indication that resonances could send material to Earth came from Williams' (*2*) investigation of secular resonances (in which orbital precession periods resonate with the planets). One resonance, labeled ν_6, could raise orbital eccentricities to the point that bodies could reach Mars. In the 1980s, using improved computing power and innovative techniques, Wisdom showed that material could reach Earth through chaotic dynamics at the 3:1 resonance (*3*).

Such orbital calculations were necessary for constructing delivery scenarios, but other processes constrain the models, including the role of collisions, the physical properties of asteroids and meteorites, and observed orbital distributions.

Collisions liberate material from main-belt parent bodies and continually grind fragments into smaller pieces. Material may be injected into orbital resonances during one of the major catastrophic fragmentation events that produce families of asteroids in the main belt, from cratering events on large asteroids, by collisional disruption of smaller fragments, or by gradual orbital diffusion (due to radiation effects, for example). Even after becoming Earth-orbit crossers, most of the bodies continue to spend part of each orbit in the main belt, remaining subject to further collisional comminution.

IMAGE PROCESSED BY PAUL GEISSLER

Chips off the old block. Galileo image of the 60-km-long asteroid Ida. The bluer regions (color is exaggerated) are freshly excavated material (*10*), suggesting that such asteroids may be ordinary chondrites whose surfaces are mostly modified by exposure. However, the spectral match (even with the fresh bluer material) is questionable, and the source of the most common class of meteorite remains an open question.

Physical properties of meteorites reflect and constrain models of their collisional and orbital histories. Most are ordinary chondrites—fairly primitive material that, if heated in a planet, would differentiate into core, mantle, and crustal layers similar to those on Earth. Models must explain why no asteroids have reflectance spectra quite like these most common meteorites (see figure). Meteorites from differentiated minor planets are mostly either iron types (from planetary cores) or achondritic stones (similar to basalt, the low-density volcanic rock that differentiates to planetary surfaces). Models must explain why no meteorites are predominantly green crystals of olivine, the substance that constitutes the bulk of rocky planets (Earth's mantle, for instance). Another constraint is cosmic ray exposure: Most stony meteorites were within about 1 m of the surface of a body for a few tens of million years, whereas iron meteorites were generally exposed for 10 times as long.

A viable scenario must fit the astronomically observed orbital distribution of main-belt objects. Another constraint comes from the actual orbits of meteorites just before their colliding with Earth, although most are imprecisely known.

In the 1980s, with new confidence that main-belt asteroids could be delivered to Earth through orbital resonances and with more laboratory data on meteorites and astronomical data on asteroids, attempts were made to create viable scenarios. Greenberg and Chapman (*4*) constructed a model to explain why meteorites from differentiated bodies only sample the crust or the core. In that scenario, the liberation of meteorites from their parents was dominated by cratering events releasing surface material from crusts or from the surfaces of iron cores that had earlier been exposed by catastrophic disruption. To yield varieties and quantities of material that correspond to the meteorite record, they inferred that at least half a dozen resonances spread across the main belt must serve as dynamical exits from the main belt.

An alternative approach was taken by Wetherill (*5*), who interpreted the early results on the dynamics of the ν_6 and 3:1 resonances to mean that those specific resonances provided the dominant exit routes. Thus, bodies from the 3:1 resonance would become planet crossers in about a million years and random walk by gravitational encounters with Earth or Mars would then remove the bodies from the resonance, with some eventually (in $\sim 2 \times 10^7$ years or $\sim 10^8$ years, respectively) impacting Earth. His theory fit the observed afternoon excess of chondritic meteorite falls (a rough indicator of orbital distribution immediately before impact). Achondrites have no afternoon excess, so Wetherill proposed that they come predominantly from the ν_6 resonance, getting as far as Mars, followed by a $\sim 10^8$-year random walk and more isotropic impacts with Earth than for the chondrites [see (*6*) for a review].

Subsequent revelations about resonant orbits have shown such a model to have been prematurely specific. One indication was the finding by Farinella *et al.* (*7*) that the ν_6 and 3:1 resonances could pump orbital eccentricities so high so quickly that

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asteroids graze the sun or escape from the solar system, rather than evolve as near-Earth asteroids. Gladman *et al.* (*8*) generalized that discovery: Only a small fraction can be removed by Earth or Mars encounters. In other words, those strongest resonances, originally thought to be the best candidates for delivering meteorites, are too strong to provide efficient routes. Moreover, evolution after bodies become planet crossers proved to be governed by chaotic resonance effects.

Now, Migliorini *et al.* (*1*) report that numerous weak resonances and interactions among the resonances cause chaotic behavior capable of raising main-belt eccentricities to Mars crossing. Objects then break away from the resonances when they have close encounters with Mars and subsequently evolve as Mars crossers, until they become near-Earth asteroids. That subsequent evolution is speeded by a series of minor resonances that yield fairly chaotic evolution, lasting a few times 10^7 years, during which a reasonable fraction is likely to hit Earth. Thus, in broad terms, the classical hypothesis seems to be restored and placed on a firm computational footing: Several resonances provide the escape route from the main belt and allow bodies to reach Earth in a few tens of million years.

Another potentially important mechanism is the Yarkovsky effect, in which thermal radiation from a small rotating asteroid causes drift in its distance from the sun. Meteorite-sized main-belt bodies may be preferentially swept into resonances, compensating for the inefficiency of delivery from the strongest resonances (*9*).

An international community of researchers is currently integrating our expanded knowledge of delivery processes, meteoritic physical properties, arrival trajectories, asteroidal characteristics, and collisional processes into comprehensive models of the formation and transport of meteorites and other near-Earth asteroids. Although the new results regarding orbital evolution include important details and evolutionary processes that had not been anticipated, the process is similar in many fundamental ways to what had been widely assumed in the past. If progress continues at the present pace, fundamental questions may be answered before long.

References

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PERSPECTIVES: QUANTUM OPTICS

Quantum Control of the Inevitable

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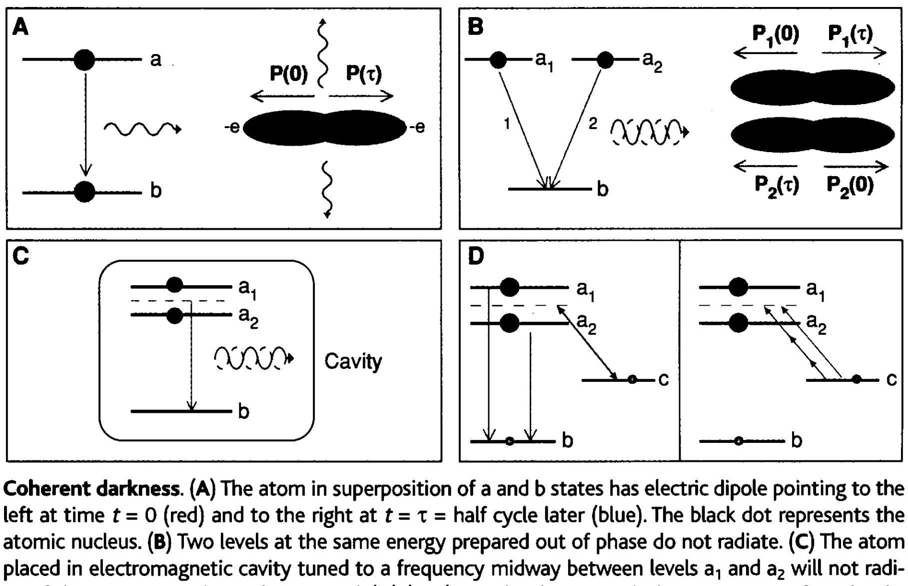
After 100 years of intensive study, we are still regularly discovering intriguing new insights and effects in quantum mechanics. For example, early in the development of quantum theory, we learned from Max Planck and Niels Bohr that atoms and molecules can "live" only in certain energy levels and not in between. But what if we prepare our atoms to have, on average, half of the energy of the first excited state? In such a case, the atoms are said to be in a coherent superposition, in which every atom is half in the ground and half in the first excited state (not half of the atoms in the ground and half of them in the excited state).

This "coherent control" has led to many interesting and counterintuitive effects (*1*) over the past decade, among them the electromagnetically induced transparency of Harris and co-workers (*2*), lasing without inversion (*3*, *4*), nonlinear optics without phase matching (*2*), and even suppression of atomic decay by spontaneous emission (*5*).

Concerning the latter, we note that the decay of optically excited atomic and molecular states is an inevitable fact of life. Knock atoms to an excited state, and they will tumble back to the ground state through spontaneously emitted light. In recent studies, however, a new and somewhat subtle technique has been developed that suppresses decay from a multilevel atom by means of quantum interference effects induced by coherent laser radiation. This is summarized in the figure, where it is shown that an excited state will decay until a coherent field is applied that "shuts off" the spontaneous emission. In the words of Paul Berman (*6*): "This is a rather remarkable result, since one might imagine that, owing to the short correlation time of the vacuum field, such modification of spontaneous emission would be strictly forbidden."

Consider the case of an optically excited atom as depicted in panel A of the figure. There we see that the electron charge cloud associates with an atom in a superposition of ground state (b) and excited state (a), which oscillates in time and radiates light as a tiny dipole antenna. The emitted light carries off energy and, to conserve energy, the atom drops to the ground state (*7*).



Coherent darkness. **(A)** The atom in superposition of a and b states has electric dipole pointing to the left at time $t = 0$ (red) and to the right at $t = \tau$ = half cycle later (blue). The black dot represents the atomic nucleus. **(B)** Two levels at the same energy prepared out of phase do not radiate. **(C)** The atom placed in electromagnetic cavity tuned to a frequency midway between levels a_1 and a_2 will not radiate if the states are coherently prepared. **(D)** (Left) Four-level atom with driven transition from level c to a point between a_1 and a_2 can also lead to cancellation of spontaneous emission. (Right) Same situation, but now the transition from c takes place through two paths and provides additional flexibility.

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