

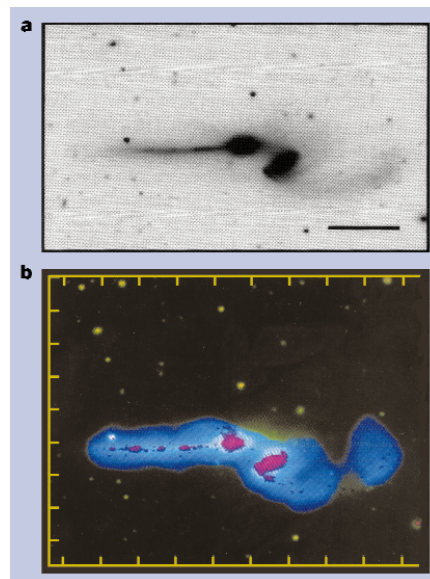
H I is expected to become largely molecular (H<sub>2</sub>) before forming stars. Star formation is also an inefficient process, so lots of molecular gas should be left over.

By far the most abundant chemical in a molecular cloud is H<sub>2</sub>, but it does not radiate detectable energy at typical cloud temperatures of 20–50 K. Like other astronomers, Braine *et al.* have to infer the amount of H<sub>2</sub> by observing radiation from accompanying trace molecules, principally carbon monoxide (CO). Crucial to this procedure is the assumed ratio of H<sub>2</sub> to CO in the cloud. This is known to depend on the chemical abundance in the surroundings, in this case the TDG. The few existing studies of TDGs suggest that their abundances are sufficiently like those in our Galaxy to justify Braine *et al.*'s use of the 'standard' CO-to-H<sub>2</sub> conversion factor derived for molecular clouds near the Sun.

Many tidal tails have been searched for CO (refs 11,12), but it has been detected in only three<sup>13–15</sup>. Two serious impediments prevent us from associating these with true TDGs. First, the detected CO is nearby and moving rather slowly with respect to the probable parent galaxies. It is not obviously escaping. Admittedly the situation is unclear because as usual the velocity is measured in only one direction, and the spatial separation relies on only two coordinates. Second, although the CO appears to accompany the atomic gas, the observations do not distinguish between molecules that were pulled out of the parent galaxy or that were formed within the ejected H I. The latter is favoured by observations suggesting that H I in most large galaxies extends farther from the centre of mass than CO, and so should be easier to remove. Such a distinction is vital if one wants the ejected material to look like an irregular dwarf galaxy after leaving the site of the interaction — a journey requiring more than 10<sup>8</sup> years. In the accepted picture, continuing star formation demands ongoing formation of molecular gas.

Braine *et al.*<sup>4</sup> present the first reasonably strong case that some TDGs can synthesize new molecular clouds. The CO in their clouds is far removed from the parent galaxy and moving rapidly. It also appears to be concentrated at the same location as the H I, and to share its velocity. Coincidence in location and motion is expected if the molecules formed *in situ* from the atomic gas in the runaway cloud, but difficult to understand otherwise. The velocities and distributions of the H I and CO are sufficiently similar to support the case for *in situ* formation. My chief reservation is that the CO emission is sampled at only a few spots — certainly enough to suggest that it follows the atomic gas, but too few to make a solid case. More complete sampling would help.

It is unlikely that all irregular dwarf galaxies were once TDGs — for one thing most



**Figure 1 Birthplace of dwarf galaxies**  
**a, Interacting galaxies in the NGC4676 system, showing the remarkably straight tail of stars pulled from one of the two galaxies<sup>16</sup>. The image is a greyscale negative of visible light. The black scale bar shows a distance of 90,000 light years — about the size of our own Galaxy. b, The same system seen with a hydrogen filter, so that atomic hydrogen appears blue, whereas hydrogen that has been ionized (presumably by young stars) appears red. Curiously, the molecular gas expected to accompany these stars is not found in the tail. Images of similar tails analysed by Braine *et al.*<sup>4</sup> do show signs of molecular hydrogen, suggesting that these tails are involved in continuous star formation.**

dwarfs have fewer heavy elements than the TDGs measured so far. To explain even the most element-rich dwarfs, TDGs must survive as long as 10<sup>10</sup> years — the age of a typical galaxy. The discovery of stars 10<sup>6</sup>–10<sup>7</sup> years old at the ends of some 10<sup>8</sup>-year-old tidal tails doesn't guarantee long-term stability. Braine *et al.* propose that *in situ* formation of

molecules is a good indicator of stability. I would agree that a gas cloud that is breaking up is not a good place to form molecules. But tidally stripped material is clumpy, probably on smaller scales than we have yet probed. It is possible that molecules could still form within small, stable clumps, however dispersed. Computer simulations of interactions cannot yet resolve this issue; meanwhile I remain sceptical.

One final question: why hasn't CO been seen in other tidal features, such as the merging galaxies shown in Fig. 1? If one assumes the most reasonable value for the CO-to-H<sub>2</sub> conversion factor, then earlier upper limits on detection are generally consistent with the CO signals seen by Braine and colleagues. Again, additional (and more sensitive) data are needed. The detections of molecular gas in TDGs are certain to stimulate such observations, and to lead to a better understanding of the formation of dwarf galaxies. ■

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### Biodiversity

## Extinction by numbers

Stuart L. Pimm and Peter Raven

**H**ow large will be the loss of species through human activities? And over what time period might that loss unfold? Habitat destruction is the leading cause of species extinction. Generally, many of the species found across large areas of a given habitat are represented in smaller areas of it. So habitat loss initially causes few extinctions, then many only as the last remnants of habitat are destroyed. Thus, at current rates of habitat destruction, the peak of extinctions might not occur for decades.

But we should not be complacent. On page 853 of this issue, Myers *et al.*<sup>1</sup> document an uneven, highly clumped, distribution of vulnerable species over the world's land surface. Within these 'biodiversity hotspots', habitats are already disproportionately reduced.

Conservatively, there are about seven million species of eukaryote<sup>2</sup> — a definition encompassing most organisms that would be generally recognized as plants or animals but excluding bacteria, for instance. Most

of these seven million are animals and about 85% are terrestrial.

Humanity is rapidly destroying habitats that are most species-rich. About two-thirds of all species occur in the tropics, largely in the tropical humid forests<sup>3</sup>. These forests originally covered between 14 million and 18 million square kilometres, depending on the exact definition, and about half of the original area remains<sup>4</sup>. Much of the rain-forest reduction is recent, and clearing now eliminates about 1 million square kilometres every 5 to 10 years<sup>4,6</sup>. Burning and selective logging severely damages several times the area that is cleared<sup>5,6</sup>.

To convert habitat loss to species loss, the principles of island ecology are applied to the terrestrial 'islands' that remain in a 'sea' of converted land<sup>7</sup>. The relationship between number of species and island area is nonlinear, and from this one can predict how many species should become extinct as the size of the forest islands shrinks. These doomed species do not disappear immediately, however.

How does one go about calculating the rate of species extinctions from habitat fragments? There have been only a few such estimates, but projections based on a species survivorship curve with a half-life of roughly 50 years seem reasonable<sup>8</sup>. Combining the rate of habitat loss, the species-to-area relationship and the survivorship curve gives a crude extinction curve (curve a in Box 1). From this, we would expect that current extinction rates should be modest — on the order of a thousand species per decade, per

million species, a figure that matches other estimates<sup>9</sup>.

Because the species–area curve is nonlinear, the clearing to date of half of the humid forests is predicted to eliminate only 15% of the species that they contain. The time delays before extinction mean that many more species should be 'threatened' than have already become extinct; that is, they are thought likely to become extinct in the wild in the medium-term future. At least 12% of all plants<sup>10</sup> and 11% of all birds<sup>11</sup> come into this category.

Of course, clearing the remaining half of the forests would eliminate the other 85% of species that they contain. The extinction curve should accelerate rapidly to a peak by the middle of the twenty-first century if the rate of forest clearing remains constant. But it will be upon us sooner if that rate is increasing — as seems probable<sup>4,6</sup>.

Once the extinction peak has passed, the extinction curve declines into the twenty-second century as species are lost from the remaining fragments of habitat. The relative height of the peak depends critically on the amount of habitat that remains. A value of 5% of remaining habitat (see Table 1 on page 854) would protect about 50% of all the forests' species; smaller percentages would lead to smaller estimates of surviving species.

Modest tinkering with parameters does not alter the 'fewer extinctions now, many more later' feature of the extinction curve (curve a in Box 1). But the calculations of Myers *et al.*<sup>1</sup> do. They show that roughly

30–50% of plant, amphibian, reptile, mammal and bird species occur in 25 hotspots that individually occupy no more than 2% of the ice-free land surface (see the map on page 853). That is, terrestrial species with small geographical ranges are numerous and they have highly clumped distributions. Myers *et al.* exclude the oceans from their analysis. But there, too, fishes and other organisms dependent on coral reefs are similarly concentrated<sup>12</sup>.

Habitat destruction acts like a cookie cutter stamping out poorly mixed dough<sup>9</sup>. Species found only within the stamped-out area are themselves stamped out. Those found more widely are not. Moreover, species with small ranges are typically scarcer within their ranges than are more widely distributed species, making them yet more vulnerable. Consequently, even random destruction would create centres of extinction that match the concentrations of small-ranged species — the hotspots<sup>9</sup>.

Worse, however, Myers *et al.* show that the cookie cutter is not random — it is malevolent. In the 17 tropical forest areas designated as biodiversity hotspots, only 12% of the original primary vegetation remains, compared with about 50% for tropical forests as a whole. Even within those hotspots, the areas richest in endemic plant species — species that are found there, and only there — have proportionately the least remaining vegetation and the smallest areas currently protected.

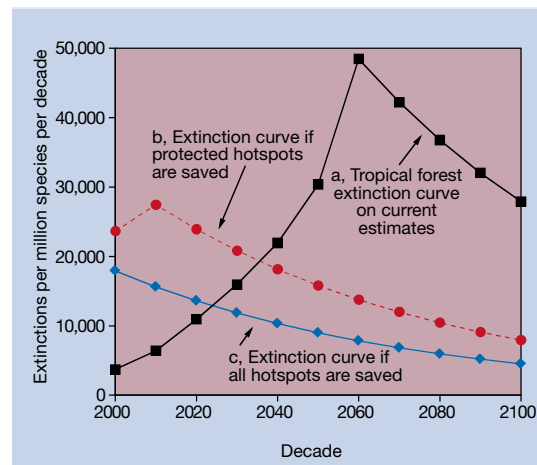
Applying the species–area relationship to the individual hotspots gives the prediction that 18% of all their species will eventually become extinct if all of the remaining habitats within hotspots were quickly protected (curve c in Box 1). Assuming that the higher-than-average rate of habitat loss in these hotspots continues for another decade until only the areas currently protected remain (curve b in Box 1), these hotspots would eventually lose about 40% of all their species. All of these projections ignore other effects on biodiversity, such as the possibly adverse impact of global warming, and the introduction of alien species, which is a well-documented cause of extinction of native species.

Unless there is immediate action to salvage the remaining unprotected hotspot areas, the species losses will more than double. There is, however, a glimmer of light in this gloomy picture. High densities of small-ranged species make many species vulnerable to extinction. But equally this pattern allows both minds and budgets to be concentrated on the prevention of nature's untimely end. According to Myers *et al.*, these areas constitute only a little more than one million square kilometres. Protecting them is necessary, but not sufficient. Unless the large remaining areas of humid tropical forests are also protected, extinctions of those species that are still wide-ranging

### Box 1: Extinctions in tropical forests, 2000–2100

Three projections of how numbers of species extinctions in tropical forests may unfold from forest clearance. Curve a is the extinction curve on current estimates, not taking into account biodiversity hotspots. According to the relationship  $S_n/S_0 = (A_n/A_0)^{0.25}$  (see refs 6–8), as habitat is reduced from an original area of  $A_0$  to  $A_n$ ,  $A_n$  will hold  $S_n$  viable species in year  $n$  from an original total of  $S_0$ . The  $S_0 - S_n$  doomed species will die off with a half-life of 50 years<sup>7</sup>. With a constant rate of forest clearance, this curve takes time to peak because of the nonlinear relationship between species and area, and the time lags for species to become extinct.

Myers *et al.*<sup>1</sup> identify 25 biodiversity hotspots around the world, of which 17 are in tropical forests. These areas



have already suffered disproportionate loss of primary vegetation, meaning that the many species they contain are under particular threat of extinction. If all remaining habitat in hotspots is saved (as shown in curve c), some 18% of their species

will be lost. The same half-life for currently threatened species is used as in curve a. However, if the hotspots are cleared in the next decade to the point where only currently protected areas are saved (curve b) then the total extinctions will be higher. **S. L. P. & P. R.**

should exceed those in the hotspots within a few decades (Box 1).

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## Laser physics

# Attosecond pulses at last

Paul Corkum

For the past five years, scientists have stood on the threshold of generating attosecond laser pulses but have been unable to cross it. (An attosecond —  $10^{-18}$  s — is to one second as one second is to the age of the Universe.) This may have finally changed with the publication of a paper by Papadogiannis *et al.* (*Phys. Rev. Lett.* **83**, 4289–4292; 1999), who claim to have measured trains of attosecond pulses. The previous record for the shortest laser pulse was  $4.5 \times 10^{-15}$  s (4.5 femtoseconds). Pulses in the femtosecond range led to the development of femtochemistry — making it possible to study chemical reactions in real time — for which the 1999 Nobel Prize in Chemistry was awarded to Ahmed Zewail. But the new science that will ultimately emerge from attosecond research will have its own unique drive.

The approach that Papadogiannis *et al.* use for generating attosecond pulses has been under investigation for some time. They use the short-wavelength harmonics generated when rare gases (such as argon) ionize as a result of irradiation from an intense femtosecond pulse. Harmonics occur at multiples of the frequency of the original femtosecond pulse. Next, the authors select a set of these harmonics, which theory indicates should combine to produce a train of pulses about 100 attoseconds in duration (Fig. 1). Such pulses have probably already been created in many laboratories, but no one has been able to measure them accurately.

Papadogiannis *et al.* may eventually be recognized as the parents of experimental attosecond science because they have actually measured the duration of these pulses. Their measurement process is experimentally simple, but theoretically complex. This is because the production of the attosecond pulses is intrinsically entwined with the measurement. They use a technique influenced by autocorrelation, which is widely

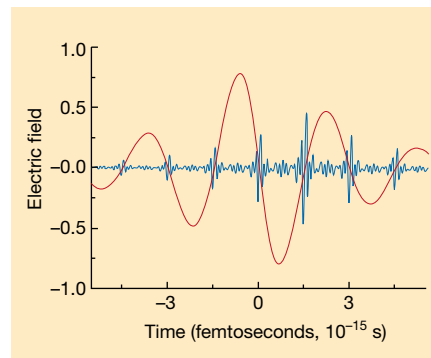


Figure 1 Train of attosecond pulses similar to that produced by Papadogiannis *et al.* Here, the initial femtosecond pulse (red) is much shorter than the one that they used, and the higher-frequency harmonic radiation (blue) is much more intense than in their experiment. The offset between the peak of the initial pulse and of the harmonic radiation illustrates the delay in the harmonic emission imposed by the laser field oscillation.

used for measuring femtosecond pulses and is a close cousin of the pump–probe technique used in femtochemistry.

For autocorrelation measurements, a femtosecond pulse is split into two at a beam splitter. (A beam-splitter functions like a window at night. In a lighted room you can see your reflection in the window while simultaneously being able to see outside.) The two beams are sent through different paths, and usually recombine within a crystal with nonlinear optical properties. Because the harmonic light produced by the nonlinear crystal is stronger when the two pulses are overlapped, observing the signal strength as a function of the difference in the path length of the two beams gives a measurement of the pulse's duration.

Unfortunately, the short duration and wavelength of attosecond pulses means that neither traditional beam splitters nor nonlinear crystals are suitable. Papadogiannis *et al.*

have sidestepped these problems by splitting the femtosecond pulse before the attosecond pulse is produced, and using a rare gas for the dual purpose of producing and measuring the attosecond pulses. All characteristics necessary for measurement are present, but because production and measurement are entwined, their measurement is not completely transparent, so the method is controversial. But the controversy will not last for long because the basic physics behind the measurements is well understood.

Although current research is naturally focused on the production and measurement of attosecond pulses, it is important to look at the future direction of attosecond science. For one thing, it will benefit from the experience gained in previous experiments with ultrashort pulses. This is because we have been performing indirect attosecond experiments (often referred to as strong-field science) for a decade or more and the necessary tools are well developed. For example, normal visible laser pulses contain electric fields that change significantly during 100 attoseconds (Fig. 1). The electric field of the light pulse is proportional to the force that the field exerts on any electrically charged particle. With modern laser technology, the forces can be very large and precisely controlled. So, hidden within the interactions of intense visible laser light with matter are attosecond or near-attosecond phenomena induced by the laser field.

Indeed, indirect attosecond science can explain the attosecond pulses produced by Papadogiannis *et al.* As the electric field of the laser becomes strong, one of the electrons is pulled free from an atom in the argon gas. Once free, it moves in response to the strong force of the laser; first it is driven away from the ion, then back. Its path can be compared to that of a lifeboat launched from a ship in a stormy sea. The ship (or ion) from which it detached is an obstacle that remains in the area and with which it can collide. As with the lifeboat and ship analogy, the wave determines the possible time of collision. In the violent electron–ion collision that may occur, very-short-wavelength radiation can be emitted. So the precise synchronization of the individual attosecond pulses with the much-longer-wavelength radiation that produced them (Fig. 1) is not an accident, but is forced by the field. Quantum mechanics adds 'fuzziness' to this essentially classical description, but does not change it much.

No experiments have yet been performed with attosecond pulses, and we cannot even produce an isolated pulse. There are, however, many ideas and proposals waiting in the wings, all involving increasingly precise control over oscillations of the strong laser field. Once attosecond pulses can be produced routinely, indirect and direct attosecond science will become increasingly integrated.

Whereas the goal behind the development