Every other Monday night, my husband, Edward, takes a bright yellow bin marked Lexington Recycles out to the curb. The next morning, a big truck comes to collect the contents of the yellow bin. We are told the truck then drives off to a recycling plant, where our discards are turned into the materials to make new cans, newspapers, and plastic bottles. Then we spend another two weeks dutifully filling up that bin with more discards. Over and over again.
between the births and deaths of stars. • By Alyssa A. Goodman

Believe it or not, the universe works in much the same way.

Okay, so there are no conscientious Edwards or bright yellow bins marked The Universe Recycles, but just about all the other pieces of this process have astronomical analogues. Before a star actually dies, it spews enough gas and dust out into the interstellar medium to make a new star almost as massive as itself. And new stars are in fact made, just like new Coke cans, from the stuff of old ones.
**THE GENESIS OF COSMIC STRUCTURE.** Gravity amplified inequities in the early universe’s matter distribution, leading to galaxy-rich filaments separated by immense voids. This false-color depiction of a computer simulation of the expanding universe shows matter in a cubical region now 300 million light-years on a side. Courtesy Michael Warren, Wojciech Zurek, and John Salmon.

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**In the beginning**

Before the extraterrestrial recycling process could ever begin, the universe needed to provide the first generation of stars. Theories about where these first stars came from are still a bit sketchy, but the agreed-upon principles can be summarized pretty easily.

Just after the Big Bang, the universe was too hot for atoms or molecules to exist. In about 300,000 years the universe cooled off enough for electrons and previously bare nuclei to come together to form hydrogen and a few other very light elements. At this time of recombination there were tiny fluctuations (about one part in 100,000) in the number of atoms per unit volume (that is, in the matter density). These density fluctuations have been observed as tiny ripples in the radiation that was produced 300,000 years after the Big Bang (which now exists in the form of microwaves), and they are thought to account for all of the large-scale structure we see in the universe today.

Once gravity started pulling matter together, it was only a question of time before the first stars, and then the first galaxies, would form. We probably still have not observed the very first galaxies, but the image known as the Hubble Deep Field (seen above) shows several odd-looking galaxies at redshifts of 4 or 5, corresponding to a time when the universe was less than 10 percent of its current age.

So, when the universe was a billion years old or thereabouts, galaxies not too unlike the ones we see in the night sky today were plentiful, and each was filled with billions of stars. For the remainder of this article we will not worry about the detailed origins of these first recyclables, and we will not ask how the Coca-Cola company came to be. We will just focus on how to make new Coke cans, and new stars, from old ones.

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**Recycling Steps Compared**

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We begin with the recycling bin. A galaxy has no conscience and does not neatly collect used stars into bins. The exact input to a galactic recycling bin (otherwise known as its interstellar medium, or ISM) depends on how many stars of a given mass die, when they do so, and in what way.

How long a star shines can be predicted from knowing just its mass, as can the manner of its death. Thus we need to know how many stars of each possible mass will form from a large reservoir of gas. That distribution is called the initial mass function, or IMF. The diagram below is a modern estimate of our galaxy’s IMF. The most important feature to note is the steep slope: there are many, many more low-mass stars than high-mass ones. This fact — that massive stars are relatively rare — will loom large in our estimate of the recycling bin’s contents.

The IMF tells us the probability that stars of a particular mass will form when any piece of the ISM produces new stars. In order to know how the interstellar recycling bin fills up, we need to know how long each star of each particular mass will live. Given that all stars live more than 10,000 human lifetimes, it is not possible for humans to measure a star’s life span directly. Instead, we calculate the lifetimes of stars from the rates at which they consume their nuclear-fuel supplies. Unlike most of the other pieces of the galactic recycling story, stellar evolution is exquisitely well understood. As it turns out, massive stars (ones with 10 or more times the mass of our Sun) burn their nuclear-fuel reserves at tremendously greater rates than low-mass (subsolar) stars.

Combined, the IMF and the theory of stellar evolution allow us to estimate how many stars of a given mass will die as a function of time. This statement is akin to saying that we know the statistical distribution of how many different kinds of recyclable materials there are in a typical grocery store, and the average time span between their being purchased and winding up in a big yellow bin at the curb. Yet this kind of information, while necessary, is not sufficient to calculate the overall efficiency of a full recycling process.

On Earth, we recycle only a small fraction, maybe 10 percent, of what is produced in factories. In practice, this 10 percent efficiency is determined by all the steps in the recycling process: storage, collection, processing, production, consumption, and discarding. Your bin may not have room to store all the items you could recycle. Your town might not collect recyclables at all. Your town’s recycling facility may not be able to process some materials. Factories may produce too much material (recyclable or nonrecyclable) to be handled by the processing plants. Humans consume various products sold in recyclable containers with different frequency and speed. And humans may choose to discard even recyclable items in the trash (especially if they smell too bad!).

In the universe, the efficiency of recycling is very high, maybe as much as 90 percent. No one knows the real number because a detailed calculation has not yet been done.* There is plenty of room for storage; most of the universe is empty, as far as we can tell. A galaxy is very good at

* The 90 percent figure is really an educated guess — the average answer calculated by a group of students in Harvard University’s Astronomy 145 course (taught by the author).
Star and Planet Formation

(a) The star-formation (and planet-formation) process begins with a very large, massive assemblage of molecular gas. That assemblage is permeated by turbulence and twisted magnetic fields, which together create overdense clumps. (b) The densest of these clumps, known as dense cores, may be decoupled from the magnetic fields and hence be able to collapse into stars. (c) During the collapse phase, a protostar gains material from an accretion disk and throws off material from each of its rotational poles. The bipolar outflow thus formed carries away angular momentum, allowing more material to be accreted onto the protostar from the disk. (d) The disk’s meager remnants ultimately break up into planets, comets, and asteroids, forming a solar system.

A DIVERSE PRODUCT LINE. What a star casts off into the interstellar medium depends primarily on its mass. Shown above is a schematic of the Hertzsprung-Russell diagram, with the masses of stars in different spectral classes denoted along the main sequence. Blue-white O- and B-type supergiants live for mere millions of years before blowing up as spectacular supernovae, while ruddy M dwarfs burn for tens of billions of years, only to fizzle out without returning much material to the interstellar medium. Data courtesy the author.

Now let us look in some more detail at what winds up in the ISM, how it gets there, and where it is headed.

The ISM is a vast collection of gas and dust between the stars. The gas is primarily hydrogen, in atomic form (H) in warm regions, and in molecular form (H₂) in cold regions (those with temperatures below about 100° Kelvin). The dust is really more like smoke in that the individual grains are very small compared to terrestrial dust particles, but each contains too many atoms to be identified as a molecule.

Interstellar dust very efficiently ob-
sctors visible and ultraviolet starlight, making high-density regions of the ISM appear as opaque black patches on photographs of Milky Way star fields. This obscuration also makes the dense ISM very cold, since gas there cannot be heated by starlight. Cold interstellar gas is well suited to the formation of new stars. Why? Because stars form from the gravitational collapse of condensations of gas, and cold gas is easier to squeeze than hot gas. Hot gas exerts a higher pressure than does cold gas at a given density. Pressure provides buoyancy against gravity and slows down or halts the collapse of a gas cloud into a star. So the parts of the ISM most relevant to the production part of the recycling story are the cold ones.

Most of the cold interstellar gas in the galaxy today is arranged into structures called molecular cloud complexes or giant molecular clouds (GMCs). While the formation of these structures is poorly understood in detail, the basic story is that gravity and pressure from large explosions combine to create large assemblages of relatively cold, dense gas.

ANATOMY OF A STELLAR CRUCIBLE. Left: This apparent “hole” in the Cygnus Milky Way is actually L977, a dusty molecular cloud. Center: These contours show the degree to which starlight is dimmed by the dusty cloud. (The outer contour represents a dimming of four magnitudes, or a factor of 40, for light in the middle of the visible spectrum, and each successive level represents an additional two magnitudes of extinction.) Right: This false-color image represents the quantity of carbon-monoxide molecules within L977. Hydrogen molecules, while more numerous, are far more difficult to detect. Courtesy Charles Lada, Elizabeth Lada, and João Alves.

PROCESSING AND PRODUCTION IN OUR ASTROPHYSICAL BACKYARD. To complement Akira Fujii's photograph of Orion (left), Thomas Dame (Harvard-Smithsonian Center for Astrophysics) prepared false-color images of millimeter-wave emissions from carbon monoxide (middle) and far-infrared emissions from dust (right). Despite Orion’s famous nebulae and glittering stars, most of the astrophysical activity in this region could not be seen until the advent of radio and infrared astronomy, since millimeter-wave and far-infrared emissions are invisible to the human eye. The Orion Molecular Cloud complex revealed by these recently discovered emissions lies about 1,300 light-years from Earth.
Once the matter density becomes high enough in these assemblages to block out ultraviolet radiation from neighboring stars, H forms H₂, and the assemblage becomes a “molecular cloud.” Substructures are formed within molecular clouds by turbulence, not unlike the bumps in our own atmosphere. The densest and coldest parts of molecular clouds, known as dense cores, ultimately collapse into spherical nuclear fusion reactors known colloquially as “stars.”

GMCs have 100,000 to 1 million times the mass of our Sun. If GMCs turned gas into stars with 100 percent efficiency, each could form up to 1 million stars. The number of GMCs in the Milky Way currently is not known, but it is probably 50 or so. Only a handful of these clouds are nearby enough for us to study in detail. The constellation Orion harbors the closest GMC, at a distance of roughly 1,300 light-years.

How do GMCs like Orion’s come to be? In spiral galaxies the gas-collection process is related, on the largest scales, to the so-called spiral density wave instability. This instability causes a spiral pattern to emerge in a spinning disk whenever the ratio of the disk’s gravitational energy to its rotational energy falls in a particular range. However, all this instability does is gather gas into big blobs arranged in an identifiable pattern. These blobs are not all necessarily massive enough for gravity to counteract their internal pressure. And if a blob or cloud is not self-gravitating it will dissipate relatively quickly, much like the helium escaping from a burst balloon.

Suddenly Voyager starts to get some disturbing readings from an uncharted yet very bright star 30 light-years off the bow. The crew fears the star is headed for a supernova explosion and flies off at Warp 9 in the other direction for fear of being blown apart. The crew also enters the coordinates of this region into the Federation data banks and makes a note that it should be explored again, about 100,000 years into the future. Why?

Ultimately the large amount of rapidly moving supernova debris will sweep up the surrounding ISM like a snowplow. Thanks to this snowplowing, a moderately dense region that was destined to disperse can be compressed to the point that it becomes self-gravitating. In fact, many types of outward pressure, including that from H II (ionized hydrogen) regions around newly formed hot O- and B-type stars, can squeeze gas with star-forming potential into actual star-forming gas. This kind of triggered star formation is sometimes called sequential star formation because the H II regions and supernovae formed in one region of a molecular cloud can compress a neighboring region, thereby triggering a new wave of star formation.

One supernova can sweep up far more mass than it contained on its own before it exploded. For example, if a 10-solar-mass star goes off in a region with an average gas density of 10 hydrogen atoms per cubic centimeter and the shock wave expands out to a distance of 60 light-years, the shock wave would sweep up about 8,000 solar masses of material. Now that is one heck of a recycling truck! Supernova explosions are much more important in the collection phase of the recycling process than in any other.

The figure at the bottom of the facing page shows infrared emission from many dust clouds. Dust and gas are well mixed in molecular clouds, so this dust image serves as an excellent (albeit indirect) map of molecular clouds. Notice that the clouds are all arranged roughly in a circle on the sky. It is hypothesized that at least one supernova went off somewhere near the middle of this circle and swept up all the surrounding gas. The swept-up clouds are now all potential sites of star formation. The most massive stars formed in the new clouds could in turn explode as supernovae in the future, blowing apart their parent clouds but sweeping up many new potentially star-forming ones in the process. This cycle can continue until all the virgin gas and recyclables...

**A NEARBY STAR FACTORY.** These false-color Hubble Space Telescope images of the Orion Nebula were taken in the visual (left) and near-infrared (right) portions of the electromagnetic spectrum; the former shows gases ionized by stellar adolescents maybe a million years old, while the latter pierces obscuring dust to reveal an even younger cluster of stars dominated by the so-called BN/KL (Becklin-Neugebauer/Kleinmann-Low) object, the bright star in the center.

**VELA SUPERNOVA REMNANT.** Oddly enough, though, other high-pressure processes actually facilitate the star-formation process. Imagine the following scenario. The USS Voyager is cruising along in the Delta Quadrant, through a relatively dense region of the ISM where there are as many as 10 particles per cubic centimeter (a density 10 times higher than average).
put back into the ISM by the cycle are used up (that is, converted into nonrecyclable material like brown dwarfs, white dwarfs, neutron stars, or black holes), or until they are thrown so far away as to rejoin the general interstellar — or even intergalactic — medium.

While the supernova example is very dramatic, the most common form of triggered or sequential star formation is that driven by the winds and high pressure around massive (O- and B-type) stars. These massive stars produce some photons that are energetic enough to dissociate \( \text{H}_2 \) and ionize the resulting hydrogen atoms, creating an H II region. H II regions, the nearest of which appear as bright nebulae in the night sky, harbor very hot gas. Often the pressure at the edge of an H II region is substantially higher than that in the surrounding ISM, and this pressure difference ultimately compresses gas near the edge of the ionized region. In fact, one often sees regions of new star formation very near the edges of the H II regions created by hot, young, massive stars.

Someday the Milky Way galaxy itself will probably collide and merge with one of the other members of the Local Group, perhaps the great Andromeda Galaxy (M 31). When this happens, our galaxy will experience a burst of star formation more dramatic than any supernova can trigger. The famed “Antennae” pair of interacting galaxies (NGC 4038 and NGC 4039) is currently evincing a great burst of such collision-induced star formation. Again, the star formation is triggered by perturbing clouds that were on the verge of collapsing anyway. In the Antennae, it is as if two neighboring communities have been forced to merge their already near-capacity “dumps” for recyclable goods, and the resulting mess compelled them to build a better recycling plant!

Perhaps we should think of the process of triggering star formation as analogous to environmentalists or benevolent politicians, facilitating the creation of recycling plants where otherwise none might exist. This analogy is good in that many communities (molecular clouds) seem to set up production plants (star-forming cores) all on their own, without any extreme “triggering” influences, as the forces of long-term common sense (gravity) triumph over low-level community resistance (kinetic pressure).

**SIGNPOST OF THE COLLECTION PROCESS?** The North Celestial Pole loop, as this structure is called, spans an impressive 20°. Might it have been hollowed out by several nearly simultaneous supernovae? Those exploding stars could have pushed surrounding material outward, creating concentrations of gas and dust that may someday give birth to new generations of stars. This false-color image depicts far-infrared emission from dust grains and was made possible by the Infrared Astronomical Satellite, which mapped the entire sky in 1983. Courtesy the author.
A CELESTIAL SMOKESTACK. A planetary nebula is the photogenic successor to the red-giant stage of stellar evolution, through which relatively lightweight stars — those with about 1 to 8 solar masses — eventually pass. Red giants slough off voluminous quantities of dust grains, providing future star factories with essential shielding and catalysis.

**Dusty Factories**

Stars, and the winds they drive, are largely responsible for the detailed (microscopic) processing of the waste products of stellar evolution into new star-forming material. The waste products themselves are created in the consumption phase of recycling, by stellar evolution. As we mentioned at the outset, stellar evolution is one of the few well-understood areas of astrophysics, so it is fair to assume that we know exactly what materials need to be recycled, how much of them will be produced, and at what time. This is akin to saying we know how much recyclable garbage a particular kind of person will produce as a function of time. The trouble is, in both the star’s case and the person’s, we do not know exactly how and where the recyclables will be tossed away.

Despite their boring spherical appearance, stars seem to enjoy throwing off gas and dust in oddly shaped winds, much like a mild-mannered accountant who suddenly feels the need to toss a Coke can out the window while driving down the highway. These winds make for beautiful images, but their properties are extremely difficult to calculate. A star with a mass near that of the Sun typically goes through a so-called red giant phase, then creates a planetary nebula, and ultimately ends up as a white dwarf. In the red-giant phase the star stays pretty spherical, but it loses near-surface material that is no longer gravitationally bound to it. Once the star is surrounded by shrouds of material it no longer can “burn” in fusion processes, the star produces a planetary nebula; mass loss becomes extreme and quite oddly shaped.

The intricacies of planetary nebulae are fascinating. But what we care about most here is that much of theISM’s dust is produced in the cool winds that emanate from stars nearing the ends of their lives and is sent off into the ISM by planetary nebulae and supernovae. The dust itself forms when some of the “metals” (elements heavier than hydrogen and helium) produced by previous generations of stars “rain out” as little grains in the cool atmospheres of dying stars.

As hinted at above, dust is critical to the production step in our recycling process because it shields star-forming clouds from destructive high-energy photons. Also, dust is key to the formation of H2 itself. It turns out to be very difficult to get two hydrogen atoms close enough, for long enough, to stick together in today’s ISM without some help from dust grains. The surfaces of dust grains are thought to have sites that any hydrogen atom landing on a grain will seek out. Once two hydrogen atoms get together at such a site, they form H2 and are ejected from the grain. Thus dust grains can be thought of as catalysts for the formation of the molecular hydrogen that makes up star-forming clouds.

The astute reader may now ask how did that first generation of stars (and the Coca-Cola company) ever form in the first place? If stars form from H2 clouds and one needs dust to make H2 — but dust forms only when stars die — have we not reached a logical impossibility? Obviously, given the current form of our universe, the answer must somehow be “no.” The likely flaw in our logic is that you need dust to form molecular hydrogen. Under high enough pressure, it is possible to form H2 in the gas phase, and that is probably how the molecular hydrogen that gave rise to the first stars formed in the early, dust-free universe.
recycling brew. These flows have now been shown to extend for tens of light-years out into the ISM, even though they originate in circumstellar regions only about the size of our solar system. The flows are very long and narrow, so the naïve orange-juice drinker would think that they cannot affect a very large volume of the ISM. Actually, though, the frozen-concentrate buyer would realize that the flows can indeed influence very large volumes. How so?

We said earlier that molecular cloud cores need to overcome outward kinetic pressure in order to collapse under their own weight. When measured, this kinetic pressure greatly exceeds what one would expect solely on the basis of the gas temperature. The best explanation for the extra pressure is that magnetohydrodynamic turbulence is continuously present in molecular clouds.

This is a nice story, and measurements confirm its plausibility. The only trouble is that recent numerical simulations show that one needs to perturb the magnetic field in molecular clouds pretty often, and on pretty large scales, for this story to be viable. Enter giant outflows from young stars. As it turns out, if outflows pluck magnetic-field lines often enough, creating turbulence, they may help set the current rate of star formation in molecular clouds. Now that is subtle, no?

Energetic photons from hot young stars eat away at gas that could have extended those stars’ families. The famous Hubble Space Telescope images of the Eagle Nebula and NGC 3603 show pillars of dense gas enduring obvious erosion. Before a giant molecular cloud gets a chance to consume all its gas, its progeny will ruin its chances for survival.

Hubble’s image of NGC 3603, shown below, presents us with a beautiful composite of the entire interstellar recycling process. At the center of the image we see the consumption phase in action, with young stars burning bright. To the upper left of the cluster we see a ringed, dying star spewing material back into the ISM, where it will be stored and collected into new star-forming clouds. To the lower right we see dense, dark, molecular clouds feverishly trying to process interstellar material in order to produce new stars. As on Earth, all of this can go on until the supply of useful resources runs out.

Alyssa Goodman is a professor at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, where she focuses on the interstellar medium and the star-forming processes that take place there. To find out more about her research, visit http://cfa-www.harvard.edu/~agoodman/.

In general, humans build great edifices and nature eventually destroys them. We humans should take solace, then, in the fact that nature sees fit to destroy not just our great works but its own as well. The great recycling plants that are molecular clouds are ultimately limited, and then destroyed, by their own success. Supernovae and other powerful stellar winds push material around, and the energetic photons from hot young stars eat away at gas that could have extended those stars’ families. The famous Hubble Space Telescope images of the Eagle Nebula and NGC 3603 show pillars of dense gas enduring obvious erosion. Before a giant molecular cloud gets a chance to consume all its gas, its progeny will ruin its chances for survival.

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