Title
Chemical evolution tomorrow

Author
Trimble, V

Publication Date
2001

Chemical Evolution Tomorrow

Virginia Trimble
Physics Department, University of California, Irvine, CA 92697 and Astronomy Department, University of Maryland, College Park, MD 20742

Abstract: The solar system is just one sample, though of course the most thoroughly studied sample, of cosmic chemistry. Some perspective on it can be gained from an overview of the chemical evolution of the Galaxy and Universe, how our knowledge of this evolution has developed, and what problems remain to be solved. The very long-range future, comparable with the age of the universe, is also potentially of interest.

1. HISTORICAL INTRODUCTION

It is reasonable to begin by asking whether the standard picture of nucleosynthesis and galactic chemical evolution is on at least roughly the right track. Thomas Gold is supposed to have said, "If we are all going the same direction, it must be forward." This can be taken as either a definition or a criticism of progress in science, making it salutary to look at where we have come from.

A century and a half ago, we had no data of any kind on the chemical composition of anything outside the earth, and indeed a philosopher (Auguste Compte) had used the composition of the planets and stars as an example of real knowledge that we could never acquire. Then, in 1858-59 Bunsen and Kirchhof demonstrated that absorption lines in the sun had the same wavelengths as emission lines from gaseous sodium and iron on earth, and the unknowable began to be known.

A century ago, it was widely supposed that the lack of spectral features due to iron, titanium, and other relatively heavy elements in the light from the hottest, blue stars meant that those elements had been broken up into smaller atoms, like oxygen, helium, and neon. An intermediate step, about

Origin of Elements in the Solar System: Implications of Post-1957 Observations.
Edited by O. Manuel, Kluwer Academic/Plenum Publishers, 2000.

75 years ago, was the assumption that the stars and sun had about the same mix of elements as the earth, dominated by oxygen, silicon, iron, magnesium, and so forth. Input of some new physics, the Boltzman and Saha equations, and of a creative mind (that of Cecilia H. Payne, later Payne Gaposchkin) were need to demonstrate that all stars have about the same mix of elements, and that the mix is heavily dominated by hydrogen and helium (Payne, 1925).

Fifty years ago, the sun seemed to be running on the CN cycle, and no one had ever seriously attempted to evolve a galaxy. Credit for the first models of galactic luminosity and chemical evolution belongs unambiguously to Beatrice M. Tinsley (1968). Credit for recognizing that only somewhat more massive, hotter stars than the sun draw more energy from the CN cycle than from the proton-proton chain can be claimed by many. I tend to think first of J. Beverley Oke, because when he first tried to pass on the information to Martin Schwarzschild, he was not believed.

Even 25 years takes us back to a time when no quantitative abundance information existed either for the emission line gas in quasars or for the clouds responsible for introducing absorption lines into their spectra (most of which are distant from both the QSOs and us). Indeed, no normal galaxies further away than $z = 0.5$ had any spectral information at all, and record "highest redshifts" have appeared erratically ever since, reaching 6.48 as I write.

As for $t = 0$, you are there, and presentations in New Orleans addressed many aspects of current understanding. Detailed (or at least numerous) references to the historical topics and to many of the items discussed below can be found in Trimble (1975,1991,1996).

"Tomorrow" in the sections that follow will include, first, time scales of $10^{10\pm1}$ years, over which the composition of galaxies can be expected to change significantly (mostly in the direction of an increased fraction of heavy elements at the expense of hydrogen; helium also gains) and, second, time scales of $10^{1\pm1}$ yr, over which our understanding of cosmochemistry should improve, particularly, I hope, in the direction of being able to calculate accurately many items that must now be derived heuristically (like star formation rates and initial mass functions) or treated as variable parameters (like gas inflow and outflow and ratios of types of supernovae in the past). The first time scale can be described whimsically as Z(z(z)), meaning mass fraction of heavy elements *vs.* position in a galaxy as a function of how far back in time we look to see it. The second is "the curse of the adjustable parameter," of which there were only one or two in 1950 and about ten today.

Many of these "adjustable parameters" were first invoked to try to solve what we now call the G dwarf problem, meaning that the fraction of nearby stars with less than 20% or so of solar metallicity is considerably smaller than the simplest models predict. The apparent complete absence of population III stars (ones with no heavy elements at all, but just the 77% hydrogen and 23% helium left by Big Bang nucleosynthesis) is closely related. It has occurred to me that, if intergalactic communication is ever established, the first thing you might want to ask the entity at the other end of the phone cord is “Do you guys have a G dwarf problem?”

2. THE LONG RANGE FUTURE

How long a future we have to explore depends, first, on whether the universe will expand forever or recontract and, second, on the lifetime of the proton. A universe that recontracts sometime between 10^{11} yr and 10^{33} yr from now (limits set by the present non-decreasing expansion and likely limit to proton decay timescale) could have a spectacular future. A second epoch of mergers of galaxies and the gas now found between them (probably more than the gas in galaxies) will produce enormous bursts of star formation and, probably, as much heavy element production as occurred when the universe was young and galaxies first formed. The fireworks will, however, be short-lived. Things will begin merging when the microwave background temperature has been heated back up to 5K, and, when it reaches 3000 K, gas will begin to evaporate from stellar surfaces, shutting off the nuclear reactions.

In a universe that expands forever, we can expect, first, that the average metallicity will increase, though probably not by much more than a factor of two. This may mean an increased number of habitable planets, based on the observation that both the sun and the hosts of known extra-solar-system planets are richer in heavy elements than the general run of nearby stars and the local interstellar medium. Causality could go either way: the stars might be metal-rich on their surfaces (only) because they have accreted cometary, meteoritic, and planetary material; or they could have planets because these are easier to form out of metal-rich gas, which cools more readily. My prejudice inclines to the latter. Next, there will be changes in the ratios of amounts of the various elements and isotopes and in the details of the supernovae (and preceding stellar nucleosynthesis) responsible for them.

Dynamical evolution will accompany chemical changes. Thus galaxies will get rounder, more massive, and fewer. Looking inside them, we will find new sorts of stellar populations (meaning correlations of age, composition, location, and kinematics of stars) developing. The Milky Way, for instance, now has a flat, rotating distribution of metal-rich stars (disk or population I) and a round, non-rotating distribution of old, metal-poor stars (halo or population II). A major merger with the Andromeda galaxy would, for instance, probably result in round, non-rotating distributions made up of the current Pop I and Pop II stars and a new, young, metal-rich population whose formation was triggered in the merger.

The fraction of mass in heavy elements (and helium, which is co-produced) could become very large in a few special environments where gas is retained through many generations of supernova recycling. The gas responsible for the emission lines from the centers of quasars may be a case where this has already happened.

Several major uncertainties remain. Some of these might be addressed by simply letting existing models of galactic evolution run on past the point where they best match the Milky Way or other observed galaxies. (It is not clear whether anyone has done this.) Others will require additional understanding. Many rich clusters of galaxies have X-ray emitting gas whose cooling time is comparable to or less than the age of the universe. This must eventually flow to the cluster center (They are called cooling flows.) and presumably form stars. Because we don't see bright, blue stars at cluster centers, it is generally supposed that the products are low-mass objects in which little nucleosynthesis will occur, but this is not certain. Even less clear is the very long terms future of gas now in diffuse filaments and pancakes at a temperature of $10^{5\text{-}6}$ K in intergalactic space. Recent simulations of galaxy formation suggest that this may comprise more baryonic material than is currently in galaxies and clusters. If so, then whether it ever cools and gathers into units that make stars will make an enormous difference to the long-range future.

3. SHORTER TIME SCALES

You will not be surprised to hear that our picture of the total sweep of things chemical in the universe is still incomplete and "more work is needed" on many aspects. The items discussed below include (3.1) laboratory and other data on fundamental atomic and molecular properties, (3.2) measured abundances, where the goal is to have all stable elements and isotopes in a full range of stars, interstellar clouds, galaxies, intergalactic clouds, and so forth, (3.3) some red herrings that need to be cleared out of the way to reveal the chemical story we are interested in (Some of them include very interesting parts of astronomy and astrophysics, but they are noise rather than signal in the present context), (3.4) processes, sites, and the scheme of stellar evolution in which they are embedded (This topic was the core of the enormously important work of Cameron (1957) and Burbidge, Burbidge, Fowler and Hoyle (1957), B^2FH), and (3.5) galaxy formation and evolution as both dynamical and chemical processes and the coupling of the two.

3.1 Basic Physical Data

We sometimes tend to think that we know all there is to know about the structure and transitions of atoms, molecules, and nuclei. This turns out not to be true even for gases (or gas-dust mixtures) in thermodynamic equilibrium, and is even more false out of equilibrium, when for instance, the amount of an ion that has to be present to make a given line strength depends on the balance between excitation and de-excitation due to photons (not in a Planck distribution) and collisions with electrons and several kinds of atoms and other ions.

A random sweep of a few weeks' worth of major astronomical journals uncovered the following examples: (1) transition probabilities (gf values) for Eu III, needed to decide just how over-abundant europium is in certain peculiar stars, (2) nuclear rates like $C^{12}(\alpha,\gamma)0^{16}$, where the stellar process is dominated by a sub-threshold resonance and so cannot be directly probed with laboratory data, but the answer determines the ratio of carbon to oxygen made in helium fusion (important if you want to end up with habitable planets), (3) the branching ratios for the slow and rapid capture of neutrons (s- and r-processes), especially when the most likely capture takes place on an excited nuclear level or on a long-lived but unstable nuclide, (4) radioactive and collisional cross-sections for ionization, recombination, excitation and de-excitation for all sorts of atoms and molecules, and (5) "missing opacity" – the observation that, especially for ultraviolet light, when you add up all the known lines and bands that will try to stop photons from getting out, the star still knows about more than you do.

3.2 Observed Abundances

Within the solar system, there are relatively few remaining discrepancies. Meteoritic and solar values for the amount of iron differ by 0.1-.2 dex; but it was a factor of nearly 10 within living memory (The meteorites were largely right.) Another solar system topic where an enormous amount is going on is the measurement of assorted isotopic anomalies in individual meteorite grains, including those associated with fossil radioactivities, like Mg^{26} remaining from the decay of Al^{26}. The goal is to associate these with particular kinds of supemovae or supernova ejecta and so learn in detail about the balance of nuclides produced from, for instance, carbon burning in a $15\ M_\odot$ star. When the task has been completed, the results will probably be comprehensible to anybody with a periodic table on his desk or disk. We are a good long ways from that now.

Among the heaviest nuclides, we have not observed the products of the p-process anywhere outside the solar system (and inside only for earth, meteorites, and solar wind). The process produces the rare neutron-poor isotopes of elements beyond the iron peak and does not dominate any element. Products of the s- and r-processes have been studied in many galactic stars and a few gas clouds, but we have almost no information on them in other galaxies, even nearby.

The unstable elements probe relatively recent nuclear reactions and the time elapsed since then. Technetium is famously present in many highly-evolved, carbon-rich stars. One report of promethium in a similar star has never been confirmed. Uranium and thorium live long enough to tell us ages in the 1-20 Gyr range, if you can figure out how much was present to begin with. Two halo stars have Th/Eu ratios at the present time that indicate (if the production ratio was what you expect from a normal r-process) ages near 15 Gyr, rather higher than is generally now coming from globular cluster studies. U has not been seen in these or other stars (except the sun), but might be equally interesting.

Moving to the lightest element, we would like to know whether there are real variations in the ratio of deuterium to hydrogen in either the interstellar or intergalactic unprocessed medium. The former would tell us about how much of the gas in various places has been through stars and had its deuterium destroyed (called astration by the modellers). The latter is vital to understand if you want to use D/H to learn the baryon density in the universe. Real variations could result from either local destruction or local production that is not associated with the formation of much in the way of heavier elements.

The amounts of both helium and heavy elements increase as more stars throw out their reaction products, but the observed ratio of the enhancements, $\Delta Y/\Delta Z \approx 3\text{-}4$ are rather higher than what you expect from a typical stellar population under present conditions $(\Delta Y/\Delta Z \approx 1\text{-}2)$. Insufficient knowledge about nucleosynthesis in stars of initially low metallicity may be part of the problem.

Still other issues where additional observations are needed include (1) Do young stars agree in composition with the interstellar gas they leave behind, or pick out more (or less) than their fair share of heavies, perhaps in the form of dust? (2) How much super metal rich stuff is really around, where (planet hosts, quasar gas, in cores of giant elliptical galaxies), and why? (3) What is the real range of variability in globular cluster stars of elements that really could not have been made in those stars themselves (aluminum, magnesium, silicon, etc.), and if it is large, how did this happen? and (4) What are the various correlations or abundance patterns, for instance of O/Fe and the alpha nuclei (Mg, Si, Ti, Ca) to Fe *vs*. Fe/H, the CNO isotopic ratios, and lithium with various stellar properties, since each of these constrains some important aspect of overall chemical evolution.

On larger scales and in stranger places, we do not know enough about (1) the real composition of the ejecta from various sorts of supernovae, nova explosions, stellar winds, and planetary nebulae (the correct bridge between calculated nucleosynthesis and the resulting average abundance), (2) the efficiency and time scale with which new ejecta are mixed into interstellar material, (3) gradients in abundances with radius and distance from galactic planes (remember Z(z(z))?!), and their correlations with galaxy types and masses; particularly one would like more detailed information than just the ratio of iron or oxygen to hydrogen, (4) compositions of stars and gas in strange galaxies like starbursters and the broad absorption line gas in QSOs, (5) "intergalactic" abundances, meaning the gas in X-ray emitting clusters (It is definitely not pristine.) and clouds responsible for narrow emission lines in quasars (and just where are those clouds anyhow, so that we know what it is whose composition we are measuring!), and (6) of course, everything as a function of redshift (with the additional difficulty of needing a good set of cosmological parameters so that data observed *vs.* redshift can be compared with calculations, which necessarily operate in ordinary time).

3.3 Red Herrings

These are the heart of some astronomical subfields, but mostly a nuisance to students (and teachers) of chemical evolution. A classic example is abundance of isotopes in molecules. Chemical fractionation is interesting and important, but it makes a CO a poor probe of C^{13}/C^{12}, and of $O^{18}/O^{17}/O^{16}$, unless you know a great deal about the conditions under which the molecules formed. Other examples include what drives the shocks out of type II supernovae and what are the progenitors of Type Ia's (though this is needed statistically to track chemical enrichment with time).

There is a whole constellation of places where the abundances we see have been modified by accretion from something odd (white dwarfs with metals; Lambda Boo stars without them), by gravitational settling, radiative uplift and so forth (peculiar A stars, helium in various contexts, and all "first ionization potential" effects and their inverses as in AR Lac), or partial ionization (like He/H in HII regions that are not completely HeII regions).

Sometimes you have to sort out which is which to make progress; occasionally the answer makes sense. A nice case is that of barium-rich stars, which could have made it for themselves or acquired it from binary companions that shed enriched outer layers and have since become white dwarfs. There is a signature: the self-polluters also show Tc. But this does not help us much in using these stars to follow the growth of barium abundance in the galaxy as a whole. Traditional carbon stars are evolved giants and thought to be polluted by carbon made from helium fusion in the stars themselves. On this basis, there "should" be no dwarf carbon stars. There are however, and they too are the victims of material deposited from evolved close binary companions (now white dwarfs).

3.4 Processes, Sites, and Stellar Physics

The set of processes and sites identified by Cameron (1957) and by B^2FH (1957) as capable of producing the full range of elements and isotopes has withstood the forces of time remarkably well. The following short paragraphs describe the processes they identified (some of which had been recognized earlier, starting with hydrogen fusion in the 1920's and 30's) and what has become of them since.

Hydrogen fusion, by either the proton-proton chain or CNO cycle. It produces helium and converts C^{12} and O^{16} into the full range of CNO isotopes in normal stars. Hot hydrogen burning also occurs, in nova explosions and probably late in the lives of massive stars. Its products continue up the periodic table from oxygen to fluorine, neon, sodium, and magnesium and are visible in certain nova ejecta.

Helium fusion, or the triple-alpha process. Neither of the two body reactions $H + He$ or $He + He$ has a stable product. Thus three helium nuclei (alpha particles) must come together to form carbon. Capture of a fourth makes O^{16}, and the two elements are produced together in roughly equal amounts. This happens because of the details of the excited levels, their spins and parities, of the C^{12} and O^{16} nuclei.

Alpha process: Additional alpha particles were supposed by the pioneers to be captured by O^{16} yielding the dominant isotopes of neon, magnesium, silicon, and sulfur. In fact, the necessary excited nuclear states are not present. Thus we get a series of heavy element burning processes that gradually synthesize elements up to the iron peak. The sequence is carbon burning, neon burning, oxygen burning, and silicon burning (which works largely through photodisintegration of some of the silicon nuclei, with the products being captured by remaining ones). There are loose single protons and neutrons in all of the stages, so that all stable elements and isotopes from oxygen up to the iron peak are produced (but have their relative abundances fine-tuned by heating during supernova explosions). As stellar cores get hotter and denser, the processes occur out of equilibrium, and the full chain of nuclear reactions begins to strain current computing power. In the future, it will be possible to track everything simultaneously, and the discrete burning phases may begin to blur together.

B^2FH and Cameron both recognized that three separate processes would be needed to account for all the nuclides heavier than the iron peak, from roughly germanium up to uranium. First, the most tightly bound (most stable) isotopes, along what is called the valley of beta stability (in a map of neutron number *vs.* proton number) could be made by adding neutrons to iron peak nuclei on time scales longer than those of typical beta decays. This s-process will occur in stars of moderate mass during the stage in their lives when both helium and hydrogen are burning in thin shells around a carbon-oxygen core. Material gets carried back and forth between the two shells, resulting in liberation of neutrons from reactions like $C^{13}(\alpha,n)O^{16}$ and others more complex. The neutrons are captured by heavy nuclei already present (thus s-process elements like barium are secondary products–as is nitrogen–made only in second generation and later stars that begin with some heavy elements).

The most neutron-rich nuclides are attributed to the r-process, rapid capture. A nucleus sweeps up as many neutrons as it can bind, then later decays. Because you need lots of free neutrons and lots of heavy elements at the same time to make this happen, the r-process is generally supposed to occur in Type II supernovae, while the iron-peak core is collapsing to a neutron star. Ejection of neutron rich material when binary systems containing one neutron star and one black hole merge is also possible. Only the r-process reaches up to U and Th.

Finally, the neutron-poor isotopes, which are all of low abundance, arise from the p-process, in which neutrons are removed, probably by photo-ejection, or perhaps protons added. Supernovae are also the most likely site for this.

The initial compilations had some nuclides left over-the isotopes of lithium, beryllium, and boron. Later it was recognized that stars cannot have as much deuterium as we see. These left-overs were blamed on an x-process. We now recognize that the deuterium, the helium-3, and most of the normal helium around us (along with a small amount of lithium-7) are left over from the hot, dense phase early in the life of the universe (big bang), and their abundances are clues to the physics of that phase. Most of the lithium, beryllium, and boron are secondary products from the break-up (spallation) of carbon and oxygen in interstellar gas when they are hit by cosmic rays.

Some of the continuing questions in this area of reactions and how they fit into stellar struction and evolution are: (1) Can you make deuterium anywhere except the big bang? (Solar flares make a bit, but far too little in relation to Li, Be, and B.), (2) Is there a contribution from very massive or supermassive objects $(100\text{-}10^5\ M_\odot)$ that formed before the first generations of stars?, (3) Just where do the r- and p-processes happen? (The problem with the most promising zones in supernovae is the difficulty in getting the products out without exposing them to further reactions), (4) Just how many types of supernovae are there from a nucleosynthetic point of view, and what does each contribute?, (5) Does star formation take a fair sample of the gas it starts with? (6) How do mixing and mass loss in stars (the amount of which is quite variable and perhaps dependent on rotation and magnetic fields) affect the range of nuclear products?, and (7) Given that most stars occur in pairs (binary stars) with some interaction between the two members, what does nucleosynthesis in interacting binaries look like?

3.5 Galaxy Formation and Evolution

It is here that we must say most strongly that "some assembly is required." A handful of major unknowns remain. First, we need to know what the dark matter is made of and how it contributes, besides gravitationally, to formation of galaxies and larger scale structures. That basic formation process has many uncertainties, beginning with its very direction: Do large-scale lumps first acquire their identities and then break up into galaxy-sized pieces that collapse as a whole, spinning up and forming stars as they go (a scenario associated with the names of Eggen, Lynden-Bell, and Sandage, 1962)? Or, alternatively, do subgalactic structures separate out first and later merge? This latter is called hierarchical formation and is currently favored, but it is required to match some of the same observed properties of the Milky Way that originally inspired Eggen, Lynden-Bell, and Sandage.

If mergers are important, then how do they affect the rate of star formation, and the spectrum of stellar masses (binaries, etc.) that will be formed? These are essential inputs to models of galaxy evolution. We generally think of discrete stellar populations, defined by the ages, metallicities, location, and kinematics of stars, but some of these may be artificial slices cut out of continua. If they are discrete, then it makes sense to ask whether an old, thick disk population can solve the G-dwarf problem in the younger, thin disk. If not, probably not. It is worth remembering that Baade's (1944a,b) definition of populations I and II involved only location and appearance of color-magnitude diagrams. The correlations with metallically and age were discovered later (though he is often given credit).

Next, when we come to compare models with data, we find a partial degeneracy in age, metallicity, and initial mass function. A stellar population can collectively look red because it is old, or metal rich, or dominated by low-mass stars (or some combination) and blue because it is young, or metal poor, or dominated by massive stars. Breaking this degeneracy requires more detailed spectral information than is generally available outside the Local Group of galaxies.

3.6 The Curse of the Adjustable Parameter

Many of the things that you need to know to put together a complete simulation of galactic chemical evolution are, in principle, causal, calculable processes, for instance the number of stars of each mass that should form from a dense molecular cloud of particular temperature, magnetic energy, turbulence, and so on. In practice, we get approximations to them by looking at clusters of young stars, etc. to find out the possible range of the parameters and then, in our models, choosing plausible values until we like the results (meaning, usually, that they agree with observations of some galaxy or stellar population). The items typically treated this way include:

1. The initial mass function, N(M), that forms out of a gas cloud (power laws with cut-offs and log normal distributions are population). The characterization of binary stars formed belongs here, too. How many compared to the single stars, and what is the distribution of mass ratios and orbit periods or sizes?

2. The star formation rate as a function of time, or of local gas density and whatever other factors may enter. Delta functions and declining power laws are popular.

3. Infall of unprocessed gas from the surroundings of the galaxy. So-called high velocity clouds of neutral hydrogen approaching the disk of the Milky Way indicate that this is an on-going process but don't much help in finding out the amount of the infall or how it has changed with time.

4. Conversely, many galaxies seem to have winds blowing (sometimes perpendicular to their disks) with large enough velocities to remove the gas completely. The existence of metals in the intracluster gas of X-ray clusters says that outflows after the onset of nucleosynthesis must be widespread. If the drivers of the flows are supernova shock waves, then metal-rich material may be lost preferentially. How much is another parameter to play with.

5. The actual composition of the gas involved in processes 3 and 4 is an issue separate from the total amount of gas. Another adjustable is the amount of gas that just moves from one place in a galaxy to another, carrying its metals with it. Inward and outward are both possible

6. The fraction of gas that goes into a generation of stars that eventually comes out as gas of some kind gets a symbol like f in the equations for

chemical evolution. Much of the returned material is still hydrogen and helium.

7. The fraction of gas that goes into a generation of stars and eventually comes out as newly-synthesized heavy elements is called y, the yield. It depends on the full assortment of details of stellar structure and evolution. Assuming that it is constant, at 1% or so, is common but surely wrong.

8. "Instantaneous recycling" is the approximation that the metals come out as soon as new stars are made. Type II supernova progenitors indeed have short lifetimes (a few x 10^7 yr is typical), but they are not the whole story, and the high ratio of oxygen to iron in some metal-poor stars says that instantaneous recycling is not good enough. Unfortunately, we don't really know the lifetimes of progenitors of Type Ia supernovae (the ones with no hydrogen lines in their spectra that are generally blamed for making lots of iron).

9. The rates of the various kinds of supernovae in different sorts of galaxies as a function of time is only very partially constrained by observations (and perfectly honest people get estimates that differ by factors of two or three, even for the common SN types and normal galaxies like ours).

10. Finally there are other inputs of heavy elements from stellar winds, planetary nebulae, novae, and other events. These will not dominate total metallicity anywhere but may be important for specific elements like carbon and nitrogen and isotopes like ^{21,22}Ne from novae on massive white dwarfs.

3.7 A Case Study: Empirical Determination of Star Formation Rate

The gold standard for measured rates of star formation would come from counting all the stars in some volume (cluster, population, whatever), measuring the mass of each, and determining its age from the extent to which it has evolved away from the main sequence. This is not entirely impossible. We can, for instance, say on evolutionary grounds that the sun is more than a billion and less than 10 billion years old. But this rigorous method is quite impossible if you cannot resolve all the individual stars (that is, anywhere outside the Local Group), and it provides no information about stars born longer ago than their lifetimes.

We have, instead, a number of "indicators" of star formation rate in various contexts, most of them sensitive only to stars of the largest masses, highest luminosities, and shortest lives (except for measuring total masses in clusters and such, which tells you about the lower masses preferentially). When more than one indicator is applied to the same population, results tend to be correlated but not identical, and it is sometimes obvious why this should be so. Examples (This is meant to be exhaustive, but I may have forgotten something.), in order from most to least straightforward include:

1. Direct radiation. This will be mostly blue and ultraviolet light, which is easily absorbed by dust and lost to the inventory, though it then comes out as
2. Reradiated photons, in the full range of infrared wavelength bands and the sub-millimeter (depending on the temperature of the dust doing the reradiating and on whether the galaxy is nearby or at appreciable redshift).
3. Radio emission from supernova remnants and electrons accelerated in them which then radiate in a general interstellar magnetic field (non-thermal radiation) plus the thermal radiation from HII regions ionized by young stars and in older supernova remnants. The thermal and non-thermal components can often be separated and used independently.
4. X-ray emission. Once again, this will come from a combination of various kinds of very hot gases, some diffuse (supernovae and their remnants), some compact, like the emission from X-ray binaries and very young white dwarfs. The sum should at least be correlated with the number of massive stars formed over the past 10^8 yr or so.
5. Supernova rates. These have the advantage that the events can be seen in quite distant galaxies, and, at least for Type II (core collapse) SNs probe a fairly definite mass range.
6. Heavy element production. This is the primary tracer used at the largest redshifts, where we indeed see that the gas clouds responsible for producing QSO absorption lines are very metal poor by solar system standards. The strongest correlations are, however, probably with where, relative to large galaxies, the gas clouds lie rather than with look-back time.
7. Gamma ray burst rate. These are even remotely useful only if you are sure that the bursters are in distant galaxies (demonstrated by data in the last few years) and that you can associate them with some definite event in the lives of massive stars, for instance failed supernova explosions or the merger of neutron star binaries (plausible but not certain). Some very preliminary evidence from statistics of the brightnesses and spectra of GRBs has suggested that their rate might track the star formation rate, with a peak at moderate redshift $(z \approx 2)$ and lower rates before and after.
8. Ionization of QSO absorption line clouds. Because the main source of ionizing photons is thought to be leakage from star forming-galaxies, this provides yet another indicator, and again correlations have been claimed. But if the correlation should be poor, I think we would claim that other sources, like active galaxies, dominated the UV background, not that star formation wasn't a well-defined process.

ACKNOWLEDGEMENTS

I am grateful to Dr. Oliver K. Manuel for the invitation to give a talk at New Orleans (though it was impossible to accept) and to Drs. Richard Kron, James Truran, and Craig Wheeler for the invitation to give a real (rather than virtual) talk on chemical evolution at the Chicago Meeting of the American Astronomical Society in June 1999.

REFERENCES

Baade, W.: 1944a, "The resolution of Messier 32, NGC 205, and the central region of the Andromeda Nebula", *Ap. J.* **100**, 137-146.

Baade, W.: 1944b, "NGC 147 and NGC 185, two new members of the local group of galaxies", *Ap. J.* **100**, 147-150.

Burbidge, E.M., Burbidge, G.R., Fowler, W.A. and Hoyle, H. **(B^2FH):** 1957, "Synthesis of the elements in stars", *Rev. Mod. Phys.* **29**, 547-650.

Cameron, A.G.W.: 1957, "Stellar evolution, nuclear astrophysics and nucleogenesis", Chalk River Report CRL-41; "Nuclear reactions in stars and nucleogenesis", *Publ. Astron. Soc. Pacific* **69**, 201-222.

Eggen, O.J., Lynden-Bell, D. and Sandage, A.R.: 1962, "Evidence from the motions of old stars that the galaxy collapsed", *Ap. J.* **136**, 748-766.

Payne, C.H.: 1925, *Stellar Atmospheres; A Contribution to the Observational Study of High Temperature in the Reversing Layers of Stars*, Harvard Observatory Monographs, No. 1, Cambridge, MA, 215 pp

Tinsley, B.M.: 1968, "Evolution of the stars and gas in galaxies", *Ap. J.* **151**, 547-565.

Trimble, V.: 1975, "The origin and abundances of the chemical elements", *Rev. Mod. Phys.* **47**, 877-976.

Trimble, V.: 1991, "The origin and abundances of the chemical elements", *Astron. Astrophys. Rev.* **3**, 1-46.

Trimble, V.: 1996, "Cosmic abundances: Past, present, and future", in *Cosmic Abundances: Past, Present and Future*, eds., Holt, S. S. and Sonneborn, G., Astron. Soc. Pacific Conf. Ser. **99**, pp. 3-35.