The following will be published in three installments in the Indian magazine Akashmitra — India's equivalent of Astronomy Magazine, or Sky and Telescope. The first installment will be in the January 2003 issue. The article was written while I was on sabbatical leave visiting IUCAA in Pune, India.

# A BRIEF HISTORY OF MATTER

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Consider for a moment the page you are now holding in your hand and reading. As with any object, we can ask a simple question : when, where and how was this made ? A quick answer, of course, might be that it was manufactured in early 2003 at a printing company in Pune. But is that a full answer ? What about the paper itself, or the ink. Were these not made earlier and in different factories ? Continuing : the paper came from trees which grew by combining water, air and nutrients which themselves have complex histories. What we find is that the creation of objects is really a story about transformations, where matter is rearranged from one pattern to another. We do not normally consider the question applying to the matter itself — when and how, if at all, was the matter itself created ? Lets now turn to consider this deeper question.

## Atoms and Atom Factories

We first need to consider the nature of matter — the kind of matter we find in this printed page. Continuously zooming down into the page, we first pass by individual letters, then fibers of wood, then tree cells, organelles within these cells, giant molecules and finally, after about eight steps each of a factor ten, we find a sea of tiny jostling spheres, all of similar size though of somewhat different weight. This page contains as many tiny spheres as there are grains of sand along all the coastlines of the world. These are the atoms from which all things are made. If we could answer how, when and where these atoms were made, surely that would bring us closer to knowing the origin of all things ?

To begin that story, we need to look more closely at these atoms. Continuing our shrinking voyage into a single atom we first pass through a cloudy cloak comprising a few lightweight electrons orbiting around a tiny heavy nucleus, a further five factors of ten smaller than the atom itself. Scrutinizing this nucleus more closely we see it is a compact bundle of heavier spheres of two slightly different kinds — protons and neutrons — tightly glued together. Our question now takes on its earlier form : when and how was this nucleus assembled and was the electron cloak created at the same time or was it added later ? [1]

From just this simple picture, we can already begin to guess at the kind of conditions we expect to find inside atom factories. First notice that the nega-

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[1] Let us postpone, for the moment, the fact that protons and neutrons are themselves made from yet smaller entities, quarks and gluons, and to complete our story we will need to consider their creation as well.

tively charged electron cloak is held in place by its attraction to the positively charged nucleus (opposites attract, likes repel). We might expect, therefore, that once a nucleus has been made, the electrons will naturally and easily just drop into place as long as the environment isn't so hostile that their relatively weak orbital attachment is broken. By far the most difficult task is to make an atomic nucleus. The problem is this : the nucleus contains positively charged protons which push hard against each other and would certainly blow the nucleus apart if it wasn't for the stronger nuclear glue which binds them together. If we want to build a nucleus from individual protons, we need to throw them together with sufficient force to overcome their mutual repulsion, so they can touch and stick. Conditions which might allow this to happen occur at very high temperatures and densities, where all particles move very fast (high temperature) and collide very frequently (high density). A simple calculation tells us that protons must move at thousands of kilometers per second if they are to make contact in head-on collisions, and such speeds occur only at temperatures between ten million and a billion degrees. Yikes ! Where do we find such extreme temperatures ?! Certainly nowhere on (or even inside) the Earth — we quickly realise, therefore, that atoms must have been made *before* the Earth formed. But where ? Telescopes sensitive to X-rays and gamma-rays can locate gas at these super-high temperatures — do they reveal the atom factories ? The answer is *no* : although they do see large amounts of very hot gas in intergalactic space, its density is way too low to create new atoms. The atom factories are hidden from us. As you may already know, the conditions at the *centres* of stars are ideal for the construction of atomic nuclei.

## Stellar Furnaces

Deep at the heart of a star, all the weight of the overlying matter presses down with enormous force, creating a very dense gas with as much as a few kilograms crammed into each cubic centimeter. In this condition, the gas contains no fully assembled atoms : electrons, protons and nuclei just zoom around independently. Not only is the gas dense, it is also kept extremely hot by the very process we are considering : the construction of new atomic nuclei. When protons collide and stick together, energy is released and it is this energy which keeps the gas sufficiently hot to keep the reaction going. In a very real sense, the heart of a star acts like a huge furnace — a fuel (lightweight atomic nuclei) "burns" giving off heat and leaving ash (heavier atomic nuclei). The heat produced keeps the furnace hot and the fuel burning. In this case the word "burn" refers not to the chemical combustion familiar to us in everyday furnaces, but rather to "thermonuclear fusion" — literally, the coming together of atomic nuclei at high temperatures. There are two byproducts of these reactions : heat and heavier atomic nuclei. Lets look at these in turn.

Heat generated in the star's central furnace keeps the whole star hot. As you might expect, the star is kept hottest at the center where the furnace is actively burning (typically 10 to 100 million degrees), while further up in the star, away from the centre, the temperature drops, becoming lowest at the surface (typically 2000 to 20,000 degrees). Depending on the kind of star, the heat energy makes its way from centre to surface either by the slow diffusion of X-rays (radiative transport) or by rising currents of hot gas (convective transport). Of course, even the "cool" surface is sufficiently hot that it glows brightly — in other words, the star "shines". We learn, therefore, that stars shine at night (and the Sun gives us daylight) because, and only because, new atomic nuclei are being made in their cores. More poetically, a star studded night sky is nature's way of announcing the birth of new atoms.

Just a little more thought provides some interesting insights into the life and death of stars. Depending on the temperature and pressure in a star's centre, its furnace can burn powerfully or feebly. The determining factor is the star's weight : a heavier star presses down harder on its furnace and, like a pressure-cooker, causes it to burn more vigorously. But more powerful furnaces yield brighter stars — and so we learn the simple fact that brighter stars are actually heavier, while fainter stars are simply lightweight. (As we shall see in a moment, however, some stars shine brightly for a different reason : they burn different fuels).[2] Now, the dependence of furnace power on star weight is very delicate, because a slight increase in furnace pressure and temperature leads to a big increase in the thermonuclear reaction rates. So, for example, a star 10 times heavier than the Sun is actually 3000 times brighter. Since stars span a wide range of weights, from about a tenth to a hundred times the Sun's weight, we find they span an enormous range in brightness, from several thousand times fainter than the Sun to a hundred thousand times brighter. Stars are really quite a diverse population ! Pushing this discussion just a little further, we can begin to consider how long stars can live. Since a burning furnace is obviously consuming fuel, we can ask how long it takes the furnace to use up all the available fuel, causing the star to cease shining and hence "die". The Sun consumes about 650 million tonnes of fuel (protons) per second and has a furnace which weighs about 200 million billion billion tonnes. Doing the arithmetic : we find the Sun uses up its fuel in about 300 million billion seconds, or about 10 billion years (it is currently half way through its fuel supply — we have another 5 billion years before it dies). Turning to heavier stars : although they have more fuel to burn, their furnaces are much more powerful and so they use up their fuel faster, causing the star to die sooner. Sirius, for example, is 1000 times brighter than the Sun and races through its fuel in only 50 million years. Summarising these simple results : heavier stars harbour more powerful furnaces and shine more brightly, but they also consume their fuel faster and die sooner. It's the star's equivalent of the old human saying : those who live in the fast lane age quickly and die young (though for humans, there is no link between living in the fast lane and being heavy !).

### Making the Elements

Lets turn now to consider the freshly made atomic nuclei — the "ash" produced in the furnace. For most stars in the sky, the fuel is hydrogen and the ash is helium. In a series of collisions, four protons stick to make a helium nucleus. Getting only a few protons together is relatively easy and so the temperatures at the centres of most stars are between 10 and 20 million degrees (the Sun's furnace, for example, burns at 14 million degrees). Unlike chemical furnaces (e.g. wood or coal), a thermonuclear furnace can exhibit a remarkable property : the ash from one burn can become the fuel for another. It is not too difficult to see why. Having made one atomic nucleus (e.g. helium) from protons, we can either add more protons to make heavier nuclei, or we can collide two or more helium nuclei to make yet heavier nuclei. Indeed, one can imagine a whole series of reactions, where nuclei keep colliding and sticking to build up ever heavier nuclei. In this way, an entire *series* of atomic nuclei can be formed, containing just a few protons up to many. We know this series by a different name : it is the series of *chemical elements* : Hydrogen (1), Helium (2), Lithium (3) .... Carbon (6), Nitrogen (7), Oxygen (8) ..... Calcium (20) ... Iron (26) .... Uranium (92), and even a few more beyond. Lets not forget that these 92 or so different kinds of atoms, when combined in different ways, generate all the molecules of all the substances known to man — just as the few

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[2] For the purist : I've used "weight" and "brightness" in preference to the more accurate terms "mass" and "luminosity".

dozen letters of the alphabets combine to make all the words in all the books ever written. To understand the construction of this sequence of elements is therefore to understand the ultimate origin of all material things.

Under what circumstances can a thermonuclear furnace create these heavier nuclei ? You may already be able to guess the answer. Since heavier nuclei contain more protons and have more positive charge, they repel each other much more strongly. If they are to collide and stick they must therefore move faster. Hence the key to igniting heavier fuels is to have hotter furnaces. Two conditions must apply before furnaces can get hot enough. First, lighter fuels which burn at lower temperatures must have all been consumed — in other words, the star must be approaching the end of its life. Second, the star must be very heavy. Here's why. When a light fuel becomes exhausted and the furnace begins to go out, the reduced heat output causes a loss of core pressure and so the weight of the star bearing down on the core forces it to contract. High school physics tells us that when the gas in the core is compressed it becomes hotter. Only if the weight of the star is great enough does the core temperature increase sufficiently to ignite the new fuel. When this happens the furnace is rekindled, crisis is averted, and the star continues to shine once more, this time powered by a much hotter furnace burning a heavier fuel to create yet heavier elements. This explains a rather simple truth : heavier elements can only be manufactured in heavier stars. The Sun, for example, will get as far as making Carbon (6) and Oxygen (8) but cannot make sodium (11) or magnesium (12), while a star like Rigel (which is 15 times more massive than the sun) will ultimately create elements up to and beyond iron (26).

### Take a Break

Lets pause for a second to catch our breath and get our bearings. We have come a long way in understanding where and how the atoms in the paper and ink of this page were originally made. The answer, rather astonishingly, is that they were cooked for millions of years in white hot furnaces deep inside stars, at temperatures of hundreds of millions of degrees, pressures of billions of atmospheres, and densities of many kilograms per cubic centimeter. Clearly, the matter in this page has had a wild and exciting past compared to its present rather calm location !

Our story is, of course, still glaringly incomplete. The atoms in this page are no longer inside a star ! Somehow they have got out of the star and found their way across interstellar space and onto the Earth, where after several billion years they were finally incorporated into a tree and hence into this page. The remainder of our story considers this extraordinary journey, and will be taken up in the next issue of Akashmitra.

## — II —

This article continues a story which began in the previous issue of Akashmitra (No. 2), where we began to trace the ancient history of the matter in the page you are now reading. The story opened by recognising that the page contains an unimaginable number of tiny atoms, and our goal is really to uncover where and when these atoms were first assembled. Scrutinizing the atoms closely, we saw they had a cloak of lightweight electrons orbiting a much tinier nucleus which itself comprised a tight bundle of protons and neutrons – the exact number determining to which of the 92 elements the atom belonged. After guessing, intelligently, what conditions might be needed to construct atomic nuclei, we recognised that such conditions exist deep within stars, where temperatures are millions of degrees and pressures are billions of atmospheres. Within such stellar furnaces, lightweight atomic nuclei can collide and stick to make heavier atomic nuclei, simultaneously releasing the heat which keeps the star hot and shining brightly. When a lightweight fuel is all used up the star's furnace gets even hotter and it begins to construct even heavier atomic nuclei. Depending on the weight of the star (which determines how hot the furnace can be), the star can manufacture all 92 of the elements we know here on Earth.

Our story ended, however, several billion years ago with these freshly minted atomic nuclei trapped deep inside an ancient star. To enter this page they must somehow rise to the surface of the star, cross interstellar space, build the Earth, and finally arrive in the tree which made the paper of this page. We pick up the story at the start of this remarkable journey......

### From Centre to Surface and off into Space

Getting matter from deep inside a star up onto the surface and off into space is no easy feat. Indeed, it is only at the end of a star's life, as its furnace readjusts to the changing fuels, that this can happen. For stars like the Sun, the core shrinks to about the size of the Earth and enters a phase of extremely vigorous thermonuclear burning in a shell near the outer parts of the furnace. The searing heat generated does two things. First, it causes the star to expand enormously, pushing its surface way out, perhaps as far as the orbit of Mars. Second, it drives strong convection currents throughout the whole star. These convection currents dredge up freshly made atomic nuclei from near the star's centre and brings them up to the surface. Close to the surface the temperature is sufficiently low for negatively charged electrons to be captured by the positively charged nuclei. At a few hundred thousand degrees the first electron is caught and held, and by the time the nucleus reaches the surface, all but one or two electrons of the full cloak are in place. We learn, therefore, that while nuclei are made first, deep inside the star at tens of millions of degrees, the final atom is only assembled later in the outer parts of the star at temperatures below hundreds of thousands of degrees.

So far so good, we now have our atoms at the surface of the star. How to get them off into space ? Conveniently, two phenomena conspire to help this occur. First, the enormous diameter of the star places the surface at such a great distance that the pull of gravity only weakly holds the surface layers to the star. Second, the strong convection currents generate and amplify magnetic fields which help push the surface layers off as a wind. Thus, our freshly minted nuclei with their new electron cloaks find themselves driven away from their parent star in a gentle wind.

Before we follow these infant atoms further along their journey, lets briefly consider how the atoms manufactured in more massive stars find their way out into space. If anything, the problem seems even more daunting for these massive stars — the atom furnaces are buried even deeper inside a huge star, with all its weight pressing down. Of course, the huge mass of the star ensures that as each successive fuel is burned, the next is quickly ignited. Indeed, so readily does the sequence of fuels burn, that they form a set of nested concentric shells — many furnaces burning simultaneously, with ever heavier elements found ever deeper inside the furnace. For reasons which are both fascinating but also rather technical, the ash from burning silicon (14) is iron (26), and when this iron tries to burn it doesn't release energy, it absorbs it. For this reason, iron nuclei accumulate at the centre of the star in a giant dense but growing ball. When it becomes a bit larger than the Earth, but with a mass more like that of the Sun, its weight becomes so great that its strength snaps and in a split second it collapses in on itself. In the next few seconds, a dozen or so fascinating processes occur, the upshot of which is that part of this catastrophic inward collapse is reversed in a mighty explosion. A powerful shock wave races up through the star heading for the surface. When it reaches the surface the star is seen to rip apart and much of the material from the interior is ejected out into space at several thousand kilometers per second : the star explodes as a supernova. From our current perspective, this explosion is an extremely effective way of getting large quantities of freshly minted atomic nuclei up from the deep recesses of the star and out into interstellar space. In particular, these supernovae (and other related types) can create many of the elements beyond iron in the element series. In the extreme conditions of the explosion, not only can a few more protons be stuffed into already heavy nuclei, but there is a huge glut of neutrons, which feel none of the nuclear repulsion force and so can easily pile into nuclei and drive them up the sequence, as far as Uranium (92) and even beyond.

## A Lonely Voyage

At this point, the life experience of our infant atoms changes dramatically. From their fiery gestation within a womb-like furnace, to their ignominious ejection by a wind or explosion, they now enter an extended period of relatively calm loneliness. Some atoms (particularly those of carbon and silicon) can band together in small communities of a million to a billion to make tiny smoke particles which, as the eons pass, gradually accumulate in a patchy interstellar smog which prevents a clear view across the galaxy. Others atoms are true loners, separated from their nearest neighbor by a centimeter or so — equivalent to one person per continent on the Earth. Like children leaving home, atoms can drift into rather different neighborhoods in the enormous spaces between the stars. Close to hot stars, atoms are vulnerable to powerful ultraviolet photon bullets which can damage their electron cloaks, perhaps even blasting a couple off. In some regions, whole armies of atoms collide at high speed as winds or sonic booms pass by each other, wreaking carnage on the fragile electron cloaks. In contrast, a few lucky atoms are gently pulled into vast but sparse communities, dark and cold, where life is sufficiently calm for pair-bonds to form small family molecules which rotate and vibrate in a dizzying dance.

It is in this cold familial region that the next stage in our story develops. The pervasive social force of gravity can cause the atoms and molecules to move ever close together. When enough of them have congregated, the pull of gravity is sufficiently great that they begin to experience a giddy free fall down onto a great heap at the bottom of the gravitational hill. As more atoms pile onto this heap it heats up, becoming hottest at the center. After a while, the temperature and density at the centre increase sufficiently that a new thermonuclear furnace is ignited — a new star is born. After a few billion years of cold loneliness, our atoms once again find themselves back in the familiar environment of their birth, at the center of a star. It is even possible that our old nuclei are incorporated into new and heavier nuclei. And so the cycle can continue — the ashes from one generation of stars can become the fuel for the next. As the process repeats, the fraction of heavier atoms gradually increases. This explains a remarkable observational fact : the oldest stars in our galaxy have almost no heavy elements in them at all, perhaps a tenth of one percent. In contrast, stars forming today have been significantly enriched by former generations and can have ten times the heavy element composition, perhaps as much as 3 or 4 percent. A moments thought brings disturbing news for the distant future : there will come a time when all the light elements have been converted into heavy elements, and stars can no longer shine. The Universe, billions of years from now, will go dark.

## Building Planets and Life and You

Rather than dwell on the atoms which enter the thermonuclear fray for a second time, lets look more closely at some of their close neighbors, those which, because of their motion, didn't head straight for the central heap but instead wound up joining an orderly procession around the newly forming central star. This minority of atoms settle into a flattened disk, sufficiently cool that gentle collisions can build larger structures : atoms build molecules, molecules form grains, grains form pebbles, pebbles form boulders, and at some point gravity takes over and attraction onto the largest boulders eventually builds embryonic planets. In a dramatic but short period of time, these embryonic planets collide and merge to form a final set — nine in the case of the solar system. At the end of the day, maybe a billion billion billion billion billion atoms find their way into a planet like the Earth. The heavier ones sink to the center (e.g. iron and nickel) while the lighter ones float to the surface (e.g. carbon, oxygen, magnesium). If the conditions are just right, the electron cloaks of these atoms can both stick and break easily, creating and modifying molecules continuously. At glacial pace, an extraordinary selection process begins to leave its mark : molecules which are stable and can duplicate become common, while those that can't become rare. This principle leads to the construction of ever more complex structures which ultimately become recognisable as life. Working as a team, natural selection and the passage of time are superb craftsmen : with unimaginable dexterity, they coax billions of atoms into huge systems, following instructions inherited from long lines of successful ancestors. Although the gulf seems unbridgeable, after thousands of millions of years it is even possible for atoms to arrange themselves in the form of a tree. Indeed, to make a human from atoms is barely more difficult than to make a tree. Even more remarkable, of course, is the fact that the matter which makes a human can even comprehend its own origins.

And so to this page. Not only has our story retraced the ultimate origin of the matter in this magazine, but it has done something much more interesting. It has brought you, the reader, into the same story. Look at the hand currently holding this page — to you the skin speaks of decades, but look again : what you see is older than the Earth itself. The atoms in your hand were also forged inside an ancient generation of stars, ejected into interstellar space, fell onto the Earth, where they joined the biosphere. Not just your hand, the atoms which enable your brain to comprehend this sentence and give you your present sense of identity have also had a long and fascinating history. In fact, the biosphere is so complex that the atoms in this page may once have been inside a functioning brain and, similarly, the atoms which are now scrutinizing this sentence may once have been inside a paper page ! While we can't be certain of this last playful possibility, we can be certain of one thing : they were all once inside a star. Stated slightly differently, you and the world and the Universe are related in a much deeper way than you might have once thought — you share a common heritage. Indeed, it can be emotionally rewarding to feel this kinship, arising from shared nature and origin, rather than focus on differences in form, which are after all only skin deep. Similarly, when looking at the night sky, it is far too easy to think about its remoteness, its separation, its coldness. So next time you look at the stars, try to feel their proximity, their warmth, the kinship you share with them and their nuclear furnaces. Take the long view : those shining points of light announce the birth of new atoms which may someday find their way into a beautiful new world and thence into some future sentient being, just as the atoms in you once heated an ancient star whose light may have been seen by a former sentient being standing on a former planet, long since gone. We all participate in this cosmic exchange. Our limited human viewpoint sees only a static image in which everything seems forever separate, whereas in truth all is in flux, the matter cycles from you to me to the ground to the air, and from star to space to planet and back again. You are a brief vehicle for your atoms, just an eye-blink in their long years — they have lived a thousand lives before you, and they will live a thousand more after you are gone. You should feel honored and awed to be their temporary keeper, these most ancient of entities, children of the stars and denizens of the Universe.

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Our story is still not over ! In the next issue of Akashmitra I will present three addenda. The first takes a closer look at the evidence we have that the story I've just told is in fact true — that the atoms in this page really were once inside stars, unbelievable though that may sound. In a second addendum I explore whether this scientifically constructed story can have the kind of emotional resonance that more traditional creation myths have provided for centuries — in other words, must we sacrifice poetic force when we demand scientific accuracy, or can both be present at the same time ? Finally I extend, and in some sense complete, this creation story by taking us back fourteen billion years to a time when the Universe was still very young, before any stars had yet been born. It was in those remote and wild times, only a minute after creation, that the lightest elements were forged out of protons and neutrons in a truly cosmic furnace. Just seconds earlier, the protons and neutrons themselves had burst into existence, condensing out of the seething energy which was released during that first instant of time, just as the Universe came into being.

## — III —

This is the third and final installment of a story which has traced the long and fascinating history of the matter in the page you are now reading. If you have not yet read the first two parts, it might be good to do so now — they can be found in the previous two issues of Akashmitra (Nos. 2 and 3). Failing that, here is a brief review !

We began by suggesting that the deep history of this page is to be found in the story of its invisibly tiny yet unimaginably numerous atoms. Realising that atoms are themselves composite, our main task was to understand how an atom's even smaller nucleus is assembled, proton by proton. The difficulty of this assembly demands special conditions which are only found at the centres of stars, where temperatures are millions of degrees and pressures are billions of atmospheres. In the star's central furnace light atomic nuclei combine to make heavier ones, releasing energy which then heats the star and makes it shine. Towards the end of a massive star's life, its central furnace can become extremely hot and dense and this enables medium sized atomic nuclei to grow even larger — constructing, one by one, all the elements from hydrogen (1) to uranium (92), and even a few beyond. Either gently (lightweight stars) or explosively (heavyweight stars) the freshly made atomic nuclei are brought to the star's surface, grabbing their electron cloaks on the way up, before being blown off into space, where they drift either alone or in small groups for billions of years. Some find their way into cold dark clouds where they are encouraged by gravity to collapse into ever denser regions, ultimately becoming hot and dense as more material crashes down from above. In this way new stars are born, with planets orbiting around them, all made from the very same atoms which had once been assembled inside that earlier generation of stars, now long since extinguished. If the conditions on a planet are just right, the atoms' electron cloaks can band together to make molecules, and soon the most stable molecules also become the most common. Natural selection and the passage of time are powerfully creative, and as millions of years turn into billions, ever more complex structures are formed which ultimately resemble life. With extraordinary dexterity, atoms arrange themselves into huge systems, coaxed by molecular instructions inherited from an ancient lineage of successful ancestors. And so, finally, a tree can grow and paper can be made, and a human can grow, with hands to hold this page and a brain to comprehend it. A beautiful moment occurs when the atoms in that brain somehow comprehend their own origins, and can even feel moved by it.

This, then, is the story of our printed page. It takes us far into space and far into history, and as the story unfolds we realise that it is also our own story — our own atoms have experienced the same extraordinary past as the atoms in all other things, great and small. Realising this shared past can give us a deep feeling of connection with the world and the stars. There is, nevertheless, a difference between you and your atoms — you are the arrangement and movement of your atoms, not the atoms themselves. To them, you are a brief (though unusual) moment in their long long lives. They have seen the inside of stars, they have watched the Earth form, they have lived a thousand lives and will live a thousand more, and when all life is gone they will still be there to watch the Sun die. How privileged to be their brief keeper, these most ancient of travellers — they bring to you their cosmic ancestry and they will carry part of you forward into eternity.

With this brief review of the previous two installments, lets now introduce some reflective critique, in the form of three addenda.

### Addendum 1 : Is it True ?

Having told this almost unbelievably wild and complex story of the origin of all material things, it is only reasonable to raise the question of its truth, or accuracy. After all, the more extraordinary the story, the more justification one demands before accepting it. While the manner of the storytelling in this article may seem rather heuristic, and at times overtly (and intentionally) anthropomorphic, it derives from a vastly more detailed and intricate body of knowledge which has been built up over the last century in the classic scientific style. While there are areas of remaining uncertainty and ignorance, it is probably fair to compare the completeness and confidence in this overall picture with our knowledge of, for example, the sequence of global events during the Second World War. While we are irretrievably separated from the past (just as we are from the stars) indirect evidence abounds in the form of records, film archives, personal accounts, and so on (matter here on Earth, observations of stellar spectra, observations of solar neutrinos, and so on). While there may be arguments amongst the cognoscenti over the finer points, the overall sequence of events is not in any real doubt. So too with the story of atoms. This confidence comes as a surprise to many people, who may feel inclined to attribute it, in part, to the hubris of scientists. While it is impossible to even sketch the evidence which supports the scientific story, I will offer one example. As any crime writer will tell you, a good fingerprint can unambiguously condemn or acquit a suspect. Does such a "fingerprint" exist for our story of atom genesis ? Remarkably, the answer is yes. It involves not the *existence* of the series of 92 elements, but their *relative abundances*. For example, we know that iron is common and gold is rare (that is why iron is cheap and gold is expensive !). Perhaps surprisingly, the relative abundances of all the elements is pretty much the same wherever you look in the Universe : averaged over the Earth, on the surface of the Sun, on other planets, within meteorites, on other stars, in other galaxies. [3] While this alone is evidence for a cosmic origin of atoms, what is really remarkable is that the story just described *predicts exactly the abundances we find in nature.* This is not an easy prediction, it should be stressed, but involves a detailed understanding of the structure and evolution of stars and the properties of atomic nuclei. However, it is one of the triumphs of modern science that the sequence of element abundances which emerges from a detailed prediction is almost exactly the same as the one observed. This is at least as impressive as the details of a fingerprint, since we are considering over 200 numbers (one for each isotope of the 92 elements) with values which span a range of at least a factor of a million. If a fingerprint can prove innocence or guilt "beyond a reasonable doubt", then so can this sequence of abundances.

### Addendum 2 : How Does it Feel ?

The second addendum concerns a more illusive quality of the story : its ability to nurture a sense of the spiritual. This might seem an odd topic to raise, but lets not forget that the fundamental themes we've been discussing have received considerable attention for thousands of years, namely : what is our relation to the Universe ? The ideas and stories from former centuries have filtered through into present times usually in association with a broader religious world view. One of the valuable aspects of these more ancient stories is their resonance with the human psyche — most have strong anthropomorphic, or

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[3] In case you are wondering how we can know the composition of distant objects : their light carries this information encoded in its spectrum.

at least animistic, themes which are readily understood at an emotional and even personal level, and usually evoke a nurturing response to nature such as feelings of connection, awe, respect, love, or even healthy fear. Can a modern scientifically based description achieve this kind of response ? At present, I feel there is a widespread prejudice that it cannot; that scientifically based descriptions are somehow cold, mechanical and emotionally sterile. I would like to suggest that this view is itself a myth. Emotional responses, at least the kind we are discussing here, depend in large part on a consciously or unconsciously chosen predisposition. With some internal readjustment, one can find much that is both emotionally and, though I hesitate to use this word, spiritually nurturing in the scientific story. For sheer drama, power and intricacy, not even the most fertile imagination could have dreamt up as spectacular a story as the one I've just told. Even the most colourful of creation myths is tame by comparison. The idea that we come from stars means we can feel an emotional bond with them. Indeed, in a sense, not only do we depend on them for our creation, but they depend on us (or at least our atoms), to keep them alive. Placing yourself inside a star to watch its nuclear furnace burn can evoke awe at nature's power but you can also feel warmth and protection, indeed in some sense you are viewing the womb in which you were ultimately made. Feeling the vast cold emptiness of space can make one doubly value warmth and companionship here on Earth. Turning closer to home, appreciating the molecular complexity of a single cell is enough to make one's heart skip a beat, limit one's pride at the most complex of human creations, and gives you renewed respect for the tiniest of insects. All these images, and many more besides, have authentic poetic power and taken together provide a world view that can be emotionally as well as intellectually richly satisfying. Indeed, if the ancient philosophers and wise men had been aware of what we know now they would have eagerly included our scientific knowledge in their own myths and world views.

### Addendum 3 : Extensions and Limitations — The Big Bang

The final addendum is to acknowledge that the story I've told is still incomplete, in two important ways. First, I've glossed over a glaring error in the prediction for the abundance of element number 2 in the series, helium. Although helium is the most commonly produced element in stellar furnaces, at about 24 percent its abundance in the Universe is way above the simple prediction. Interestingly, this abundance is found even for the oldest stars which have received almost no enrichment by heavier elements. This points to the fact that helium atoms are older than all stars, and their origin is different from all other atoms. In a second triumph of modern science, we now know where and when the helium atoms were made : in the Big Bang itself. Here is not the place to review all the evidence for the fact that the Universe started life in a mighty hot explosion, but in that description the early history of the Universe is characterised by extremely high densities and temperatures which rapidly decrease as the expansion proceeds. It is perhaps surprising that the physical properties of this early time are relatively simple and can be analysed using well known laws of physics. A detailed calculation shows that between about 10 seconds and three minutes after the bang began, the temperature of the Universe dropped from 3 billion to 3 hundred million degrees, while its density dropped from 4 to 0.04 kilograms per cubic centimeter. Do these conditions sound familiar ? Yes ! They are similar to the conditions in the centres of stars ! It comes as no surprise therefore, that during the first 3 minutes, thermonuclear reactions were raging, and a quarter of the matter in the Universe was converted from hydrogen to helium (and a tiny amount even got as far as lithium). Luckily for us, the expansion was sufficiently fast that the burn was incomplete and lots of hydrogen was left over to fuel future generations of stars like the Sun, and ultimately provide the hydrogenic molecules so necessary for life (for example, water : $H_2O$).

In an even more impressive cosmic fingerprint test, a detailed calculation of the early Universe predicts the abundances of the five or so lightest isotopes of hydrogen, helium and lithium, exactly as they are observed, including the ubiquitous 24 percent helium. Thus, we have remarkably strong evidence that the Universe passed though a very hot dense phase when it was only a few minutes old. This is surely one of the great intellectual achievements in human history : to ascertain not only that the Universe had a beginning, but to know what it was like a minute after its birth. Interestingly, not one of the thousands of creation myths humans have invented down the centuries comes remotely close to the truth. We learn that our imaginations alone are no match for nature's subtlety, but we also learn that if we allow our imaginations to be guided by the scientific method, together they make a stunningly powerful team which can take us to places we could never otherwise go.

The second limitation of the story I've told is that it has not, in fact, explained the "ultimate" origin of the matter in this page. It has explained why the page is made of carbon/oxygen/nitrogen rather than of single protons. We have yet to ask how these protons themselves were formed. Ultimately, we need to break the infinite regression of considering transformations from one thing to another, and try to consider creation itself. At the present time, modern cosmology can add two or three prior steps in the lives of protons. These earlier steps occurred when conditions in the Universe were so extreme that we begin to be less certain of the physics. Hence the story is not on as firm a footing as the later stages of helium creation or stellar nucleosynthesis. It is thought that an important moment in the lives of all protons occurred when the Universe was only a tenth of a millisecond old : a phenomena called "proton freezeout". Before that time, when the temperature was above 1000 billion degrees, the kinetic energy of particles was so great that collisions between them could transform that energy into mass (recall : $E = mc^2$). According to the laws of physics, when energy is turned into matter, it makes equal amounts of matter and antimatter. Similarly, when matter and antimatter come together they are converted (annihilate) into energy, usually in the form of gamma ray photons. At this very early time, therefore, the Universe was filled with a dense sea of protons and antiprotons, continuously condensing out of energy and reverting back to it. In quite a real sense, this is the true birth moment for matter : its creation out of energy in the early Universe. As the Universe expanded and cooled, the particle kinetic energy dropped below the threshold necessary to yield the proton mass, so proton-antiproton production ceased. However, proton-antiproton annihilation continued, and in a brief instant of carnage, all were converted into a flood of gamma rays. If that were the full story, there would be no protons left and *the Universe would contain no matter at all !* Fortunately, before annihilation, there had been a minute excess in the number of protons over the number of antiprotons (one extra proton for every billion proton-antiproton pairs), and so at the end of the annihilation massacre a few lucky protons were left standing. It is these lucky few that now make up all the galaxies, stars, planets and people in the Universe. It is a remarkable fact that all present-day matter is just the leftovers from an original quantity a billionfold larger. Pursuing our story of protons to yet earlier times, before 10 microseconds the temperature was too high for protons to even exist : they were smashed by collisions into free quarks and gluons. Only after this time could the quarks and gluons actually remain bound together, to become the protons. What about the generation of the imbalance in the matter/antimatter ratio ? Without that imbalance, no matter would now exist. While the details are still uncertain, it is thought that the slight excess of matter arose at a moment extremely close to the big bang itself, when the temperature was so high that the nuclear, weak, and electromagnetic forces were all combined as a single superforce. As the temperature dropped, the nuclear force became distinct and an aspect of this force changed slightly : the creation of matter and antimatter from energy became unequal, with matter being produced slightly more efficiently than antimatter. From that time onwards, we were destined to be in a Universe containing matter, from which stars and people could ultimately evolve, rather than a Universe filled with just light, which might have been simpler and more beautiful but there would have been no one to know that.

We have tracked the matter in this page back though time right into the heart of the Big Bang, where we learn that it condensed out of energy when the Universe was less than a millisecond old. But what of the energy itself, from which the matter came ? How did this arise ? Indeed why was there a Big Bang at all, in which not only energy but also space and time were created ? Here we arrive at a question which has been asked by philosophers and wise men for centuries : Why is there something and not nothing ? Perhaps amusingly, we and they are in the same boat : we really don't know why. Any statements made are, and always have been, more speculation than knowledge. Nevertheless, we can wonder if, after several thousand years, we are any closer to answering this ultimate question. I think we are. Scientific cosmology is still very young, and already progress has been made which would have been unimaginable even 50 years ago. We may not know the answer now, but perhaps in another 50 years we will.