GRESHAM

COLLEGE

WHERE WILL IT ALL END?

A Lecture by

PROFESSOR COLIN PILLINGER
Gresham Professor of Astronomy

4 February 2000

Where will it all End

Although man will probably have extinguished himself long before (that is if a giant meteorite impact does not get him first) the Earth and the rest of the solar system will come to an end when it is enveloped by the sun becoming a red giant star.

In a very early lecture of the current series (Twinkle Twinkle Little Star, October 1996) we considered the early history of the Universe and discussed how the formation of the elements of life derived by the cycling of matter through different generations of stars. So perhaps it is poetic justice that these same elements will themselves be contributed back to space when our star becomes a runaway nuclear reactor. Perhaps this is the ultimate meaning of the expression "dust to dust, ashes to ashes". Maybe the secret of eternal life is that somewhere, somehow the carbon, nitrogen and oxygen from Earth will resurface in a future biological form. Unfortunately this is only the short term future, in the long term the elements we know as life will disappear forever.

In considering the evolution and lifetime of stars, and the elements they produce, one concept which is very important – size matters! Stars are born when a cloud of dust and gaseous material, mostly hydrogen, eventually becomes big enough and is prompted to collapse under the influence of gravitational attraction. These clouds may begin by being as much as 1000 to 10000 times the mass of the sun but soon they break up so that about 25% of the cloud will form into a cluster of stars and the heat these infant stars generate will blow away the remaining dust and gas. The further collapse of each of the protostars under gravity causes their cores to heat up and nuclear reactions to begin. It is easy to see, that with gravity involved, the bigger the fragment of the original cloud, the faster the process will go.

All stars at some time in their life will be what are called main sequence stars and they plot diagonally across a graph of luminosity versus surface temperature called the Hertzsprung-Russell diagram. How long stars stay as main sequence stars is again a function of how fast they are burning their fuel. So how they evolve and at what speed is dependent on how big they are.

The most massive stars have a mass 50 to 100 times that of our sun and shine with a brightness of 100000 to 1000000 times greater during their brief lives. They very rapidly use up all their hydrogen by mass loss or conversion to helium and have nuclear reactors which are capable of converting helium to carbon to silicon to iron in shells from the outside to the inside of the star. Their collapse is so rapid that almost nothing escapes after a type I supernova explosion when the core condenses to a black hole out of which no light can escape.

Stars which are not quite so big (11 to 50 solar masses) move more slowly through these evolutionary stages. Before the hydrogen is completely used, the helium is burnt to carbon and on through the C N O cycle to oxygen, hence to magnesium, silicon and then iron. The lighter elements are reacting in layers according to density, with the iron settling to the centre. If the iron core exceeds the mass of 1.4 suns, the core begins to collapse like before but this time the iron nuclei decompose back to helium which then fragments into neutrons. Again a very dense core object is created called a neutron star which have densities so great that 1.5 to 2.0 solar masses might be compressed into the size of a small city. But if this is not so dense as a black hole, since radiation can be and is emitted by neutron stars as pulsating radio-waves leading to them being referred to as pulsars. The crab nebula is a well known example.

The core collapse in producing a neutron star is so quick (one tenth of a second) that all the gravitational energy is released at once as an explosion of about 10^{53} ergs. This blows away the outside layers of the star in what is called a type II supernova, as was observed in 1987 when an object in the Magellanic cloud shone with a brightness equivalent to 10 to 100 billion suns for a few weeks. When they explode, type II supernovae enrich the interstellar medium with the heavy elements so familiar to us which make up the majority of the land surface of the planet on which we stand.

The next type of star for which life and death is not quite so cataclysmic are those with masses between 0.8 to 10 solar masses. As is obvious, the sun is just at the bottom end of the limit. The main source of energy which keeps these smaller stars burning is the conversion of hydrogen to helium by nuclear fusion. The rate at which they proceed again is mass dependent. At the top end of the range their lifetime is only about 10 million years long compared to the supernovae, we have already considered, which have existences measured in thousands of years. Thankfully for us the smallest stars in this category can live for 10 billion years, our sun for example is already 4.5 million years old.

For a star of 0.8 to 10 solar masses however there will come a time, rather suddenly in its evolution, when helium begins to be converted to carbon. When this happens the outer shells swell by maybe 10 to 100 radii and cool as the inside core contracts. With the expansion and temperature drop, the colour of the star changes towards red which gives the object its characteristic name, a red giant. In the case of our star we do not expect the onset of helium burning for at least another 1.1 billion years but then the enlargement process will engulf Mercury and Venus as the sun becomes a fully fledged giant by an age of 7 billion years. Long before however the Sun will have been mounting in luminosity. Earth's environment will have ceased to be benign and conducive to life. In its final stages of becoming a red giant the Sun will probably re-melt the Earth's crust completely obliterating all trace of biology, geology and the history of civilisation. One small solace however might be the encroachment of the star into our space, will warm Mars and the moons of Jupiter and make them possible zones of habitation.

A consequence of a star becoming a red giant or to give it its more correct name an asymtotic giant branch (AGB) star, is the relatively slow (as opposed to rapid in really massive stars which become supernovae) production of carbon and its C N O cycling to oxygen. This means that almost all the mass 13 isotope of carbon is generated in AGB stars, as are the other elements so important for life, nitrogen and oxygen and their heavy isotopes. The abundance of oxygen –17 and 18 which are the genetic test of various solar system materials are derived this way.

Observations of red giants show that they pulse with a frequency of several hundred days and matter is ejected from their surface by powerful stellar winds. Therefore the elements which constitute life and their isotopes are widely disseminated into space for the purpose of spreading life to other stars and other solar systems. Thus it is thanks to red giants that one of the most powerful ways of detecting biology (the isotopic fractionation of carbon) is created. The actual mass loss from red giants might mean that Earth itself will not be destroyed completely but will be pushed further from its host star and eventually precipitated into space to wander, if not for eternity, for a very long time.

The mass loss from red giant stars is frequently observed in our galaxy there are some 10000 stars surrounded by haloes of material that are called planetary nebulae which, from what has just been said, have nothing much to do with planets. In fact the planetary nebulae are molecules fluorescing under the influence of the UV and X-ray radiation emitted by the residual stellar core. What is left over at the end of the red giant phase of star formation is a stellar corpse known as a white dwarf. Like everything else which is a stellar remnant, white dwarfs are dense and as might be expected the more mass they have the smaller they will get. Although there are 10 billion white dwarfs in the galaxy they emit so little light that we can only observe those which are less than 600 light years away. A typical example is the faint companion to Sirius.

In the earlier lecture already referred to, we discussed how we can recognise relict material left over from a type II supernova explosion in the solar system by the isotopic signatures imposed during nucleosynthesis. It can be found in the form of tiny nanometre-sized diamonds in primitive meteorites (ones which have never undergone geological processing into any significant sized body since they coalesced into objects as part of the solar system). The mechanism of extracting these diamonds was to destroy the fabric of the meteorite by dissolving away the majority of silicate minerals. This is a technique which makes use of the fact that diamonds are impervious to attack by almost all reagents. The end product of this dissolution process was found to be rich in carbon isotope 12, and contain nitrogen predominantly of the mass 14 isotope. Implanted into the diamond core are noble gases which could only have come from a manufacturing process in a very massive star.

The same primitive meteorites may also contain other evidence of a distinct supernova source. Occasionally within their fabric are located inclusions of extremely high temperature minerals made from the elements magnesium, calcium, aluminium, titanium and oxygen. These refractory oxides would be amongst the very first species to condense out of a gas comprising a protosolar cloud. Close examination of the oxygen isotope composition of one of these refractory substances, spinel ($MgAlO_4$), suggest that it contains an almost pure spike of oxygen–16, As might be synthesised in a supernova source. In some scientist's view this is evidence for a process that happened just before the cloud of dust and gas which made our solar system begin to collapse and condense. It might just be that the death of one star (a supernova explosion) is the mechanism which triggers the gravitational instability which causes another to be formed.

Little did we know when we started experiments looking for presolar grains that, in true matroyshka doll fashion, the diamond hid a residual of the other major form of carbon contributed to the solar system from pre-existing stars. Analysis of the diamond for its isotopic composition was carried out by burning the carbon, to release the nitrogen and noble gases, in stepped combustion experiments. After the carbon associated with the diamond was all destroyed, it was apparent the residues still contained carbon in another form. This time it was highly enriched in carbon-13 and had quite different nitrogen isotopic and noble gas characteristics. Since these discoveries were made by burning away the diamond, which is present in the samples in large quantities, to locate another kind of much less abundant presolar grain, it is often referred to as burning down the hay stack to find the needle.

The grains which are enriched in carbon-13 have been subsequently identified as silicon carbide which is more stable to combustion than diamond. They are much coarser being in some cases a few microns in size but existing as complicated aggregates as big as thirty microns. Because they are so huge (relatively anyway compared to diamond) they can be individually studied by ion probe and different characteristic isotopic compositions identified for red giants at various stages of their evolutionary history.

The discovery of isotopic anomalies in primitive meteorites has been a very productive research area for meteoriticists for the last fifteen years as distinct minerals, several kinds of diamond, silicon carbide, silicon nitride, aluminium oxide etc have all been characterised and assigned provenances from before the birth of our solar system. During the next decade when we visit comets, to carry out analysis and even bring back material, we expect to find enormous repositones of presolar grains. Not just the ones, which because they have a particularly robust mineralogy and are able to stand some geological processing but, others which are less enduring and need to have been kept in cold storage to have survived. These experiments will go a long way to tell us about the great cosmic cycling process of which we are a part.

But that does not provide us with the answer to the question where we will all end? For that we have to resort to theory. We are currently in what might be called the stelliferous era of the Universe – one where the majority of matter is still hydrogen and helium. There are many examples of protostars which are simply not big enough for the onset of nuclear reactors, those on the sub 0.8 solar mass stars or brown dwarfs. It is only when protostars are bigger than 0.8 that nuclear processing can begin. Nevertheless larger stars are continually forming, burning their fuel to heavy elements and dying. Thus one might be tempted to think that everything will end up with a mass greater than iron. Indeed the last stars to be born will be very enriched in heavy elements and will occur at a time when little or no hydrogen or helium exists to create more than brown dwarfs. The major products of stellar evolution however are the super dense white dwarfs, neutron stars and black holes and these are themselves on an evolutionary trend. Instead of clouds of dust and gas being formed in the Universe, it will be a case of super dense objects devouring each other. Even our world, the wandering Earth will be consumed by a passing stellar remnant unless it has been incorporated into the dust and gas cloud to produce other stars first.

As the universe gets older and older, white dwarfs will collide and create new kinds of stars with a brief life time but for the most part these sources of light (like the occasional flash when one brown dwarf meets another) will be tiny beacons in a dark universe of neutron stars trending to black holes. Protons once believed to be eternal are doomed on a 10^{40} year timescale, neutrons also, as everything is consumed by the growing number of avaricious massive black holes.

Yet even calculations show that black holes do not last forever, they have a finite surface temperature and must evaporate by a process known as Hawking radiation. As evaporation occurs, a black hole will shrink and eventually vanish in a puff of γ-rays. Mind bogglingly, a black hole comprising the mass of our galaxy with a surface temperature only 10^{-180} above absolute zero will take 10^{100} years to disappear. During its final dying gasp it will produce a temperature approaching room temperature for 10^{35} years! At that time all that will exist will be a few neutrinos plus electrons and positrons, inconceivably far apart, but orbiting each other at distances larger than the size of the observable universe today. Nevertheless these two oppositely charged entities will spiral and eventually annihilate each other over time scales impossible to imagine.

In comparison with its violent and rebellious youth the Universe will end in uninteresting darkness and silence. Or will it? Maybe we just really don't have any comprehension of what will happen and the future will be just as exciting as now. We have lived with passing fads like the sun going round the Earth, and discovered that instead of being the centre of the Universe the solar system was shunted up some inconsequential backwater of a minor galaxy called the Milky Way. Why should we be so naïve as to believe our generation has been chosen to know the truth about the way it will all end.

Further Reading

I Iben and A V Tutukov (December 1997) The Lives of Stars, Sky and Telescope

F C Adams and GL Aughlin (August 1998) The Future of the Universe, Sky and Telescope

C.T.Pillinger and S.S. Russell (1993) Interstellar SiCgrains in Meteorites. J. Chem. Soc. Faraday Trans., 89 (13) 2297-2304

S.S.Russell, U.Ott, C.M.O'D. Alexander, E.K. Zinner, J.W.Arden and C.T.Pillinger (1997) Presolar silicon carbide from the Indrach (EH4) meteorite: Comparison with silicon carbide populations from other meteorite classes. Meteoritics and Planetary Science, 32 719-732

A.B.Verchovsky, A.V.Fisenko, L.F. Semjonova, I.P. Wright, M.R. Lee and C.T.Pillinger (1998) C, N, and noble gas isotopes in grain size seperates of presolar diamonds from Efremovka. Science 281, 1165-1168

GRESHAM COLLEGE

Policy & Objectives

An independently funded educational institution, Gresham College exists

- to continue the free public lectures which have been given for 400 years, and to reinterpret the 'new learning' of Sir Thomas Gresham's day in contemporary terms;

- to engage in study, teaching and research, particularly in those disciplines represented by the Gresham Professors;

- to foster academic consideration of contemporary problems;

- to challenge those who live or work in the City of London to engage in intellectual debate on those subjects in which the City has a proper concern; and to provide a window on the City for learned societies, both national and international.

Founded 1597

Gresham College, Barnard's Inn Hall, Holborn, London EC1N 2HH
Tel: 020 7831 0575 Fax: 020 7831 5208
e-mail: enquiries@gresham.ac.uk
Web site : www.gresham.ac.uk