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The oldest stars and the age of the Universe

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The Big Bang created primordial material from which the first stars formed. These stars exploded as supernovae and polluted the material from which subsequent generations of stars were made. Astronomers have had difficulty in finding stars made of the pure Big Bang material, but they have found stars with very little polluting material. The age of these cosmological relics of the first eras sets a lower limit for the age of the Universe we live in. European astronomers and their colleagues worldwide have joined in the effort to discover and date these, the oldest stars, and cast a glance into the obscure phases between the very first seconds of the existence of the Universe and the epoch at which galaxies and clusters of stars matured. Many independent techniques have been devised to date the oldest stars and stellar systems in the Universe. Some of them are briefly reviewed. The age of the oldest stars is now converging on a value in the range from 12 to 15 thousand million years. However, a large uncertainty still exists and a value as a large as 17 to18 thousand million years cannot be totally ruled out. Such a large value would be difficult to reconcile with the age of the Universe based on cosmological data. Significant improvements in the uncertainties of this situation are expected from the 8–10 m telescopes and space missions of the next decade.

1. The formation of the first stars

How old is the Universe we live in? When did the first galaxies, and the stars within them, form? Are there surviving witnesses of those early eras, when the Universe took shape from the Big Bang? What can they tell us about those first times?

Dating the Universe, unveiling the 'dark ages' when the first stars were forming, is one of the most fascinating topics in Astronomy and a major challenge for the astronomical community worldwide. European astronomers are deeply involved in this research area, which is one of the major targets for several of the space missions of the European Space Agency (ESA). The largest ground-based telescopes of the 8–10 m class, as for instance the Very Large Telescope (VLT) of the European Southern Observatory (ESO) at Paranal, Chile, as well as the Hubble Space Telescope (HST) launched in 1990 by NASA with ESA collaboration, continue searching the sky for the fossil relics of the old times. Precise determination of the properties of the cosmic microwave background radiation, the fossil signature of the primordial explosion – the Big Bang – are being obtained by recent balloon experiments BOOMERANG and MAXIMA (see the article by Andrew Liddle in this issue), and provide stringent constraints on the cosmological parameters. The era of precision cosmology, which is just beginning, is – in particular – providing estimates of the age of the Universe through measurements of the rate of expansion of the Universe (the Hubble Constant) and measurements of the anisotropies of the cosmic microwave background. Independent techniques exist for determining the age of the Universe, by – for example – examining the age of the oldest things in it. These techniques constitute a test for cosmology.

The theoretical background is that the Universe formed in the Big Bang, and that the lightest elements (hydrogen, helium and lithium) formed in the first few minutes. Some stars and galaxies formed from this material fairly quickly it seems. The earliest stars shone by nuclear fusion and the most massive among them exploded as supernovae. They created further elements, some of which were radioactive and also created stellar cinders, such as white dwarfs. The ejecta from the supernovae, containing newly made elements, spread into the residual pure primordial material. Subsequent generations of stars were recycled from this material, exploding in their turn and progressively contaminating the residue.

In order to date the oldest of the old stars, astronomers have to find them and model their properties to determine their ages. The technique of dating the radioactive elements themselves, from meteoritic material and old stars, is called ‘nucleocosmochronology’. To be strictly accurate, this dates isotopes of the chemical elements.

The oldest stars are indeed among the cosmological relics of the first eras. They tell us when star formation began in galaxies and provide a minimum age for our Universe. The oldest stars in the galaxies formed from the primordial plasma composed of hydrogen and some light elements. Hydrogen (^{1}H), deuterium (^{2}H), helium-3 (^{3}He) and helium-4 (^{4}He) and lithium-7 (^{7}Li) were the only isotopes produced by the primordial nucleosynthesis, which occurred a few seconds after the Big Bang. According to the standard Big Bang models, the earliest stars, usually referred to as Population III stars, contain detectable amounts of only hydrogen and the four other isotopes. Population III stars contain no other elements at all.*

Thus the oldest stars are the most metal-poor ones. Only subsequent nucleosynthesis occurring in star interiors was able to produce elements heavier than helium. No star has yet been found with a pure primordial composition – presumably Population III stars lived and died quickly; all the known stars have some 'metals'. The oldest stars known are thus the stars with the lowest heavy element content (metallicity).

The most metal-poor star has about 1/10 000 the heavy element content of our Sun. The 100 lowest-metallicity stars detected typically have a heavy element content less than 1/1000 the solar heavy element content. These stars were born no longer than 100 million years after the formation of our Milky Way Galaxy and this is only 1% of the age of the Galaxy. Therefore, these stars are almost as old as the Milky Way. These stars are living records of the conditions at the earliest times and, from their properties, astronomers can deduce constraints about important phenomena of astronomy:

(a) the Big Bang,
(b) its nucleosynthesis,
(c) the nature of the first supernovae,
(d) the manner in which the ejecta from these first generations of stars polluted the primordial medium,
(e) the way this material was incorporated into subsequent generations of stars,
(f) the age of the Galaxy,
(g) the epoch of galaxy formation.

2. The globular clusters

Among the first stellar systems to form were the globular clusters. Globular clusters are agglomerates of about 10 000 to 1 million stars. About 200 globular clusters have been discovered in the Milky Way, and more than 350 in the Andromeda galaxy. Figure 1 shows the Andromeda galaxy (M 31) and an enlargement of one of its globular clusters. Almost all galaxies have globular cluster systems. In some cases (e.g. M 87) they may contain several thousand.

Globular clusters are typically old and metal poor, with metallicity as low as 1/300 the solar value. The globular clusters of our own Galaxy, the Milky Way, are old, and are among the most favourable objects in the Galaxy for which

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*Ignoring chemistry, astronomers call all other elements apart from hydrogen and helium 'metals'.

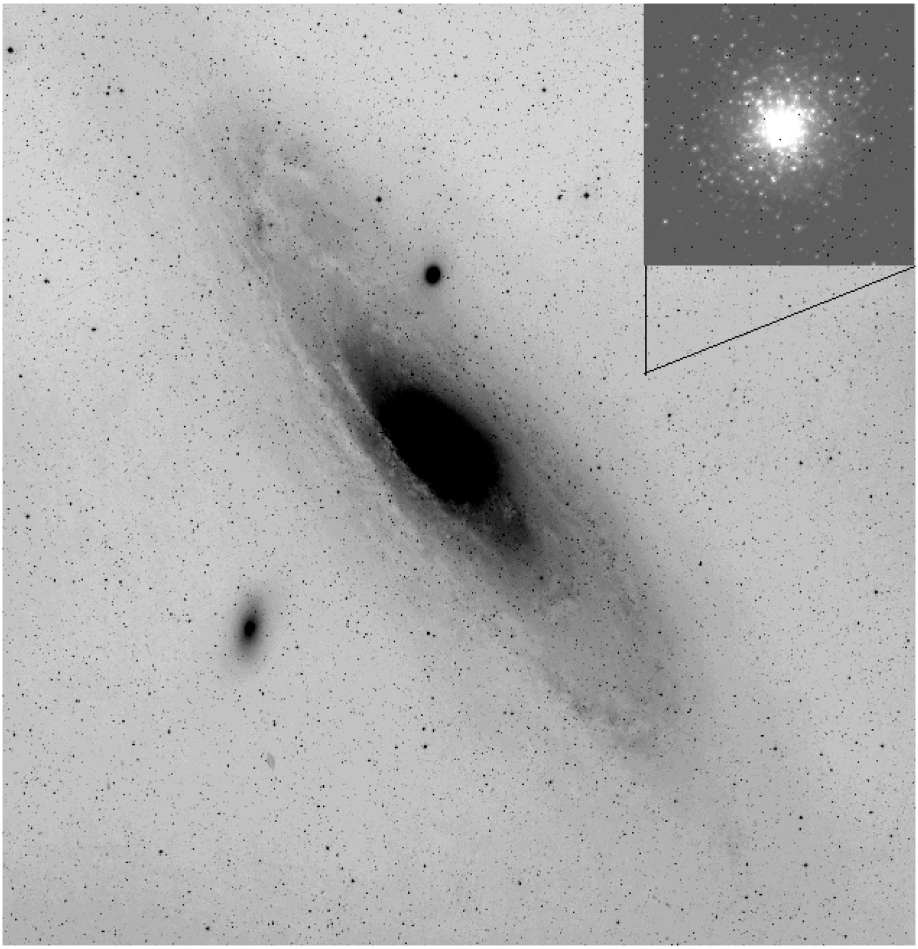

Figure 1. The Andromeda galaxy (M31) with its two major satellites (NGC205 and M32), and an enlargement of one of its 350 globular clusters (G302).

relatively precise ages can be derived, based on the principles of stellar evolution, and they include the oldest objects so far observed in the Galaxy. They were presumably born during the very early stages of the Galaxy's formation and provide a lower limit to the age of the Universe.

Stars in a given globular cluster are all at the same distance from us. They form a so-called 'simple population', since they all formed at the same time out of the same isolated cloud of gas. They all share a similar chemical composition which, because the gas was nearly primordial, has low metallicity. Nevertheless, the stars in a given globular cluster differ in temperature and brightness. The differences

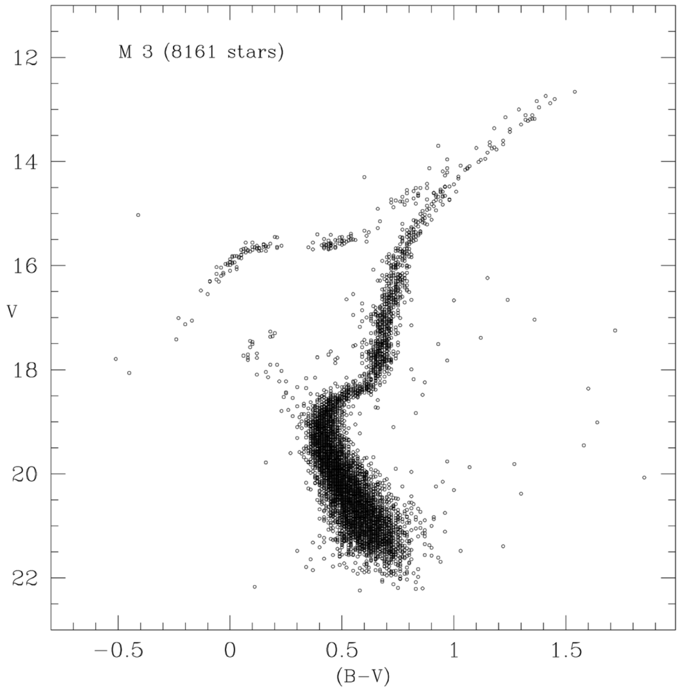

Figure 2. H-R diagram of the Galactic globular cluster M3.

from star to star within a given globular cluster are due only to differences in their masses, which has affected the rate at which each star has evolved. Thus, each star looks different in temperature and brightness, even though they all started their evolution at the same moment with the same initial conditions.

The evolution of stars in a cluster is conveniently shown on a diagram described, about 1911, independently by Enjar Hertzsprung and Henry Norris Russell, and which is known by their initials as a H-R diagram. The H-R diagram is a plot of stars with the temperature (or a proxy measurement for the temperature, such as colour) of a star on the x-axis and its brightness on the y-axis. In the H-R diagram of a simple population, stars of equal mass all cluster together around the same point. Figure 2 shows the H-R diagram of the Galactic globular cluster M 3.

Stellar evolution theory aims to describe the stars at each point of the H-R diagram in terms of their structure and the physical processes by which they move from one point to the next. Modern stellar evolution theory started from the discoveries of the physical principles of stellar structure by Arthur Stanley Eddington and of the nuclear fusion processes in stars by Hans Albrecht Bethe. Since then, astronomers have succeeded in calculating the luminosity of a star at any given point of the H-R diagram, depending on the star's age, its mass and the nuclear reactions occurring in its interior. Theory lets us follow the evolution

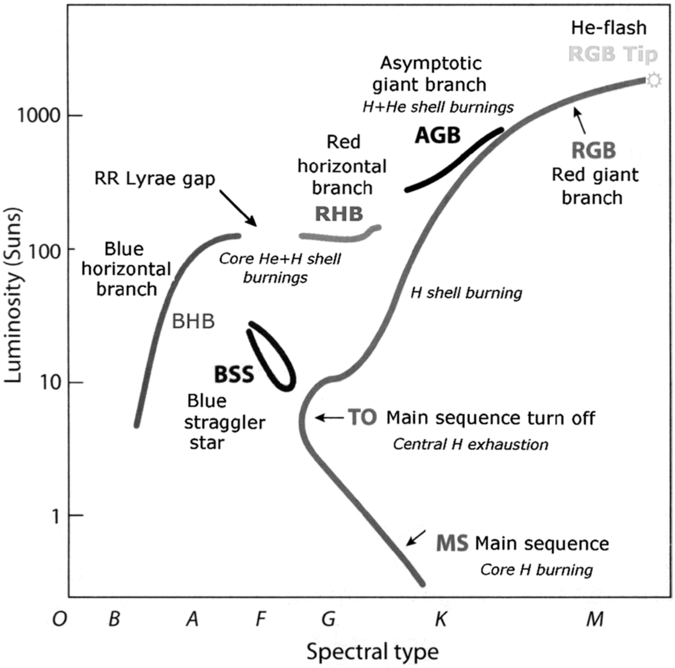

Figure 3. Schematic H-R diagram of a typical globular cluster with the specific evolutionary phases labelled along with the corresponding nuclear burnings.

of a star of a given mass from point to point in the H-R diagram, from its formation to its death.

The success of the theory of stellar structure can be judged from a recent episode. Over several decades it has become increasingly clear that there is a significant deficiency in the flux of neutrinos seen from the Sun. There are several times fewer neutrinos seen than astronomers calculated that the Sun makes. Because the calculations of the structure of the Sun seemed so reliable, it was inferred that the discrepancies were due, not to errors in the theory, but to an undiscovered property of neutrinos relating to their lifetime. In 2001, it was found that the neutrinos decay as they make their eight-minute flight from the Sun to the Earth, which solved the discrepancy and so the theory of stellar structure survived a challenging test.

Figure 3 shows a schematic H-R diagram of a typical globular cluster. It is labelled with the specific evolutionary phases of stars of different masses. Stars with masses in the range from about 1/10 to 1 solar mass pass across the various evolutionary phases shown in Figure 3.

The most prominent zone of the H-R diagram is called the Main Sequence – a band of the diagram stretching from hot bright stars to cooler fainter ones. It is the zone in which stars lie that are turning hydrogen into helium in their cores via nuclear fusion. Stars with 1 solar mass or less spend most of their lifetime in the Main Sequence. It lasts for about 85–90% of the total stellar lifetime (about 10 thousand million years for these stars – this is why the age of such stars is a challenge for cosmology, which suggests 12–14 thousand million years for the age of the Universe).

When its basic hydrogen nuclear fuel has been totally consumed, a star ‘turns off’ the Main Sequence and moves to another part of the H-R diagram. The more massive stars lie towards the hotter, brighter end of the Main Sequence and leave the Main Sequence before less massive ones. At any particular age, stars of lower mass are still on the Main Sequence, while stars of larger mass have evolved off.

The ‘Turn-Off’ point is the brightest and hottest point on the Main Sequence. As the globular cluster ages, the Turn-Off point in a globular cluster slides down the Main Sequence towards stars of decreasing mass. Stellar evolution theory shows that the precise location of the Turn-Off point is a good stellar clock. A straightforward relationship can be derived between the location of the Turn-Off point and the age of a star at that point. This provides a powerful tool for determining the age of the globular clusters.

To exploit the information of the Turn-Off point in a globular cluster, and to make the calculation of its age through stellar evolution theory, astronomers need to know the luminosity of the stars at the Turn-Off point. The main uncertainty is our poor knowledge about distances to clusters. An error of about 5% in the brightness of the Turn-Off produces a corresponding error in the derived age of the globular cluster of about 10%, or 1 billion years.

ESA’s Hipparcos satellite was launched with the express intention of determining accurately the distances to stars, in order to remove such uncertainties, and it has determined more accurately the astronomical distance scale of several globular clusters. Many galactic objects, including the globular clusters, seem to be at distances about 10% further from us than previously thought and are brighter by about 20% – their ages were in error by several billion years. The latest estimates of globular cluster distances through the measurement of the luminosity of the Turn-Off point, have led to an age of 12 to 14 billion years for most of the globular clusters. M92 is the most metal-poor and therefore (presumably) the oldest globular cluster known so far. Its age is 13–14 billion years; the universe must, of course, be at least as old than this. This measurement is in conformity with measurements of Hubble’s constant, and other techniques of cosmology.

The method using the Main Sequence Turn-Off is not the only technique for measuring the distances to globular clusters and their ages, the brightness of stars that fall in the so-called Horizontal Branch of the H-R diagram are also available. Hipparcos has also been invaluable in making these measurements. There is a 10–15% difference between this method and using the Main Sequence Turn-Off,

Figure 4. The Helix planetary nebula is one of the closest, at a distance of about 400 light years.

which implies that the oldest globular clusters are about 3–4 billion years older, i.e. 16–18 billion years. There is a real discrepancy here. Hipparcos thus provides support for both time-scales. The difference must be in our understanding of astronomy, not in the instrumental techniques. More work is needed to reconcile this discrepancy.

3. White dwarfs

Another method, of great potential but considerable practical difficulty, uses the cooling time of white dwarfs. Once they have consumed all available nuclear fuel, small and intermediate mass stars (that is, stars with a mass smaller than about 7 solar masses) gently eject into the surrounding space their outer layers. They make spectacular planetary nebulae. Figure 4 shows the beautiful Helix planetary nebula and, at its centre, the star that made it.

As the planetary nebula dissipates into space, its creator star ends its life as a white dwarf. White dwarfs are extremely compact, with all the mass of the star (typically, of the same order of the solar mass) concentrated in a sphere the size of the Earth. These very compact structures are made of an unfamiliar state of matter, called 'degenerate'. This means that the structure of a white dwarf is very similar to a single enormous crystal, with the weight of the star supported by the crystal structure. In general, a white dwarf remains a white dwarf forever. It takes a long time, several billion of years, for a white dwarf star fully to crystallize. During this phase, its structure evolves, and the star becomes increasingly compact and cool. It radiates its thermal energy as light, moving from a hot star to a cooler one, changing colour from white to red, and then fading into blackness.

A newborn white dwarf, surrounded by its planetary nebula, is still very hot (perhaps as hot as a million degrees), and hence quite luminous. The early evolution of a white dwarf is very fast, and in a few tens of million of years the surface of the star cools down to temperatures below 10 000 K. At this epoch, the white dwarf is already very faint and, in its subsequent evolution, it becomes even fainter. Hence, if we find a white dwarf and apply to it an appropriate model of white dwarf evolution, we may then reconstruct how much time has elapsed since it ejected its planetary nebula. Groups in France, Italy, England and Spain are in the forefront of modelling these calculations.

It is not possible to know the age of individual stars unless we know the initial mass of the star, and hence what happened before it ejected its planetary nebula. However, if we can find a white dwarf in a globular cluster of stars, the faintest white dwarfs are those that originated first, from the evolution of those stars that most rapidly ended their nuclear burning phase and ejected planetary nebulae. Their nuclear burning lifetimes were rather short, of the order of one hundred million years, usually much less then the time spent cooling down as white dwarfs. The luminosity of the faintest white dwarfs then gives us the age of the cluster.

Hence, in principle, white dwarfs may be used directly to derive the age of a star system from determination of the faint end of their cooling sequence. However, this is difficult to achieve because it requires observations of extremely faint white dwarf stars, which have not so far been observed. However, the brighter white dwarfs can be used indirectly to determine the distances to star clusters and independently confirm ages from the Main Sequence Turn-Off. As pointed out a dozen years ago by Alvio Renzini and Flavio Fusi Pecci at the Bologna Observatory, the white dwarf cooling sequence is a powerful distance indicator for globular clusters, since it is insensitive to some of the uncertainties in the method of the Main Sequence Turn-Off. Renzini (now at the European Southern Observatory) used the Hubble Space Telescope to derive distances in two globular clusters (NGC6752 and 47 Tucanae) using the white dwarf cooling sequence, although practical use of this technique is not without problems.

4. Nucleocosmochronology

Stellar ages can be also derived using radioactive decay, essentially in the same manner as in geology and palaeontology. When applied to stars, this technique is called ‘nucleocosmochronology’. The principle is very simple. Comparing the present abundance of an unstable radioactive isotope with its original abundance gives its degree of decay. Because radioactive decay proceeds at a known rate, one can calculate how long the decay has taken. In order to provide useful answers about the age of old objects, the time for the decay of the isotope should be of the same order of the time interval we wish to measure. Of course, some assumptions have to be made, the most important of which is the original abundance of the unstable isotope.

In the case of old stars, with ages of several billion years, the most suitable isotopes are thorium-232 and uranium-238, with half-lives of 14.05 and 4.47 billion years. A practical difficulty is related to the weakness of the spectral features due to these elements, since only traces of them are actually present in the stellar atmospheres, so their abundances now are very difficult to measure.

Thorium and uranium are made in tiny quantities in supernovae through the so-called r-process, first discovered by Geoffrey and Elizabeth Burbidge, William Fowler, and Fred Hoyle more than 40 years ago. The exact site of the r-process is far from being well established, and there is a considerable debate about how supernovae produce elements through the r-process, and whether this production occurs in all supernovae or only in some of them, and this uncertainty weakens the use of the r-process elements in nucleocosmochronology.

In the spectra of most stars, the spectral lines of thorium and uranium are very faint; however, Chris Sneden and co-workers at the University of Texas, have discovered a rare group of extremely metal-poor (hence likely to be very old) stars in which the signature of the r-process is extremely strong, while other elements are scarce. These stars are so metal-poor that only a very few supernovae, perhaps just one, had polluted the primordial gas from which they formed.

One of the stars analysed by Sneden and co-workers is an extreme case: CS22892–52. The star has about a thousandth of the solar metal content, and the features due to elements other than the r-process are very weak. On the other hand, the astronomers could measure many features due to elements produced by the r-process, including lines due to thorium. Indeed, this is the only star for which accurate abundances have been determined from spectra for many of the elements (including, for example, gold). This is even including the Sun, whose brightness makes measuring its spectrum easy. A spectacular result is that the distribution of the abundances of the r-process elements is, in many respects, similar to that determined from meteorites. Although meteorites contain much more, in total, of the r-process elements, the relative proportions of the ones that can be observed in CS22892–52 are the same. Because laboratory measurements of the individual isotopes in meteoritic material are feasible, the original abundances of unstable elements in meteorites can be deduced. Lead is, mostly, stable; Sneden's group were able to measure lines of lead in the star and, from the observed abundance of lead, which has not changed over time, they inferred the original abundance of thorium, assuming it was the same relative to lead as in meteorites. They found the star's age to be 14 ± 5 billion years.

In principle, more accurate results could be obtained from the observations of uranium. The first detection of uranium lines in metal-poor stars was obtained recently by Roger Cayrel's group at the Observatoire de Paris. They used the VLT to obtain a spectrum of a newly discovered extremely metal-poor star, CS31082–001, which is an extreme case of a star with the r-signature. The age of 12.5 ± 3 billion years for this star represents an improvement in precision.

The age of extremely metal-poor stars determined from nucleocosmochronology agrees fairly well with the ages of globular clusters from the Main Sequence Fitting technique. This agreement is encouraging, since the two techniques are completely independent of each other. Nucleocosmochronology does not make any use of stellar evolution models or distance estimates. It is still uncertain in several respects and does not distinguish unambiguously between the young universe and the older one, although it favours the former. Further progress is expected in the near future from observation of the largest sample of extremely metal-poor stars being extracted from the new ESO-Hamburg objective prism survey by Norbert Christlieb and co-workers.

5. Is the Universe older than the stars in it?

While many of the questions that we listed at the beginning of this review still lack a firm answer, several independent dating techniques are converging towards an age for the oldest objects in the Universe that is in the range from 12 to 15 billion years. The uncertainty affecting this estimate is still uncomfortably large, and a value as large as 17–18 billion years for the very oldest objects cannot be totally ruled out at present.

Will we ever see Population III stars, which contain no elements heavier than helium? If they have totally disappeared, why is that so? Possibly the first generation of stars was quite massive (about 100–300 solar masses) and evolved very quickly. Putting these questions about the early Universe aside in order to concentrate only on its age, the most metal-poor stars have been the means to further progress.

What is the correct choice between the long and short astronomical distance scales and the 'young' or 'old' globular clusters' age they imply? A definite answer to this question is expected from the successors to Hipparcos, including the space missions SIM (Space Interferometry Mission) and GAIA (Global Astrometric Interferometer for Astrophysics), scheduled for launch by NASA and ESA in 2009 and 2012 respectively. These satellites will measure directly the distances of the globular clusters and hence determine their age. The Next Generation Space Telescope (NGST) to be launched by NASA/ESA in 2009 will provide detailed pictures of the very distant galaxies that formed when the Universe was a few percent of its present age. For the first time, we will be able to see the stars that formed in those early eras.

Meanwhile, astronomers are in the same position as Rutherford and his co-workers were on an occasion when his attempts to get money for some equipment had failed. Announcing this to his laboratory, he said ‘Colleagues, fortunately we do not yet have the equipment to do what we had planned. We therefore have time to think.’ A decade of reflection on the question of the age of the Universe will be opportune.

About the Authors

Gisella Clementini is an astronomer at the Osservatorio Astronomico di Bologna. Previously she spent two years at the Space Telescope Science Institute in Baltimore on a fellowship of the European Space Agency. Her research interests are the study of the oldest stars in the Galaxy and in the Local Group (globular clusters and variable stars of RR Lyrae type, in particular) and their use as distance indicators

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