Inside the Stars, IAU Colloquium 137
ASP Conference Series, Vol. 40, 1993
Werner W. Weiss and Annie Baglin (eds.)

OUTSIDE THE STARS

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INTRODUCTION

It is a great pleasure and privilege to give the opening lecture at this IAU Colloquium "Inside the Stars". It is particularly appropriate that it is held in Austria, the country of Ludwig Boltzmann whose name will appear explicitly or implicitly in every lecture.

My task is to describe the astrophysical and cosmological setting within which our discussions will take place. I emphasise that I am an **outsider** at this colloquium in all possible senses. My own research interests are in the areas of high energy astrophysics, extragalactic research and astrophysical cosmology. In lecturing to my students, however, I emphasise that the subject of the present colloquium is at the very heart of virtually all astrophysics and these studies are quite essential in order to make sense of galaxies and extragalactic systems. If we did not have this confidence in our ability to understand the stars, at least in principle, we would worry about the reliability of the enormous astrophysical edifice which has been built up to explain the large scale features of our Universe. I also emphasise to my students that the study of the stars is among the most exact of the astrophysical sciences — in my enthusiastic moments, I claim that, in the very best of these studies, astrophysics approaches the precision of laboratory experiment. I hope to find many examples this week to reinforce this belief.

From my perspective, what I need is a **User's Guide to Stars and Stellar Evolution**, in other words, a reliable set of rules about the origin and evolution of stars in order to diagnose the physical properties of the systems I am trying to understand. I will illustrate the types of information we need by discussing three case studies in the areas of (i) high energy astrophysics, (ii) classical cosmology and (iii) astrophysical cosmology and the origin of galaxies. Necessarily, these studies will be far from complete, but I hope they will illustrate some of the issues which come up in these disciplines. In the course of the discussion, it will become apparent that I will touch upon essentially all branches of contemporary astrophysics. I will take very different approaches to the three case studies.

HIGH ENERGY ASTROPHYSICS

One of the reasons I was delighted to accept the invitation of the organisers to deliver this lecture was that, at this very moment, I am writing Chapter 14 of my text-book *High Energy Astrophysics: Volume 2.* Here are its title and contents:

14 Aspects of stellar evolution relevant to high energy astrophysics

- *14.1 Introduction*
- *14.2 Nucleosynthesis in stars*
    - *14.2.1 Observations of solar neutrinos*
    - *14.2.2 Solar and stellar oscillations*
    - *14.2.3 Nucleosynthesis of the heavy elements*
- *14.3 Stellar evolution in globular clusters - the age of the Galaxy*
- *14.4 Post main-sequence evolution and mass-loss*
- *14.5 Binary stars and stellar evolution*

These topics will be familiar to everyone in this room but let me run through them from my position as an outsider. This may give some impression to the insiders of our perception of their disciplines.

Solar neutrinos

The first thing we ask is "Do we really understand our own Sun?" All of us would worry very deeply if the combination of nuclear physics and stellar structure could not get our own Sun right. The subject is dominated by two complementary studies, the observations of solar neutrinos and helioseismology. Let me deal with my impression of the solar neutrinos first. What most of us are familiar with are the various assessments by Bahcall, admirably summarised in his monograph "Neutrino Astrophysics" (Bahcall 1989). There is much excitement in this area because of the recent results from the Kamiokande II and SAGE experiments and the imminent publication of the results of the GALLEX experiment. Let me summarise what I believe to be the situation from the outsider's point of view.

The longest-running experiment is the famous Davis experiment in which the high energy neutrinos from the decay of ^{8}B are detected by the nuclear transmutations which they induce in ^{37}Cl. According to Bahcall, the discrepancy between the observed and predicted fluxes of the high energy neutrinos is as follows:

$$\begin{aligned}\text{Observed flux of solar neutrinos} &= 2.1 \pm 0.9\ \text{SNU}\\ \text{Predicted flux of solar neutrinos} &= 7.9 \pm 2.6\ \text{SNU}\end{aligned} \qquad (1)$$

Confirmation that this flux of high energy neutrinos indeed originates in the Sun is provided by the beautiful Kamiokande II experiment for which a deficit

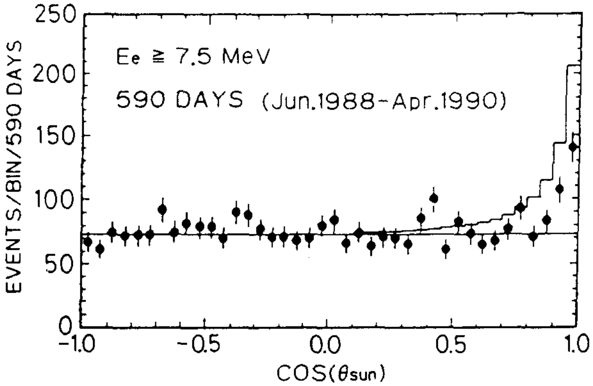

FIGURE 1 The distribution in $\cos\theta_{\rm Sun}$ for the 590-day sample for $E_e \geq 7.5$ MeV. $\theta_{\rm Sun}$ is the angle between the momentum vector of an electron observed at a given time and the direction of the Sun. The isotropic background which is roughly 0.1 events day^{-1} bin^{-1} is due to spallation products induced by cosmic ray muons, γ-rays from outside the detector and radioactivity in the detector water. The angular resolution of the detector system has been taken into account in calculating the expected distribution of arrival directions of the neutrinos from the Sun (Hirata et al 1990).

of solar neutrinos is again reported relative to Bahcall's Standard Solar Model. The deficit is quoted to be

$$\frac{\text{Measured flux of neutrinos}}{\text{Predicted flux of neutrinos}} = 0.46 \pm 0.13\ (\text{stat}) \pm 0.08\ (\text{syst}) \qquad (2)$$

The beauty of the Kamiokande experiment is the fact that it provides information about the arrival directions of the neutrinos. The excess of neutrinos is found only in the direction of the Sun (Figure 1: from Hirata et al 1990). The discrepancies illustrated by the results (1) and (2) are the famous **Solar Neutrino Problem.**

Less well-known than Bahcall's analysis are those of other solar modellers and, generally, they have predicted somewhat smaller neutrino fluxes than Bahcall's Standard Solar Model. For example, the models of Turck-Chièze et al (1988) predict a solar neutrino flux of 5.8 ± 1.3 SNU which would reduce considerably the discrepancy between the Kamiokande observations and the theoretical predictions. According to some workers, there may not be a solar neutrino problem at all (see, for example, Morrison 1992). These are technical issues which need to be addressed by the experts. It is encouraging that this key problem is now being addressed by a number of independent solar modellers.

The most eagerly awaited results are those of the SAGE and GALLEX experiments which seek to detect the much more numerous low energy neutrinos associated with the weak p-p reaction which forms deuterium

$$\mathrm{p} + \mathrm{p} \rightarrow {}^2\mathrm{D} + \mathrm{e}^+ + \bar{\nu}_e$$

The importance of this reaction is that it is directly related to the primary energy source in the Sun, unlike the ^{8}B neutrinos. The SAGE consortium has already reported an preliminary low flux as compared with the predictions of the standard solar model (Abazov et al 1992). The expected rate of arrival of low energy antineutrinos is estimated to be 132 $^{+20}_{-17}$ SNU where the errors are 3σ errors. The preliminary result from 5 runs during the period January to July 1990 was a neutrino flux of 20 $^{+15}_{-20}$ (stat) ±32 (syst) SNU. This results in a upper limit to the flux of low-energy antineutrinos from the Sun of less than 79 SNU at the 90% confidence level. The GALLEX team will release their first results in June 1992.

My interest in these results is whether or not we can use the standard solar model as a baseline for stellar evolution. If the GALLEX experiment finds no deficit of solar neutrinos, most of us would regard that as the end of the story and go on to other problems. If the flux is low, we will have to incorporate some new features into the physics of the neutrino. If this is necessary, the best bet at the moment seems to be the MSW effect which is discussed in some detail in Bahcall's book and in the paper by Bahcall and Bethe (1990).

Solar and stellar seismology

Solar and stellar seismology have revolutionised the study of the Sun and stars and are, of course, one of the most important motivations for the present colloquium. Until the discovery of solar oscillations, the solar neutrinos provided the only way of studying the interior of the Sun. Otherwise, the stellar astrophysicist was restricted to studying the surface properties of the stars and inferring indirectly from these their internal structures. I have always been impressed by how well the observations and the theory of stellar evolution can explain the evolution of stars from one part to another of the H-R diagram and many astrophysical studies depend upon the reliability of these results.

As everyone at this meeting is aware, the resonant frequencies of the Sun provide detailed **dynamical** information about its internal structure. What I find quite incredible is the phenomenally good agreement between the theory of the internal structure of the Sun and the structure inferred from inverting the solar oscillation data. Each time I discuss this problem with Douglas Gough, he tells me that the oscillation data have confirmed the predictions of stellar structure with exquisite accuracy. The most recent data of which I have knowledge from the Birmingham group indicate that the models of stellar structure remain very good indeed right into the central nuclear burning regions of the Sun (Elsworth et al 1990). This is the reason why we take the point of view that, if there is a solar neutrino problem, it is probably in the nuclear physics rather than in the astrophysics of the solar interior. This makes many of us very happy because we feel that we can at least trust the astrophysics.

I eagerly await the most recent developments in this story, not only for our own Sun but also for the nearby stars. These data already provide glimpses of what might be achieved by a dedicated space mission such as PRISMA. Among topics of the greatest interest will be the impact of the new opacity data provided by the OPAL and OP programmes to be discussed at this meeting by Michael Seaton. The reason for stressing the importance of these studies is that outsiders such as myself take the results of these studies as the datum for extrapolation to more distant systems and to much more exotic environments.

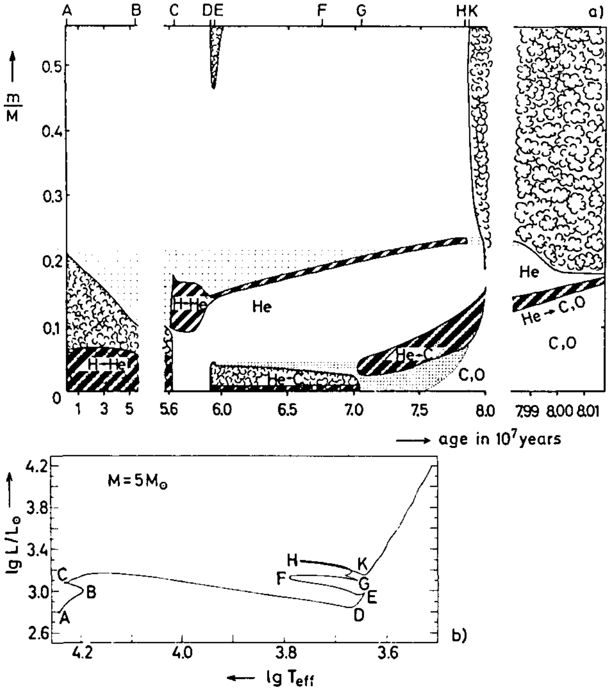

FIGURE 2 The evolution of the internal structure of a star of 5 $M_\odot$ of extreme population I illustrating the synthesis of carbon and oxygen in the core of the star. The abscissa shows the age of the model star after the ignition of hydrogen in units of 10^7 years. The ordinate shows the radial coordinate in terms of the mass m within a given radius relative to M the total mass of the star. The cloudy regions indicate convective zones. The corresponding positions of the star on the H-R diagram at each stage in its evolution are shown in the bottom diagram. (from R. Kippenhahn and A. Weigert 1990)

Nucleosynthesis of the heavy elements

The next issues we outsiders need to address for a vast number of different reasons are the sites of synthesis of the heavy elements. Thus, all of us give lectures showing the "onion-skin" model of stellar evolution showing heavier and heavier elements being created in the most massive stars until the synthesis proceeds through to iron in the cores of the most masive stars. The famous picture of Kippenhahn et al (1965) shows us how the heavier elements are built up in massive stars (Figure 2). What we need are the best modern versions of these diagrams with the corresponding yields of the heavy elements when the stars die. These data are crucial for many aspects of contemporary cosmology. Examples include

(1) The chemical evolution of galaxies;

(2) The chemical composition of dust grains formed in stellar explosions and in the interstellar gas;

(3) The abundances of the elements in the cosmic rays;

(4) Clues about the epochs when the metals were first formed during the evolution of galaxies.

We also need to be able to answer somewhat more subtle questions. A good example concerns the origin of the light elements, lithium, beryllium and boron. The standard Big Bang picture can account remarkably successfully for the abundances of light elements such as deuterium, helium-3 and helium-4 as well as for the abundance of lithium found in old cool stars, provided the mean baryon density of the Universe Ω_b is about one tenth of the critical value. The determination of the primaeval abundances of these elements in old stars is obviously of the greatest interest for cosmology because traces of beryllium and boron are created as well in the standard picture.

There has been great interest recently in studying the cosmic abundance of beryllium. It is synthesised in small amounts in the early stages of the standard Big Bang but its abundance can increase significantly if there were inhomogeneities in the distribution of matter during the epochs of nucleosynthesis. Any information, however indirect, on fluctuations in the early Universe is of crucial importance for cosmology. There is therefore the greatest interest in understanding whether all the beryllium is created in stars or whether there is an excess which might be attributed, for example, to an inhomogeneous Big Bang. Figure 3 shows a summary by Pagel (1991) of some recent observations of the abundance of beryllium in which it can be seen that there may be a small excees. The origin of this excess is of considerable interest and importance.

One of the long-standing problems in cosmic ray physics is exactly why the overall abundances of the elements in the cosmic rays are not so different from the cosmic abundances of the elements. This is strongly tied up with the acceleration mechanisms for the cosmic rays. Precise element and isotope abundances can help disentangle the most important sites for the injection of particles into the acceleration regions.

Stellar evolution in globular clusters - the age of the Galaxy

In the last subsection, we have already touched upon the evolution of stars off the main sequence. What we need are evolutionary tracks for stars of different masses so that we can build models of galactic evolution under different assumptions about their star formation rates. The type of picture we need is shown in Figure 4 which displays the evolutionary tracks of stars of different masses from the main sequence onto the giant branch. This classic picture assumes that there is no mass loss from the stars during evolution from the main sequence onto the giant branch.

There are at least three reasons why these tracks are important for outsiders.

(1) The H-R diagrams of open and galactic clusters provide tests of the theory of evolution onto the giant branch. An aspect of special importance is the use of these diagrams in detemining the ages of globular clusters. In Figure 5, I show the beautiful analysis of Hesser et al (1989) of the H-R

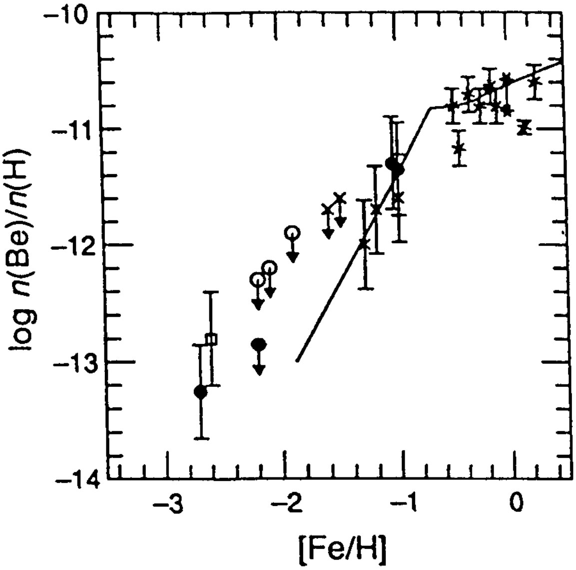

FIGURE 3 The beryllium to hydrogen ratio as a function of the iron to hydrogen ratio for a sample of stars studied by Ryan et al, Gilmore et al and others. The two left-hand points are for HD 140283, a nearly primordial subdwarf. The solid line represents a standard model of beryllium evolution through normal galactic nucleosynthesis. Is the slight excess of beryllium cosmological or not? (from B. Pagel 1991)

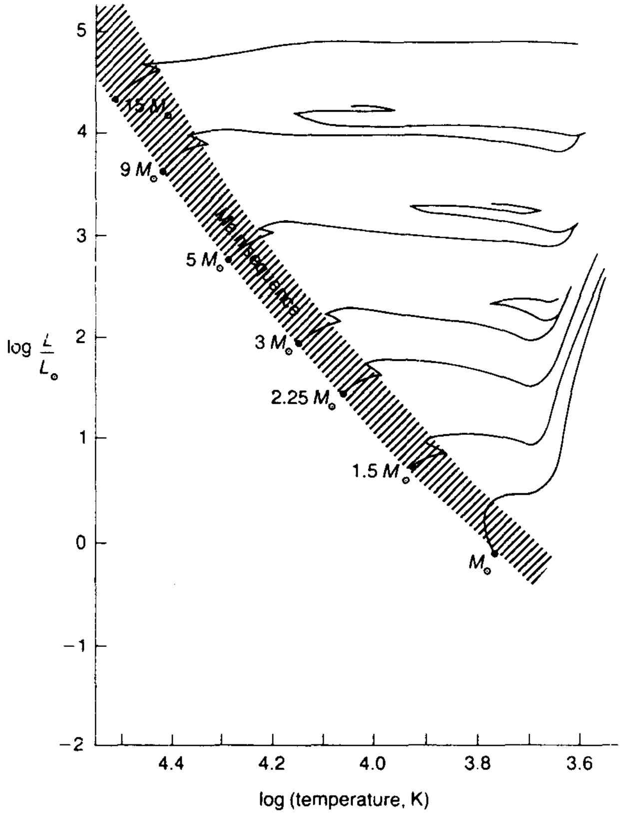

FIGURE 4 Evolutionary tracks for stars of different initial masses on the H-R diagram. These models assume that there is no mass loss from the stars. Most of the lifetime of the star is spent on the main sequence and all the subsequent phases of evolution on the giant branch take place over much shorter timescales. (After D. Michalas and J. Binney *Galactic Astronomy: Structure and Kinematics* 1981)

diagram of the globular cluster 47 Tucanae. The isochrones shown on the diagram have been derived by VandenBerg. It is apparent that, in this well-studied cluster, the theoretical isochrones can provide an excellent fit to the data.

(2) It follows that the study of the H-R diagram provide an age for the cluster and, according to VandenBerg's analysis, the cluster must be between 12 and 14×10^9 years old. This figure is of great cosmological significance since it sets a lower limit to the age of the Galaxy and to the age of the Universe. This is a crucial piece of cosmological data and, in the simplest world models, implies that Hubble's constant should be closer to 50 than to 100 km s^{-1} Mpc^{-1}. It is crucial for cosmology to know exactly how accurately this age can be determined. By exactly the same token, the study of such diagrams for open clusters provide ages for much younger systems. The general point of importance for extragalactic astrophysics is that the study of the H-R diagrams and the synthesised colours from populations of stars provide one of the few ways of determining ages for the events observed in galaxies. I will come back to this point in Section 3 on classical cosmology.

(3) I emphasise again how important these studies are for understanding the circulation of the heavy elements from the sites of their synthesis inside stars to the interstellar medium and to the next generation of stars. Much of the enrichment is thought to be due to supernova explosions of massive stars but it is far from clear how much is produced per explosion. Indeed, we need to know much more about the evolution of the most massive stars which burn their fuel all the way through to iron and beyond.

Post main-sequence evolution and mass loss

The above discussion leads naturally to the role of mass loss in stellar evolution. When stars begin their evolution up the giant branch there is observational evidence, supported by theoretical arguments, that mass-loss plays a key role in the evolution of stars from the giant branch to the horizontal branch, at the tip of the red giant branch and finally in the final demise of the star as a white dwarf, neutron star or black hole. This much is well established and leads to the circulation of matter between the stars and the interstellar gas.

However, mass-loss is also likely to be important for massive stars on the main sequence. Figure 6 shows the modifications to the evolutionary tracks of massive stars if strong mass loss from their surfaces plays an important role. In a simple interpretation of what is happening, it can be seen that the effect of mass loss is to remove the surface layers exposing the hotter interior and thus moving the stars to the left across the H-R diagram. This behaviour, which has been described in detail by Maeder (1981), can account for a number of important features for other aspects of astronomy. One example is the explanation of the observation that there seem to be only hot blue stars on the H-R diagram and not the corresponding luminous red stars predicted by the tracks without mass-loss. It may be that it is the process of mass loss which leads to only massive blue stars being observed in galaxies. This idea has been used to support the use of the most luminous blue stars in galaxies as distance indicators.

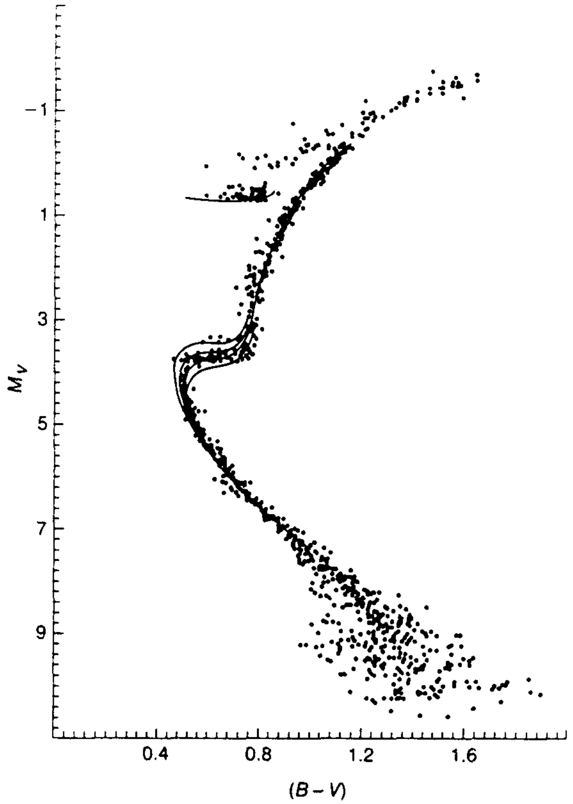

FIGURE 5 The H-R diagram for the globular cluster 47 Tucanae. The scatter in the points increases towards faint magnitudes because of the increase in observational error associated with the photometry of faint stars. The solid lines show best fits to the data using theoretical models for the evolution of stars from the main sequence onto the giant branch due to VandenBerg. For this cluster, the best-fit isochrones have ages between about 12 and 14 × 10^9 years and the cluster is metal rich relative to other globular clusters, the metal abundance corresponding to about 20% of the solar value. (From J.E. Hesser, W.E. Harris, D.A. VandenBerg, J.W.B. Allwright, P. Stetson 1989)

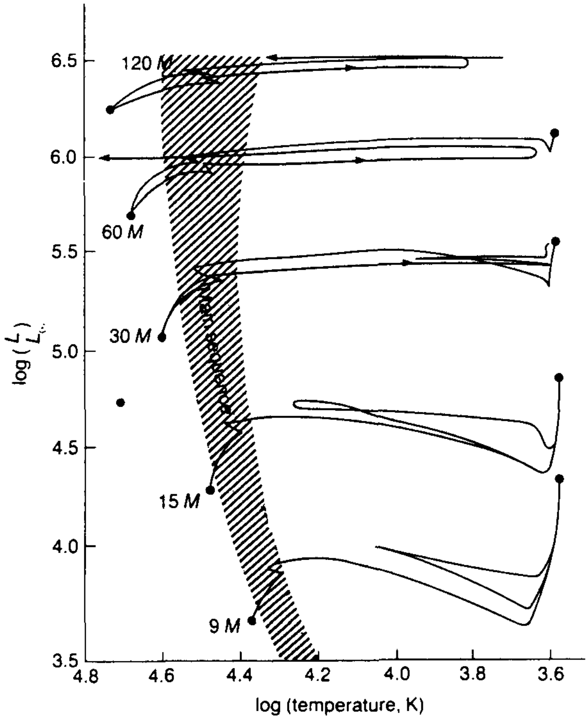

FIGURE 6 Examples of theoretical evolutionary tracks of massive stars once account is taken of the effects of mass loss during their evolution on the main sequence and during the red giant phase. The solid dot at the end of each track corresponds to the onset of carbon burning. Those tracks which end at the right of the diagram include no mass loss. The lines which show major excursions to the left across the H-R diagram include the effects of strong mass loss. (After A. Maeder 1981)

A second example of the importance of these studies for high energy astrophysics is that the Wolf-Rayet stars, which are among the most luminous stars known, have chemical over-abundances of the isotope of neon ^{22}Ne, similar to the isotope anomalies found in the cosmic rays. It might be that these stars are important progenitors for these heavy elements in the cosmic rays.

The general point of importance is that mass loss from stars is a key issue for many of the most important processes in high energy astrophysics and astrophysical cosmology. Processed gas clouds are observed very close to the massive black holes in active galactic nuclei and we know that the accretion of mass onto supermassive black holes is a very attractive energy source for these objects. Likewise, the enrichment of the interstellar gas from which new generations of stars form is a key process in the early evolution of galaxies and potentially the observation of these processes can help define the sequence of events which lead to the galaxies as we know them now.

Binary stars and stellar evolution

The key role of binary stars in providing the basic calibration of the mass-luminosity relation for stars is very well-known and to the outsider pictures such as Figure 22.3 of the text-book by Kippenhahn and Weigert (1990) give us a lot of confidence that the basic physics of main sequence stars is in good shape. Obviously, there will be an enormous potential for improving the accuracy with which this comparison can be made with the magnificent data-base which will become available from the Hipparcos satellite of the European Space Agency.

Binary star evolution is, of course, of the greatest interest in its own right from the point of view of the formation of systems such as the low-mass X-ray binaries and the more exotic systems in which there is evidence for black holes. I consider this topic to be an integral part of the theme of this colloquium because the white dwarfs, neutron stars and black holes are the ultimate products of what is going on inside the stars. It would be a great advance if we had secure estimates of what types of dead star form from which types of star and why.

Star formation

Finally, I have to say something about the process of star formation and, in particular, the internal structure of pre main-sequence stars. In this case, the internal structure is very different from that of a main-sequence or post main-sequence star. According to the standard picture of Shu et al (1987), the energy source in protostars and pre main-sequence stars is accretion rather than nuclear energy generation. The removal of the gravitational binding energy of the accreted matter is effected by the reradiation of heated dust at far infrared wavelengths at which the protostellar cloud is transparent. The signature of this process is to be seen everywhere in infrared maps of our Galaxy and of regions of star formation. Whilst no one would claim that the relation of these observations to the detailed processes of star formation are fully understood, infrared and sub-millimetre observations of these regions have revolutionised our understanding of the necessary ingredients of an acceptable theory. Besides the intrinsic importance of understanding the processes of star formation, these studies are crucial for galactic evolution.

To give only one example, we know that the IRAS galaxies which are the most powerful far infrared emitters are associated with interactions or collisions between galaxies. The implication is that the strong gravitational interaction between the galaxies results in a high rate of star formation which in turn results in the extreme far-infrared luminosities observed in these galaxies. But this concept is not only important for galaxies now. Among the favoured scenarios for the formation of galaxies is the hierarchical clustering picture which is a necessary part of the cold dark matter scenario of galaxy formation. Presumably the strong IRAS galaxies are examples of the types of process which lead to the formation of more massive galaxies out of the coalescence smaller galaxies.

Summary

My intention has been to show in these examples how the understanding of the internal structures of the stars is directly related to processes which are of importance in a wide range to different astrophysical disciplines. Although in some cases, the relation may appear quite distant, there is no question but that the foundations of many of these disciplines depend upon the reliability of our understanding of the internal processes which go on in stars. I will be intrigued to learn of how many of my preconceived notions survive this meeting intact.

CLASSICAL COSMOLOGY

In the second case study, I look at the old problem of determining the deceleration of the Universe from observations of distant galaxies. Let me treat first the traditional problem of the Hubble diagram and then look at the problem of determining timescales at large redshifts.

The infrared K-z relation

I will tell this story from a personal point of view. The traditional way of tackling this problem is through the redshift-magnitude relation for the brightest cluster galaxies (see, for example, Gunn 1977). The problem with this approach is that the sample of clusters extends only to redshifts of about 0.5 at which the differences between the expectations of different world models is still small. In the early 1980s, Simon Lilly and I (1984) began studying the infrared properties of radio galaxies in the J, H and K infrared wavebands (that is, the 1.2, 1.65 and 2.2 μm infrared windows). It had been known for some time that the radio galaxies have more or less the same absolute magnitudes and are among the most luminous giant elliptical galaxies known. By the early 1980s, complete samples of radio galaxies were available with redshifts which extended up to about 2. Figure 7 shows what we found when we plotted the K (2.2 μm) apparent magnitudes against redshift. I still find this an astounding diagram.

However one wishes to interpret the diagram, the key points are that the dispersion in apparent magnitude about the mean line through the points does not change with redshift and that the diagram extends to redshifts well beyond 1. As more and more points have been added to this diagram, the miracle continues (Figure 8). For whatever reason, there is clearly some systematic behaviour going on in these galaxies. In the most naive interpretation one might say that it is only the most massive galaxies which can become radio galaxies.

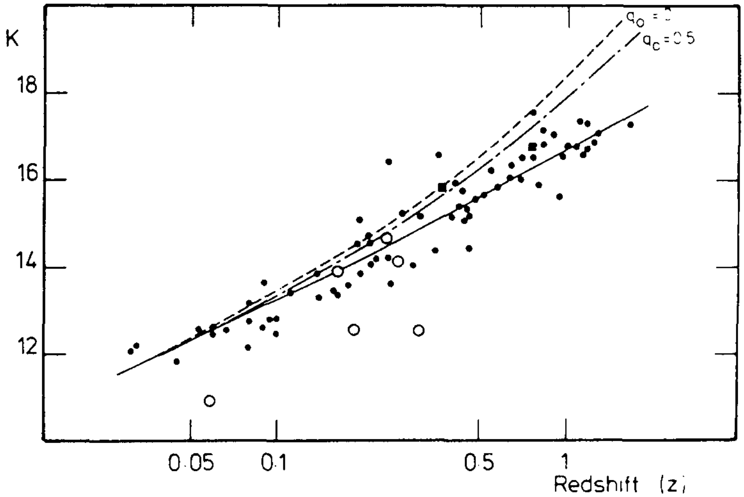

FIGURE 7 The infrared K-z relation for a complete sample of 3CR radio galaxies. The sample consists of those galaxies in which the infrared flux is the starlight of galaxies and is not contaminated by non-thermal optical or infrared emission. (S.J. Lilly and M.S. Longair 1984)

The second key point is the importance of the infrared waveband for carrying out this analysis. If this diagram were redrawn using optical instead of infrared magnitudes, there would be a much greater dispersion in apparent magnitude at redshifts greater than about 0.5 because these galaxies display a wide range of optical-to-infrared colours, reflecting the different amounts of star formation going on in these galaxies. However, if one uses infrared magnitudes, most of the light is due to giant stars which are derived from the old stellar population rather than the more transient populations which can dominate the optical spectrum. Thus, the great advantage of using the 2.2 μm waveband is that the absolute magnitudes should reflect the gross properties of the underlying stellar population averaged over cosmological time-scales.

Also shown on Figure 7 are the expectations of uniform world models with deceleration parameters $q_0 = 0$ and 0.5, corresponding to the empty and critical Universes respectively. It can be seen that both lines lie significantly above the mean line through the points in the sense that the galaxies at redshifts about 1 seem to be more luminous than is expected in these models. If one attempts to find a best fitting Friedmann model, the answer is $q_0 \approx 3.5$ corresponding to 7 times the critical value of the deceleration parameter.

Of course, what we have not taken into account is the effect of stellar evolution upon the luminosities of the galaxies and this is where the significance of the considerations of this colloquium comes in. At a redshift of 1, the galaxies are less than half the age they are now and so the whole of the stellar population was much younger. We need to be able to make corrections for the evolution of the stellar populations of the galaxies as a function of cosmic epoch. In fact, by restricting our attention to the infrared luminosity of the galaxy, this correction becomes much simpler than one might imagine. If we assume that the only

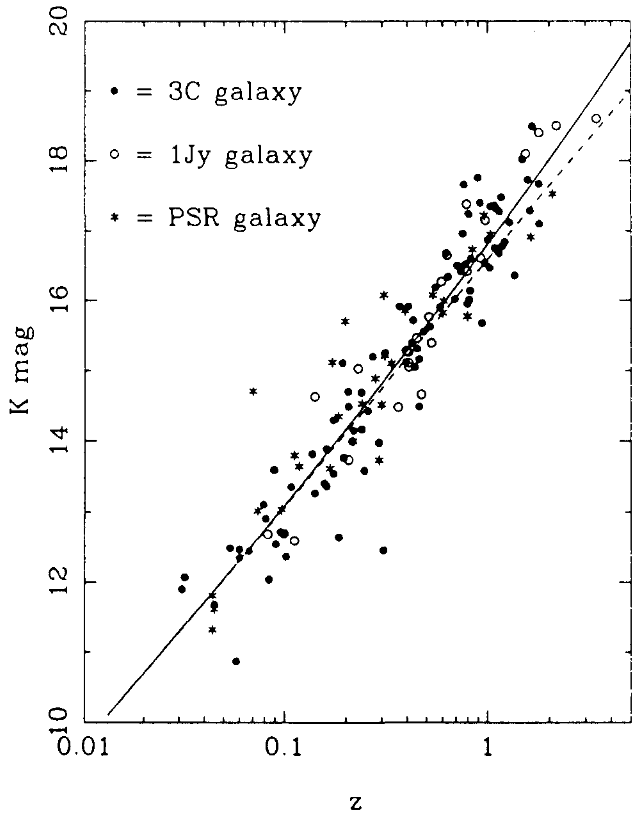

FIGURE 8 The K-z relation for radio galaxies. This compilation includes radio galaxies from the 3CR sample (solid circles), from the 1 Jy samples (open circles) and the 0.1 Jy samples (asterisks) (From J. Dunlop and J.A. Peacock 1990)

correction we have to make is for the ageing of the stellar population, we can work it out in a simple way. Since the bulk of the luminosity is simply the integrated light of stars on the giant branch, the evolution of the luminosity in the infrared waveband is determined by the rate at which stars evolve from the main sequence onto the giant branch. In a simple calculation, we can write that the luminosity of galaxy is proportional to the number of red giants N_{rg} which can be written

$$N_{\mathrm{rg}} = \left[\frac{dN(M)}{dM}\right]_{MS} \left(\frac{dM_{\mathrm{to}}}{dt}\right) \tau_{RG}$$

where $dN(M)/dM$ is the main-sequence mass function, M_{to} is the mass at the main-sequence termination point and τ_{RG} is the lifetime of a star on the giant branch. Putting in reasonable values for the main sequence mass function and the mass-luminosity relation for stars, we find that, at a redshift of 1, the galaxies are expected to be about 1 magnitude brighter than they are at the present epoch. It can be seen from Figure 7 that this is exactly the difference we find betweeen the observed locus of points and the expectations of models with $q_0 \sim 0 - 0.5$. We interpret these results as meaning that we have observed the effects of stellar evolution upon the luminosities of galaxies at redshifts of 1 and greater.

If one is then feeling very ambitious, one can try to solve simultaneously for the effects of stellar evolution and for the value of the deceleration parameter. Doing this, we found that there is a 90% probability of the value of q_0 lying in the range 0.1 to 0.9. In other words, so far as we can tell q_0 has the value 0.5 ± 0.5. Now, this may not look all that wonderful but at least we believe that we have done as reasonable a job as one can using straightforward methods and that the result is not implausible. The relevant comparison is with the density parameter Ω which, according to the Friedmann world models should satisfy the relation $q_0 = \Omega/2$. Most workers would agree that the value of Ω derived from observation is at least 0.1 and so it is likely that the equality $q_0 = \Omega/2$ is correct within about a factor of 10. Optimists would argue that if they really are so similar, they must be the same. Most of us would, however, like to improve the accuracy with which this equality is known to be correct but that is a very big job indeed.

The central role which studies of stars and stellar evolution play in this type of work can now be appreciated. I have included only the simplest possible correction to the luminosities of the galaxies for the effects of stellar evolution. Obviously, one would like to do much better than this by including the best models available for the evolution of stars. My own view is that this type of analysis is indicative of the studies which will unquestionably be important in the future. It is still very difficult to make high quality observations of these galaxies but, with the next generation of large telescopes, it should begin to be possible to undertake proper spectroscopic studies of the populations of stars in these galaxies and so much better models of the evolution of the stellar populations will be needed. I have no illusions about the fact that there will certainly be many other effects to take into account but we can be certain already that stellar evolution is one of them.

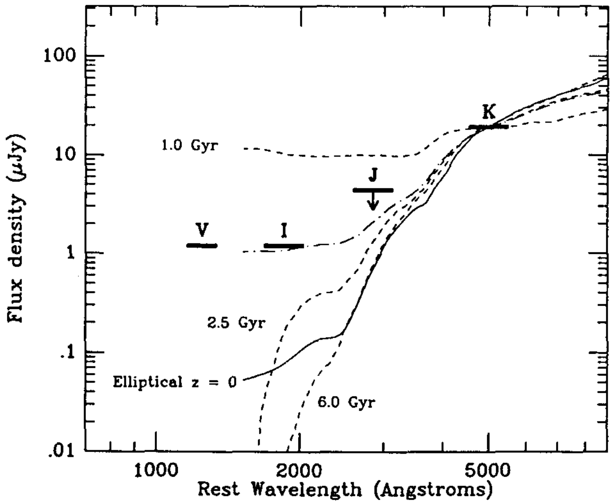

FIGURE 9 The rest-frame broad-band spectral energy distribution of the radio galaxy 0902+34 from 100 to 500 nm. The curves represent different stages of evolution Bruzual's C model and a zero redshift elliptical galaxy. The flat spectrum for *V* to *I* indicates substantial star formation. The steep rise into the observed infrared is interpreted as representing a massive older population. (From S.J. Lilly 1988)

The ages of stellar populations at large redshifts

There is a similar way in which observations of this type can be used to set important limits to cosmological parameters and which depend in a central way upon the understanding of the stellar evolution in galactic populations as a whole. Again, I use this example as an illustration of the types of issue which cosmologists can now address and which are revelant to the theme of this colloquium.

The example concerns the work of Simon Lilly who has continued the studies described above and found some radio galaxies with very large redshifts among the 1 Jy sample of radio sources. An example of interest is the radio galaxy 0902+34 which has redshift 3.395 (Lilly 1988). It is important that this galaxy lies precisely on the K-z relation shown in Figure 8. From broad band photometry, Lilly was able to define a broad band spectrum for this galaxy which is shown in Figure 9. Also shown on the diagram are the results of modelling the evolution of a stellar population which is formed with the standard initial mass function and then simply allowed to age. The aim of the calculation is to estimate the minimum permissible age for the population responsible for the infrared emission. It can be seen from these models that, if the galaxy were any younger than about 2×10^9 years, the optical emission would be relatively too bright as compared with the infrared emission.

The argument then proceeds as follows. The observation of the strong infrared emission is interpreted as the radiation of a popultion which is at least 2×10^9 years old. If we were to adopt cosmological parameters $\Omega = 1$ and $H_0 = 100$ km s^{-1} Mpc^{-1}, then the Universe would be only 7.3×10^8 years old at a redshift of 3.4! In other words, this simple observation can lead to significant constraints on cosmological parameters. Plainly, the problem is relieved if we adopt a value of $H_0 = 50$ km s^{-1} Mpc^{-1} and a smaller value of Ω. From the astrophysical point of view, the important point is that the argument hangs upon the question of the reliability of the lower limit to the age of the stars emitting in the K waveband from studies of stellar evolution. In principle, it is not so different from VandenBerg's analysis of the properties of the H-R diagrams for globular clusters although now we are dealing with very faint galaxies without the possibility at the moment of obtaining much more than photometric spectra for these objects.

Not surprisingly, this work has been the subject of some controversy. Perhaps the most fascinating development has been the discovery that the radio structures of some of these distant radio galaxies are aligned with their optical continuum and line emission (e.g. Chambers, Miley and van Breugal 1990). Since the radio source lifetimes are much less than 10^9 years, this suggested that the aligned components must have lifetimes much shorter than 10^9 years. This has led to a number of models in which the aligned component is created by the passage of the radio jet through the interstellar gas and thus has nothing to do with the old stellar population (Rees 1989, Chambers and Charlot 1989). The key quesion is the degree to which these phenomena impact the idea that there is an old stellar population in the radio galaxies as a whole. The recent detailed analysis of Rigler et al (1992) strongly suggests that the aligned component has a flat spectrum and is independent of the old stellar population which represents the bulk of the stars in the galaxy and which shows no alignment with the radio structure.

I personally find the argument of Rigler et al (1992) quite compelling that there indeed exist old stellar populations in these very distant galaxies. If this is the case, the observation has important consequences for the origin of galaxies. Evidently, in a few cases, the galaxies have developed to a considerable state of maturity by a redshift of 3. Adopting the most straightforward interpretation of the data, if $H_0 = 50$ km s^{-1} Mpc^{-1} and $\Omega \approx 0$, the stars in the galaxy would have to be formed at redshifts much greater than 4, at least at a redshift of 7 in the empty world model.

THE ORIGIN OF GALAXIES

The big problem in understanding the origin of galaxies is to reconcile the quite remarkable smoothness of the Cosmic Microwave Background Radiation with the gross irregularity in the distribution of galaxies, most vividly portrayed in the three-dimensional pictures of the local distribution of galaxies provided by the Harvard-Center for Astrophysics survey of almost 30,000 galaxies. As is well known, the problem arises because, whereas the Jeans' instability in a static medium grows exponentially with time, in an expanding medium, the rate of growth of the perturbation is only *algebraic*. The result first derived by Lifshitz can be written

$$\frac{\Delta\rho}{\rho} \propto R = \frac{1}{(1+z)}$$

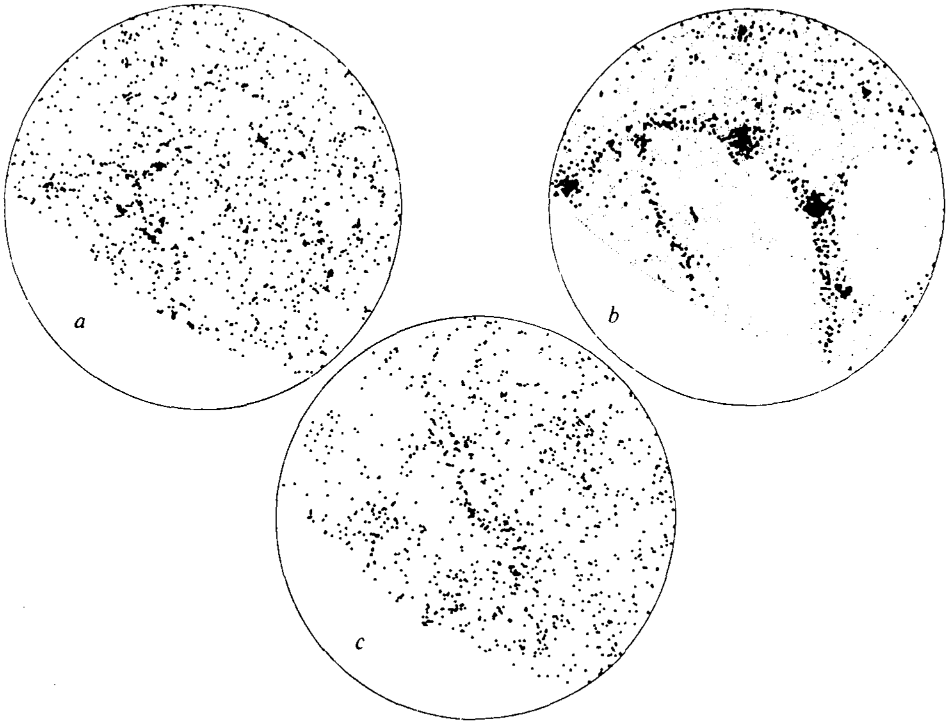

FIGURE 10 Equal area projections of the galaxy distribution on the northern sky and in artificial catalogues made from n-body simulations. (*a*) The standard cold dark matter model including biased galaxy formation; (*b*) the neutrino-dominated model in which galaxy formation began at a redshift of 2.5; (*c*) the galaxies observed in the Harvard-Center for Astrophysics northern sky survey. The outer circle represents galactic latitude +40° and the empty regions lie at declinations below 0°. (From M. Davis, G. Efstathiou, C.S. Frenk and S.D.M. White 1992)

provided $\Omega z \gg 1$. In this expression $\Delta\rho$ is the density enhancement relative to the mean background density ρ. R is the scale factor of the Universe which describes how the distance between two points expanding uniformly with the Universe changes with time, normalised to $R = 1$ at the present epoch, and z is redshift. In the limit $\Omega z \gg 1, R \propto t^{2/3}$ and the above relation describes the algebraic time development of the density perturbations. The problem is that the matter and radiation decoupled when the scale factor was about 1/1000 of its present value and so, since we observed lots of collapsed structure now, there must have been significant density perturbations in the matter distribution at the time when the photons of the Cosmic Microwave Background Radiation were last scattered. There should therefore be fluctuations in the intensity of the Cosmic Background Radiation in different directions on the sky. This is the line of reasoning which leads to the difficulty of reconciling the smoothness of the background radiation with the irregularity of the distribution of galaxies.

The most popular solution is to build dark matter into the model universe so that it is dominant gravitationally. Then, the fluctuations are assumed to be present in the dark matter at the moment of decoupling but these are not reflected in the distribution of the baryonic matter which is closely coupled to the background radiation. Although the nature of the dark matter is unknown, this is the current orthodoxy and the question is whether or not astrophysical arguments can cast more light on its nature.

The most popular picture is the *Cold Dark Matter* model in which the dark matter fluctuations on a wide range of scales collapse and begin to form galaxies by a process of hierarchical clustering. Large scale structures are all rather recent features of the Universe. A less popular version is the *Hot Dark Matter* model in which the neutrino has a finite rest mass. In this case, all fine scale structure is obliterated by the free streaming of the neutrinos and the large scale structures form first. Galaxies form within the potential wells created by the large scale structure. Neither picture gives exactly the right answer without some additional astrophysical considerations (Figure 10). The cold dark matter picture can account for the correlation function for galaxies but has difficulty producing enough power on the very largest physical scales. The hot dark matter picture produces too much large scale structure.

Recently, there has been great excitement in the press and in the astronomical community because at last fluctuations in the Cosmic Microwave Background have been discovered by the COBE satellite at an intensity level about one part in 100,000 on angular scales of 7° and greater. These angular scales correspond to physical scales in the Universe very much greater than the large holes in the distribution of galaxies. What has encouraged many theorists is that this is roughly the level of intensity fluctuations expected in the most popular variant of the Cold Dark Matter picture, if the initial spectrum of fluctuations is extrapolated in the most natural way to these large physical scales.

From the point of view of the present discussion, the interesting question is when the galaxies first formed. Unfortunately, this is not a well posed question because it is not clear what we mean by the expression "When did the galaxies form?". Do we mean when the system was first bound, or when the first stars formed? Do we mean when the bulk of the stars formed or do we mean the time by which it had more or less attained its present mass? This list simply emphasises that one must be careful when one tries to quantify what one means by the epoch of galaxy formation.

The area in which these considerations bear upon the subject matter of this colloquium concerns the question of when the elements were created. There is a variety of evidence to suggest that the process of galaxy formation and metal formation must have taken place over a considerable redshift range. None of these pieces of evidence is unambiguous but taken together they are suggestive.

(1) Galaxies and quasars at large redshifts seem to have remarkably normal chemical abundances;

(2) There exist radio galaxies at redshifts of 3 and greater which seem to be younger counterparts of radio galaxies at the present epoch;

(3) The cosmological evolution of the quasar population shows a maximum or plateau at redshifts betweeen about 2 and 3:

(4) The abundances of the elements in G-dwarfs suggest there may have been an initial burst of element enhancement;

(5) The intergalactic gas needs more than simply the ultraviolet emission of quasars to ionise it fully at redshifts 2 to 4 and the emission of young galaxies in these redshift ranges could be responsible for the ionisation of the gas.

(6) Young galaxies may be able to produce a significant fraction of the metals which we observe today.

This list is not complete and certainly not uncontroversial but it makes the point that there is evidence for metal formation over a wide range of redshift. If we were able to pin down the history of chemical enrichment as a function of cosmic epoch, this would help constrain the global pictures of galaxy formation.

A very elegant argument was presented recently by Lilly and Cowie (1987) which indicates how the rate of element formation can be related to the surface density of young galaxies. In its simplest form, the argument goes as follows. When a density $\rho_{\rm m}$ of metals is created, an energy $0.007\rho_{\rm m}c^2$ is released, corresponding to the binding energy liberated when helium is synthesised from hydrogen. Now models of galaxies with continuous star formation have very flat spectra. Figure 11 shows the predicted spectra of a "young galaxy" in the sense that the star-burst lasts 12×10^9 years and the spectra at different ages during that period are illustrated.

It can be seen from Figure 11 that, to a good approximation, the intensity spectrum can be taken to be flat, F_ν = constant, for all wavelengths longer than the Lyman limit. A simple calculation then shows that there is a simple relation between the integrated intensity of young galaxies in a particular redshift interval and the contribution which these galaxies make to the density of metals now. In simplified form, the relation is

$$I_\nu = 7.5 \times 10^{-25} \left(\frac{\rho_{\rm m}}{10^{-31}\ {\rm kg\ m^{-3}}} \right) \quad {\rm W\ m^{-2}\ Hz^{-1}\ sr^{-1}}$$

The meaning of this formula is that, if one measures a certain intensity I_ν from a given redshift interval from these young galaxies, then the density of metals $\rho_{\rm m}$ observed now was synthesised in that redshift interval.

In fact, Cowie (1989) claims to have discovered a class of such flat spectrum galaxies in very deep multicolour surveys. The integrated flux density of these objects suggests that they can account for a significant fraction of the metals observed now, possibly most of it. The redshift at which most of the metals were formed is not certain but it appears that a significant fraction occurred at redshifts of the order 1.

The important point from the perspective of this conference is the way in which processes occurring in the interiors of stars have a key role to play in providing further evidence on the origin and evolution of galaxies. This type of argument needs to be refined using better models of star forming galaxies and the yields of metals from stars of different types.

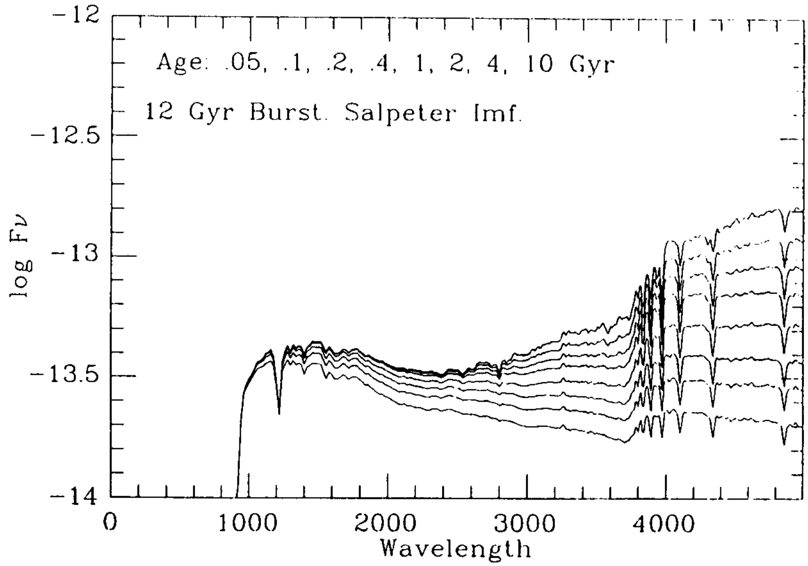

FIGURE 11 Synthetic spectra for a region with constant star formation rate at the ages indicated. A Salpeter mass function is assumed with cut-offs at 75 and 0.08 $M_\odot$. The spectra were generated by Gustavo Bruzual from a recent version of his evolutionary synthesis programmes. (From S.D.M. White *The Epoch of Galaxy Formation* 1989)

CONCLUSIONS

It is my firm conviction that the whole of the edifice of modern astronomy and cosmology is only as strong as the foundations upon which it is built. Central to the whole of astronomy is the understanding of the stars and the processes which occur in their interiors. As I have indicated, these studies have significance far beyond interest in the stars themselves.

What no one could have predicted is the spectacular way in which the subject has been rejuvenated by solar and stellar seismology. It is always rash to make predictions about the birth of new eras in astronomy but I would be surprised if, in ten years time or sooner, stellar seismology had not joined photometry and spectroscopy as one of the standard tools of the astronomer for the study of the stars. In my view, in the case of projects such as PRISMA, it is not a question of "If it will fly" but rather "When it will fly". The scientific significance seems to me unassailable.

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