Harley Wood Winter School 1998: Roseworthy College: First Light in the Universe Exercise

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1 Introduction

This exercise was run at a winter school of Australian astrophysics grad students, and was designed to acquaint them with current progress in the study of high redshift galaxies. The class were divided into 11 groups. Their briefing papers are listed below.

One group (representing the IAU) had the unenviable task of organising and chairing the meeting: their briefing paper is different in format, and is listed first below.

Please don't take offence at the stereotypes, please: they are simply designed to make the exercise more memorable!

2 You are the International Astronomical Union

2.1 Research Interests

You have the unenviable job of chairing this meeting of the IAU 'New Facilities' committee. You have to get this fractious bunch of ego-maniacs to come to a consensus on which new facilities should be funded, to advance our knowledge of galaxy formation and evolution. You are a group of astronomers from various small institutions in Europe, Asia and South America.

Everybody here will have a pet instrument or telescope they want to promote. They will also have some particular science questions that appeal to them, and some special expertise in particular areas of high redshift research.

Your job is to get them to focus on the science: get them to think not purely about getting their own instrument or facility funded, but about what we, the human race, want to know about the early universe, and how we can best use our limited resources to learn these things.

You have to get this group to come up with a ranked shortlist of the five best proposals. If you just take a vote at first, everyone will probably vote for their own ideas: every proposal will get one vote, and the whole meeting will collapse in acrimonious failure. You will have to think of how best to manage the process of getting a consensus. You could let people vote at the end, but not for their own project. You might try and force the different groups to join in consortia to propose particular shortlists. You might try a preferential voting system, or simply try and steer the discussion with assertive chairing. Perhaps you should assemble sub-groups made up of representatives from the different institutions to discuss separate issues (eg. infra-red vs. optical, or ground vs. space).

In the final session, you may with to get representatives from each group to stand up and make brief presentations, before calling for some sort of decision. This might be dangerous, however, as it could lead to a hardening of negotiating positions, and make finding a compromise acceptable to all impossible.

You should talk to all the various groups repeatedly as they work on their proposals, and keep tabs on any consensus that might emerge. Hopefully you can spot fights before they start and pour oil on the troubled waters.

2.2 Proposed Agenda

Bear in mind that, once this meeting has decided a priority list, it then has to go the world governments for funding. There is no point in coming up with a scientifically wonderful proposal that you cannot sell to the politicians. Something exciting, thrilling, and easy to explain to numb-skull politicos is what you need.

Secondly, you have to ensure that virtually everyone is happy with the compromise ranking you come up with. All it takes in one irate astronomer to go to their congressional representative and tell them that the proposal is a big mistake, and you can say goodbye to your funding for any of these projects. Politicians (unreasonably) require that the astronomical community be completely uniform in its proferred views, before they will give us any money.

You have two personal biasses, and if possible, you should steer the meeting towards a conclusion that reflects these biasses. Firstly, history shows over and over again that the biggest results from any new telescope or facility are not the ones that were expected when it was built. Most of these facilities will not see first light for years: by then, the whole field of astronomy will have moved on. You have to make sure that whatever is funded has enough flexibility to cope with this.

Secondly, progress in astronomy depends on having a wide range of intelligent and imaginative astronomers. You have to make sure that these facilities can be used by young researchers, researchers at minor institutions, and from third world countries. And you have to make sure that people with unfashionable, maverick ideas, can get time to try them out. If, for example, you only had one, highly over-subscribed mega-facility, most of the time will tend to go to people with political clout, doing projects which conform to the current orthodoxy, and which have a very high probability of success. Original science, and new researchers might be squeezed out.

Good luck!

3 You are the Anglo-Australian Observatory

3.1 Research Interests

Your main research interests concern redshift surveys.

Why are people so fixated with redshifts above 3? Over half the history of the universe has occurred since redshift one. If we observe out to redshift 1.5, that is around 70% of the whole history of the universe! And we don't need fancy new-fangled techniques to work at these redshifts: tried and tested techniques will work just fine, and the galaxies we find and study are close enough that we can really learn something about them.

You are world authorities at redshift surveys. You start off by getting deep images of some part of the sky. Then, using the multi-fibre or multi-slit instruments you have pioneered, you obtain spectra of them all. This sounds simple, but the scientific pay-off has been huge, especially when combined with Hubble Space Telescope imaging of the galaxies, to determine their colours and morphologies.

Little evolution in the numbers of elliptical galaxies is seen out to redshift one. The major evolution is in a vast population of small blue galaxies, the so-called 'faint blue galaxies', which were abundant at redshift one, but which have mostly disappeared by now. They have probably faded into obscurity, as their initial burst of star formation dies away.

The nett effect of all of this is that the star formation rate per unit co-moving volume was much higher at redshift one than it is today, which actually agrees well with theoretical calculations.

Galaxy clusters have also changed: at redshifts around one, clusters seem to contain more spiral galaxies, fewer S0s and the same number of giant elliptical galaxies as we see today. This is presumably because the spirals are merging to form S0s. One puzzle: the velocity dispersions, weak gravitational lensing measurements and X-ray fluxes of these high redshift clusters imply that they are just as massive as clusters today, which is in strong contradiction to most current theoretical models. If this holds up with better data, it implies that something may be wrong with theories of structure formation in the universe.

You are now working on enlarging your samples, and actually measuring velocity dispersions for galaxies at redshifts around 1, to derive their masses. This will really help nail down the evolution of different types of galaxy.

3.2 Proposed Facility

All of this is good, solid science, unlike the flaky stuff the high redshift people are doing. These techniques use well-understood techniques, have good statistics and allow us to trace the different galaxy populations in detail as they evolve. It might not be as trendy and 'Gee Wizz' as going after fuzzy blobs at redshift 5, but it is slowly, securely extending our knowledge of the universe.

The main challenge is to extend this work into the infrared. All the main emission-lines of typical galaxies disappear into the IR beyond redshift one, which puts an upper limit on what this technique can do. What is needed, therefore, is an infra-red multi-object spectrograph on an 8-m class telescope (or preferably several of them). With this, you can push all the good solid work you've been doing at lower redshifts out to redshift 2 or 3 and beyond, and come to really understand, in detail, the evolution of different classes of galaxies throughout the history of the universe.

You see your role in this meeting as bring all the crackpot high redshift people down to Earth (figuratively speaking). All their proposals may sound exciting, but the aim is not to produce excited astronomers but to learn about the history of the universe: anything that won't produce good solid interpretable data should be thrown out.

4 You are the Australia Telescope National Facility (ATNF)

4.1 Research Interests

Your main research interests concern neutral hydrogen.

In the early universe, most galaxies have presumably not yet formed. That means that there must be enormous quantities of gas lying around, waiting for the chance to collapse under its own weight into lumps and form stars and galaxies. If we could actually observe this gas, as it moves around and assembles itself into lumps, we would be directly observing the process of galaxy formation. If we look at the amount of gas as a function of redshift, it should drop as galaxies form, telling us the era of galaxy formation.

Optical astronomers seem to think that they can observe galaxy formation by taking optical images. What emits visible light? Stars. And where do stars live? In galaxies. So you can only see visible light once a galaxy has formed. So how do they propose to study galaxy formation using optical telescopes? This has always puzzled you. Furthermore, even once a galaxy has formed its first stars, it will probably be dusty for a while, just like local starburst galaxies, and dust is remarkably good at blocking optical radiation.

In the local universe, gas can be studied in enormous detail using 21cm radiation. This has been responsible for a large fraction of our knowledge of galaxies in the local universe. Alas, with current technologies it is impossible to use this technique at even moderate redshifts: telescopes simply aren't sensitive enough.

The only way we can study gas in the early universe at present is through QSO absorption-line spectroscopy. If the gas lies directly in front of a bright background QSO, then high resolution optical spectroscopy of the absorption it causes in the spectrum of the background QSO can tell us many things about the gas. This technique has been brilliantly sucessful: a wide variety of exciting and important things have been learned. But QSO absorption-line work is forever restricted to statistical sampling: all you can ever measure is what happens to lie in front of a background QSO: something even a milli-arcsec away is completely unknown. Thus the shapes, sizes, geometries and velocity structures of whatever gas clouds are causing the absorption are almost completely unknown.

4.2 Proposed Facility

Clearly, what we need is a really large and sensitive radio telescope that can observe gas in the high redshift universe, using 21cm radiation. This will not be easy: the signals will be very faint and susceptible to interference, as the redshifted wavelengths of 21cm are crowded with commercial transmissions.

The solution is to go to a very large collecting area: one square kilometer, and to use fancy nulling techniques to screen out interference. This will not be easy or cheap, but a one square kilometer telescope (called the 1kT) would be an awesome instrument for studying the processes of galaxy formation. It promises to be the only technique that can study the motions of gas in the very early stages of galaxy formation, before the first stars light up.

Few of the people at this meeting seems to be radio astronomers, and so they may need to be persuaded of the manifest advantages of radio telescopes over optical in this type of research. Go out there and persuade them!

5 You are CALTECH

5.1 Research Interests

Your main research interests lie in Lyman-break galaxies.

You are the best, and you know it. Every one of you gets more 8-m class telescope time than the whole of Australia combined. You lead the world: you have the smartest faculty, the hardest working students, the biggest telescopes, and the smoggiest atmosphere. How irritating that all these lesser minds from other, low-grade institutions, get to vote on which facilities should be funded: by rights, the choice should be yours alone!

Until a few year ago, almost no galaxies had ever been found in the high redshift universe. You changed all that: you pioneered the Lyman-break technique, which finds galaxies by searching for the break in their spectra caused by Ly-limit absorption. You take a series of broad-band images: say U, B and R. Galaxies that show up as blue in B and R but are very faint in U will be the ones which have the Ly-limit at around 4000Å: ie. redshift 3 galaxies. With the two Keck telescopes for follow-up spectroscopy, you have identified several hundred galaxies between redshifts 2 and 4. This technique only finds young, dust-free galaxies, but what other sorts of galaxies would you expect in the early universe?

These galaxies (when observed with the Hubble Space telescope) appear as tiny blue specks. Their spectra show that they are young, compact blue galaxies, forming stars at rates of a few solar masses per year. You are finding many of these galaxies per square arcmin: they appear to simply be normal galaxies in the early universe.

What are these galaxies? You hypothesise that they are the ancestors of the bulges of normal spiral galaxies today. These galaxies seem to be forming slowly and steadily: not in single monumental bursts, as some people once thought.

In collaboration with those moderately intelligent people at Lick Observatory and the Space Telescope Science Institute, you used the Hubble Space Telescope observations to extend this technique to fainter galaxies and different redshifts. The Hubble Deep Field (an enormously long pointing at a blank bit of sky) allowed you to find Ly-limit galaxies at redshifts ranging from 1-6. Keck spectra confirmed the redshifts of the brightest galaxies. Piero Madau used your data to calculate the star formation rate of the universe as a function of redshift: he found that it peaks at redshift 1, declining slowly on either side of this redshift.

You are now busily measuring the clustering of these galaxies. They seem to be remarkably strongly clustered. You hope to use this clustering to constrain the geometry of the universe and the nature of dark matter.

5.2 Proposed Facility

What this work needs is a good space telescope to get high resolution images of these galaxies, and some really big ground-based telescopes equipped with low resolution, multi-object spectrographs, to measure their redshifts. So, the money should be spent on keeping the Hubble Space telescope going (or launching a replacement), and on a few more Keck telescopes. Or maybe a private 50m telescope for Caltech would be a good idea...

Rumor has it that some low individuals, jealous at your great success, are claiming that you have missed most of the galaxies in the early universe: that these galaxies are too red or too dusty for the Ly-limit technique to detect.

They will doubtless be pushing for money to buy expensive toys to search for these non-existent red galaxies. It would be sad if it wasn't a threat to your research: you have to make sure that these poor deluded individuals don't warp peoples minds and persuade them to vote for these hair-brained schemes.

6 You are from **The University of Durham**

6.1 Research Interests

Your main research interests concern the computer modelling of galaxy formation.

How very unpleasant: here you are stuck in a meeting with a pack of observers and instrument builders! New telescopes and detectors are all very good: they have led to a revolution in observational astronomy. The observers think that they are smart, but it is only thanks to these new telescopes that all the exciting recent progress has been made in the study of the high redshift universe. Even more dramatic advances in computer power have had a similar effect on theoretical studies of the early universe. For the first time, it is now becoming possible to simulate a representative chunk of the universe in a computer.

You have long been pioneering this approach, using a combination of analytic maths, n-body simulations and hydrodynamics codes to simulate galaxy and cluster formation. You start your simulations with a uniform gas-filled section of the universe, rippled with tiny primordial fluctuations. You then let the code run: slowly, the overdense regions suck matter (both dark and baryonic) in towards them. At redshift $z \sim 1000$, many tiny ($\sim 10^6 M_{\odot}$) matter concentrations collapse: to stop these from forming vast numbers of stable globular clusters, you add a line to your computer code, which means that the first stars that form in these tiny concentrations go supernova and blow the remaining gas out of the gravitational potential well.

As time continues, the matter starts to form sheets and filaments: the exact shapes and densities determined by the cosmology and form of primordial fluctuations you chose in this simulation. By redshift ten, some knots (where filaments and sheets join) are getting dense enough to form galaxies, and the first light in the universe switches on. You had to cheat here a bit: you have no idea what densities are needed to trigger galaxy formation: you just chose a number that made your simulation come out right at redshift zero.

By redshift 5, clusters of galaxies are centred on these knots. These clusters have not yet assembled much matter, but maybe enough has assembled to power quasars.

By redshift 2, more galaxies have formed, filling in the sheets and filaments. Galaxy formation rates peak at redshift one, after which most of the gas has been consumed, and the universe quietens down, and the galaxies just drift around, slowly being sucked into the high dark matter concentrations in the sheets ('great walls') and knots (' superclusters').

The remarkable thing is that the predictions from these simulations quite accurately match the observations of Ly-break galaxies and QSO absorption-line systems. The galaxies seen at high redshifts are indeed small, strongly clustered, and forming stars slowly and gently, just as you predict. Just as you predict, the star formation rate in the universe seems to peak around redshift one.

6.2 Proposed Facility

These computer models are doing very well, but not yet well enough. The problem is dynamic range: any simulation that models a large enough piece of the universe to be representative (a cube of 100 Mpc on a side seems sufficient), cannot have the resolution to accurately follow what happens on galactic scales ($\sim$ kpc). At present, each point in the n-body code represents around $10^8 M_\odot$, and you cannot model star formation and galaxy dynamics with only ~ 1000 particles. This means that ad-hoc rules have to be introduced to model the formation of stars and galaxies, eg. you could assume that a galaxy forms whenever the density passes some arbitrary threshold, with a luminosity proportional to its baryonic mass.

This is unfortunate: the computers can accurately simulate things we cannot observe, such as the large-scale distribution of dark matter, but not things that we can, like the galaxy luminosity functions, star formation rates and clustering.

So surely the best thing to spend money on is faster supercomputers! With a network of massively parallel modern supercomputers, the simulations will become so good that they can accurately predict observable quantities without the necessity of making so many ad-hoc approximations. The supercomputers will be welcomed by scientists in many other disciplines, as well as by other astronomers. Forget obtaining more data: a relatively modest investment in computer power will allow us to better understand the data we already have.

7 You are the Royal Observatory, Edinburgh

7.1 Research Interests

Your main research interests lie in starburst galaxies.

From your base, high on a rocky crag overlooking the capital of Scotland, you have long been studying starburst galaxies in the local universe. Perhaps it is the howling wind and lack of insulation in your offices that does it, but the glowing warmth of a galaxy violently forming vast numbers of stars has a great attraction to you.

Over the last few years, you have watched with incredulity as group after group has claimed to detect new-born galaxies in the rest-frame UV! If there is one thing you learn from low redshift galaxies, it is that star formation *always* takes place accompanied by dust. And dust is really extremely good at blocking UV light. In our own galaxy, star formation takes place in giant molecular clouds, and you won't get very far studying them in the UV. All the nearby galaxies that are forming stars at reasonable rates are very dusty: most of the radiation from their young stars and supernovae is absorbed by dust and re-radiated in the far-IR.

So it is no wonder to you that the Caltech mafia and their friends are only finding wee little galaxies forming stars at some pathetically gentle rate. Any decent, strapping starbursts will be so dusty that the little dears won't see a thing with their fancy UV Lyman-limit techniques. There could be any number of new-born galaxies in the early universe, forming stars at enormous rates, and the Ly-limit people would never know.

How do you find and study starbursts in the local universe? You look in the far-IR, where these galaxies stand out like sore thumbs (they are called ultra-luminous IRAS galaxies for a reason, you know). Another possibility is to use mm-wave telescopes to look for molecular emission from these galaxies.

You have just finished building a new instrument, called SCUBA (Sub-mm ContinUum Bolometer Array), which goes on the 15-m James Clerke Maxwell Telescope (JCMT) that you run on Mauna Kea. With this, you could, in principle, detect redshifted far-IR thermal radiation from dusty high-z galaxies. And this is just what you are finding: many galaxies, which are almost certainly at high redshifts, with enormous amounts of hot dust. These things must be forming stars at colossal rates: far more actively than those pathetic Ly-limit galaxies. Clearly everyone has been looking in the wrong wavelengths to find new-born galaxies.

7.2 Proposed Facility

With current telescopes, finding dusty starbursts in the early universe is hard work. What you really need is a mm-wave telescope with really good resolution and collecting area on a high, dry site. That is why you are interested in proposals to build a mm-array: a network of lots of mm-wave telescopes, with oodles of collecting area, built at 5000m elevation at a site in the altiplano of northern Chile, near the Bolivian border. Using aperture synthesis, this telescope would have fantastic angular resolution. Not only could you find high redshift dusty galaxies, but you could use their molecular emission lines to map them, measure their velocity fields, temperatures and chemical compositions. It will be awesome! It should also be able to search for galaxies at redshifts beyond five, which are very hard to find with normal optical telescopes.

It is obvious to you that this is the best way to study the early universe and the formation of galaxies. Some of your colleagues seem to persist in the bizarre notion that you can study galaxy formation in the optical: you must gently show them the error in their ways.

8 You are the NASA Goddard Space-Flight Center

8.1 Research Interests

Your main research interests lie in the inter-galactic medium.

For years, you have been fascinated by what lies in the gaps between the galaxies. Your colleagues often derided your fixation with empty space, but you remained convinced that this was an interesting and important field. After all, galaxies only occupy a tiny tiny fraction of the universe: if there is anything at all, however tenuous, in all those vast inter-galactic spaces, it could dominate the mass budget and dynamics of the whole universe.

The first big breakthrough occurred in the late 1960's, when high redshift QSOs were first discovered. If intergalactic space was full of neutral hydrogen, then all wavelengths shortward of Lyα (1216Å) in the rest-frame of the QSOs should have been absorbed (the Gunn-Peterson effect). It was not: this indicated either that intergalactic space at high redshifts is completely empty (which was very hard to understand theoretically), or that the gas was extraordinarily hot, and hence too higly ionised to absorb at the wavelengths of Lyα. Note that these absorption-lines occur in the UV: you can only observe this phenomenon in the early universe, where cosmological redshifts shift the relevant absorption-lines into the near-UV or optical.

This observation posed great problems: what is the energy source that heated up all this gas? Even at redshift 5, the inter-galactic medium is almost completely ionised: this means that a lot of very powerful ionising sources, hitherto undetected, most have existed way back then.

The second big breakthrough occurred about three years ago: Peter Jakobsen used the Hubble Space telescope to look for absorption due to He II in the far-UV (304Å). This would only show up if the inter-galactic medium was indeed very hot: strong absorption was seen, showing that there is a hot medium out there. This absorption has now been seen in four QSOs.

Very recently, HST observations of the He II Gunn-Peterson effect have shown that this hot gas is patchy: every now and then, voids are found in the hot gas: regions which may really be completely empty, or in which the intergalactic gas is either cold, or very very hot, so that He II is not found.

So: exciting days. The mystery of what lies between the galaxies is slowly being cracked, and the answer is turning out to be complex: remarkably hot gas, with a total mass probably exceeding that in all galaxies and denser gas clouds combined, and with these mysterious voids all over the place.

8.2 Proposed Facility

Clearly, the burning need is for more data on this thrilling topic. Mid-UV spectra of faint QSOs are the way to go, and this means a space mission. Some sort of space telescope: a successor to the HST, with good spectrographs that work in the UV is what you want. With such an instrument you could investigate when and how the intergalactic gas became so hot, how it is distributed, and what it is made of. With good coverage far into the UV, you could trace how this gas changes as the universe evolves.

Other useful facilities would include smaller telescopes for finding lots of nice high-redshift QSOs for you to study.

You will have to be careful: unless you can get funding for a big space mission, your budget will probably be cut by Congress. Some of the other people at this meeting will try and argue for other space missions or (horror of horrors) ground-based telescopes. Fight them – your jobs are on the line! You must try and persuade other groups that a UV spectroscopic satellite will be useful for them too: without their support you could be in serious trouble. Bear in mind that this telescope could have other instruments on as well: perhaps optical imaging cameras and spectrographs. This might be the bait that lures the other astronomers into helping you!

9 You are the Institute d'Astrophysique de Paris

9.1 Research Interests

Your main research interests lie in QSO absorption-line systems.

The wretched anglo-saxons seem fixated on seeing things: unless they have an images they can flog to the media, they are just not happy. You, however, are more enlightened about these things (it comes naturally, being French).

The trouble with trying to see galaxies in the early universe is that all you can see will generally be stars. What's wrong with that, the English-speaking fools may ask? Well, most of the universe is made up of dark matter and gas: stars are only a trace impurity, even today. And in the early universe, before most of the stars have formed, stars must be an even less significant component of the universe.

It clearly makes far more sense to study the gas in the early universe. Gas is simple: we understand how it behaves. There is far more mass in gas than stars. By looking at the dynamics, distribution and metallicities of the gas, we can learn about dark matter, nucleosynthesis and galaxy formation in ways that picture fixated astronomers will never do.

So, how do you study gas in the early universe? QSO absorption-lines, of course. You have spent a decade obtaining high resolution spectra of distant QSOs, studying the gas that lies along the sight-lines. This technique has taught the world far more about the early universe than all others combined. Highlights include:

- As stars form, they must use up gas. By watching the decline in the space density of damped Lyα absorption-line systems (clouds of neutral hydrogen with column densities of $> 10^{20}\mathrm{cm}^{-2}$, Mike Fall and collaborators were able to calculate the star formation rate of the universe as a function of time: five years before anyone else came close.

- The tiny, low column density Lyα forest lines are by far the most common denizens of the high redshift universe, and probably contain more baryons than all galaxies and bigger objects combined.

- You yourselves were able to show, by comparing QSO absorption-line data with deep images and spectra of galaxies near the sight-lines, that huge halos of absorbing gas surround all galaxies out to at least redshift one.

- Max Pettini and collaborators used QSO absorption-lines to measure the average metalicity of the universe as a function of redshift, showing that it steadily increases between $z = 5$ and today, giving a measure of the metal (and hence star) formation rate of the universe as a function of redshift.

9.2 Proposed Facility

Clearly, what we need is big telescopes with high resolution spectrographs, to get good data on QSO absorption-lines. With bigger and better telescopes, you could measure the clustering and 3D distribution of gas in the early universe, by looking at lots of faint QSOs in the same parts of the sky. You could measure the abundances of many elements and learn about the relative importance of different nucleosynthesis processes at different redshifts. With the high resolutions made possible by big telescopes, you could look at the internal velocity structure of the absorbing clouds.

So, you propose that the money be spent on lots of giant ground-based telescopes, fitted out with highly efficient high resolution echelle spectrographs. Another 3 or 4 VLTs should do the trick.

You would also be interested in some telescope to find more QSOs: perhaps a smaller telescope with a wide field multi-colour imager. A space telescope capable of obtaining UV spectra would be good, for looking at QSO absorption systems at low redshifts (for example, the Lyα line disappears into the UV below redshift 1.9).

You anticipate that some of your competitors for this money will propose fancy expensive space-missions to go on wild goose chases after bizarre (and probably undetectable) objects. Your mission is to stop them: you suspect that the best way to do this is to point out to others all the wonderful things that they could do with suitably equipped 8m telescopes.

10 You are the Imperial College, London

10.1 Research Interests

Your main research interests concern dust.

From your offices, high in a tower block in South Kensington, London, you have long been leading a crusade for dust. One of your main pleasures in life is going to conferences, and asking the question 'have you considered dust obscuration?' after every talk by an optical astronomer, and watching their embarrassed evasions. The universe is full of dust! Whenever stars form, dust is produced. Just look at the Milky Way any clear night (not that you can see it through all the streetlights and fog from your offices). The dust clouds are obvious. The whole field of star formation studies relies on using radio or infra-red telescopes to peer deep inside giant molecular clouds.

Wherever massive amounts of stars are forming locally, they form in dust clouds. Just look at any starburst galaxy: they are the most luminous objects in the local universe, but they are so dusty that the optical astronomers never even noticed them until the infra-red astronomers pointed them out!

The history of astronomy is a long saga of optical astronomers ignoring dust, and being horribly wrong in consequence. Those fools never seem to learn: they just keep on pretending that visible light gives the true picture, when it is abundantly, overwhelmingly clear that most of the interesting pieces of the universe are hidden by dust.

Now, those optical idiots are at it again. They are busy studying new-born galaxies using optical telescopes: ie. looking at the rest-frame UV emission from galaxies. If there is any dust at all in the early universe, it will completely stuff them up. They are probably missing all the most active star formation regions in the universe: thousands if galaxies are probably forming out there, and the optical astronomers will never know.

You have found a number of clues suggesting that there are some dusty starburst galaxies in the early universe. The most famous example is IRAS10214, an extremely dusty, molecule-rich violently star-forming galaxy, which is a gravitational lens as well.

More recently, the ISO (Infrared Space Observatory) satellite, despite it's ghastly French detectors, discovered a large population of mysterious things in the high redshift universe that emit lots of far-IR emission. The DIRBE (Diffuse Infrared Background Experiment) detector on the COBE satellite has also recently picked up a diffuse background glow of far-IR light, above and beyond the cosmic microwave background. This is probably the integrated light of billions of dusty high-redshift starburst galaxies.

10.2 Proposed Facility

So, it seems clear that the high redshift universe, just like the local universe, is full of dust. This dust will mop up all the optical and UV light produced by star-forming galaxies, and re-radiate it in the far-IR. So, we need a good, sensitive far-IR satellite.

This is what SIRTF (the Space InfraRed Telescope Facility) will be. A cryogenically cooled satellite capable of both imaging and spectroscopy from 3–180 μm, it will have sensitivities two orders of magnitude better than anything that has flown before. It should be able to see normal galaxies, regardless of their dust contents, out to redshifts beyond three, and it will pick up starbursts out to far beyond redshift 5. It will be able to measure the star formation rate of the universe as a function of redshift throughout most of its history.

This awesome instrument, the last of NASA's 'Great Observatory' program, must go ahead. It will do so much exciting science in all sorts of fields. The optical astronomers will doubtless say that it isn't needed: that they have already discovered the answers. Your answer to them must be *DUST!* Get out there and show them the evidence for dust in the early universe!

11 You are the Institute of Astronomy, Cambridge

11.1 Research Interests

Your main research interests lie in the very first stars and galaxies to form.

Ever since those chaps at Caltech started finding large numbers of galaxies at redshifts up to about 6, the astronomical world has been in a frenzy of theoretical and observational activity. People have flooded into the field from all directions. It is really quite tiresome to work in a field so crowded with parvenues. You, therefore, have turned your interest where nobody else has dared look: to really high redshifts. Nobody has yet found anything more distant than redshift $z = 5.2$, but as theorists, that doesn't stop you. In fact, lack of observational evidence is a positive blessing!

Nobody has seen anything above redshift $z = 5.2$, but there must be still more distant objects. By redshift 5, you are already seeing well developed luminous QSOs and radio galaxies, for example. These need massive black holes to power their activity, and it is hard to form $10^8 M_\odot$ black holes without forming stars and galaxies around them in the process. These galaxies must have started forming well before redshift 7. The gas between galaxies is already very highly ionised at redshift five: this requires vast amounts of energy, which must have come from somewhere. Furthermore, QSO absorption lines show that even at redshift 5, large parts of the gas in the universe have metals: something must have produced all this. The distribution of fluxes of gamma-ray bursts suggests that many of them too must have taken place before redshift 5.

So, clearly, lots must have been going on in the dark ages before redshift 5. Why hasn't anybody seen any of this? It may just be too faint, people may have been looking in the wrong way, but most likely, it is just that all the light from things beyond redshift 6 is shifted into the infrared, and infrared detectors are not as sensitive as optical ones yet.

Simple theories suggest that $10^6 M_\odot$ objects should have formed in vast numbers at redshift ~ 1000. If they had, the universe would be full of very old globular clusters and nothing else, which is manifestly not the case. You are suggesting, therefore, that as these things form, the first stars created go supernova and inject so much heat into the gas that it is blown out of the potential wells (which are defined by the dark matter). Slowly the gas cools, falling back down the potential wells until, Poof! it is all blown out again, leaving a few more neutron stars and low mass stars.

Meanwhile, low-level star formation may be taking place throughout the universe: these so-called Population III stars enrich the inter-galactic medium with metals and help ionise it. Eventually, by redshift 10 or thereabouts, recognisable galaxies start to form. Only small ones, mind you, but they will repeatedly merge together until some fairly large ones have formed by redshift 5, ready for the observers.

11.2 Proposed Facility

You have predicted what the very early universe will look like. Unfortunately, some of the details are somewhat obscure, and so some observational data would be handy. Alas, the observers are lagging somewhat, busily engaged in a feeding frenzy at boringly low redshifts such as 3.

Over morning tea, some of your more observationally inclined colleagues suggested a way out of this bind: a new space telescope specifically designed to look for very high redshift galaxies, the real 'first light in the universe'. The telescope will clearly have to work in the infra-red, but some people at NASA have come up with a clever design whereby a space telescope, equipped with a suitable sun-shield, can be passively cooled down to very low temperatures. The telescope will also have to be pretty large to see such faint objects, but it seems to be possible to use light-weight fold-out mirrors to put a six metre infra-red telescope in space. The designers of this telescope call it the Next Generation Space telescope, or NGST.

You are here at this meeting to persuade your colleagues that it would be really jolly interesting to try and look beyond redshift 5, and that the NGST is the way to do this. Observers often suffer from tunnel vision and devote far to much time to adding details to already well studied problems, rather than going after the really interesting new territory. Your job is to gently persuade them of this!

12 You are from Mt. Stromlo Observatory

12.1 Research Interests

Your main research interests concern galactic structure.

The study of high redshift galaxies has become enormously trendy in recent years. Researchers are flooding into the field from all directions, gobbling up vast amounts of telescope time, and now are asking for yet more money to build some huge and expensive facilities to indulge their hobby.

You find this all rather premature. Sure: if we understood galaxies in the local universe well, it might be time to go out and study more distant ones. But, as it happens, we really don't know very much even about our very own galaxy, the Milky Way! How can we possibly hope to understand some little smudge in the corner of a CCD frame, a high redshift galaxy, when we have so little idea about what is going on right here?

Surely, if you want to investigate what happened 10 billion years ago, one sensible way is to look at what that period produced: ie. galaxies like our own. This has been the tried and tested way of studying galaxy formation, and has led to most of the current theories. For example, the division of stars in our galaxy into dynamically and chemically different populations (the thin and thick disks, halo and bulge) is surely telling us something crucial about how our galaxy formed. A good example is the famous G-dwarf problem: even the oldest, lowest metallicity stars in our galaxy are not that metal poor. Somehow, the cloud that formed our galaxy must have already been metal enriched. How did this happen? There must presumably have been some primordial, pre-galactic population of stars that did the enrichment and then disappeared.

By looking at the different stellar populations, we could determine when different bits of gas arrived in our galaxy, and what types of stars they formed. The dynamics of the different populations and their metalicities and abundances tell us how and where they formed. We are never going to be able to learn this much about galaxy formation by looking at some smudge at the edge of the universe.

12.2 Proposed Facility

The crucial problem that limits our knowledge of our own galaxy, and prevents us from working out how and when it formed, is our inability to measure direct distances to distant stars, and to determine their proper motions. If we could get accurate parallaxes and proper motions for every star in the galaxy, we'd have things completely wrapped up, and surely we'd be able to figure out galaxy formation.

All this requires awesome angular resolution. Luckily, this is just what should be achievable using space interferometers. A number are on the drawing board: most of them will be quite capable of measuring a parallax distance and a proper motion for every star in the galaxy with enormous precision. Just think what that would mean for astronomy!

In addition, these missions would find planets around other stars, image the central regions of AGN, and measure the proper motions of other local group galaxies. This is too good an opportunity to miss: you have to persuade all these high-redshift types to forget about staring at infinity for a bit and concentrate on the galaxy on their doorstep: if they cannot figure this one out, surely they are doomed in their attempts to study things at the edge of the observable universe!