AN OUTSIDER'S VIEW OF EXTRAGALACTIC INFRARED ASTRONOMY

M. S. Longair*
Mullard Radio Astronomy Observatory
Cavendish Laboratory, Cambridge

1. INTRODUCTION

No one could be more of an outsider to infrared astronomy than myself. Like all outsiders, one forms preconceived notions about disciplines outside one's own speciality. In my own case, I can summarise these under three headings.

(i) Infrared astronomy is "obscured" by dust. Nobody really knows what dust is made of or what the shapes of the dust grains are.

(ii) Infrared astronomy will solve the problems of star formation.

(iii) Ultimately, many of the most important cosmological problems will be solved in the infrared waveband.

It is always pleasant to find that one's preconceived notions are either totally shattered or confirmed beyond one's expectations and this has happened to me several times during this week. The scope of the subject as it unfolded throughout the week is vast. Zuckerman urged infrared astronomers to claim what is rightly theirs in the fields of star formation and the distance scale in our own Galaxy. I would go further and claim that many of the fundamental questions of extragalactic astronomy and cosmology are part of the birthright of infrared astronomers. It was apparent that no field of astronomy will remain unaffected by the great advances and discoveries of infrared astronomy. Infrared astronomers must expect an influx of outsiders such as myself into their area - it will soon acquire the ultimate accolade of being regarded as a conventional diagnostic tool in the equipment of all astronomers.

---

* Present address: Royal Observatory, Blackford Hill, Edinburgh.

C. G. Wynn-Williams and D. P. Cruikshank (eds.), Infrared Astronomy, 351–360.

What has happened to my preconceived notions as the week has gone on? To be honest, I still don't like dust but I am prepared to come to an accommodation with it. I was particularly impressed by the prospects of understanding more about the chemical and molecular constituents from very high resolution infrared studies and by the idea that simultaneous observation of the solid state and gas phase constituents would lead to real knowledge of the dust and its environment. It is a very ambitious goal but one which is so important that it is worth a major observational and laboratory effort.

So far as star formation is concerned, I found things had somewhat changed direction from questions to which extragalactic astronomers naively expect infrared astronomers to provide answers - what determines the rate of star formation? What is the initial mass function? How does it depend upon density, chemical composition, dust-to-gas ratio and so on? The new view of the Orion Nebula and its various constituents revealed how much we can potentially learn about regions of star formation but raised a whole new range of problems summarised by Zuckerman rather than solving the old. The beautiful observations and analyses of the hot molecular hydrogen in OMC1 adds to the complexity of the region and it was intriguing how the focus of attention shifted from BN to IRc2 to IRc4 as the protostellar objects or extremely young HII regions responsible for the shock waves and expansion of the molecular maser sources. I found myself wondering if we are really certain that we know which objects are protostars.

An outsider can only be deeply impressed by this wealth of new information about regions of star formation and the intriguing problems summarised by Zuckerman. Nonetheless, it is worthwhile remembering that we look to infrared astronomers to give us insight into the fundamental problems which I briefly mentioned above. They are crucial for our understanding of galaxy formation and evolution. I will return to this point repeatedly.

So much for the preliminaries - what about the central questions of importance for extragalactic astronomy?

2. OUR OWN GALAXY AND NORMAL GALAXIES

In all branches of astronomy, an understanding of the properties of our own Galaxy has proved crucial in defining the framework within which we attempt to understand extragalactic systems. On the small scale, I have already referred to the importance of studies of regions of star formation. On the large scale, the new results on the large scale distribution of infrared continuum emission, and its relation to giant HII regions, molecular clouds and radio continuum emission described by Okuda illustrate very clearly how we may hope to relate the infrared morphology of the Galaxy to other tracers of gas, dust, stars and regions of star formation. Drapatz showed the way in which we may eventually hope to relate all these large scale features to the general picture of the evolution of our own Galaxy. However, he also indicated clearly the grave problems of interpretation which have to be solved. It is studies of these types which will generate the prejudices which we will adopt in contrasting our own Galaxy with others.

Gatley gave us a remarkable review of the crucial evidence on the Galactic Centre and told us that there was a black hole there. Rather, I should say, he "guided our intuition," as Zwicky would have said, towards a position in which no other interpretation was reasonable. Why did nobody object? Partly because the wrong sorts of people were present in the audience. More important, I believe, is the fact that black holes are now very much "part of the furniture" of Galactic and extragalactic astronomy. Black holes are very reasonable things to form in astronomical systems and galactic nuclei are particularly natural places for the massive varieties to form. As Gatley emphasised, the centre of our own Galaxy is the closest active galactic nucleus and at infrared wavelengths we can obtain a higher resolution picture than in any other Galaxy. We should recall that the Schwartzschild radius of a 10^7 $M_\odot$ black hole at the Galactic centre subtends an angle of 0.02 milliarcsec which is very small, but not inconceivably small, for study by interferometry at radio and infrared wavelengths.

The studies of the stellar content of nearby normal galaxies by Aaronson, Persson and their colleagues indicate the direction in which studies should proceed. I found the evidence for the intermediate age population rather convincing but it clearly requires us to modify our view of galactic evolution and the birthrate function of stars as a function of age. This necessarily complicates our picture of Galactic evolution which, in any case, is not in a particularly healthy state.

The most ambitious attempt to tie together all the observations of a strong infrared normal galaxy was that of M82 by Rieke. His lecture was a classic example of the wealth of diverse information which can be wholly derived from observations in the infrared waveband, the infrared bolometric luminosity, the integrated light from red giants from the deep CO bands at 2 μm, the extinction from the intensities of the Brackett lines, the ionising flux from the hydrogen recombination lines, and the mass of the central regions from the Ne II rotation curve. Rieke then showed how all of these observations could be reconciled with a simple picture for active recent star formation in M82 involving a mass of $\sim 2 \times 10^8$ $M_\odot$ in new stars. It is certainly encouraging that this can be done but one wonders how unique the procedure is and in particular what the most important constraints on the models are. Specifically, how many free parameters do you need to build an integrated picture of M82? What happens if you add more? One also wonders what will happen when more detailed observations are available at all wavelengths? None of this is criticism of what was done. This type of modelling exercise is essential and will lead to a refinement of the questions we can reasonably hope to answer observationally.

An important goal is to reach a position in which similar types of analyses can be performed for all types of normal galaxy.

3. ACTIVE GALACTIC NUCLEI

We heard a large number of presentations about different classes of galaxies with active galactic nuclei - Seyfert galaxies, X-ray and radio galaxies, quasars and BL Lac objects. We were asked to assimilate a vast amount of data and we should remember what the astrophysical aims of these studies are. To put it crudely, we are trying to distinguish the various contributions to the total spectrum - the stellar component, that due to dust, the continuum and line emission of ionised gas clouds in the nucleus and what I will call the "other components". The contributions of Rieke and Lebofsky and of Scoville and his colleagues were particularly impressive accounts of how high resolution infrared spectroscopy can add to the interpretation of the optical spectrum of the Seyfert galaxies NGC 4151 and 1068 respectively. Other authors showed convincingly how the infrared colours of galaxies with active nuclei fall along a more or less continuous sequence from pure galaxy spectra to pure quasar spectra.

My own view is that the most intriguing aspects of these studies are those which shed some light on the properties of the gas close to the active nucleus and the emission mechanism responsible for the "other components". In turn, I believe these must shed light on the supply of fuel to the galactic nucleus and the structure of its innermost regions.

According to the conventional view, it is the broad line components of the line-emitting regions which originate closest to the nucleus. The infrared observations of the hydrogen recombination lines are crucial in this respect in providing good measures of the extinction in the broad-line regions and, as we heard from Allen and his colleagues, it appears that the Balmer line intensities are considerably enhanced with respect to Lyman α, confirming earlier work on much smaller numbers of objects. The most reasonable interpretation of these data are that collisional excitation of the Balmer lines enhances their line intensities at the expense of Lyman-α and this requires high particle densities, $N \sim 10^8-10^{10}$ cm^{-3}. This means that the gas clouds are of relatively small size and mass which is consistent with the variability seen in some of the broad emission line profiles. These are the most compact regions about the nucleus from which we observe line emission and we would like to know how much infrared spectroscopy can add to this picture. Is there dust associated with these regions with normal gas-to-dust ratio?

A second important aspect of the infrared observations is the extraction of the underlying continuum spectrum. Neugebauer and Soifer made an excellent case for the infrared emission in the case of Seyfert II galaxies being dust emission, including a few cases where the variable component could be associated with dust. I would emphasise the importance of delineating as precisely as possible the spectrum of what is normally called the non-thermal component which I have preferred to call the "other" component. The essential point is that any emission mechanism involving ultrarelativistic electrons such as synchrotron radiation or inverse Compton emission results in a broad-band emission spectrum having $\Delta\nu/\nu \gtrsim 1$. This is because the continuum emission is the Fourier transform of the beaming pattern of the relativistic electron and this is more or less independent of how the particle is accelerated in the emission process. Thus, even if the electrons all had the same energy, it would be very difficult to attribute any sharp feature in the observed spectrum to the emission of ultrarelativistic electrons.

I believe we have seen some spectra which are supposed to represent the "other" component which possess features which are too sharp to be explained by the emission of ultrarelativistic electrons. This is not a problem confined to the infrared waveband. A "blue bump" is observed in the ultraviolet spectrum of 3C273 and the spectra of many quasars show wiggles which look real. It is very important to find out whether these features are real or not. This requires a very careful assessment of all the possible contributions to the integrated spectrum from stars, dust and regions of ionised hydrogen as well as the various absorption processes, by interstellar gas and dust, which convert smooth spectra into jagged spectra.

When this is done, we may indeed find a smooth spectrum in which case the emission process may be attributed to ultrarelativistic particles. I would find this result a bit disappointing because the information we can hope to derive from the emission of relativistic particles is very limited. We have to specify how the particles were accelerated to relate them to specific regions in the nucleus. I believe we are still far from being able to understand this.

I find the alternative that the spectrum ends up not being smooth much more intriguing. For example, it is a real possibility that the continuum emission is the thermal emission of an accretion disc about a central massive black hole. The standard model of an accretion disc results in a spectrum which rises to ultraviolet wavelengths as $\nu^{1/3}$. However, there are ways of distorting this by injecting "fuel" in a non-steady manner to the disc. In general, the types of information which can potentially be derived from such studies are of much more direct relevance to the structure of the accretion disc.

We heard of two cases where the above type of analysis seems particularly relevant. Lebofsky showed us the spectrum of a quasar with a steep spectrum in the near infrared which then showed a cut-off at longer wavelengths. Sherwood showed us the millimetre spectrum of a radio quiet quasar which looked dangerously high as compared with the radio and optical continuum spectra. We need to know in more detail the precise spectra of these objects and the nature of the emission mechanism.

Finally, let me emphasise the importance of studying variations in the "other" component over a wide frequency range, extending from the ultraviolet to the far infrared. It is customary to assume that the "other" component varies up and down contemporaneously at all wavelengths in this waveband. If there are "sharp" features in the spectrum these may or may not vary in the same way as the underlying continuum. Rieke's analysis of the spectrum of NGC4151 is precisely the type of analysis needed to throw some light on this question. It might, for example, be that all the variability could be attributed to the "bump" component which would be a very important result.

4. CLASSICAL COSMOLOGY

By classical cosmology, I mean attempts to find the Hubble constant H_o and the deceleration parameter q_o (or the density parameter Ω) from observations of galaxies. The Tully-Fisher method of estimating the distances to spiral galaxies must be Hawaii's greatest contribution to cosmology. Aaronson showed how close the correlation is between the 21-cm velocity width of the neutral hydrogen distribution and the infrared luminosity of spiral galaxies. It is remarkable how close his result agrees with the classical methods of Sandage and Tammann within the Local Supercluster and how his inferred velocity of infall towards the supercluster is in general agreement with that determined from the dipole anisotropy of the microwave background radiation. The major problem which I see with the values of about 95 km s^{-1} Mpc^{-1} is that it results in a rather short cosmological time-scale, $T \leq H_o^{-1} = 1.1 \times 10^{10}$ years, compared with the ages of the oldest globular clusters. I am no expert in the latter field and it requires a very detailed investigation to find out how much room for manoeuvre there is in the globular cluster ages. Equally, how much flexibility is there on Aaronson's value of H_o?

The other urgent requirement is an independent analysis of the Aaronson, Huchra and Mould version of the Tully-Fisher method. Nonetheless, it seems that this infrared-radio technique may provide us with the most accurate estimate of the extragalactic distance scale.

The other aspect of the redshift-distance relation is its extension to large redshifts where differences in the global geometry and dynamics become important, i.e. the redshift-magnitude relation depends upon the world model. Grasdalen's infrared redshift-magnitude relation showed how powerful this technique is in general terms. To put it crudely, the K-correction which dims galaxies in the optical waveband makes them brighter in the 2-3 μm waveband as they move to larger redshifts because of the maximum in the spectrum of a giant elliptical galaxy at about 1 μm. No one is guessing values of q_o yet but the fact that a respectable redshift-magnitude relation can be constructed is encouraging. Lebofsky and Spinrad showed that there is little evidence of colour evolution in the giant ellipticals and this is encouraging if you are interested in using this as a possible route to the geometry of the Universe.

I would make three comments about this work. First of all, there is the question of how you find such distant giant elliptical galaxies. Most of them have been found as a result of searches for radio source identifications. It is legitimate to worry whether or not a giant elliptical galaxy which is a strong radio source really is a typical giant elliptical and whether or not the total light is entirely starlight. My impression from studying the optical spectra of radio galaxies is that their optical spectra can be properly decomposed into a nuclear component consisting of continuum emission and emission line spectrum and a standard giant elliptical galaxy spectrum. Indeed a significant fraction of the most powerful radio galaxies do not contain the nuclear component at all. So, I am quite optimistic about the use of radio galaxies although we need the direct observational evidence that they are not significantly different from normal giant ellipticals.

Second, if you need any convincing that the study of distant galaxies is the birthright of infrared astronomers, you need only look at the identification content of the faintest radio source identifications which we are now making. Jim Gunn and I have been trying to complete the identifications of 3CR radio sources for the last 8 years. At the beginning of this year, we effectively completed this project thanks to the development of the TI/JPL CCD camera. All the new identifications, which could not be made with conventional photography using IIIaJ plates, are with very distant galaxies. All of these are much brighter in i than they are in r. We know that this continues to hold into the infrared waveband for some of the galaxies studied by Grasdalen and by Rieke and Lebofsky which have been easily detected at 2 μm. Indeed, Grasdalen detected 3C65 at 2 μm before we could identify it optically - it is barely detectable in r with the CCD camera. Another example is 3C184 which is about 1.2 magnitudes brighter in i than in r and for which we have measured a redshift of 1 on the basis of a strong emission line spectrum. Thus, as we have always known, as soon as galaxies are observed at large redshifts, they become infrared objects rather than optical objects, the whole of the energy distribution shifting into the 1-5 μm region.

The third point concerns evidence for evolution over cosmological time-scales. We can list a number of separate pieces of evidence all of which suggest that things do change over relatively short time-scales and that there are significant changes between redshifts of 0 and 1. First, the V/V_{max} test for quasars and radio galaxies and the counts of radio sources show that there was very much more high energy astrophysical activity at redshifts $z \sim 2-3$ than there is now. Even over the redshift interval $0 < z < 1$, this activity has increased by a large factor. In exponential models of the evolution, the typical time-scale for decay of these populations is only 10^9 years. Second, significant changes in the colour distribution of the galaxies in distant clusters as compared to similar clusters at the present epoch have been observed by Butcher and Oemler. Third, the counts of faint galaxies have been interpreted as showing an excess of faint galaxies compared with the predictions of uniform models. Fourth, the Westerbork workers have found that the colours of faint radio galaxies at $z \sim 0.5$ may be bluer than those of nearby radio galaxies. Finally, Gunn and Oke find a larger fraction of blue spectra among the brightest cluster members for galaxies with $z > 0.6$ than those with $z < 0.6$.

Obviously some of these pieces of evidence are much stronger than others but the warning is plain. The first thing to be done is to look empirically at the properties of distant galaxies in the infrared and see whether or not they are the same as those of nearby objects. This is a field where theory is not of much help. The models of galactic evolution can explain the above phenomena but they are a posteriori rationalisations rather than firm theoretical predictions.

5. PHYSICAL COSMOLOGY

Ever since the predictions of Peebles and Partridge, it has been clear that if galaxies liberated a large amount of energy when they were first formed, these objects should be infrared sources and contribute to the infrared background emission. These ideas have been revived by various authors from time to time but have floundered for the lack of any firm observational evidence for their existence. I suspect that the main cause for their lack of detection is that they are genuinely infrared objects. As we have seen above, as soon as giant elliptical galaxies are redshifted to $z = 1$, they become invisible in the r waveband. Now, it would be rash to claim that we know what the spectrum of a young galaxy would look like and indeed we can invent a wide range of models for galaxies which would be consistent with all current observations and yet have a vastly different appearance when they were much younger. I believe that this is a field in which we can only find out the answers by direct observation in the infrared waveband.

We could imagine that the programme would proceed in two stages. First of all, the thorough study of current objects as they were when a bit younger than at present i.e. at $z \sim 1$. Then one should proceed to the study of much younger objects having $1 < z \lesssim 10$. This programme will only become feasible once infrared panoramic detectors having reasonably large fields of view become available. However, let us note the importance of these observations for our understanding of how the large scale structure of the Universe came about.

There are two rather extreme views about how galaxies first formed in the Universe. In the strict adiabatic theory propounded by the Moscow group led by Zeldovich, all fine scale structure in the primordial matter at the epoch of recombination is washed out by various damping processes and the first structures to begin forming are large scale regions, on the scale of superclusters. Galaxies form by condensation from this collapsing cloud. The characteristic scales associated with clusters and superclusters can only begin to collapse at redshifts $z \sim 5$ and consequently all galaxies must form at redshifts of 5 or less. An alternative view proposed by Press and Schechter and developed by Rees and White begins with globular cluster size units immediately after the epoch of recombination. Larger systems are built up as a result of hierarchical clustering so that galaxies form very much earlier $z \sim 20$-30.

In this simple example, a direct test of these hypotheses is the search for the young galaxies at redshifts $z \lesssim 5$. One theory predicts that that is when all galaxies must form whereas in the other it takes place at much larger redshifts. Young galaxies at $z \lesssim 5$ should be detectable with the next generation of panoramic infrared detectors if indeed such objects exist.

If we can discover young galaxies at $z \gtrsim 1$, we can imagine all sorts of exciting prospects. Can we compare their clustering with the clustering of galaxies at the present day? Can we detect the remnants of the primordial gas clouds out of which they condensed? How are these phenomena related to the evolution of powerful radio galaxies and quasars? Our ultimate aim is to define direct from observation the sequence of events which led to the present large-scale structure of the Universe. I believe that in many ways these prospects are unique to the infrared waveband.

6. FUTURE PROSPECTS

It is clear that we are on the verge of a huge expansion in infrared astronomy. There are few branches of astronomy which have not been discussed at this conference and infrared astronomy is already making a major impact on all of them. The new facilities here in Hawaii and elsewhere and the new types of detectors and spectrographs under discussion will enable us to capitalise on the breakthroughs summarised at this conference.

A second conclusion is that this must surely be the last conference entitled "Infrared Astronomy". We have all received a marvellous panoramic view of the discipline but we should no longer regard it as an isolated subject. The issues discussed here have spanned essentially the whole of the electromagnetic spectrum. In future, I expect conferences involving infrared astronomers to be much more "mission-oriented" in which infrared astronomy can be seen as one among many different ways of tackling problems such as dust, star-formation, the evolution of galaxies and so on. If this turns out to be the last infrared conference, and I regard that as a token of the maturity of the subject (when was the last "optical astronomy" conference?), it will certainly have gone out with a bang.

Finally, we must look to the future and ask what are the most urgent needs for furthering all these areas of infrared astronomy. On Tuesday evening, space infrared astronomy was discussed and on Monday we talked about astronomy from aircraft. I think we should also ask what the next generation of ground based telescopes ought to be. We hear a great deal about the Next Generation Telescope as large versions of optical telescopes. But might it not be that the next generation ground based telescope should be a very large infrared telescope dedicated to, say, the 1-5 μm window rather than 0.3 to 1 μm. If the choice were to be based entirely upon the importance of the science, it is not clear that the most important questions will be answered in the optical waveband.

I may have started this symposium as an outsider. I have now advanced to the status of "convert". It has been a marvellously stimulating symposium.

DISCUSSION FOLLOWING PAPER DELIVERED BY M. S. LONGAIR

TOVMASSIAN: I would like to make a comment on black holes. You said that black holes exist in astronomy. I would correct this expression. Yes, they exist, but exist in the minds of astronomers, mainly theoreticians. Black holes imply a sense of contraction of a huge mass to a point and the following accretion of the surrounding matter. We have to admit anyhow that everywhere in the universe we see explosions, outflow of matter, but never implosions, infall.

LONGAIR: There are two separate answers to this comment. First of all there are, of course, very good reasons why we expect the presence of a black hole in a galactic nucleus to result in energy generation, outflow of matter and the acceleration of charged particles. The second part of the comment verges on the philosophy of science which means that we are treading on very dangerous territory. The point about black holes is that they provide a very efficient source of energy which is based upon sound physical principles. I believe it is by far the most economical and natural hypothesis for the energy source in active nuclei. I believe this view is shared by a very large number of astronomers. When such a view is held by the majority of astronomers and used as part of the framework for proceeding to solve further problems, I think it is fair to say that black holes have become part of the conventional apparatus of astronomers.