RADIO ASTRONOMERS, X-RAY ASTRONOMERS AND THE SPACE TELESCOPE

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My original brief was to cover all non-optical observations of all objects in the Universe but I have limited the scope of this presentation to the radio and optical wavebands and within them mostly to the study of extragalactic objects. The paper is in two parts. Sections 1, 2 and 3 contain some general remarks about the use of the Space Telescope and the study of objects in the radio and X-ray wavebands. The remaining sections outline the scientific objectives of a number of projects which involve observations with the Space Telescope.

1. INTRODUCTION

Every time a new waveband has been opened up, the astronomers working in this band do as much as they can using information specific to that waveband. The principal examples of this phenomenon are the early histories of radio and X-ray astronomy. For example, the large scale distribution of sources on the celestial sphere may indicate whether the objects are Galactic or extragalactic, source counts provide information about their distribution in depth and so on. In some cases, the information obtained may be sufficient to study the detailed astrophysics of the objects. Radio pulsars are an example in which the astrophysics is studied almost exclusively through their radio properties. Similarly, much can be learned from the observation of X-ray emission and absorption lines from all types of X-ray source.

It is generally true, however, that following this initial phase, the non-optical astronomer is heavily dependent upon optical observations for much of the information which is crucial in studying the new astrophysical problems which arise from his observations. The obvious questions are: What sorts of objects are the sources associated with, how are their optical counterparts different from other similar objects, how common are these objects in the Universe, what are their distances and so on. Generally speaking these are questions which can only be answered by making observations in the optical waveband.

This is not a one way process in which the non-optical astronomer requires his optical colleague to perform a service function. The optical astronomer reaps the benefit of making important discoveries. Probably the most striking example of this was the discovery of quasars which arose directly out of optical identification programmes of extragalactic radio sources. Significant contributions to the detailed understanding of high energy astrophysical objects have been made in many fields. For example, observations of the primary stars in X-ray binary systems, the discovery of the optical counterpart of the pulsar in the Crab Nebula and the discovery of significant differences in the spectroscopic properties of radio galaxies and other active systems.

It is therefore evident that there will be considerable demand for Space Telescope observing time from non-optical astronomers. It should be noted that many of these programmes will be at the forefront of important areas of research and thus they are likely to be rated highly when the final allocation of time is made. It should also be noted that, in many cases, the driving force for making observations will come from the radio and X-ray astronomers so that the pool of potential Space Telescope observers will be significantly increased.

My task is to predict what these demands are likely to be. Plainly, this is a task even more impossible than those of other speakers at this colloquium. A field in which my information is based on rumour and hearsay is the new data from the Einstein X-ray observatory (HEAO-2). I hope that the HEAO 2 observers present will be able to describe what they foresee as the new demands stimulated by their magnificent X-ray observatory. In exculpation of this lacuna in my knowledge, I believe that many of the optical demands will be similar to those of radio astronomers with which I am much more familiar.

2. PRELIMINARY REMARKS

As everyone is aware, there will be considerable pressure to carry out programmes which make the fullest use of the unique capabilities of the Space Telescope. To oversimplify grossly, these unique features are:

(a) the observation of all objects at the diffraction limit of a 2.4 metre telescope, i.e., with angular resolution $\lesssim$ 0.1 arcsec;

(b) photography and spectroscopy of all objects in the ultraviolet waveband, $110 < \lambda < 320$ nm, with very high sensitivity.

In devising observing programmes, the following points should be borne in mind.

(i) Despite these unique capabilities, there are many types of astronomy which are not appropriate for the Space Telescope and are better executed from the ground. For example, there is relatively little advantage in studying extended objects such as diffuse galaxies or the optical emission from the lobes of radio galaxies if there is little fine structure on angular scales $\theta \lesssim 1$ arcsec. Intermediate and high resolution spectroscopy in the optical waveband demands shear photon collecting power and thus a large ground-based telescope is to be preferred. Another example is the problem of measuring the spectra of normal galaxies at large redshifts to which I will return later. The specification of the Faint Object Spectrograph is such that it has relatively low sensitivity at wavelengths $\lambda \gtrsim 600$ nm. Another important restriction is that programmes requiring fields of view much larger than 3 arcmin make rather inefficient use of the Space Telescope since a mosaic of many Wide Field Camera frames would be required. There is thus much essential complementary optical work to be done from the ground.

(ii) The quality of Space Telescope observations will be consistently very high. All the data will come back in digital form, will be rapidly calibrated and presented to the observer in a form ready for scientific analysis. There are two related problems. First, do data of corresponding quality exist for complementary ground based observations? I know of many fields where this may well not be the case particularly in the field of photography. Second, it will be important to have access to detectors of similar quality to those to be flown on the Space Telescope for ground-based observations. In the case of spectroscopy, there already exists a wealth of ground-based experience with Digicon detectors and Image Photon Counting Systems. However, the CCD detectors and the two dimensional imaging mode of the IPCS are only now becoming available and then only at a few observatories. I will show later some examples of what can be done with these detectors in the field of the optical identification of radio sources. Many programmes which appear to be possible only from space are in fact possible from the ground. Scarce Space Telescope observing time can be very significantly saved if these high sensitivity detectors become generally available soon. In the case of X-ray astronomy, the pressures are even greater because the Einstein observatory is generating vast amounts of high quality material which will require large amounts of ground based observing time. There is not much time left before the first round of requests for observing proposals with Space Telescope will be issued.

(iii) The capability of taking deep photographs in the far ultraviolet will surely lead to discoveries and new understanding of all types of object in the Universe. Observing programmes must be flexible enough to capitalise on these discoveries. For example, the far ultraviolet morphology of galaxies in clusters will provide clues to their dynamical state and the role of intracluster gas in determining the morphological types of the galaxies.

A final preliminary remark concerns what I call the astronomical mode of use of the Space Telescope. There are three modes which I term the Astrophysical mode, the "Look and see" mode and the Serendipity mode. The astrophysical objectives of the observations are monotonically less well defined along this sequence. The first mode has well defined astrophysical objectives, for example the determination of the physical conditions in and around an active nucleus. The "look and see" mode refers mainly to the use of the cameras with the highest possible angular resolution. The experience of radio astronomy indicates how dramatic an improvement of a factor of 10 in angular resolution is. The sort of result which may be found in the optical waveband is exemplified by observations using the 6-metre telescope of the Special Astrophysical Observatory which have shown that the nuclei of a number of active Markarian galaxies are multiple. Such a result can only be found from observations of an exploratory character. The serendipity mode is well-known - these observations will be of more or less random regions of sky which happen to fall within the fields of view of the cameras when another instrument is prime.

It is very important that the proper balance be maintained between the astrophysical and the look and see modes. The former provides the bread-and-butter of the observatory whilst the latter is likely to produce the most unexpected results.

3. THE SKY AT RADIO AND X-RAY WAVELENGTHS

There are significant methodological differences in the ways in which radio and X-ray astronomers select their targets for study as compared with optical astronomers. At optical wavelengths it has always been easy to observe the sky with high angular resolution and high sensitivity and millions of objects can be seen with small telescopes. In contrast, at radio and X-ray wavelengths, it is not easy to detect sources and telescopes have developed from relatively low resolution survey instruments with relatively poor sensitivity to the present generation of instruments which now have angular resolving powers similar to those of large optical telescopes and high sensitivity. In the former category one may include the 3CR and Parkes surveys of radio sources and the UHURU and Ariel V X-ray surveys. The present generation of telescopes in the latter category include instruments such as the Westerbork Synthesis Radio Telescope, the Cambridge 5-km telescope and the VLA at radio wavelengths and the Einstein observatory at X-ray wavelengths.

The total number of objects observed in these wavebands is very much smaller than those in the optical waveband and this means that it is much more feasible to undertake systematic studies of significant fractions of all known objects. It is also much easier to be confident about completeness limits because initially sources are discovered in surveys with low angular resolution and thus integrated flux densities are relatively easy to measure. For example, in the radio waveband at high flux densities at low frequencies, $S_{408} \geq 10$ Jy, there are only ~ 35 sources sr^{-1} in directions away from the Galactic plane. At a high frequency, say 5 GHz, the corresponding figure at 1 Jy is ~ 50 sources sr^{-1}. For the X-ray sky, the corresponding figures are ~ 15 sources sr^{-1} at a limiting flux density of 1 UHURU unit. When surveys of very much higher sensitivity are performed, much larger surface densities are naturally found but even so it is only feasible to survey relatively small areas of sky. For example a typical 5C radio survey has limiting flux density 0.01 Jy at 408 MHz and the surface density of sources is $\sim 10^5$ sr^{-1}. However, the typical survey area contains only about 250 sources. In the same way, a deep survey with the Einstein X-ray observatory has limiting flux density about 0.01 UHURU units but only a small area of sky is surveyed and typically about 20-30 sources are observed.

Much of the complementary optical work is thus concerned with relatively small samples of objects which are selected in an unbiassed manner and consequently suitable for statistical analyses. This situation contrasts with the case of, say, galaxy counts which are plagued by all sorts of nasty selection effects which vary from one class of galaxy to another. The statistical properties of the optical objects found by radio and X-ray astronomers are correspondingly much easier to handle.

The significance of these remarks is best understood in the context of studies of the radio source population. I will consider this case first and show how the Space Telescope can play an important role in elucidating some of the central problems of extragalactic astronomy and cosmology.

4. EXTRAGALACTIC RADIO SOURCES

There are two separate aspects to the study of extragalactic radio sources, the astrophysics of individual objects and their distribution in space. The evidence on their spatial distribution will be presented first in order to define the cosmological problems which arise. How feasible it will be to pursue these studies using the Space Telescope is determined by consideration of the astrophysical properties of individual objects which will be given in the following sub-section along with other programmes of astrophysical importance.

4.1 The spatial distribution of extragalactic radio sources

The counts of extragalactic radio sources disagree with the predictions of all cosmological models in which it is assumed that the distribution of sources is uniform (Figure 1a and b). All uniform models predict a monotonically decreasing value of $\Delta N/\Delta N_o$ with decreasing flux density whereas at high flux densities $\Delta N/\Delta N_o$ increases with decreasing flux density. Even a value $\Delta N/\Delta N_o$ = constant which is the case at the highest frequencies (ν = 5 GHz) is inconsistent with a uniform world model. A similar result has been inferred for quasars by application of the V/V_{max} test to samples selected according to strict criteria. In both cases it is inferred that there has been strong evolution of the average properties of sources with cosmological epoch in the sense that their comoving space densities were much greater in the past, i.e., radio sources and quasars were relatively much

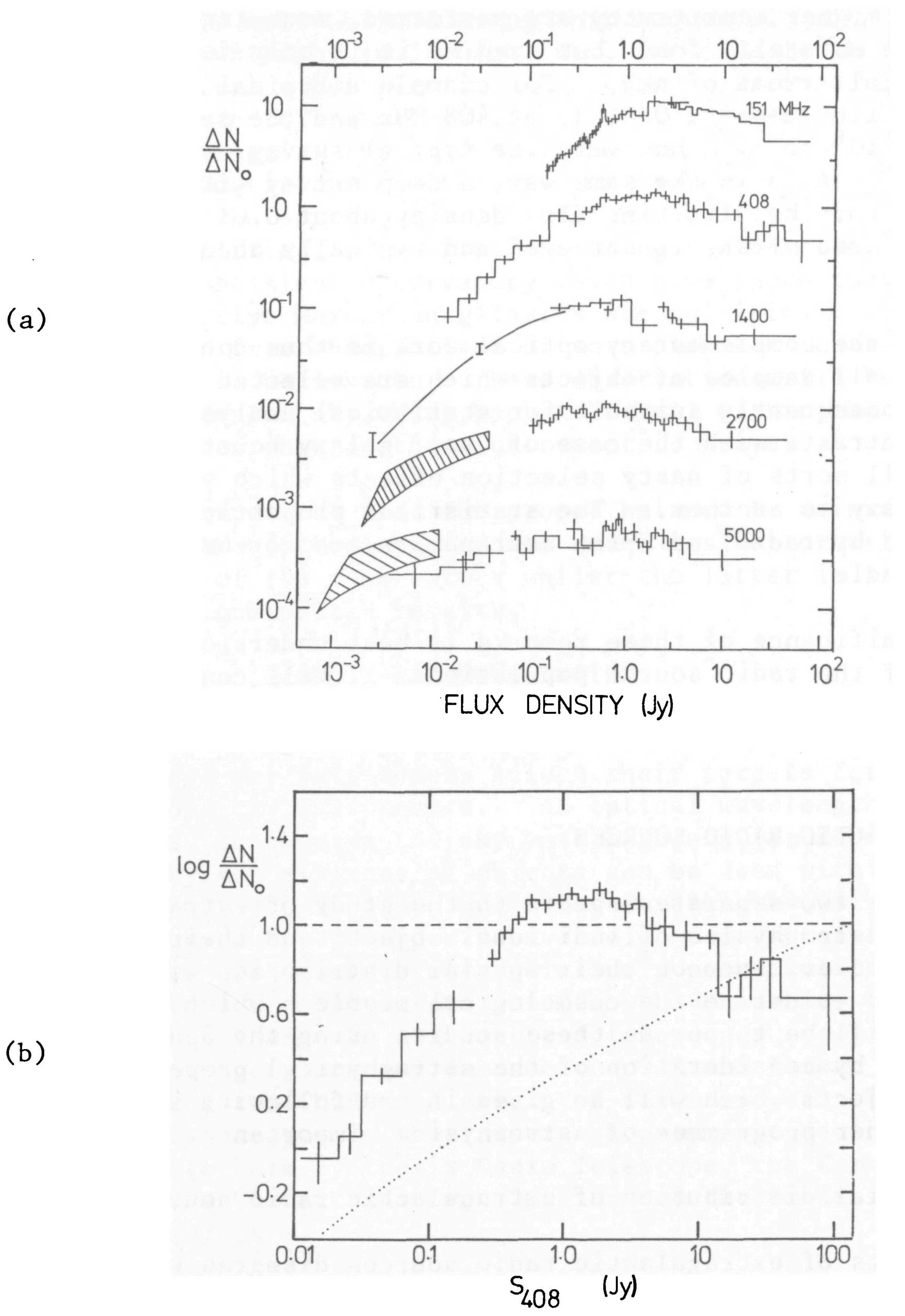

Figure 1 (a) Counts of radio sources at five frequencies in differential form. ΔN is the number of sources in the flux density interval S to $S+\Delta S$ and ΔN_o is the expected number in a Universe in which $N(\geq S) \propto S^{-1.5}$ (Wall 1979).

(b) The differential source counts at 408 MHz compared with the law $N(> S) \propto S^{-1.5}$ (dashed line) and the expected relation for a Friedmann world model having $\Omega = 1$ assuming the sources are uniformly distributed (dotted line). (Wall 1979).

more common phenomena at earlier epochs.

The problems of understanding these results may be understood by considering the optical identification content and redshift distribution for a sample of 3CR radio galaxies which has been studied particularly intensively over the last 8 years. This sample is selected at high flux densities, $S_{178} \geq 10$ Jy, and includes the range of flux densities over which the anomalies in the source counts are observed. This work was only completed last week using results which will be described below and the sample is now effectively 100% completely identified (Figure 2a).

The identification situation is therefore very encouraging but redshifts are generally only available for objects with apparent magnitudes less than about 19.5. The redshifts are essential in a complete analysis because they determine how space is filled up with these objects. In this sample, the redshifts range from zero to about 2, all those with redshifts greater than 0.8 being quasars (Figure 2b). It is the combination of these data from the highest flux density samples plus the detailed knowledge of the source counts which lead to models of how the radio source population has evolved with cosmological epoch. The types of model which can account for all the data at low radio frequencies, 408 MHz, are shown in Figures 3a and b as contour plots of enhancement factors in a plane showing radio luminosity against redshift. Notice that the evolution is restricted to the highest radio luminosities i.e. to the classical double radio sources and quasars and that the enhancement factors are greater than 1000 in some regions of the diagram. This is exactly the sort of evolution which quasars alone are known to exhibit. The interpretation of this result is that at epochs in the relatively recent past, there was very much more high energy astrophysical activity than there is at the present epoch. All the models require the evolution to flatten off at redshifts $z \sim 2$ to 3 and some of them have cut-offs at redshifts $z \sim 3 - 4$. These results have important astrophysical consequences and it is important to make the models much more precise by incorporating information on larger samples of sources at lower flux densities.

The problem of extending these optical identification programmes to lower flux densities can be understood from Figure 2. Even at the highest flux densities, many of the objects are very faint optically and thus in deeper samples of radio sources extending to values about 1000 times fainter than the above sample, the optical counterparts of these radio sources will be very faint indeed. This has been found to be the case in the detailed studies of deep radio surveys. The deepest optical identification surveys at 408 and 1400 MHz have been able to achieve a success rate of at best 40% (de Ruiter et al. 1977, Perryman 1979). So far only optical identifications and colours have been available for these sources because they are mostly very faint.

The picture is somewhat different at high radio frequencies, 2.7 and 5 GHz, where a much larger fraction of sources with flat radio

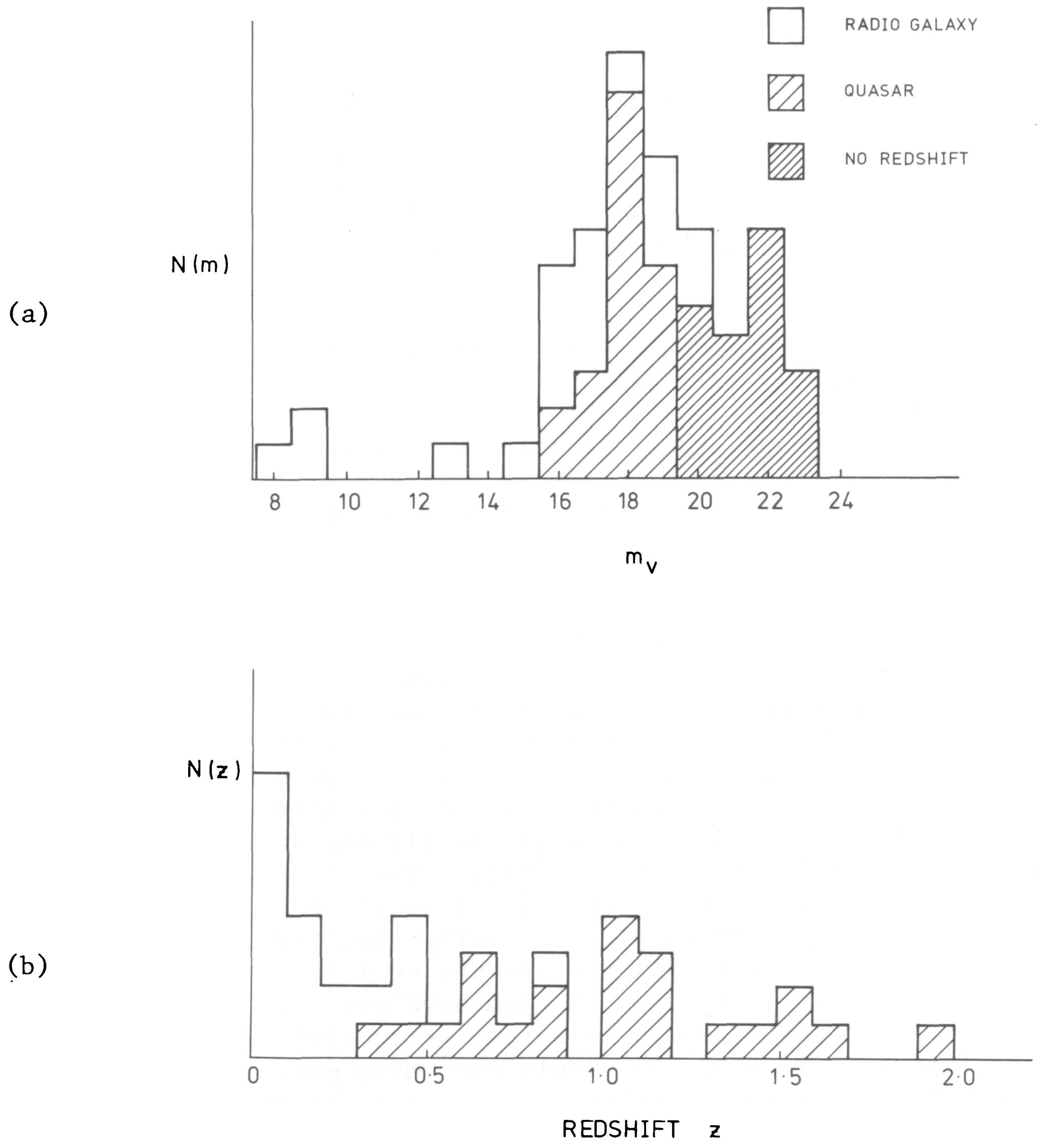

Figure 2 (a) The apparent magnitude distribution for a complete sample of 60 3CR radio sources all of which now have optical identifications (Gunn et al. 1980)

(b) The redshift distribution for the sample of 60 3CR radio sources. Redshifts are only available for 41 of these, the apparent magnitudes of those without redshifts being indicated in Figure 2(a).

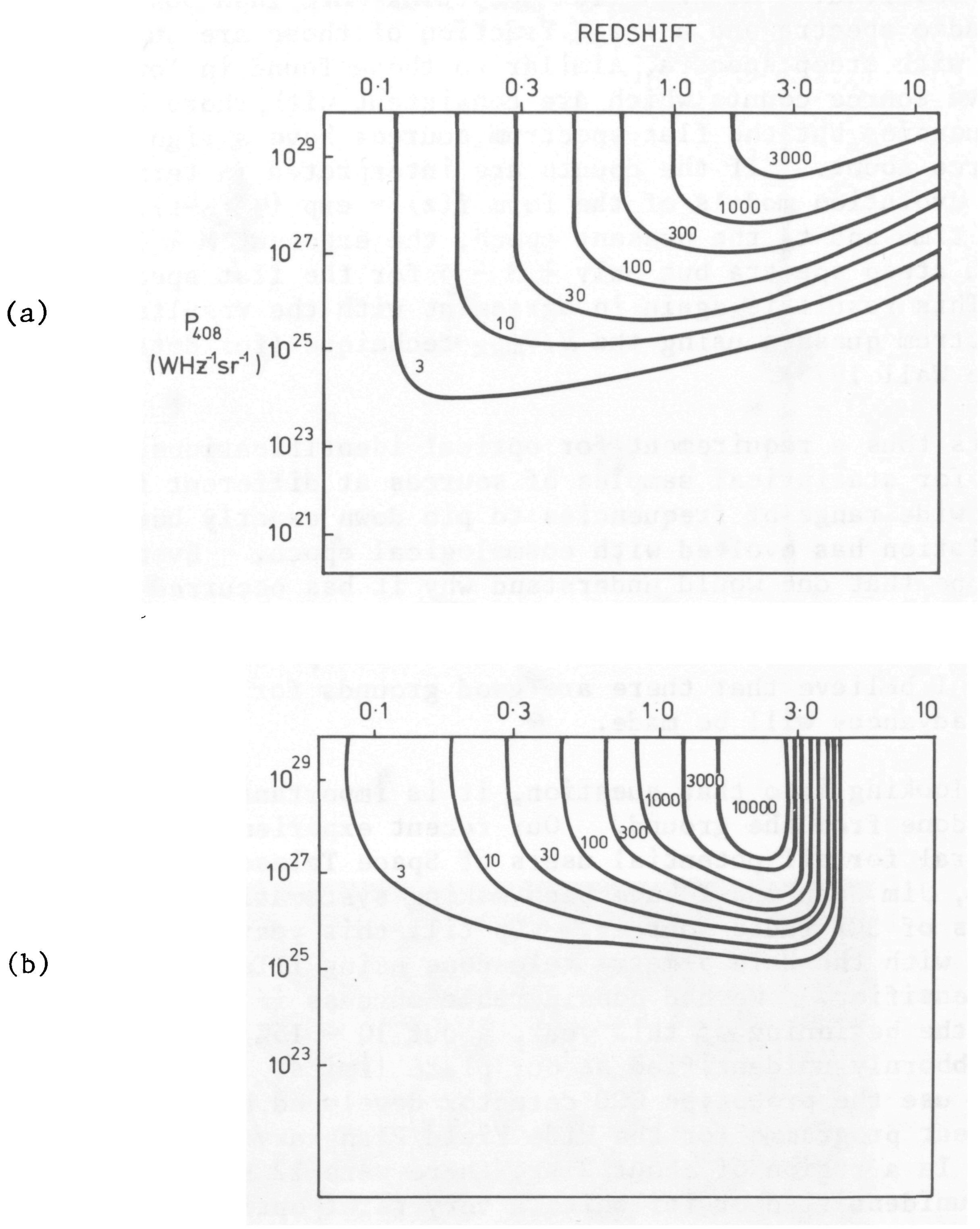

Figure 3 Two models for the evolution of the radio source population as a function of cosmic epoch (or redshift z) and radio luminosity. These models which are designed to account for the source counts at 408 MHz are models 5 and 4b (Figures 3a and 3b respectively) of Wall et al. (1977). The lines are contours of equal "enhancement factors" f(P,z). For radio quasars at low frequencies $f(P,z) = \exp(M(t_0-t)/t_0)$ where $M \approx 10-12$ and t is cosmic epoch.

spectra are observed. At high flux densities more than 50% of sources have flat radio spectra and a large fraction of these are quasars. The sources with steep spectra, similar to those found in low frequency surveys, have source counts which are consistent with those of sources at low frequencies but the flat spectrum sources have a significantly flatter source count. If the counts are interpreted in terms of exponential evolution models of the form $f(z) = \exp\{M(t_0-t)/t_0\}$ where t is cosmic time and t_0 the present epoch, the exponent $M \approx 10 - 12$ for sources with steep spectra but only $\approx 3 - 4$ for the flat spectrum sources. This result is again in agreement with the results of surveys of flat spectrum quasars using the V/V_{max} technique (for detailed discussion, see Wall 1979).

There is thus a requirement for optical identifications, colours and spectra for statistical samples of sources at different flux densities at a wide range of frequencies to pin down exactly how the radio source population has evolved with cosmological epoch. Eventually, one might hope that one would understand why it has occurred as well, directly from the observational data. The question to be addressed is to what extent observations with the Space Telescope will help this programme. I believe that there are good grounds for believing that substantial advances will be made.

Before looking into that question, it is important to assess how much can be done from the ground. Our recent experience provides an important moral for all potential users of Space Telescope. For the last 7 years, Jim Gunn and I have been making systematic observations of the fields of 3CR radio sources. Up till this year, we have made observations with the Hale 5-metre telescope using IIIaJ plates with an image intensifier. We had considerable success in this programme but up till the beginning of this year, about 10 - 15% of 3CR sources remained stubbornly unidentified at our plate limits. This year, we were able to use the prototype CCD detector developed by JPL as part of the development programme for the Wide Field/Planetary Camera of Space Telescope. In a region of about 2 sr, there were 12 sources which were either unidentified or for which a very faint optical object required confirmation. With the CCD camera, we have obtained 100% success. Of these 6 are new identifications and 6 are confirmations. Figure 4 shows an example of the quality of the CCD images as compared with the 48-inch Palomar Sky Survey.

The moral is that if you can gain access to these advanced detectors, you may well be able to do from the ground programmes which initially look accessible only with the Space Telescope. Obviously, it is in the interests of all prospective Space Telescope users to have access to these devices. This will undoubtedly save a large amount of Space Telescope observing time.

4.2 The optical properties of extragalactic radio sources

The characteristic properties of the optical objects associated

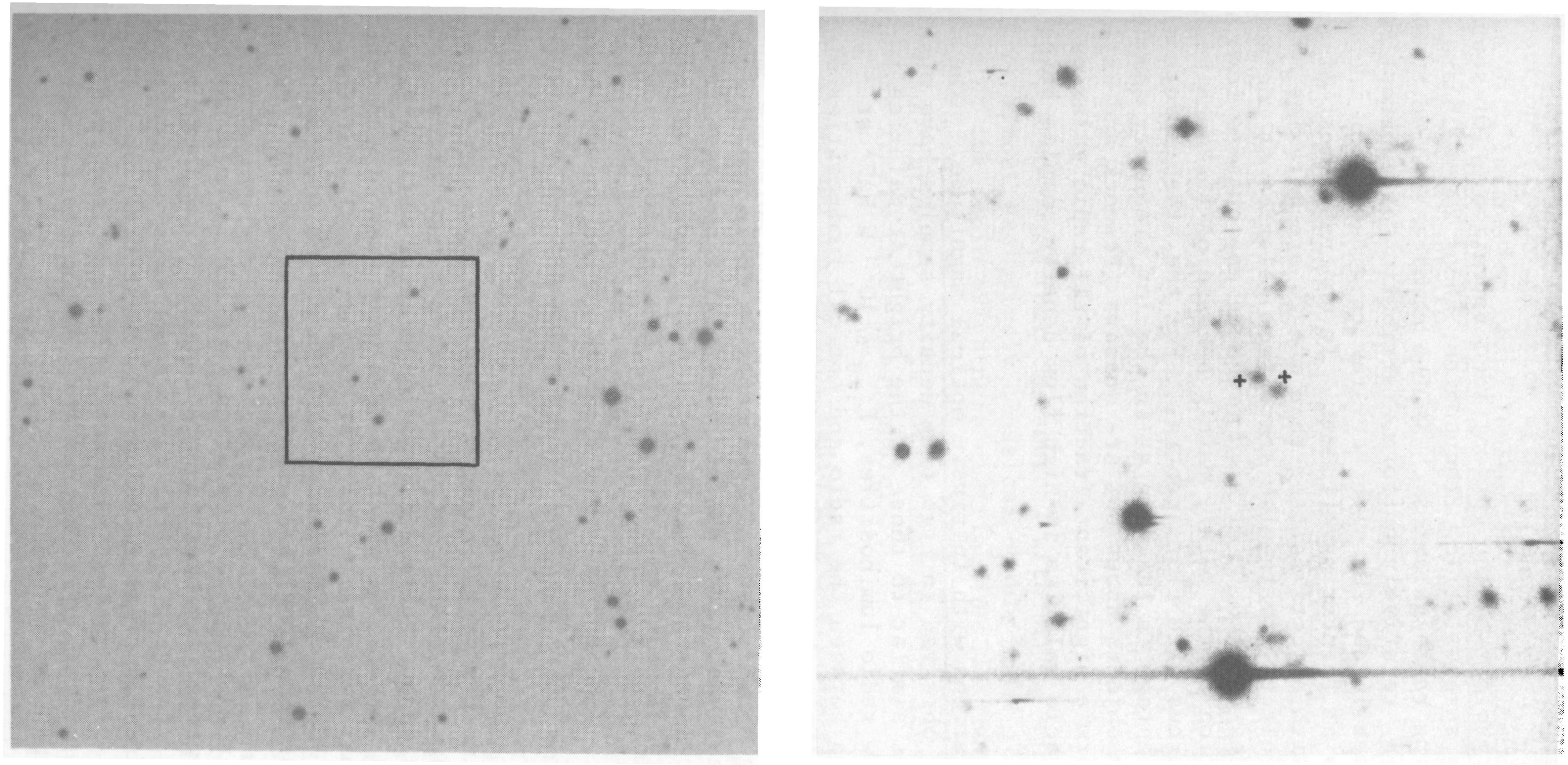

Figure 4. Comparison of the optical field of 3C 280 on the red print of the Palomar National Geographic Society Sky Survey and the CCD image of the area within the black square. The crosses on the latter picture indicate the maxima of the radio brightness distribution (Gunn et al. 1980).

with extragalactic radio sources may be summarised under the following headings.

(i) The morphology of the optical identification. Of sources in high flux density samples at low frequencies, about 20 - 25% are quasars, the remainder being radio galaxies. In the samples studied to date, the quasars have a relatively uniform distribution of apparent magnitudes between about 16 and 20, with very few candidates for identification with quasars at fainter magnitudes. In contrast, most of the identifications with objects fainter than m = 20 are galaxies, although it becomes difficult to distinguish stars from galaxies at the very faintest magnitudes studied. At high frequencies, quasars form a very much larger fraction of the total, mainly because of the much higher proportion of sources with flat spectra. For the steep spectrum quasars, the percentage is the same as in the low frequency samples but for flat spectrum objects about 60% are quasars (Peacock and Wall 1980). The N-galaxies form a significant fraction of all radio galaxies, about 10 - 20% of the radio galaxies in high flux density samples being of this type.

(ii) Correlations with intrinsic optical magnitude. The majority of radio galaxies observed in high flux density samples have absolute optical magnitudes similar to those of the brightest galaxies in clusters. At low radio luminosities, $P_{178} \lesssim 10^{24}$ W Hz^{-1} sr^{-1} there is a weak correlation between the radio and optical luminosities of radio galaxies so that the weakest radio emitters are of lower absolute optical magnitude, e.g., Auriemma et al.(1977). Those radio galaxies which have strong compact central components in their nuclei in addition to the extended radio structure generally possess significant non-thermal optical emission from the nucleus. Indeed the total optical luminosity of radio galaxies can be synthesised by adding to the standard luminosity of a giant elliptical galaxy a non-thermal optical component. As the relative strength of the non-thermal optical component increases, N-galaxies and quasars may be accommodated within the model.

Many of the most powerful radio sources are associated with quasars indicating an overall correlation between non-thermal radio and optical emission but there exist radio galaxies which are as strong radio emitters as quasars but which possess only weak or undetectable optical non-thermal emission. The most famous examples of the latter are Cygnus A and 3C 295. There must therefore be a wide dispersion in the relation between total radio luminosity and optical luminosity.

A significantly stronger correlation is found if only the central non-thermal and optical luminosities are considered. Those sources which possess the strongest central radio components also have the strongest non-thermal optical emission and almost invariably those with no central radio component turn out to be associated with radio galaxies with no evidence of a central optical component. The quasars fall naturally into this sequence.

(iii) Correlation of optical spectral type with radio luminosity. The proportion of radio galaxies with strong emission line spectra increases with increasing radio luminosity. For very weak radio galaxies $P_{178} < 10^{24}$ W Hz^{-1} sr^{-1}, only about 10% of radio galaxies possess strong emission line spectra, the remainder showing either weak emission lines or a pure absorption spectrum. With increasing radio luminosity, the percentage of sources with strong emission line spectra increases. For the highest radio luminosity classes, the percentage is about 70%, there remaining a significant fraction which have no strong emission lines. These conclusions are based upon detailed studies of all the radio galaxies in the 3CR catalogue with measured spectra (Hine and Longair 1979). This is an important result because the radio luminosities of the faintest identified radio galaxies are inferred to be large and thus there is a good chance that many of them will possess strong emission line spectra which makes the determination of their redshifts much easier.

We have also found that the sources with strong emission line spectra are almost exclusively classical double radio sources in which the maxima of the radio brightness distribution lie towards the leading edge of the radio source structure. Since these are invariably sources of high radio luminosity, it is possible to predict those sources whose redshifts are likely to be measureable.

(iv) Broad and narrow line radio galaxies. Osterbrock and his colleagues (e.g. Osterbrock 1977) have shown that the radio galaxies with strong emission line spectra can be divided into two classes similar to the distinction between Seyfert I and II galaxies; they are known as broad line and narrow line radio galaxies (BLRG and NLRG). The NLRGs are apparently indistinguishable from Seyfert II galaxies. There are however, significant differences between the BLRGs and Seyfert I galaxies, the radio galaxies having weaker FeII emission lines, stronger lines of O^{++} and steeper $H\alpha/H\beta/H\gamma$ ratios. We find that there is a correlation between the breadth of the emission lines and the luminosity of the central radio component. Again, it appears that this correlation extends to the quasars studied by Miller and Miley (1979). The latter authors also found a significant difference between the line profiles of those radio galaxies which possess extended radio structure and those which do not. The extended radio sources possess significantly broader and more complex line profiles than do the compact radio sources.

(v) Clustering of galaxies about extragalactic radio sources. There has been considerable debate about the differences between radio galaxies inside and outside clusters of galaxies, the main observational problem being finding comparable sets of sources with comparable radio luminosities and morphologies. In a recent analysis of the clustering of galaxies about 3CR radio galaxies, we have used cross-correlation functions to describe objectively the degree of clustering about the radio source (Longair and Seldner 1979). For a complete sample of 3CR radio galaxies which have redshifts $z < 0.1$, we measured their cross correlation with the Lick counts of galaxies. The diffuse radio sources with no prominent emission lines in the optical spectrum of the galaxy belong to associations of galaxies intermediate in strength between objects selected at random in the Universe and rich clusters of galaxies On the other hand, the classical double sources belong at best to very weak associations. In fact, so far as their cross-correlation with galaxies in general is concerned, the classical double sources are indistinguishable from galaxies selected at random in the Universe. We have interpreted this result as meaning that on average, the galaxies which can become strong classical double sources must be essentially isolated galaxies - or rather galaxies which dominate the nearby intergalactic environment. If this result is confirmed by further observations, it suggests a way of finding galaxies as bright as the brightest members of clusters but without the cluster round about them. If used as standard candles there will be no corrections for dynamical friction or cannibalism. This result is similar to that of the quasars which are all classical double radio sources when observed in low frequency samples. They are very rarely found in rich clusters of galaxies. We believe the same physical processes are operating in both cases.

5. OBSERVATIONS WITH THE SPACE TELESCOPE

There are a number of distinct ways in which Space Telescope observations will advance these studies.

5.1 The optical identification of very distant radio sources

The Space Telescope is obviously the ideal instrument for studying the most distant quasars since its sensitivity is greatest for starlike objects. The technique of optically identifying radio sources provides one answer to the question "How do you find the most distant quasars?". In principle, those quasars with redshifts as large as 10 or even greater should be observable by Space Telescope if they exist. Unidentified radio sources which turn out to be very faint quasars when studied with the Space Telescope are prime candidates for "the most distant quasar". The best approach is to study complete samples of radio sources selected at flux densities considerably smaller than those studied in detail optically to date. Equally, at high frequencies, where a larger proportion of the sources are quasars, there is great incentive to extend the surveys to fainter flux densities. To pursue these studies, it is essential that high quality radio observations of these samples of sources are available and that all the complementary optical work has been completed from the ground. I expect these observations to give information about the reality of the cut-off at large redshifts or otherwise.

For radio galaxies, the gain in using Space Telescope might appear to be less because they are extended objects. Even at the most pessimistic level, it is worthwhile exploring these fields because the sky background is significantly fainter from space. Probably the standard giant elliptical galaxy will be observable out to redshifts $z \sim 1 - 1.5$. This provides a direct method for discovering giant elliptical galaxies at large redshifts and may prove useful in studies of the redshift-magnitude relation. However, I believe the prospects of identifying distant radio galaxies are somewhat better than this might suggest because of the known facts about the optical properties of radio galaxies listed above. According to the models of the evolution of the radio source population, a significant fraction of sources in the flux density interval $10 > S_{408} > 0.1$ Jy are distant powerful radio galaxies. These are objects which on average have stronger non-thermal optical nuclei and strong emission line spectra. Thus there is evidence that these distant radio galaxies should be similar to the N-galaxies which should be identified to redshifts of 2 or more.

5.2 Are quasars really massive galaxies with hyperactive nuclei?

All the astrophysical evidence described above shows that the properties of quasars are continuous with those of strong radio galaxies which are giant ellipticals. It is very important to find out directly by observation of quasars with the highest angular resolution whether this is indeed true.

5.3 The redshifts of distant galaxies and quasars

For quasars, there should be little problem in measuring their redshifts because of their strong emission lines. Equally for those radio galaxies with strong emission line spectra, there should be little problem. One of the most intriguing questions about Space Telescope to which I believe there is no definite answer yet is how well it will be possible to measure the redshifts for distant galaxies. The problem is greatest for those galaxies with no prominent emission lines and only a pure absorption spectrum. At wavelengths $\lambda > 600$ nm, the sensitivity of the Faint Object Spectrograph is low and measurements of the spectra of faint galaxies in this spectral region will not be feasible. It is not clear that the transmission grating-diffraction prism in the Wide Field Camera will be able to measure low resolution spectra of galaxies in the red and infrared spectral regions and it is not clear what the limiting magnitude of these observations would be. How successful the measurement of redshifts by narrow band multicolour photometry with the Wide Field Camera will be is not yet known. It may be that in the end this programme will have to be carried out from the ground with long exposures using CCD detectors attached to spectrographs. The alternative would be to design a "distant galaxy" spectrograph for the next generation of instruments for Space Telescope.

5.4 The astrophysics of the nuclear regions of radio galaxies and quasars

This topic will undoubtedly be discussed in detail by other speakers at this colloquium. There are however distinct problems posed by spectroscopic observations of radio galaxies and the ultraviolet region of the spectrum remains more or less unexplored. The IUE satellite observatory has had considerable success in studying the brightest quasars but this is only the tip of the iceberg. There is vast amounts to be done with the Faint Object Spectrograph on the bulk of known quasars which fall in the range of apparent magnitude $16 < m < 20$ which will all be readily observable in the ultraviolet with Space Telescope.

The problem of studying radio galaxies has proved very difficult and only in a few cases have successful observations been obtained with IUE so far. Only the brightest and strongest emission line objects have been readily observable. For example, we have recently had success in obtaining a good ultraviolet spectrum of 3C 390.3 which is a classical double radio source associated with an N-galaxy (Ferland et al. 1979). It has proved particularly interesting because the spectrum contains both broad and narrow line components and they can be easily separated. The Lyα to Hβ ratios are different in the two regions, being normal for the narrow line region and anomalous in the usual sense for the broad line region. We have also observed 3C 382 which shows evidence for major structural changes in the emission line profile of Lyα over a time scale of a year. However, these are very time consuming programmes with IUE. We have devoted 20 hours of observation in order to measure a good spectrum of 3C 390.3 and each short wavelength exposure of 3C 382 requires 6 hours of observation. With the Space Telescope these observations should take only about a twentieth of the time. This means that it will be feasible to study large samples of narrow and broad line radio galaxies in the ultraviolet for the first time.

5.5 Clustering of galaxies about radio sources

It would be very important if the clustering of galaxies about distant radio sources could be measured with the cameras on board the Space Telescope. As indicated above, the samples suitable for study so far are restricted to small redshifts. By going to faint samples of galaxies, one is investigating the clustering about the most powerful sources for which the evidence to date is fragmentary. The problem is that the fields of view of the cameras are small. Thus at cosmological distances, the physical size of the field observed by the Wide Field Camera is about 1.6 Mpc which is not large enough to measure the background of galaxies away from the cluster core. Some information will be obtainable about the clustering of galaxies about sources but ideally much larger fields are required.

5.6 The "look and see" mode and radio sources

As a matter of principle, I am sure that it will prove very revealing to look at a sample of brighter objects with the highest possible resolution to see what these optical objects look like. It may be that it will be possible to find non-thermal nuclear components in all strong radio galaxies. Other radio galaxies may possess compact non-thermal optical knots as in M87. There is recent evidence from the Westerbork workers that the colours of the faintest identifications which they have made are bluer than the normal colours of radio galaxies (Katgert et al. 1979). This may suggest significant colour evolution of these radio galaxies at comparatively recent cosmological epochs. This evidence is similar to the evidence on the colours of distant clusters and of the counts of galaxies where one reasonable interpretation is that the colour properties of galaxies change remarkably rapidly with redshift. If this is so, it can be readily checked by studies with Space Telescope and will have substantial implications for the study of distant radio galaxies.

6. CONCLUDING REMARKS

I believe the sorts of observational demands which observers from non-optical wavebands will make upon the Space Telescope are similar to those described above for the radio waveband. These are optical identifications, the determinations of distances, the physical conditions in the objects derived from the optical and ultraviolet waveband, the comparison with other types of object of the same optical morphological types and so on.

Table 1

Topics of Central Importance to Radio and X-ray Astronomers discussed in Other Lectures presented at the Colloquium

	Radio	X-ray
Planets	✓	
Supernovae	✓	✓
HII regions Planetary Nebulae }	✓	
Interstellar medium	✓	✓
Globular clusters		✓
Normal galaxies	✓	✓
Their evolution	✓	✓
Active nuclei	✓	✓
Absorption lines in quasars	✓ (HI)	
Clusters of galaxies	✓	✓
Cosmology	✓	✓

Taking a broader astronomical view of the subject, it is interesting that essentially all the invited lectures at this symposium are of great importance to the interests of non-optical astronomers. In Table 1, I have indicated those areas which are particularly significant for radio and X-ray astronomers. Observations of relevance to the high-energy astrophysics of all these classes of object have been made in the radio and X-ray wavebands and consequently will have an important bearing on observations with Space Telescope.

We should also be prepared for more speculative types of proposals. For example, the high resolution imaging of gravitational lens. There is the one possible example which has already been mentioned but of course many more quasars will be discovered by Space Telescope and the probabilities are not so small of finding a few examples. If there is optical emission associated with the superluminal expansions of compact radio sources, do we observe the centre of gravity of the optical image jittering on the scale of 1 - 10 m arcsec? The most exciting examples will be those that we have not thought about.

References

More details of many of the aspects of radio astronomy and cosmology may be found in the following volumes :

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DISCUSSION

Burbidge: This is a comment on the urgent need for ground-based work in preparation for observing with the ST and also a comment on a remark by Dr. Spinrad after Dr. Groth's talk in the session on ST instruments. Spinrad asked if the DOT were considering all the difficulties encountered by ground-based observers in working on really faint objects - putting the invisible object down the hole, making on-the-spot decisions etc. It is, of course, a very important problem for the FOS, and it is a software problem - to think of all the options and alternatives, and have pre-programmed choices which the observer can make. For the FOS Hollard Ford is the DOT team member and he is working on this, also Greg Schmidt at UCSD and co-investigator Bruce Margon. The programs ought to be thoroughly tested on the ground.

Van der Laan (Discussion leader): Our experience of nine years operation of the Westerbork Synthesis Telescope is that virtually no project in radio astronomy can be completed astrophysically without the use of complementary information from other wavebands, in particular optical, X-ray and UV data. In particular, as illustrated by the previous lecture, radio astronomers are addressing themselves particularly to the relation between the activity observed at radio wavelengths and the optical properties of the related objects.

I will give three examples from our current research programmes which illustrate these points and which will benefit from observations with the Space Telescope.

(i) Is the optical jet in M87 unique ? Van Breugal, Miley and Butcher have searched for optical jets in four radio galaxies which possess strong radio jets. In the cases of 3C66B and 3C31 they have found optical knots coincident with the local maxima in the radio jets. In addition, unresolved optical cores in the galactic nuclei have been discovered. These observations are at the limit of the 4-metre telescope and there will be advantages in pursuing these studies with the FOC and WFC of the Space Telescope. These observations provide important information about the processes of energy transport and transformation in radio galaxies.

(ii) As mentioned in the previous lecture, we have found that radio galaxies at redshifts $z \gtrsim 0.5$ are excessively blue. The blue excess appears to be associated with extended objects but its nature is not at all clear. Is the light dominated by a non-thermal nuclear component or is the blue light associated with the stellar population ?

(iii) At Westerbork, we have been making complementary radio

> observations to the deep X-ray survey fields observed with the Einstein X-ray observatory. Those objects which are simultaneously bright radio and X-ray sources are obviously important examples of high-energy astrophysical phenomena. This programme leads to much complementary optical work, first of all optical identification and cross-correlation of the radio and X-ray data and then optical spectrophotometry.

These programmes illustrate the importance of complementary optical work for radio and X-ray astronomy.

Burke: When the VLA is completed, it will consist of a Y-shaped array of 27 antennas, each 25-metres in diameter. The operating frequencies are 1.3, 2, 6 and 21 cms and provide maximum resolution ranging from 0.1 to 2 arcsec. The maximum sensitivity to faint objects is at 6 cms where the angular resolution will be 0.5 arcsec. Thus the angular resolution will be similar to that of the Space Telescope. At present, approximately half of the array is working and we can attain 0.8 arcsec resolution at λ 6 cm. In about a year the whole array will be completed and subsequently spectral-line facilities will become available. The sensitivity is currently a few tenths of a mJy with ultimate sensitivity limit about 0.1 mJy. The angular accuracy for astrometric work will be ∿ 1 m arcsec.

VLBI observations will also continue throughout the era of the Space Telescope, the current maximum angular resolution being 0.2 m arcsec. Perhaps one day we will be able to do ten times better. There will also be other large powerful telescopes in operation throughout this era - the 1000-ft Arecibo dish, the 36-ft Kitt Peak millimetre telescope, the Westerbork Synthesis Telescope and the Cambridge 5-km telescope. All of these instruments will provide information supplementary to that provided by ST.

The types of astronomy to be done with these instruments is huge. One class of observation which has not been mentioned so far is that of stars. It was predicted theoretically that the thermal radio emission associated with mass loss from stars would be observable by radio means and this has indeed turned out to be the case. It has the advantage of being independent of temperature.

A major problem will be the oversubscription of observing time. Already the VLA in its incomplete state is oversubscribed by about a factor of 3. Cooperative programmes will have to be developed just as it proved to be essential for VLBI. The system must also be responsive to new discoveries. A good example is the recent discovery of the binary pulsar. It was possible to schedule "quick look" observations with the VLA which required in total only 42 minutes of observation. The subsequent cleaned maps showed radio components of roughly equal intensities associated with each quasar but one of them also showed extended structure, not dissimilar from that of a typical radio galaxy and quasar. The observations are thus at present inconclusive. What is now required is a proper set of observations with much more complete filling of the aperture plane and this will be carried out in a more leisurely fashion as part of the normal observing programme.

Hemenway: The aim of the Texas radio survey is to provide large sky coverage for very large numbers of radio sources. Accurate radio positions (± 1 arcsec) are derived from interferometric observations at 335, 365 and 380 MHz for sources in the range $+ 70^{o} > \delta > - 36^{o}$. The flux density limit will be about 0.25 Jy and we expect to observe more than 50,000 sources. We already have about 6700 sources in a 10^{o} declination strip centred on $+18^{o}$. Optical identifications are being sought for all survey sources on glass copies of the O and E plates of the Palomar-National Geographic Society Sky Survey. The relative accuracy of the radio and optical positions should be 0.7 arcsec for all sources. We intend publishing finding pictures, radio positions, flux densities and other relevant information.

Vidal - Madjar: I wish to draw attention to the importance of a very restricted spectral range which will not be accessible to Space Telescope, i.e. the 900-1100 Å wavelength range. The observation of interstellar absorption lines in this wavelength range can provide important information which will supplement that obtained with the Space Telescope. Absorption lines due to many important ions and atoms fall in this wavelength range, including N, O, F, P, Cl, Ar, Zn for which depletion factors of 1 are found and Mg, Al, Si and Fe for which depletion factors $D \sim 0.1$ are observed, these figures reflecting the observational situation for slightly reddened stars. There are many important aspects of such studies but I draw attention to only a few of them.

(i) The deuterium line can be observed only below 1100 Å and therefore this very important determination can only be achieved in this specific wavelength range.

(ii) Above 1100 Å, the only available HI line is Ly α which is strongly saturated and which may lead to erroneous HI abundances especially if high velocity clouds are present along the line of sight. The observation of the other Lyman lines below 1100 Å provide crucial complementary information on which to base accurate determinations of the atomic hydrogen abundances.

(iii) For NI, many unsaturated lines are available below 1100 Å whilst above 1100 Å the lines are most often saturated. It is important to obtain both sets of data in order to determine the structure along the line of sight. As illustrated by our recent work on the γ Cas line of sight (Ferlet, Laurent, Vidal-Madjar and York, Ap. J., Jan 15, 1980) the weak lines allow the main components to be determined and the saturated lines show that some other weak components also exist along the line of sight. The combination of all NI lines leads to a structure along the line of sight involving 4 clouds.

Finally, we would like to know the total hydrogen abundance and for this we need to determine both HI and H_2 abundances. To determine the latter, it is necessary to determine abundances of H_2 from the different rotational levels. Most of these lines are below 1100 Å, a few of them being around 1100 Å.

Brandt: There will certainly be some response shortward of 1100 Å on the HRS, 25 perhaps even 50 and we should see some lines of H_2 and other important lines. It is not yet clear how well we can do this.