Chapter ~~IX~~ XI - QUASARS AND EXPLODING GALAXIES

Despite the current popularising of science on radio and television many people still think of astronomers as members of a strange and detached cult who spend their nights with eyes glued to their telescopes gazing out on a static and changeless world of stars. No story better illustrates how modern astronomers go about their business, and how far from unchanging are the starry skies above us, than that of the quasi-stellar objects, or "quasars" - "crazy stellar object" according to the ten year-old daughter of a wellknown American family of astronomers, the Burbidges. These extraordinary objects are the most luminous known in the Universe: they appear to emit up to one hundred times as much energy as the brightest galaxies yet are only about one millionth the size of one of them, and their images in fact appear as stars on plates taken with the largest optical telescopes. The opening up of this new and momentous chapter was primarily the work of the radioastronomers but the next significant steps came from the optical side, ~~xxxxxxx~~ ??? which illustrates how fruitfully ??? radio and optical astronomy complement each other. Right from the outset ~~xxxxxxxxxxxxxxxx~~ radio astronomy has demonstrated its uncanny knack for singling out corners of the Universe where disturbances are in progress and dramatic events in course of unfolding: optical astronomers have been keen to turn their telescopes on these unusual events but were hampered at first by the relatively crude directions that radioastronomers were able to give them. Steady progress came as they succeeded in identifying more and more of the optical objects which were the source of the tell-tale radio emissions.

As we saw in Chapter , the first such identification was with the remnants of 900-year-old stellar explosion. Radio sources are concentrated in the direction of the plane of the Milky Way and many of them belong to our own Galaxy - often associated with gaseous nebulae, regions in which the interstellar gas is ionized and heated by ultra violet light from a star within it until the electrons are energetic enough to emit light and radio waves. Away from the Galactic plane, however, a large proportion of the sources that have been identified lie outside our own system i.e. are extragalactic remote "island universes" which are resolved on photographs taken on large telescopes as vast assemblies of individual stars distributed through a volume tens of thousands of light years across. The first extragalactic source to be identified as such was that in Cygnus, when in 1952 Baade and Minkowski found a faint object with an unusual spectrum near a position obtained by F.G. Smith of Cambridge: its red shift indicated a velocity of recession of .05 that of light, which, though small by today's standards, was at that time among the largest known. Further progress was slow however until the early 1960's when the availability of larger radio telescopes capable of working at shorter wavelengths (the combination providing substantially higher resolution) has made more identifications possible, and also provided a more detailed picture of the structure of some of the radio objects. A characteristic feature of many is that the radio emission originates from two regions on either side of and symmetrically placed in relation to the optical galaxy, the whole forming a dumb-bell shaped structure. The separation between the two components ranges from less than to several times the diameter of the visible galaxy. This suggests origin in an explosion in the parent object, the emitting areas being gas shells moving rapidly outwards; polarization measurements indicate that the magnetic field is aligned with the line joining the two components.

After Cygnus the next remote galaxy identified as a radio source (1960) was a member of a cluster of galaxies associated with the source 3C 295: its spectrum showed only one prominent emission line, but if this were the oxygen line 3727 A° then it had the large redshift value of 0.46. During the next few years instances began to accumulate, however, where the star-field around what was undoubtedly a well-determined radio position contained no obvious galaxy, but only a faint object resembling a star. The first radio source found to be associated with one of these objects was 3C 48, whose optical counterpart was an apparently ~~insigif~~ insignificant star of 16th magnitude. A new series of photographs taken with the 200" Palomar telescope revealed a faint wisp of nebulosity, and that the object emitted more strongly than usual at ultra violet wavelengths. Its spectrum was also unusual and curtained some broad emission lines that did not correspond to those of any known star. This gave rise to the possibility that objects of this kind were radio galaxies at even greater distances, or that they represented the initial stage of the catastrophic explosions in the nucleus of a galaxy which later developed into the more familiar double structure which characterise most of the known radio galaxies. The peculiar features shown by 3C 48 were responsible for initiating a closer study of these unusual celestial objects which, for want of a better name were referred to as quasi-stellar objects or Q.S.O's.

As better radio positions became available other quasi-stellar objects appeared. A major step forward occurred when Hazard, Mackey and Shimmins, using the 210-ft radio telescope at Parkes, observed the radio source 3C 273 during its occultation by the Moon on 5th August 1962, and obtained a very accurate position for it. There was a clear indication that it consisted of two components which they designated A and B, separated by 19.5 seconds of arc: they noted that component B coincided with a starlike object of 13th magnitude. Maarten Schmidt of the Mt. Wilson and Palomar Observatories definitely identified the QSO ~~xxx~~ associated with 3C 273 and found that, like 3C 48 it had a wisp of nebulosity but in the form of a faint, visible jet. The jet appeared to protrude from component A and the radio source, B, lay at the end of the jet (see Figure).

By this time a number of other quasi stellar objects had been located, 3C 147, 3C 196, and 3C 286, which all showed considerable ultra-violet excess, and the mystery deepened when they too showed unidentified emission lives in their optical spectra. The exciting breakthrough xxxx came in 1963 when Schmidt recognized that four harmonically-spaced lines in the spectrum of 3C 273 would fit those of hydrogen if there were a red shift of 16 per cent: one of the remaining lines then corresponded to a forbidden line of doubly-ionized oxygen (i.e. stripped of two electrons) shifted towards the red by the xxx same amount. Subsequently it was found that the first line of the hydrogen series, Hα, whose undisturbed wavelength is 6563 angstrom units, had been shifted into the infra red region, to about XXX 7590 angstrom units. Schmidt thus provided the clue that solved the puzzle of the unidentified emission lines. Matthews and Greenstein found that lines in the spectrum of 3C 48 fitted those from singly ionized hydrogen and doubly and quadruply ionized neon shifted toward the red by 47%. Later Schmidt and Matthews deduced redshifts of 42 and 54 percent respectively for the other QSO's, 3C 47 and 3C 147.

Since the pioneer work of Edwin Hubble at Mt. Wilson it had been known that light from distant galaxies shows a redshift which increases as the distance increases, the commonly accepted xxx explanation being that the Universe is expanding and all the galaxies are receding from us and from each other. The largest measured redshift in 1963 was 46%, for a very distant galaxy which was associated with the radio source 3C 295. The large observed redshift for 3C 273 and 3C 48 came therefore as a surprise because their optical appearance suggests that they are not distant objects at all. On the usual distance-red shift scale 3C 273 is about 2000 million light years away, and 3C 48 about twice as far. If this interpretation of the red shift is the right one then this raises a further puzzle: how can they look so bright, both optically and by radio, if they are so far away? An average *bright* galaxy at the distance of 3C 48 has a visual magnitude of 20-22 and can only be photographed with the largest telescopes: 3C 48 however is of 16th magnitude. On the other hand if 3C 48 were an *ordinary* galaxy close enough to appear of 16th magnitude, then our big telescopes would be able to resolve some of the stellar detail within it (which they cannot); or if it were actually a star - in which case it would have to be within our own Galaxy - then how could it possibly have such a large red shift?

There was no end and certainly no answer to the intriguing questions raised by the enigmatic quasars. Their discovery came at a time when astronomers were still wrestling with the problem of accounting for the energy broadcast by the radio galaxies. The brightest of these emit radio frequency energy at the rate of 10^{45} ergs per second - as well as unknown quantities of infra red, ultra violet and X-radiation - and they have presumably been doing this for at least a million years (judging by their distance from us). Over the years their output has, therefore, exceeded the fantastic total of 10^{58} ergs, which means that the energy originally stored in the particles and the magnetic field must have been even greater, of the order 10^{60} ergs. As an indication of what this implies the complete conversion to nuclear energy of a mass of hydrogen equivalent to that of our Sun would yield only 10^{52} ergs, so the original explosion which produced the radio galaxy must have had a driving force equivalent to the total nuclear energy output of more than 100 million Suns! Theoreticians have been struggling for years with the problem of envisaging how so many solar masses of hydrogen can be made to explode simultaneously, and how this can be converted into the high speed electrons and magnetic fields which are obviously the source of the emission picked up by radio telescopes. No satisfactory solution has been reached: and now, the discovery of a completely new class of object with even more mystifying properties has compounded the problem still further.

The years following the identification of the true nature of 3C 273 saw feverish activity to find more of these strange objects. Several new or revised catalogues of radio sources became available in 1965-66, notably the Parkes (PKS), the Cambridge 4C and the National Radio Astronomy Observatory, and the big telescopes of the Mt. Wilson and Palomar Observatories, and the Lick Observatory have been busy photographing likely areas. The fact that QSO's radiate strongly in the ultra violet means that they usually appear brighter on blue-sensitive than on red-sensitive plates and this feature has been one of those widely used in identifying QSO's. Sandage at Mt. Wilson used the 100" telescope to make successive exposures on blue-sensitive plates, one through a blue and the other through an ultra-violet filter. The telescope was displaced slightly between exposures: a normal star gave images of about the same intensity but one showing ultra violet excess was likely to be a QSO. If it lay within the error rectangle of the radio position, and in addition, had a stellar appearance, broad emission lines in its spectra which showed a large redshift, and perhaps a varying light output it was almost certainly a quasar. Bolton and his associates in Australia, in collaboration with astronomers of the Lick Observatory, have been responsible for the identification of more than 100 quasars. Bolton used the precise positions obtained with the Parkes 200" telescope to derive, by means of a computer, transparent overlays with which he searched the Palomar Sky Atlas for objects showing a blue excess. Most of the quasi stellar objects found in this way were subsequently confirmed optically by astronomers at Lick, or Mount Wilson and Palomar Observatories in California, or at the Mt. Stromlo Observatory in Australia. An important result established in the course of this work at Parkes is that a certain type of radio source can be distinguished as a quasar by having a distinctive flat or curved spectrum at radio wavelengths; ~~further~~ further, for quasars of this type the red shift can be forecast with reasonable accuracy from the spectrum. One such object, PKS 0237-23, is one of the most distant sources known: on the basis of its red shift of 2.223 it is receding at a speed of more than 80 per cent that of light, and the radio waves which we are now receiving from it have been travelling on their way ot us, for two to three times the age of the Earth.

By no means all stars showing a strong ultra violet excess are quasars. Before the identification of 3C 273 a number of astronomers had found and listed blue stellar objects which occurred at about four per square degree of sky: the brighter of these are almost certainly galactic stars. Those fainter than about 15" optical magnitude however have properties very similar to those of quasars, except that only a small proportion of them are the powerful radio emitters through which the whole class of objects was first discovered. So far only a few of the blue stellar objects which have no detectable radio emission show a pronounced red shift, and we do not know whether the quasars which are such powerful radio emitters belong to the same class and so have the same physical origin as those which have marked ultra violet excess, a stellar appearance and appreciable red shift but no or insignificant radio emission.

Optical variations

Astronomers regularly photograph the skies as part of their search for new stars and to keep a watch on those which are known to vary in light output. Some of these fluctuate in brightness with great regularity, like the double-star systems periodically eclipse each other as they rotate around their common centre of gravity, or the Cepheids, with atmospheres pulsating under gravitational forces; others show sudden unpredictable variations from the barely perceptible to the cataclysmic explosions of the supernovae. The latter are sometimes easily visible by the naked eye but the majority of variable stars can only be detected by a careful comparison of photographic plates taken at different times. On such plates the majority of stars are of fixed luminosity and serve as reference points: variable stars are distinguished by changes in brightness relative to others in their vicinity.

Following the discovery of the first quasi-stellar object, 3C 48, it was natural to look through old photographic records to check on its past history. The old plates were poor and nothing certain was found, but accurate photoelectric measurements in 1963 (by Matthews and Sandage) revealed an optical variation of about 0.4 magnitude over a period of about 13 months, together with an indication of night-to-night variations of much smaller amounts. Plates taken at Harvard and Pulkova Observatories over the past 70 years showed x that 3C 273 had apparently varied by a factor of 2 over the years, and that there may have been shorter period variations of weeks or months. Since then a careful watch for optical and spectroscopic changes has been maintained: it seems probable that optical variability is a common property of quasi stellar objects, although only a minority of them show major or short period fluctuations.

One of the most spectacular of these is 3C 345 which has been studied by Kinman at Lick Observatory. It fluctuates over a period of about one year but every three months or so it doubles in brightness in a couple of weeks and just as rapidly decreases again: spectroscopic studies indicate that this is associated with strong magnetic fields. Another quasar, 3C 279, behaves in much the same sort of way but outdoes 3C 345 in its short-period flashes during which its light output goes up by a factor of sixteen. The largest variations of short period that have so far been observed in quasi-stellar objects occur in 3C 446: this object has shown almost continuous variation since its discovery in 1964: in a 10 day period in July 1966 it fell in brightness by about two magnitudes but then increased again, on several occasions by 0.5 to 0.8 magnitudes within a y or so. A high degree of linear polarization of the light has been observed, xxix thus confirming that it has a synchrotron origin. The short-duration light variations also set an upper limit to the size of the region which is varying. It cannot be larger than the time taken by light to traverse it, and for 3C 446 this means a maximum extent of about one light-day.

Variations in Radio Emission

That there is also a variation in the radio output from some quasars is now undoubted, although initially there was some disagreement between various observers on this point. The first to kx be confirmed as a variable is 3C 273 B, whose flux is increasing at the rate of about 17% per annum: significant changes also occur over periods of months or weeks at a wavelength as short as 3.4 mm. Another variable is 3C 345, which is also a striking performer at optical wavelengths. The variations at radio wavelengths for the quasars so far confirmed as variable are, however, of larger period that at optical wavelengths. The upper limit to their size as derived from the period of their variations is invariably smaller than that indicated from long base line interferometry or scintillation techniques.

QSO's and Galaxies

In the earlier radio surveys no distinction was made in listing what we now know to be quasi-stellar objects and radio galaxies: it is of interest, therefore, to compare their properties.

An outstanding difference is in their appearance. Galaxies, the largest units of matter in the Universe, shine by the light of the thousands of millions of individual stars which they contain, and appear as extended sources: the quasi-stellar objects, as their name indicates, are scarcely distinguishable from stars. The apparently smaller size of the QSO's is confirmed from other considerations: the observed fluctuations in the radio and light output indicates a diameter of the order 10^{-5} that of a normal galaxy, and measurements of the angle subtended by several quasars, using very long baseline interferometer techniques, confirm that they must indeed be very small if they are at cosmological distances.

The property of QSO's which created so much interest is their spectrum, consisting of red-shifted lines characteristic of a hot gas, together with a continuum of non thermal (almost certainly synchrotron) origin. The spectrum of a normal galaxy is predominantly a composite of those of the stars which it contains, but the radio galaxies often show strong emission lines in their spectra, superimposed on a continuum, which are comparable to those of QSO's. The Seyfert galaxies, a special class which are mostly spirals with a bright star-like nucleus, have spectra which are similar to QSO's: at least one of them has been found to emit strongly in the infra red. Another unusual type of Galaxy, N-type x of which only a few are known are also similar to QSO's, except that they have sizes of a few seconds of arc and are thus not star-like in appearance.

The radio output of quasi stellar objects is very similar to that of the radio galaxies: if they are at the distances suggested by their red shifts then they are comparable to the strongest radio galaxies, while if they are relatively local, to the weaker radio galaxies. A convenient way to compare the radio properties of QSO's and radio galaxies is to consider their radio luminosity in relation to their surface brightness. In Fig.   the absolute radio luminosity (L) is plotted against the surface brightness (B) (both computed from measurements at 1400 MHz) for QSO's, radio galaxies and spiral and irregular galaxies: the QSO's are assumed to be at cosmological distances indicated by their redshifts.

The points suggest that the QSO's fit into an orderly evolutionary sequence in the sense that a small but very intense xmxrx source (a QSO) grows into the large double radio source which constitutes a radio galaxy; this gradually expands still further and grows weaker in the process. The apparently smooth form of the curve can also be taken to support the interpretation of the QSO's red shift as cosmological.

Thus, while there are some apparent similarities between QSO's and galaxies there are many differences. A more detailed comparison between them is difficult in the absence of any satisfactory understanding of the origin of quasars and the mechanism by which they radiate. The bulk of the faint radio sources have not yet been identified with optical objects and further work in this direction would be helpful. They could contain a proportion of fainter or more distant QSO's, or perhaps consist only of radio galaxies whose optical xxx counterparts are fainter than the limit recorded on the plates of the Palomar Sky Survey. Bolton favours the latter on the basis of his observations at Parkes, which show that the spectra of the unidentified sources resembles that of radio galaxies. This is indicated on Fig. from which it can be seen that the spectra of QSO's is recognizably different.

Summary of QSO properties

Since the discovery in 1962 that QSO's were a startling new kind of object further observations have shown successively larger red shifts, with some mysterious clustering around particular values: large changes in light output in a short time: and variations in radio flux. On the theoretical side however not even qualitatively satisfactory models have been advanced to explain these properties. As a preface to considering the various problems that are awaiting solution it is relevant to summarise the observed properties of QSO's. These are:-

1. Most of them are radio sources. The majority have at least one component of very small dimensions, but some are

physically double (like radio galaxies) and others show two distinct peaks in their radio spectra, suggestive of origin in two separate sources. Their radio spectra are consistent with a synchrotron origin.

2. Their optical spectra show broad emission lines whose relative strengths are consistent with origin in a hot gas of normal, i.e. solar neighbourhood composition. The emission lines show red shifts varying from $Z \sim 0.1$ to about 2.4: several QSO's show several different red shifts. In a number of them absorption lines are also present and, if so, with a red shift corresponding to that of the emission lines.
The red shifts are not randomly distributed over the above range but seem to show marked clustering, the most prominent peak being at $Z = 0.06$, while there are a number around $Z = 1.95$. The number of red shifts so far determined, however, is not enough to rule out the possibility that this effect is due to inadequate sampling. (If their red shifts are true Doppler shifts this suggests that they lie near the outer edge of the expanding Universe.)
3. Variations in optical luminosity of up to 3 magnitudes have been observed (e.g. 3C 446), and by a factor of two in one day: in 3C 446, at least, this is accompanied by strong linear polarization. Striking variations also occur in the radio emission from a number of QSO's, but these appear to be of a secular nature rather than short period fluctuations.

Problems raised by the QSO's

The basic problem in explaining QSO's is reconciliation of their red-shifted spectra with their other properties, particularly their radio and optical emission. Let us consider the various possibilities.

1. They may genuinely be at the cosmological distances indicated by their red shifts.

This is probably true if the red shifts originate from Doppler effects: the apparent simplicity of the radio luminosity-surface brightness relationship (Fig.) lends qualified support to this, as also does the fact that all the observed shifts are towards the red, i.e. there are no blue shifts. The existence in some QSO's of more than one series of red shifts could be accounted for if one is appropriate to the receding QSO and the others are due to the intervening medium, but there are observational features which suggest that both series originate in the same source. The outstanding difficulty in accepting this model is to account for the huge emission from a source of the small dimensions which are indicated by the short-period fluctuations observed. Nevertheless many of the known characteristics of QSO's are still consistent with the idea that they are situated at very great distances.

2. They are not situated at cosmological distances but the red shifts are genuine Doppler effects, so they must either be moving themselves at relativistic speeds, or contain matter that is.

   One difficulty in accepting this possibility is that QSO's show only red shifts in their spectra i.e. none are observed to be approaching us. This could be accounted for if the explosion occurred relatively nearby, and the objects have now passed us. It is not likely however that all the QSO's originated from a single explosion, and if they are ejected symmetrically from their parent galaxy then a proportion of them should show blue Doppler shifts. Apart from this it is difficult to see how QSO's could be ejected at speeds which are such an appreciable fraction of that of light; the energy involved would be very great.

3. The QSO's are not at the cosmological distances suggested by their red shifts, because the redshifts are due to gravitational fields.

The outstanding difficulty in accepting this explanation is the fantastically high densities that would be required to produce the observed shifts; further the observed optical spectrum is quite incompatible with such high electron densities.

4. A further possibility is that the redshifts which are proving so difficult to explain are due to some physical mechanism which has not yet been discovered.

There is no particular reason for supposing that there are important laws of physics yet to be revealed - except that in the QSO's a <u>new</u> class of object has been discovered so that a new theory to account for it may be appropriate.

Modern radio and optical astronomers have thus concocted an absorbing puzzle for the theoreticians: further progress is largely in their hands to produce a model based on established physical principles which is able to satisfy the conflicting observational evidence.