

THE NATURE OF THE QUASI-STELLAR OBJECTS*

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In this paper I shall give a brief account of the properties of the quasi-stellar objects (QSO's) with special bearing on the question of whether they are local or cosmological objects.

Redshifts

At the present time redshifts are available for more than fifty QSO's. A plot of redshift against apparent magnitude shows a large scatter though there is a weak trend in the sense that the fainter objects tend to have the larger redshifts. As the number of redshifts has increased the scatter in this plot has grown larger. The fact that we have so far seen only redshifted objects can be interpreted in various ways:

- (a) That the objects are at cosmological distances and the redshifts are Doppler shifts associated with the expansion of the universe.
- (b) That the objects are moving at relativistic speeds and have been ejected from a center comparatively near to us - the center of our own Galaxy, or a nearby galaxy, and have all gone past us.
- (c) That the objects have been ejected from a variety of galaxies at relativistic speeds and that those which have a component of velocity towards us and thus should show blueshifts are not seen because of selection effects.
- (d) That the shifts are not due to the Doppler effect but are gravitational in origin.

Since this talk was given the author, together with E. M. Burbidge, has completed a monograph, "The Quasi-Stellar Objects" (W. H. Freeman, San Francisco, 1967), in which these topics are discussed more fully and in which full references are given

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The first two of these possibilities are directly compatible with the observations, and since all previous redshift measurements have been interpreted as due to the expansion of the universe it is natural from this point of view that (a) is preferred. As far as (c) is concerned it is now known that if QSO's are moving relativistically in all directions, having been ejected from many galaxies, then since blueshifted objects will appear much brighter than redshifted objects of the same intrinsic luminosity, if we survey to a given apparent brightness, we shall survey a much larger volume of space for blueshifted objects than for redshifted objects. It is then found that the theoretical ratio of blueshifted to redshifted objects is $(1+z_m)^4$, where z_m is the maximum redshift. Since $z_m \approx 2$, blueshifted objects should predominate about 80 to 1. Thus if this model is applicable there must be very strong selection effects at work so that only redshifted objects are seen. It can be shown that it will be very much more difficult to detect infrared lines which will be shifted into the visible region by the blueshift effect because they are much fewer than the lines seen in the ultraviolet, intrinsically weaker, and also the continuum flux may rise steeply into the infrared as it does in 3C 273. Thus such objects may appear to show no lines, but they will include some of the apparently brightest objects. Objects with small blueshifts should be detected, but none have been found so this is an objection to the argument given. Another possibility is that the radiation from the relativistically moving QSO is not emitted spherically symmetrically, in its own frame, but tends to be emitted backwards along the tail.

Finally, we may consider possibility (d). The alternative explanation is that the redshifts are gravitational in origin. There are severe spectroscopic difficulties associated with this interpretation but it is not safe to say that it can be ruled out entirely.

Luminosities and Radio Fluxes

The properties of the optical flux from the QSO's have been studied by means of UVB photometry, and in a few cases using spectrum scanners. Also, for 3C 273 we have flux measures in the infrared, and in the millimeter region. If the objects are at the distances given by their redshifts then the integrated optical luminosities are $\sim 10^{46}$ erg/sec. In the case of 3C 273, the total flux emitted is about 2×10^{47} erg/sec and the bulk of the energy is emitted in the infrared and millimeter regions. If the objects are comparatively close by at distances of about 10 Mpc, then the luminosities lie in the range $10^{42} - 10^{43}$ erg/sec, comparable with the energies emitted from the nuclei of Seyfert galaxies.

The radio fluxes from the QSO's are among the largest from radio sources. If the objects are at cosmological distances they lie in the range $10^{44} - 10^{45}$ erg/sec. If they are local their fluxes lie in the range $10^{40} - 10^{41}$ erg/sec, comparable with the weaker radio galaxies. Frequently at least one component of the radio source associated with a QSO is very small, less than 0.1". If the radio flux is all of synchrotron origin and if the objects are cosmological, then from arguments based on the size and synchrotron self absorption theory, we find that if the source is uniform the total particle energy content must be $\sim 10^{60} - 10^{61}$ ergs and the magnetic energy content several orders of magnitude less. A model of this type is, however, very unsatisfactory. Alternative suggestions have been made by Ginzburg and Ozernoy who have proposed that some part of the radio flux may be generated by coherent plasma oscillation mechanisms.

The spectral distribution of the energy emitted in the optical and infrared flux regions shows that the bulk of it is generated by a non-thermal process. It is almost certain that the synchrotron process is responsible.*

* Since this talk was given it has been found that the optical radiation from 3C 446 shows a high degree of linear polarization. This is strong evidence that it is synchrotron radiation.

As we shall see, this energy must be generated in an exceedingly small volume.

Variations in Flux

It appears that variability is a common property of the QSO's. 3C 48, the first QSO to be discovered, was found by Sandage to vary in light. It is well known that 3C 273 can be traced back on old plates some seventy years and varies by factors of the order of 2 over time scales of months and years. In many cases objects observed in successive observing seasons are seen to have changed in brightness though there has been little systematic study of variability involving many objects. The object 3C 345 was studied in detail by Kinman and Goldsmith in the summer of 1965 and it was found to increase in brightness by $\sim 0.4^m$ in about 20 days. It then declined, showing what appeared to be smaller variations on a shorter time scale. At the same time some spectroscopic variations were seen. Radio variations were first detected in 3C 273 by Dent, and Kellerman has described at this meeting a number of QSO's which are found to be varying at high frequencies.

The importance of the variation data is that they set an upper limit to the size of the object, independent of its distance. Unless the emitting surface is moving relativistically, or the objects consist of relativistically moving coherent blobs, the size $R \leq c\tau$, where τ is the time over which a significant change in flux occurs. For variable stars $R \leq 10^{-3} c\tau$. If the synchrotron process is responsible for the flux, then there are two processes at work in the region where the flux is being generated. These are (a) the synchrotron process, and (b) the inverse Compton process in which relativistic electrons lose energy by scattering of low energy photons. Now it is necessary, if the synchrotron process is to dominate, that the energy density in the magnetic field is greater than the energy density of photons, i.e.,

$$U_r < U_m, \text{ where } U_r = \frac{L}{\pi R^2 C} \text{ and } U_m = \frac{B^2}{8\pi} .$$

Suppose we choose a magnetic field such that the particles lose half their energy in traversing a distance R . This field is of the order of 0.1 gauss to give rise to photons in the infrared region. If now we suppose that the QSO's are at cosmological distances, and put $R \approx 10^{17}$ cm, based on variation data which suggests that significant variations occur in times of order one month, so that this is an upper limit, then we find that $U_r \approx 10^5 U_m$, where $L \approx 10^{47}$ erg/sec, which leads to a complete contradiction.

To avoid the difficulty we can suppose either that the objects are comparatively local, so that L is much reduced, or else that the magnetic field is much stronger than the value assumed above. In the latter case the magnetic field must be of order 50 gauss in order that $U_m \approx U_r$. If this approach is taken as is assumed by Shklovsky and Ginzburg, another complication must be considered. If the magnetic field is as strong as this then the half lives of the electrons (which now must be of lower energy to radiate in the observed frequency range) will be very short and will only be of the order of minutes or seconds. Thus if it were supposed that the electrons are injected at a single point, the size of the object would only be of the order of light minutes, and in this object the radiation density would be many orders of magnitude larger than it was previously and the contradiction would still be present. Thus it must be assumed, if the magnetic field is this strong, that electrons are injected, or continuously accelerated at many millions of injection points all through the object and then the radiation from them must be phased in such a way as to give the observed flux. Such a model is not out of the question but it is not clear whether it is acceptable. If this class of model is not acceptable, then this appears to be a strong indirect argument in favor of the idea that the QSO's are comparatively local objects.*

*The recent observations of variation in 3C 446 suggest that $R \lesssim 10^{15}$ cm. This places even more severe restrictions on the classes of QSO's at cosmological distances than the arguments given here.

It might be argued that perhaps the whole of the flux is generated by the inverse Compton process. This would require a model in which there was a central "machine" which generates a fantastic flux of very low energy photons. Also the electrons must be injected or accelerated through the object; otherwise, as has been discussed earlier for the synchrotron process, the contradiction will remain.

Thus these arguments based on the variation data set very severe limits on the classes of models of QSO's which are compatible with the idea that the QSO's lie at cosmological distances. However, since we do not understand the energy generating mechanisms in detail it cannot be said that such models are not possible. We simply do not know. It is equally unreasonable to argue that such models have to be right simply because one believes that the objects must be cosmological.

Absorption Features

When the first object with Ly α in emission was found, 3C 9, it was pointed out by Scheuer, and by Gunn and Peterson, that it might be possible to investigate the properties of the intergalactic medium by looking for the beginnings of the trough due to Ly α absorption by neutral intergalactic atomic hydrogen. Gunn and Peterson believed that they had found such an effect and deduced from it that the density of neutral hydrogen was only about 10^{-34} gm/cm³. However, studies of a number of objects in which Ly α in emission is seen have led the spectroscopists to the conclusion that there is really no evidence for this type of absorption measured by a depression in the continuum. This leads to the conclusion either that the density of intergalactic neutral hydrogen is less than $\sim 10^{-35}$ gm/cm³ or that the objects are comparatively nearby. Most theoreticians have taken this result to indicate that the intergalactic medium, which they assume to have

a density near 10^{-29} gm/cm³, is largely in the form of ionized gas. However, the other alternative is equally possible, and the refusal to take it seriously is a measure of the extent to which the cosmological interpretation of the QSO's has taken hold.

The suggestion that absorption lines might be produced in discrete clouds in the intergalactic medium was made by Bahcall and Salpeter, and by Shklovsky. However, the identification of the lines in 3C 191, the first QSO in which many absorption lines were found, showed that the redshift from them is in very close agreement with that for the emission lines. This indicates that both absorbing and emitting regions are associated with the object. In the case of PKS 1116+12 Bahcall, Peterson, and Schmidt have argued that the absorption lines found in this object either are intergalactic or, if they are associated with the object, they are due to a shell which has been ejected. In the latter case they conclude that if the QSO is local a very large mass must be involved and hence that this is an argument against the local hypothesis. I do not believe that this is a strong argument since it depends on many assumptions. At present we are really not clear as to the conditions under which the absorption lines are formed. For example, it could be that the absorption lines are formed in a region which is to be treated as the local standard of rest. In this case the emitting region is produced by gas falling into the object.

Koehler has claimed to have detected absorption of 21 cm radiation in the radio spectrum of 3C 273 at a redshift corresponding to the mean redshift of the Virgo cluster. Since 3C 273 lies in a direction a few degrees from the center of the Virgo cluster, this observation taken at its face value indicates that 3C 273 lies at a distance of a few Mpc from us. It certainly does not prove, as has been claimed by some, that it lies at the

distance given by its redshift. It does not even necessarily mean that it lies at a distance > 10 Mpc, the mean distance for the Virgo cluster, but only that the cloud giving rise to the absorption is part of the Virgo cluster which happens to have a velocity close to the mean. The distance must be of order $(10 \pm x)$ Mpc where x measures the size of the cluster or supercluster.

Distribution of QSO's

While there may be a very large population of QSO's, only a comparatively small number have positively been identified, and from these it is impossible to deduce anything very significant about their distribution over the sky. The radio sources taken as a whole show a fairly high degree of isotropy, but both radio galaxies and QSO's are included. The statistics from the identifications made in the 3C (revised) catalogue by Véron suggest that at that power level about $2/3$ are galaxies and $1/3$ are QSO's. If the QSO's are at cosmological distances they should be isotropic. If they are associated with comparatively nearby galaxies, then the brighter ones which have presumably come out of those galaxies will show a distribution reflecting their mode of ejection. However, fainter ones may have come out of a wider population of galaxies, and there will rapidly come a flux level at which the objects will become indistinguishable in their radio properties from the galaxies with which they are associated. Consequently, if the galaxies are isotropic the whole population will show an isotropic distribution.

Although no conclusions can be drawn about the whole sky distribution of the optically identified QSO's, Arp has drawn some very startling conclusions from his studies of the distribution of pairs of radio sources (one of which is sometimes a QSO) and peculiar galaxies. He believes that the occurrence of pairs of radio sources with separations of 1 to 3 degrees and

with the line joining them intersecting a certain type of peculiar elliptical galaxy is not due to chance and that this indicates that these radio sources have been ejected from the parent galaxies. I think that most of us are rather unhappy about the statistical analysis, but it may be that he is correct. If this is so, then the local origin of the QSO's will have been established. Since some radio galaxies are identified with the sources discussed by Arp, he has concluded that galaxies can be ejected from galaxies. This, however, is very hard to accept. If the QSO's are ejected from galaxies in the manner suggested by Arp, then the redshift-blueshift difficulties discussed earlier must be overcome, and I have already outlined the various possibilities.

The Log N - Log S Curve

Over the last decade many surveys of radio sources have been made and from these it is possible to investigate the large scale properties of the universe simply by counting the numbers of radio sources (N) observed at power levels greater than a flux level S at a given frequency. The only assumptions underlying this method are that the radio sources are indeed distributed through the extragalactic universe, and that we are looking at a volume distance effect. This means that on the average the fainter the object, the greater its distance. For a Euclidean universe, and for the steady state universe, the $\log N - \log S$ curve has a slope of -1.5 . However, the observed slope is about -1.8 . This result has been thought by many to be strong evidence against the simple steady state theory. However, Véron's separation of the identified 3C sources into the two categories of radio galaxies and QSO's, with different slopes in their $\log N - \log S$ plots, is exceedingly interesting. The slope of -1.5 for the radio galaxies is simply due to the fact that the Euclidean space approximation holds for them. It

is clear that for this sample of radio sources at least, the question of whether the slope of -1.8 is to be taken as evidence against the steady state model rests with the QSO's. Their slope could be due to cosmological effects of an evolutionary nature if they are at the luminosity-distances given by their redshifts, or it must be due to local effects.

A further point is of importance. If one plots the radio magnitudes of a sample of QSO's against redshifts (about 30 3C objects) one finds a complete scatter in the data points. At the same time these same objects give a $\log N - \log S$ curve whose slope is uncertain but which is near 2. About half the data used by Véron is included here. This result shows that whether the QSO's are local or cosmological, we are seeing a luminosity effect and not a distance volume effect. Thus this result cannot be taken as evidence that the QSO's are cosmological. The result can be explained on the cosmological hypothesis, or on the local hypothesis.

The Composition of the Quasi-Stellar Objects

Whether the QSO's are local or at cosmological distances they are a unique class of objects. Their energetic properties are such that it appears that the matter contained in them has gone through much more complex and violent evolutionary processes than the bulk of the matter which we see in the stars and gaseous nebulae in our own Galaxy. Moreover, if the objects are at cosmological distances we are looking, in the case of an object with a redshift $z \approx 2$, back to an epoch many billions of years ago. Thus, for a number of reasons, we might expect that the composition of the gas observed spectroscopically in the QSO's would be very different from that of the gaseous nebulae, and yet the compositions look comparatively normal. Also, if there is progressive enrichment of the elements heavier than hydrogen as a function of time we might have expected the objects with the largest

redshifts to have very different compositions from that of 3C 273, but no large effects are present. It seems to me that these arguments may favor the idea that the QSO's are nearby, but even so there are difficulties. Perhaps, whatever the nature of the QSO's, the gas that we see has been accreted by the central object and has never gone through the processes which the bulk of the mass must have experienced.

To summarize, it seems to me that the idea that the QSO's are local objects cannot easily be dismissed. We are all conditioned to interpret redshifts directly as due to the expansion of the universe, but this to a large extent is due to the age in which we live. There are, however, so many difficulties associated with all of the hypotheses that have been suggested that it may be a considerable time before the true nature of the quasi-stellar objects is understood.

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