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Quasi-Stellar Objects: Possible Local Origin

Ejection by a gravitational collapse may explain not only quasars but also many radio galaxies.

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The conventional interpretation of the red shift of quasi-stellar objects (quasars) as a Hubble shift continues to face serious problems. Each new discovery seems to rule out most previous models of these remarkable objects (*1*). The local model of quasars (*2–5*), discussed later in this article, avoids these difficulties. It gives a possible explanation not only of quasi-stellar objects but also of some of the most puzzling features of radio galaxies.

Difficulties of Cosmological Distance Assumption

The usual assumption (*1*) is that quasi-stellar objects are at the tremendous distances of billions of light-years given by the Hubble relationship of distance and recession velocity. The difficulties of this assumption have been pointed out many times (*2–5*), most recently by Hoyle and Burbidge (*4, 5*). The basic difficulty is that quasars are not even remotely of galactic size or nature, and thus may be local objects, with red shift due to relativistic velocities.

As Smith and Hoffleit first pointed out (*6*), the rapid light fluctuations (*6–10*) set an upper limit of a few light-days on the optical size (diameter of the optical light source) of these objects (*2, 3*); galaxies, by contrast, can be 100,000 light-years in diameter. No evidence that quasars are part of distant galaxies, or even in clusters of galaxies, has been discovered, whereas galaxies are routinely found to be in clusters (*11*). There is thus no a priori reason to believe that quasars are similar to galaxies, or at galactic distances. The quasars so far reported do not seem even to be in random directions from our galaxy, but it is difficult to establish to what extent this is due to normal observational avoidance of the galactic plane.

One of the most serious difficulties for the assumption of Hubble distances is the source of the resulting enormous light output of approximately 10^{46} ergs per second, equaling the brightness of 10^{12} suns, or 100 large galaxies, for millions of years. Such lifetimes would be required because of the continuing discoveries of jets or double radio sources of considerable angular extent associated with quasars. The quasi-stellar object 3C 47, for example, has two radio sources separated by 62 seconds of arc, or a million light-years if it is at a Hubble distance of 4×10^9 light-years (*12*). A satisfactory explanation of sources of such power and lifetime has yet to be produced.

Recently another difficulty for the cosmological distance assumption has been discovered. Schmidt's spectrum for 3C 9, one of the most red-shifted of quasars, does not show as much absorption on the blue side of the red-shifted Lyman-α line as had been expected (*13*). Either there is less neutral hydrogen near 3C 9 than had been expected, by a factor of at least 10^6, or 3C 9 is a local object, with red shift not due to Hubble's law. The spectrum, and the conclusions, seem to be much the same for other highly red-shifted quasars (*14*).

Another baffling problem has been the matter of radio-source counts. These have persisted in having slopes of about −1.8 on a logarithmic graph of number versus strength (*15*), whereas a uniform distribution in Euclidean space would lead to a slope of −1.5. The most recent count by Véron indicates a slope of −2.2 ± 0.2 for quasi-stellar and unidentified radio sources, as compared with −1.55 ± 0.05 for identified radio galaxies (*16*). Longair has found similar results (*17*). The radio-source counts and the lack of Lyman-α absorption have both helped to throw cosmology into turmoil (*4*).

The rapid light fluctuations mentioned above have long been a puzzle, and have forced a steady downward revision of estimates of the size of these objects. For a spherical radiating surface, of diameter D, which undergoes fluctuations in brightness that are in phase in its own reference system, the observed luminosity L cannot change more rapidly than the relativistic limit (*2*) given by

$$L^{-1}dL/dt \leqq 4c/D\,(1+z), \qquad (1)$$

where c is the velocity of light and z is the red shift due to recessional motion (see Eq. A-10 in the appendix). For more general cases, with D an effective diameter, Eq. 1 still represents a conservative physical limit for expected fluctuations (*2*). Equation 1 leads to optical sizes of the order of light-days (*2, 6, 7*) rather than the light-years assumed in earlier models (*1*). At the temperatures and densities indicated by the observed spectrum (*18*), the radiation of the light of 10^{12} suns would require an optical diameter of at least

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several light-weeks (*7*). Thus the diameter indicated by the fluctuations may not be large enough for radiation of the power required by the assumption of Hubble distances. A plausible model to reconcile the required optical radiation and the small size has not been easy to find (*18–20*).

Radio-Source Size Discrepancies

A similar difficulty for the *radio* source diameters of quasi-stellar objects has recently appeared. Unexpected variations in radio output have been reported by Sholomitskii (*21*), Dent (*22*), and others (*23–25*), leading to a drastic reduction in radio-size estimates. The radio diameters in several cases cannot be more than a matter of light-years, which is far less than had been originally expected (*18, 19*). Such a diameter may also be insufficient for radiation of the required power.

It seems clear that thermal radiation cannot account for either the shape of the radio spectra or the high brightness temperatures required—temperatures of at least 10^9 degrees Kelvin (*26*). The radio output is evidently synchrotron radiation from electrons spiraling within magnetic fields. Self-absorption sets a physical limit to the possible output power. Both Slish (*27*) and Williams (*28*) have given approximate relations between the angular size and the radio power received from synchrotron sources. [Because of the significance of the angular size, more exact relations have been worked out (*3*); they are given here in the appendix.]

The radio angular sizes of two quasi-stellar objects, 3C 273B and CTA 102, present serious difficulties for the assumption of Hubble distances. Dent (*22*) has estimated the angular diameter of 3C 273B, the starlike part of 3C 273, as $> 0.1''$, on the basis of Slish's formulas (*27*). Similar angular diameters have been estimated by Shklovskii (*20*) and by Menon (*29*). From the radio fluctuations which Dent reported, amounting to about a 17-percent increase per year at a frequency of 8000 megacycles per second (Mc/sec), he estimated a radio diameter of $<$ 13 light-years. As Dent stated (*22*), the combination of these two results would exclude a cosmological interpretation of the red shift. However, as Field (*30*) pointed out, there was evidently a numerical error in Dent's estimate of angular diameter θ. Field calculated θ to be $> 0.003''$, a value small enough to save the cosmological hypothesis.

A more accurate estimate of the angular diameter may be made from Eqs. A-11 and A-12 in the appendix, which have the virtue of being applicable to the flat spectrum of 3C 273B. The radio spectrum is observed to be relatively flat down to a frequency of 100 Mc/sec. (*31*). It is probably safe to assume an optical depth $\tau \leqq 1$ here, since $\tau = 1$ would correspond to a drop of 37 percent in signal strength (see appendix: $S/S^* = 0.632$ for $\tau = 1$, from Eq. A-7). The magnetic field H may be assumed to be at least 10^{-4} gauss, the value used by Slish (*27*) and Williams (*28*), since equipartition of field and particle energies would occur at values of H considerably higher than this (*18, 20*), and even larger values of H would be necessary to prevent escape of particles if 3C 273B were closer than is usually assumed. On the basis of the observed spectrum (*31*) we may assume the extrapolated flux $S^* \cong 30 \times 10^{-26}$ watt m^{-2} $(c/sec)^{-1}$ at 100 Mc/sec and a spectral index $\alpha \cong 0$. Equation A-11 then gives $\theta \geqq 0.04''$ at 100 Mc/sec. [This is consistent with the interferometer data of Adgie *et al.* (*24*), which indicate that 3C 273B is composed of two radio sources, each $< 0.1''$ in diameter, at 1420 Mc/sec.]

On the basis of Dent's measurement of a 17-percent increase per year (*22*), a red shift (*32*) of $z = 0.158$, and Eq. 1, it appears that 3C 273B must be less than 20 light-years in diameter at 8000 Mc/sec (*33*). A source of this maximum size, with $\theta \geqq 0.04''$, cannot be more than 10^8 light-years away. Thus these calculations lead to a discrepancy, of a factor of 15, with the usually assumed distance of 1.5×10^9 light-years [474 megaparsecs (Mpc)] given by a Hubble constant of 100 km sec^{-1} $(Mpc)^{-1}$.

In the case of the quasi-stellar object CTA 102, the discrepancy between the radio sizes and the assumed distance is much larger. Sholomitskii has reported large fluctuations in the radio strength at 920 Mc/sec, with a period of the order of 108 days (*21*). The most rapid changes have amounted to about 10 percent in 8 days, for which Eq. 1, with $z = 1.037$ (*34*), indicates a maximum diameter of 0.4 light-year; Sholomitskii estimated 0.3 light-year. The radio spectrum of CTA 102 is flat down to a frequency of 178 Mc/sec or lower (*35*) and seems to indicate an optical depth $\tau \leqq 0.5$ (21 percent absorption) at this frequency. Equation A-11, with $H \geqq 10^{-4}$ gauss, $S^* = 7 \times 10^{-26}$ watt m^{-2} $(c/sec)^{-1}$, and $\alpha \cong 0$, then yields an angular diameter $\theta \geqq 0.02''$ at 178 Mc/sec. This is larger than the estimates of $0.01''$ made by Slish (*27*), Williams (*28*), and Menon (*29*) on the basis of different equations, but is still consistent with the interferometer result, $\theta < 0.1''$ at 1420 Mc/sec (*24*).

Thus, if the maximum diameter of 0.4 light-year and the minimum angular diameter of $0.02''$ refer to the same diameter, CTA 102 can be no farther away than 4×10^6 light-years, which is less than the usually assumed distance by a factor of at least 1000.

Hoyle and Burbidge (*5*) have discussed a way of salvaging the cosmological hypothesis in the face of these conflicts, at least for the case of 3C 273B. They consider a model in which the size of the synchrotron source varies with frequency because of variations of magnetic field H with radius r. The predominant frequency radiated by electrons of energy E in a magnetic field H is proportional to E^2H, as discussed in the appendix. Hoyle and Burbidge calculate that a spherically symmetrical synchrotron source in which the magnetic field varies as r^{-n} and the electron density as r^{-m} would produce a radio spectrum of the form $\nu^{(n+m-3)/n}$, which would be flat for $n + m = 3$. This result needs correction for self-absorption effects, since at any frequency a large fraction of the output would come from the far interior of this model. The assumptions are also clearly untenable for very small values of r.

Hoyle and Burbidge are in any case correct in their basic point, that the size of the synchrotron source can be a function of frequency. Somewhat similar calculations based on a combination of synchrotron sources of different sizes, such as a high-frequency core inside a low-frequency shell, have been made by Rees and Sciama (*36*), by Maltby and Moffet (*23*), and by Field (*30*). The greatest possible success in reconciling radio-size data and cosmological distance would be achieved with an extreme multiple-source model, in which the effective source size would be near the minimum possible for each frequency, with large effective optical depth τ throughout the radio-frequency range. No synchrotron source model, however, can lead to an angular diameter less than that given by Eq. A-11, with $\tau >> 1$, or $S \cong S^*/\tau$, from Eq. A-7.

As an example of this minimum angular diameter, let us consider the fluctuations of 3C 273B reported at 1420 Mc/sec by Adgie *et al.* (*24*). Their data indicate changes in strength of about 10 percent per year, giving a maximum diameter of 35 light-years (from Eq. 1). If the source is assumed to be optically thick at this frequency, the measured flux $S \sim 27 \times 10^{-26}$ watt m^{-2} $(c/sec)^{-1}$ can be set equal to S^*/τ. Equation A-11 then gives $\theta \geqq 0.002''$ at 1420 Mc/sec. These figures correspond to a maximum distance of 4×10^9 light-years, slightly greater than the Hubble distance of 1.5×10^9 light-years. For the 8000-Mc/sec fluctuations reported by Dent (*22*), the calculated maximum distance would be even greater. Thus the concept of Hubble distance is at least momentarily safe in this case.

The situation is different for CTA 102. Even if the source is required to be optically thick at 920 Mc/sec, the frequency at which Sholomitskii reported fluctuations (*21*), Eq. A-11 gives a minimum angular diameter of $\sim 0.002''$. Together with a maximum diameter of 0.4 light-year, this gives a maximum distance of 4×10^7 light-years, in absolute conflict with a cosmological distance approaching 10^{10} light-years.

However, Maltby and Moffet, Dent, Kellermann, and others have all been unable to detect any significant radio fluctuations in CTA 102, at various frequencies and times (*37*). It is not clear whether there is a direct conflict with Sholomitskii's data in these instances. It is clear that either Sholomitskii's data or the cosmological distance hypothesis must be rejected. Many people prefer to reject the data (*36*).

Possibility of Local Origin

A local model of quasi-stellar objects does not face the difficulties of the Hubble-shift model. The possibility of a gravitational-red-shift explanation has been ruled out on spectroscopic grounds, in the classical paper of Greenstein and Schmidt (*18*). The alternative possibility that quasi-stellar objects could be local, rapidly moving, objects was at first also ruled out (*18*), on the ground that no proper motion (change of angle of observation) could be detected (*38, 39*). However, it was later pointed out by Terrell (*2*) that little proper motion would be expected if the objects had originated in an explosion at the center of our own galaxy and had now moved well outside the galaxy.

A relativistic calculation of the proper motion which would then be observed is thus of interest. Consider an object which originated at the galactic center, a distance R from the sun, and is now seen to be at an angle θ from the direction to the galactic center, to have a proper motion rate $d\theta/dt \equiv 1/T^*$, and to have a red shift z due to recession. The time T from the explosion to the present, in our reference system (relative motion of the sun and galactic center is neglected in these calculations), is given by

$$cT = [R/(2z+z^2)]\{-\cos\theta \pm (1+z) \times [\cos^2\theta + (2z+z^2)(1+2cT^* \sin\theta/R)]^{1/2}\} \quad (2)$$

The distance r to the presently observed (retarded) position of the object may be shown to be:

$$r = RcT^* \sin\theta/(cT - R\cos\theta). \quad (3)$$

The velocity of ejection βc may then be found from the relation

$$\beta = [R^2 + r^2 - 2Rr\cos\theta]^{\frac{1}{2}}/(cT - r). \quad (4)$$

To apply these formulas to the brightest, slowest, and presumably closest quasi-stellar object, 3C 273, we may take $z = 0.158$ (*32*), $\theta = 81.4°$, $R \cong 27{,}000$ light-years, and $d\theta/dt \leqq 0.002''$ (10^{-8} radians) per year. Equations 2 and 3 then give $r \geqq 600{,}000$ light-years (180,000 parsecs), and $T \geqq 5 \times 10^6$ years. These limits on r and T are based on proper-motion data of Jefferys (*38*) and would be smaller by a factor of about 2 on the basis of Luyten's observations (*39*). The value of β given by Eq. 4 (0.1458) is similar to the value which Eq. A-10 would yield for purely recessional motion (0.1457). The minimum distance of 600,000 light-years is relatively small, less than the 1.6 million light-years to the nearest major galaxy, Andromeda. However, it is considerably larger than our galaxy, so there would be no reason to expect highly blue-shifted objects to be observed now moving toward us from such an explosion.

It is interesting to note that a time of about 5 million years ago is similar to the time of $\sim 10^7$ years ago suggested by Burbidge and Hoyle (*40*) and by Oort (*41*) for the origin of the hydrogen gas clouds (total mass perhaps 10^7 solar masses) observed to be moving away from the galactic center. If all observed quasi-stellar objects were also ejected at that time, the velocity and (present) distance would have the same proportionality as in the Hubble law for galaxies, but the time scale would be perhaps 2000 times smaller. The *observed* distances r would all be less than $cT/2$, or 2.5×10^6 light-years, due to retardation of signals.

Gravitational Collapse as Source

Only a gravitational collapse, it would seem, could produce the required speeds of massive objects, on this hypothesis. If a gravitational collapse has indeed taken place, there should still be a considerable mass at the center of our galaxy. The radio observations of motion near the galactic center (*41*) are consistent with a central mass of as much as 10^9 solar masses. With a local origin the quasi-stellar objects would have a mass of 10^3 to 10^4 solar masses (as is discussed below), so that a central mass of 10^9 solar masses should be adequate for the ejection of a considerable number of such objects.

Such a gravitationally collapsed galactic center would have dimensions not much larger than the Schwarzschild radius, which amounts to 2.7 light-hours for 10^9 solar masses, and, from our distance of $\sim 27{,}000$ light-years, would subtend an angle of $0.002''$. There is a strong radio source (Sagittarius) at the galactic center, but optical observations of the center are not possible because of obscuration.

Violent explosions at the centers of galaxies seem now to be of almost universal occurrence (*42*). Recently recognized examples include M 82 (*43*) and the Seyfert galaxy NGC 1275 (*44*). Ejected masses of gas amounting to 10^7 solar masses, with velocities of several thousand kilometers per second and time scales of a few million years, seem to be common features. It has been suggested (*42, 45, 46*) that Seyfert galaxies, with exceedingly bright nuclei, may be examples of galaxies undergoing gravitational collapse, and may be a phase through which most galaxies go repeatedly. Hoyle and Fowler have also suggested masses up to 10^8 solar masses at the centers of radio galaxies, serving as energy sources (*45*).

Various mechanisms have been proposed for the ejection of large masses by a gravitational collapse, particularly in the presence of rotation. Among the possibilities are reduction of the gravitational potential of the outer parts of the collapsing mass, either by emission of mass as neutrinos (*47*) or by collapse of a disk-shaped rotating center. Other possibilities include fission into two or more parts, because of gravitational instabilities (*45*), or ejection of matter along the axis of rotation (*48*).

Properties of Local Quasi-Stellar Objects

Thus it seems reasonable to assume that gravitational collapse could have occurred at the center of our galaxy, leading to the ejection of the observed quasi-stellar objects (*2, 3*). This local model reduces the energy requirement for the radiation from quasi-stellar objects by a large factor—by almost 10^7 for an origin 5×10^6 years ago. The total radiation emitted by 3C 273 (if local) over 5×10^6 years, at the present rate of emission, would amount to less than the equivalent of one solar mass (2×10^{33} grams). A quasi-stellar object with mass of the order of a few thousand solar masses could easily produce such amounts of radiation by ordinary nuclear processes, which can release nearly 1 percent of the mass as other forms of energy.

The catastrophic collapse of such a massive object or collection of objects would be most readily prevented by rotation, which would produce a disk-like shape (*46*). The extraordinary optical line width of quasi-stellar objects, corresponding to a velocity spread of several thousand kilometers per second (*18, 49*), is also most readily explained by rotation. High temperature is not a likely explanation, as $\sim 10^9$ degrees Kelvin would be required. Continuous expansion of the surface (*49*) would not be a possible explanation for a long-lived object having a diameter amounting to light-days or less (*50*).

If rotation is thus assumed to be the cause of the large line width (*7*), it is possible to estimate the mass of a quasi-stellar object. Smith (*7*) has estimated that the area of radiating surface needed to produce the optical spectrum of 3C 273 has a minimum diameter of about 15 light-days, for the usually assumed distance. This diameter would be reduced to about 11 light-minutes for the local model, for $T = 5 \times 10^6$ years; a slightly larger diameter would be required for a radiating surface less optically thick. A rotating object of such size in which the outermost parts were moving at a velocity v of the order of 1000 kilometers per second and were just held in orbit at radius r by gravitational forces would necessarily have a mass ($\sim v^2r/G$, with G the gravitational constant) in the range 10^3 to 10^4 solar masses. Such a mass could easily produce the required radiation, as we have seen. It is interesting to note, from the equation given by Roxburgh (*51*), that a rotating main-sequence star of such mass would also necessarily have such a diameter.

The unexpected rapid changes in optical line structure and the few-week "cycle" of brightness reported (*10*) for the quasar 3C 345 could readily be accounted for in terms of rotation, since the rotational period of an object of the size and surface speed considered here would also be of the order of weeks.

The radio output power of such a quasi-stellar object might be due basically to passage of the object, or of jets spun off from it, through intergalactic gas. The relativistic velocities transferred to the gas would result in radiation, a part of which would undoubtedly be synchrotron radiation. If the gas density were the typically assumed cosmological density $\sim 10^{-5}$ atom per cubic centimeter (and it might be higher near a galaxy) then the observed power of quasars would be accounted for if the relativistically moving local object interacted strongly with all the gas within a radius of the order of a light-year. Such interaction could occur at this gas density if magnetic fields of the order of 10^{-4} gauss—sufficient to withstand the shock-wave pressure—extended out to this distance. It is interesting to note that this is also about the maximum size indicated by fluctuations of radio signals, as discussed above.

Thus the radio output of quasi-stellar objects, or of jets ejected from them, could be readily accounted for on this basis. The kinetic energy of such objects would be sufficient to furnish the radio power for as much as 10^9 years. The range of radio strengths found for quasars, as well as fluctuations of strength with time, could also be accounted for in a number of ways, such as nonuniform density of intergalactic gas, or varying magnetic fields. Such factors would tend to limit the correlation of radio output with velocity which would otherwise be expected on the basis of this model. However, there does appear to be some correlation of radio output and red shift, or at least a lack of correlation between *received* radio strength and red shift (*52*).

The blue stellar objects with large red shifts but little radio output reported by Sandage (*53*) could probably also be accounted for by this model. Little is yet known of their characteristics, although there are evidently many thousands of them. The original estimate of hundreds of thousands (*53*) has been considerably reduced by later evidence (*54*). Even if all of them were essentially radio-quiet quasars, there would not necessarily be an energy problem produced by assuming their ejection from a gravitationally collapsing galactic center with total mass 10^9 solar masses.

Objections to the Local Model

One common objection to the local model of quasi-stellar objects is the question of whether massive self-gravitating bodies could actually be ejected at high speed from a gravitational collapse. There seems little doubt that matter could be ejected from a gravitational collapse, as discussed above. However, it may be argued that temperatures and random velocities within ejected parts would be too high to permit any coherence.

The dynamics of rotating collapse, especially in general relativity theory, are too complex to yield easy answers to this question. However, it would seem that local turbulence, velocity-sorting, gravitational instabilities (*45*), or other effects could reasonably lead to the production of coherent masses. It may be significant that the optical dimensions approaching a light-hour that are calculated for quasars on the basis of this model are similar to the dimensions of the gravitational collapse necessary to eject them, also a matter of light-hours (as would be likely if condensation followed ejection).

Another objection to the local model of quasi-stellar objects is based on the recent data of Koehler (*55*) on absorption in the vicinity of the 21-centimeter (1420 Mc/sec) line of hydrogen for 3C 273. His data show a drop of up to ½ percent in the radio spectrum at Doppler-shifted frequencies corresponding to recession velocities averaging $\sim$ 1400 kilometers per second. The absorption line is rather broad, corresponding to a velocity spread of the order of 1000 kilometers per second. The velocity is roughly that of the Virgo cluster of galaxies, near the direction of 3C 273, and about 4×10^7 light-years (12 Mpc) away. Hence the data have been interpreted as proving that 3C 273 is at least this far away (*55, 56*). A similar absorption (*55, 57*) is found for the radio galaxy Virgo A (M 87).

Koehler's data indicate that there is a receding neutral hydrogen cloud in the line of sight to 3C 273 and Virgo A. The assumption that this gas cloud is part of the Virgo cluster seems to be in serious conflict (*58*) with the Lyman-α spectrum of 3C 9, which indicates (on the basis of Hubble distance for quasi-stellar objects) almost no neutral intergalactic hydrogen.

It thus seems more reasonable to assume that the hydrogen cloud is associated with our own galaxy, and is not far away. Such clouds have been observed leaving a number of other galaxies at several thousand kilometers per second, as discussed above (*42–44*). There are lower-velocity hydrogen clouds near the nucleus of our own galaxy, evidently ejected at several hundred kilometers per second about 10^7 years ago (*40, 41*). If our galaxy had also ejected, at this time, high-velocity clouds such as those ejected from other galaxies, the effects produced would be just those reported by Koehler. The time interval is long enough to have allowed the hydrogen to move from the galactic center to our line of sight to 3C 273, about 26 degrees from the galactic pole.

If the hydrogen clouds were thus ejected $\sim 5 \times 10^6$ years ago, perhaps at the same time as quasars, those portions having a velocity of 1600 or more kilometers per second would have moved far enough out by now to appear on the line of sight to 3C 273, as calculated from Eqs. 2–4, with R = 27,000 light-years and $\theta = 81.4$ degrees. The purely recessional velocities which would be calculated (Eq. A-10) from Doppler shifts now observed in such clouds would range from zero, for hydrogen moving nearly perpendicularly to the line of sight, to several thousand kilometers per second for hydrogen ejected more nearly along the galactic axis. A Doppler shift corresponding to the average recessional velocity of 1400 kilometers per second observed by Koehler would then correspond to a full velocity of 2100 kilometers per second and a presently observed (retarded) distance of 27,000 light-years, in the direction of 3C 273. Doppler shifts nearly equal to zero would perhaps not be observed, because hydrogen moving so close to the galactic plane would encounter more interfering matter. The hydrogen clouds ejected from other galaxies are also found to be moving in the general direction of the galactic axis (*43, 44*).

Thus Koehler's results may perhaps most reasonably be interpreted in terms of a hydrogen cloud ejected from our own galaxy a few million years ago, in a manner similar to events observed in other galaxies. His data are thus not only not in conflict with the local model of quasars but may even lend support to the hypothesis of a catastrophic explosion at the center of our galaxy.

Another objection, often raised against the local model of quasi-stellar objects, is this: Why are such objects not seen ejected from galaxies other than our own, perhaps with blue shifts (*59*)? This should not be a serious objection, considering the difficulty of identifying many of the quasars which may have come from our own galaxy. If their distance scale and brightness are determined on the basis of ejection 5×10^6 years ago, similar objects near other galaxies would be identifiable only for a few of the nearest galaxies. Thus optical discovery of such objects could not be guaranteed, on the local model. However, their radio output should be detectable, and may have been detected (see below).

Many other objections to the local model have, of course, been raised. Some of these are now recognized to be invalid, some are considered at least implicitly in other sections of this article, and some are matters of personal taste.

An Explanation for Radio Galaxies

The radio output of quasi-stellar objects ejected from other galaxies would be more easily detectable than their optical output, particularly if a galaxy has emitted large groups of such objects. The radio output of quasi-stellar objects, on the basis of the local model, would be of the order of 10^{37} or 10^{38} ergs per second, less by several orders of magnitude than that of radio galaxies, which typically have a radio power of 10^{40} to 10^{44} ergs per second (*60*).

Radio galaxies thus might be explained, at least in many cases, as galaxies which have emitted groups of quasi-stellar objects. This could explain the peculiar location of the radio sources associated with the strong radio galaxies (*60*). In many of these galaxies the radio sources are double or multiple, symmetrically placed well out from the galaxy, and usually near the galactic axis of rotation. In the case of Cygnus A the two radio sources are about 100,000 light-years away from the galaxy, a fact which has more or less ruled out (*42, 44*) the earlier explanation of the unusual radio strength as due to colliding galaxies. In another case, the nearby galaxy Centaurus A (NGC 5128), there are at least four such external radio sources, extending out to a million light-years from the galaxy (*60*). Arp has recently reported evidence that peculiar galaxies are associated with multiple radio sources extending out even to 10^7 light-years or more. (*61*).

It is thus apparent that violent events have taken place in the nucleus of many galaxies, ejecting strong radio sources to great distances, generally along the galactic axis (*42, 45, 60–62*). The explanation of these phenomena, and of the source of such radio power, has been a matter of considerable difficulty. If the quasi-stellar objects observed were ejected from our own galaxy, it would be natural to suppose that other galaxies would also eject such groups of massive radio sources. This would solve at one stroke the problems of the strange location and great power of the radio sources in many galaxies. Possibly only massive objects could attain such distances. On the basis of this theory the kinetic energy of the ejected objects would be the basic source of radio power.

Conclusion

Thus, the hypothesis that the observed quasi-stellar objects were ejected from a gravitational collapse at the center of our galaxy (*2*) has the possibility of resolving many difficulties simultaneously, for both quasars and radio galaxies. It thus has the great attraction of giving a unified picture for perhaps most of the astronomical radio sources observed. The alternative possibility suggested by Hoyle and Burbidge (*5*)—that the nearby radio galaxy NGC 5128 (Centaurus A) is the source of the observed quasi-stellar objects—has some of these same virtues, but has the difficulty of much larger power and mass requirements, and thus is less plausible physically (*63*).

Further observation of quasi-stellar objects and blue stellar objects will no doubt produce crucial evidence for or against the local hypothesis, as discussed by Hoyle and Burbidge (*5*). Local origin would be disproved by definite association with distant galaxies or clusters of galaxies, for instance. Cosmological distance would be ruled out by evidence of asymmetrical distribution, blue shifts, or more rapid fluctuations in either radio or optical strength. It might even be possible to detect changes within the long jets emitted from 3C 273 and other quasars, if they represent relatively recent events.

Summary

Many difficulties face the conventional interpretation of the red shift of quasars as a Hubble shift, with associated immense distances. These objects are not of galactic size or nature, and are not associated with galaxies or clusters of galaxies. The continuing energy source for such enormous powers for a period of 10^6 to 10^7 years has not been clearly revealed. The absence of the expected absorption for the Lyman-α spectral line of hydrogen is a new difficulty. Because of the relativistic limit on the diameter which can produce rapid fluctuations of light output, there may not be enough surface to radiate the required light.

A similar and perhaps more serious difficulty exists for the fluctuating radio output. Calculations given here for synchrotron radiation self-absorption lead to a reasonably accurate formula for the angular diameter of a radio source. For the quasar 3C 273B these relations indicate a conflict with the usually assumed distance. However, the discrepancy may be explained in terms of strong variation of radio diameter with frequency. For CTA 102 the conflict is more serious, and could be explained —for cosmological distance—only by rejecting the data of Sholomitskii.

These difficulties are removed by the hypothesis that the observed quasars were ejected from a gravitational collapse at the center of our own galaxy, which may have occurred roughly 5 million years ago. The resultant distances, of the order of a million light-years, reduce the energy problem by a factor of 10^6 or 10^7. On this basis the optical diameter would be less than a light-hour, about the size of the earth's orbit. A rotating mass of a few thousand solar masses with this diameter would account for the unusual line width, could easily produce the required radiated energy, and could readily account for observed short fluctuation periods and variations in spectrum.

It is suggested that the radio output may be produced by high-speed passage of the quasar through intergalactic gas. This would probably correspond to a radio size of a few light-years or less, in agreement with the fluctuations. Since the radio power would be considerably less than that of radio galaxies, it is suggested that radio galaxies may have ejected groups of quasars. This would explain the peculiarly distant locations of the radio sources for many such galaxies.

The objections to this model that have been raised are apparently not fatal. In particular, the receding hydrogen cloud discovered by Koehler to be in the line of sight to 3C 273 is more plausibly interpreted as having been ejected from our own galaxy, in the manner observed for other galaxies, than as being associated with the Virgo cluster of galaxies. The latter interpretation, which would place 3C 273 further away, is in conflict with Lyman-α absorption data for 3C 9 and other quasars.

Thus the local model seems to give a reasonable explanation not only of quasars but also of radio galaxies, both of which seem largely to defy explanation on other grounds. Whether or not this model is valid, it is clear that an understanding of quasars will radically change our understanding of the universe.

Appendix: Angular Size of a Synchrotron Radiation Source

Many good discussions of synchrotron radiation emitted by ultrarelativistic electrons in the presence of magnetic fields have been published (*8, 35, 43, 64–66*). The present discussion is intended primarily to clarify the limits on angular size of astronomical synchrotron sources (*3*).

The surface brightness of a synchrotron source is limited by self-absorption, just as thermal radiation from a black body is. The most complete calculations on self-absorption of synchrotron radiation are those published by Le Roux (*64*) and by Ginzburg and Syrovatskii (*65*), based on the earlier work of Schwinger and others (*66*). Schwinger was the first to calculate the spectrum and angular distribution of radiation emitted by an electron of ultrarelativistic total energy E (much larger than its rest-mass energy m_0c^2), in a magnetic field H. The radiation spectrum has its maximum, and its average frequency, near the "critical frequency" $(3\nu_0/2)(E/m_0c^2)^2$, in which ν_0 is the cyclotron frequency of nonrelativistic electrons of charge e, given by

$$\nu_0 = He/2\pi m_0c. \qquad \text{(A-1)}$$

The rate of absorption of radiation by the same electrons can be calculated from the relations between Einstein transition probabilities.

For an astronomical synchrotron source the basic problem then is one of multiple integrals over the electron energy spectrum and over the relative angles of electron motion, magnetic field, and radiation. Le Roux's results for a uniform source, with random directions of magnetic field, may be written (in Gaussian units) in the form:

$$S^*(\nu) = (ae^2Al/r^2c)\nu_0{}^{\alpha+1}\nu^{-\alpha}\varphi(\alpha) \qquad \text{(A-2)}$$

$$\tau(\nu) = (ae^2l/m_0c)\nu_0{}^{\alpha+(3/2)}\nu^{-\alpha-(5/2)} \times (\alpha+\tfrac{3}{2})\varphi(\alpha+\tfrac{1}{2}). \qquad \text{(A-3)}$$

In these equations S^* is the energy flux density per unit frequency range which would be received at frequency ν, in the absence of self-absorption, from a synchrotron source of visible area A, line-of-sight thickness l, and distance r. The optical thickness τ is the product of absorption coefficient and path length l. The quantity a is proportional to the electron density: the electron energy spectrum per unit volume is taken to be of the form

$$N(E) = (a/m_0c^2)(E/m_0c^2)^{-\gamma} \qquad \text{(A-4)}$$

where γ is the electron spectral index. The quantity α is the radio spectral index observed for frequencies high enough not to be affected by self-absorption (that is, for $\tau << 1$), for which the observed radio flux S is proportional to $\nu^{-\alpha}$ with α related to the electron spectral index γ by

$$\gamma = 2\alpha + 1. \qquad \text{(A-5)}$$

Thus, experimentally, S^* may be determined by extrapolation as $\nu^{-\alpha}$ from frequencies above the region of self-absorption. Finally, $\varphi(\alpha)$ is a numerical factor given, in the explicit form due basically to Ginzburg and Syrovatskii (*65*), by

$$\varphi(\alpha) = (\tfrac{1}{16})(3\pi)^{1/2}\,3^{\alpha}\Gamma(\tfrac{1}{2}\alpha+\tfrac{1}{2}) \times \Gamma(\tfrac{1}{2}\alpha+\tfrac{1}{6})\,\Gamma(\tfrac{1}{2}\alpha+\tfrac{11}{6})/\Gamma(\tfrac{1}{2}\alpha+2). \qquad \text{(A-6)}$$

Self-absorption of synchrotron radiation, which will necessarily occur if a source of given strength is small enough, reduces the observed radio flux from S^* to S, given by

$$S = (S^*/\tau)\ (1 - e^{-\tau}). \qquad \text{(A-7)}$$

For sufficiently low frequencies the self-absorption is high (optical thickness $\tau >> 1$), and the radio spectrum is thus of the form S^*/τ, proportional to $\nu^{5/2}$ regardless of the electron energy spectrum. This limiting flux density S^*/τ may be seen, from Eqs. A-2 and A-3, to be proportional to the solid angle A/r^2 of the source, and has the advantage of not involving either the unknown electron density constant a or the depth l.

Thus the effective angular diameter θ may be calculated to be given by

$$\theta^2 \equiv \frac{4A}{\pi r^2} = (S^*/\tau)\nu^{-5/2}\,(He/2\pi m_0^3 c)^{1/2} f(\alpha), \qquad \text{(A-8)}$$

where the numerical factor $f(\alpha)$ is given by

$$f(\alpha) = (4\alpha + 6)\ \varphi\ (\alpha + \tfrac{1}{2})/\pi\varphi(\alpha) \qquad \text{(A-9)}$$

Finally, these results need a relativistic correction term if they are to apply to a synchrotron source receding at velocity βc, with a Doppler red shift z given by

$$1 + z \equiv \lambda/\lambda_0 = [(1+\beta)/(1-\beta)]^{1/2}, \qquad \text{(A-10)}$$

in which λ and λ_0 are the observed and unshifted wavelengths, respectively. The term necessary to correct for the effect of relativistic motion on the observed radio spectrum and angular diameter θ, in Euclidean space, is of the form $(1 + z)^{1/2}$, and was first given by Slish (*27*). With this correction, and with numerical values of constants, Eq. A-8 becomes

$$\theta^2 = 1.837 \times 10^{33}\ (S^*/\tau)\ \nu^{-5/2} H^{1/2}\ (1+z)^{1/2} f(\alpha), \qquad \text{(A-11)}$$

with θ expressed in radians, S^* in watts per square meter per cycle per second, and H in gauss (*3*).

The numerical factor $f(\alpha)$ may be calculated from Eqs. A-6 and A-9, and may be represented with error less than 1 percent in the range $-0.25 \leq \alpha \leq 1.50$ by the least squares fit

$$f(\alpha) \cong 0.85 + 2.63\alpha + 0.33\alpha^2. \qquad \text{(A-12)}$$

Equations A-11 and A-12 permit estimation of the angular diameter θ for any synchrotron source, given sufficient information about its spectrum. The chief unknown in determining θ is the magnetic field H. It could be estimated from equipartition of energy, and has sometimes been taken as $\sim 10^{-4}$ gauss (*27, 28*). The uncertainty in H is not a crucial matter, since θ is proportional to $H^{1/4}$.

Slightly simpler equations may be derived which are applicable only at the frequency ν_m for which the radio spectrum $S(\nu)$ has its maximum (possible only for $\alpha > 0$). From Eqs. A-2, A-3, and A-7 it may be shown that the optical depth τ_m at this maximum point is given by the relation

$$e^{\tau_m} - 1 = \tau_m\,[1 + (2\alpha/5)]. \qquad \text{(A-13)}$$

Evaluation of $f(\alpha)/\tau_m$ reveals it to be equal to 6.1 to within $\pm$ 4 percent for $0.5 \leq \alpha \leq 1.50$, so that a simplified form of Eq. A-11 can be written, with this substitution. Similarly, $S^* f(\alpha)/\tau$ in Eq. A-11 can be replaced by 8.2 S_m ($\pm$ 9 percent), with S_m the observed flux at the frequency ν_m, for $0.25 \leq \alpha \leq 1.25$. However, the equations derived in these ways should not be used for very flat spectra ($\alpha \sim 0$), as they would be considerably in error in this case.

Slish (*27*) and Williams (*28*) have derived equations of these forms, valid for $\nu = \nu_m$, but without accurate evaluation of the numerical factor. Both of Slish's equations give values of θ^2 too low by a factor of about 10. Williams's equations are more accurate. Menon, Shklovskii, Scheuer, Moffet, and Ginzburg and Ozernoy have also given approximate relations (*29, 67*).

However, Eqs. A-11 and A-12 furnish a more accurate basis for calculations of θ, with τ estimated from Eqs. A-7 or A-13, and are also valid for relatively flat spectra, such as those of the quasi-stellar objects 3C 273B and CTA 102. These equations give generally larger angular diameters than have been previously calculated.

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Circular Dichroism of Biological Macromolecules

Circular dichroism spectra of proteins and nucleic acids provide insights into solution conformations.

Sherman Beychok

In the continuing search for relationships between structure of biological macromolecules and their function, the study of conformation in solution must play a leading role. For many years, there was simply no objective method of discerning the three-dimensional arrangements of molecular groups within the macromolecular substance, and solution investigations were largely restricted to description of gross hydrodynamic properties. It is only within the last 10 years that investigators have succeeded in establishing experimental techniques for estimating, with a high degree of confidence, the number of amino acid residues in a protein which are present in the highly ordered periodic arrangement of the α-helix. This outstanding feat was accomplished, in large measure, by the analysis of the optical rotatory dispersion spectra of polypeptides and proteins (*1*), just prior to the dramatic and pioneering elucidation of the crystal structure of myoglobin (*2*). On the basis of correlation with the structure established by x-ray analysis (*3*), it later became possible to assign the sense of helix (right-handed in myoglobin), as well as content of helix, in other proteins and polypeptides. Not the least interesting aspect of these studies was the demonstration that helix content of myoglobin (secondary structure) was essentially preserved on passing from the wet crystalline state to a solution of the protein at high dilution (*3*).

There is, today, much interest in a still more particular aspect of structure-function relationship—namely, the possible conformational alterations which accompany interaction of the biological macromolecules with other cellular constituents. Studies of changes in optical activity appear to offer much hope of detection of change in the fraction of residues within α-helical segments which occurs consequent to a particular interaction (one such case is described below). In addition, circular dichroism spectra appear to shed light on structural alterations in proteins which are not primarily due to overall change in helix content, but rather are due to local, confined changes at particular sites which may not importantly affect any periodic or nonperiodic arrangement of peptide bonds. Clearly, studies of enzyme complexes, organized protein structures (subunit structures), polypeptide hormone interactions, and antibody-antigen complexes are examples of cases in which detailed studies of optical activity may be valuable aids in gaining the understanding we seek. In nucleic acids and polysaccharides in solution, elements of order—or periodicity—are well discerned by measurements of optical activity, and it may be that more subtle aspects of structure, too, will yield to sensitive measurements of optical activity. Finally, all the biological macromolecules have the characteristic ability of inducing asymmetry in small bound molecules which are symmetric in the unbound condition. The nature of the induced asymmetry depends on the asymmetry

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