YOUNG GALAXIES, QUASARS AND THE COSMOLOGICAL EVOLUTION OF EXTRAGALACTIC RADIO SOURCES

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The V/V_{max} test for quasars and the counts of radio sources show that the most powerful extragalactic radio sources exhibit strong evolutionary changes with cosmological epoch (see M. Schmidt and J.V. Wall et al., this volume). It should be emphasised that these are very large changes indeed. Schmidt, for example, has shown that for the world model with $\Omega = 0$, evolution functions of the form $F(t) \propto \exp(-10t/t_o)$ can account for the observations, t_o being the present epoch and t cosmic time. Since the quasar population from which this law is derived extends at least to Z = 2.5, corresponding to $t = t_o/3.5$ if $\Omega = 0$, the comoving space density of quasars at Z = 2.5 must have been about 1300 times greater than it is at the present epoch. It is not known whether or not this law continues to hold at larger redshifts but even if it does, the increase in comoving space density from Z = 2.5 to infinity is only a further factor of 17. Therefore the bulk of the evolution occurs within the range of observationally accessible redshifts. Notice that a characteristic time-scale for the decay of the quasar population of $\approx t_o/10 \approx 10^9$ years comes out of this analysis.

These evolutionary changes are empirical results derived from observation but there has been little interpretation of their cosmological significance. This is because neither the theory of the origin and evolution of galaxies nor that of radio sources is in a state where it can account for the properties at a single epoch, let alone how they might change with time. Nonetheless, speculation about the signficance of these results may be useful if it suggests potentially fruitful lines of observational and theoretical investigations.

1. THE NATURE OF THE COSMOLOGICAL EVOLUTION OF RADIO SOURCES AND QUASARS

The radio structures and properties of extragalactic radio sources bear little relation to the properties of the parent galaxy or quasar. It is therefore important to investigate whether the evolutionary changes should be associated only with the radio properties or whether they must

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be associated with the parent object which is believed to be ultimately responsible for the source of energy. Rees and Setti (1968) for example showed that it is possible to account for part of the inferred cosmological evolution by embedding a given type of double radio source in an intergalactic medium with increases in density with increasing redshift. Some aspects of this model are discussed by Scheuer (this volume). Two pieces of evidence suggests that the evolution is more likely to be associated with the parent object. First, there appears to be little change in the physical properties of the extended radio structures of quasars with redshift (J.M. Riley et al., this volume). Second, the same cosmological evolution laws are found for quasars which are powerful radio sources and for radio-quiet quasars. These statements are based upon rather small statistical samples but they both suggest that the evolutionary changes are associated with the parent objects and therefore that understanding the evolutionary problem must be related to the origin and evolution of galaxies and quasars.

2. OTHER EVIDENCE ON THE ORIGIN AND EVOLUTION OF GALAXIES

2.1. The formation of the heavy elements in the Galaxy

According to the well-known argument of Schmidt (1963), the uniformity of the heavy element abundances in red dwarf stars which have ages as old as the Galaxy suggests that most of the heavy elements were formed in a burst of star formation when the Galaxy was about one tenth of its present age. Models to account for these observations have been made by a number of authors and characteristically it is found that such "young galaxies" are expected to be 10-100 times more luminous than our own Galaxy for periods $\approx 10^9$ years.

2.2. The Epoch of Galaxy Formation

None of the arguments concerning the epoch of galaxy formation are unambiguous. Perhaps the strongest comes from comparison of the sizes and densities of clusters of galaxies with their mean separation and the mean intergalactic density. The average density of matter in the Universe was equal to the mean density of clusters at a redshift $Z \sim 10$-30, implying that the epoch at which they became distinct physical systems must have occurred at a somewhat later epoch, probably $Z \sim 5$-10. The latter redshifts correspond to timescales $\approx 10^9$ years, similar to the timescales found from the evolutionary models and the argument of 2.1.

Whether or not the epoch corresponding to $Z \approx$ of 5-10 also corresponds to the epoch of galaxy formation in general, depends upon the model of galaxy formation. In the model of primaeval adiabatic fluctuations, galaxies form by fragmentation of the clouds associated with clusters and hence the epoch of galaxy formation corresponds to $Z \approx 5$-10. In the models of isothermal and whirl perturbations, however,

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galaxies form much earlier at redshifts Z $\gtrsim$ 30 and clusters of galaxies form later.

We do not enter into all possible scenarios for the origin and evolution of galaxies but consider only the case of the adiabatic model in which galaxies and clusters form at redshifts Z $\approx$ 5-10. The reasons for this choice are: (i) the inferred evolution of radio galaxies and quasars requires strong evolution at small redshifts and this is expected to occur if the redshift of formation of galaxies is small; (ii) at such small redshifts, young objects soon after the epoch of formation may be directly observable and therefore make the hypotheses susceptible to observational verification; (iii) adopting this model, we do not violate constraints set by the observed lack of fluctuations in the microwave background radiation and we alleviate the problems of ionising and reheating the intergalactic gas.

3. YOUNG OBJECTS

We adopt a scenario in which galaxies form at redshifts Z $\sim$ 5-10 by collapse on a hydrodynamical time-scale which is expected to be $\sim$ 10^8 years for a galaxy such as our own. In the first few hydrodynamical timescales, the first generations of stars form, the most massive ones evolve rapidly, explode and return material enriched in heavy elements to the interstellar gas. This general picture agrees with the requirement that the bulk of the heavy elements be formed in the first 10^9 years. The galaxy is therefore expected to be much brighter at these epochs than it is now, (i) because the luminosity of a galaxy is proportional to its rate of heavy element formation and this rate must have been at least 10 times the present rate and (ii) because during the first generations of star formation, there are many more hot young massive blue stars in the luminosity function in comparison with the function at the present day. Various estimates suggest that young galaxies should be $\sim$ 10-100 times brighter than our own Galaxy.

It is interesting to speculate further what the observable properties of young galaxies might be.

3.1. Optical Wavelengths

The optical luminosity of the young galaxy is of the same order as that of quasars. Probably most of the luminosity originates within a sphere of diameter $\sim$ 10 kpc. Therefore adopting a Hubble constant of 50 km s^{-1} Mpc^{-1}, the observed angular size of the galaxy will be less than 1" arc at all redshifts Z > 1 and hence it is indistinguishable from a star (cf Weymann 1967). The optical spectrum is likely to be dominated by the integrated light of young blue massive stars. If the birth rate function follows the Salpeter law, the superposition of their spectra will not result in a Planckian distribution but a spectrum more akin to a power-law extending into the ultraviolet region of the spectrum because of the presence of very hot stars. Whether or not this is the observed spectrum depends upon the amount of dust and interstellar gas present which will absorb strongly the ultra-violet photons. Because of the high inferred rate of star formation, there must also be many giant HII regions present emitting strong recombination and forbidden line radiation.

As noted by Field in 1964, such a model of a young galaxy resembles in many ways the properties of quasars. Let us look at the statistics of quasars at large redshifts in comparison with the numbers of galaxies. At the present day roughly 1 in 100 quasars is a powerful radio source and the space density of radio quiet quasars is about 10^{-5} that of galaxies such as our own. If we adopt the exponential evolution law for the quasar population, at large redshifts, quasars of all types were more common by a factor of 2×10^4 and hence, within the uncertainties in these numbers, the space density of quasars was of the same order as young galaxies (Lynden-Bell 1969, 1971; Komberg and Sunyaev 1971). It is also clear that this population of quasar-like young galaxies must decay rapidly with time, a time-scale of 10^9 years appearing naturally in this scheme, which might account for the results of the V/V_{max} test and the counts of radio sources.

In this type of model, there is no danger of exceeding the upper limits to the extragalactic optical background as may be seen from the following simple order of magnitude estimate. When primordial hydrogen is transmuted into heavy elements, a binding energy of $\sim 0.007\ m_p c^2$ per nucleon is released which is eventually converted into light. Therefore the ambient energy density in starlight U_{rad} due to the formation of an abundance of x% of heavy elements is

$$U_{rad} = \frac{0.007 \times \Omega_{gal} \rho_{crit} c^2}{100(1+Z)} \ \text{eV cm}^{-3}$$

where ρ_{crit} is the critical cosmological density, $3H_o^2/8\pi G \approx 5 \times 10^{-30}$ g cm^{-3}, and Ω_g is the density parameter corresponding to the mass in galaxies; the factor (1+Z) takes account of the effects of redshift upon the energy of photons. Taking, as an example, x = 5%, $\Omega = 0.03$, Z = 5, we find $U_{rad} = 5 \times 10^{-3}$ eV cm^{-3}, a figure of the same order of magnitude as the upper limit to the energy density of the optical background of 3×10^{-3} eV cm^{-3}.

Although the above models resemble quasars in many ways, they are quite distinct in three respects:

(i) they have angular sizes $\sim 0''.1$-1" arc;

(ii) they should not exhibit strong optical variability because the integrated light is the superposition of the light of many stars. Although supernovae might make a contribution to the total light, individual supernovae are incapable of changing the luminosity of an object having $M_V = -26$ by a factor of 2.

(iii) they should not exhibit optical polarisation because the light is the superposition of the emission of many stars.

These properties are different from those normally attributed to quasars but one wonders whether a significant number of quasars already catalogued might not turn out to be this second type of quasar. We note that the "typical" properties of quasar are based upon intensive studies of relatively small numbers of the brightest objects and that some quasars are much more stable in optical output. It would seem to be an observational programme of great interest to discover if any of the catalogued quasars turn out to be "quasars of the second type". A possible programme might consist of selecting those quasars which are optically stable, measuring their optical polarisations and then studying their angular sizes by, say, speckle interferometry.

3.2. Radio Wavelengths

According to this model supernova activity must have been much more intense during the first 10^9 years of a galaxy's life than it is at the present day. The question of how much brighter the galaxy would have been as a radio source depends upon many intangibles, in particular the question of how long the particles are confined within the young galaxy. To produce the observed abundance of heavy elements, we estimate that $\sim 10^9$-10^{10} supernovae must have exploded within the first 10^8-10^9 years, corresponding to supernova rates $\sim$ 30 to 3000 times greater than that of our own Galaxy at the present time. Therefore, we might expect the radio luminosity of a young galaxy to be $\sim$ 1000 times stronger as a radio emitter than our Galaxy, putting it in the class of weak radio galaxies. Radio sources of these luminosities can now be observed at cosmological distances in the deep surveys made by Earth-rotation synthesis radio telescopes. The radio structures are expected to be similar to those of normal galaxies, rather than double sources, and their angular sizes $\sim$ 1" arc. Thus an investigation of the quasars found in deep radio surveys may provide candidates for young galaxies.

3.3. X-ray wavelengths

Because there are many O and B stars in the first generations of stars, there are likely to be many binary X-ray sources consisting of O and B stars and a compact companion. These are expected to be intense X-ray emitters like those observed in our Galaxy. If a Salpeter mass function is adopted, there should be $\sim 10^3$-10^4 times more binary sources in a young galaxy than in our own Galaxy. Therefore, the X-ray luminosity of a young galaxy should be $\sim 10^{42}$-10^{43} erg s^{-1}.

Because there are more supernovae, there will also be more supernovae like the Crab Nebula which is an intense X-ray emitter at soft and hard X-ray energies ($L_x \sim 10^{38}$ erg s^{-1}). If there are 10^9-10^{10} supernovae in 10^8- 10^9 years, there will be $\sim 10^3$-10^5 supernovae with ages less than 10^3 years at any time. If a significant fraction of these are Crab-like, the luminosity of the young galaxy will be $L_x \sim 10^{41}-10^{43}$ erg s^{-1}, even at hard X-ray energies.

Both of these types of X-ray source may be observable at cosmological distances with the next generation of X-ray telescopes.

3.4. Summary

Naturally, these are crude estimates but they make the important point that if the epoch of galaxy formation occurred at redshifts $Z \lesssim 5-10$, young galaxies are potentially observable in many wavebands. Indeed, some young galaxies may already be present in catalogues of quasars and radio sources. Although the programmes to identify those objects are time consuming and arduous, the importance of the results would seem to justify this effort.

4. THE COSMOLOGICAL EVOLUTION OF QUASARS AND RADIO SOURCES

Do the above considerations have anything to do with the problem of the cosmological evolution of quasars and extragalactic radio sources? We may answer with a guarded "yes" in the sense that we can make a case for enhanced astrophysical activity of all types on a time-scale $\sim 10^9$ years which was most intense when galaxies first formed and which has decayed since that epoch. We have argued that we do not have to account for the appearance of radio sources because it is the parent object which evolves cosmologically. What we have not explained is why real quasars, rather than quasars of the second type, exhibit cosmological evolution. Quasars and radio galaxies require the formation of a compact nucleus and we have given no discussion of how this might come about. A deeper understanding of the nature of galactic nuclei is required.

We give only one example of how real quasars and radio galaxies might fit into the overall picture. We adopt a model in which the nucleus consists of a massive black hole and the source of energy is accretion of interstellar matter. Many authors have discussed how the liberation of energy in an accretion disc can lead to optical phenomena which can account for the observed properties of quasars. During the early stages of evolution, the time-scale for mass loss from stars must have been short to account for the thorough mixing and build-up of the heavy elements. At the present epoch, however, the time-scale for mass exchange is $\sim 10^{10}$ years. If the luminosity of the quasar depends upon the available ambient interstellar gas density, as it does in accretion models, quasars should be much more active during the first 10^9 years. Speculation along the lines of accretion models of this type is encouraged by the observation of small scale archetypes of quasar-like phenomena in our own Galaxy. The X-ray binary system Sco X-1 is believed to be a typical accretion binary system. In addition it is known to "flicker" at optical wavelengths, possesses a highly variable compact radio component coincident with the binary system and has a

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double radio source on either side of the nucleus with angular separation ≈ 3' arc. In other words, this accretion system possesses all the characteristics of the most powerful quasars but on a very small Galactic scale. It may be that further studies along these lines will provide further insight into the nature of quasars, double radio sources and their cosmological evolution.

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DISCUSSION

Tinsley: I would like to draw attention to a recent letter and paper in the Astrophysical Journal by D.L. Meier of the University of Texas at Austin. Meier has constructed synthetic spectra for young galaxies in the early stage of evolution discussed by Longair, with predictions of the colors, angular sizes, surface brightnesses, etc. that one would observe, as a function of the redshift of galaxy formation. Meier's calculations are based on Larson's dynamical models for galaxy formation, in which the metals do indeed form early, presumably with the high supernova rate mentioned by Longair and Sunyaev. In his first paper (Astrophys. J. Letters, 203, L103, 1976), Meier notes that primeval galaxies could be masquerading as red quasars. Of course, as Longair remarks, the general properties of primeval galaxies predicted by Meier do not depend strongly on the specific galaxy models used.

Longair: I would emphasise Dr. Tinsley's last remark. The hyperluminous nature of young galaxies at optical and radio wavelengths and their mimicing quasars would seem to be a very general property of young systems if the epoch of formation is $z \sim 5$ to 10 and does not depend very strongly on the assumed model.

Madore: Considering the large supernova rate necessary in your model is this not contradictory to your non-variability criterion to be used in selecting quasars to be studied? More specifically, if the number of supernovae is proportional to the number of early-type stars, won't the supernova contribution to the light (and variability) always be significant?

Longair: The integrated light due to supernovae may be significant but it is not possible to produce several magnitudes variability due to a single supernova explosion - it is just not bright enough in comparison

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with the total luminosity of the quasar, say $m_v \sim -26$. Supernova activity may produce statistical fluctuations of, say a few hundreds or tenths of a magnitude but not the very large fluctuations.

Kafka: I wonder whether your 100 supernovae per year wouldn't dominate the whole picture. Especially if you think of the nucleus being embedded in gas and dust it will be difficult to predict the observable features. I think you might as well expect to observe what we call quasars now.

Longair: I have covered the first part of this question in my answer to Dr. Madore. There are very many possibilities when we know so little about young galaxies. I would prefer to isolate those aspects which would help us to distinguish genuine young galaxies from quasars where, for the various reasons expressed in our paper, we believe that young ordinary galaxies should be quite distinct from quasars.

Schmidt: Labeyrie has recently attempted to measure the angular diameter of 3C 293 with the 200-inch telescope. Although no definitive results are known yet, it is most likely that he did not resolve the object. Hence the diameter is probably less than 0.02 seconds of arc, i.e. less than 100 parsecs.

Longair: This is exactly the type of work which we would like to see extended to faint quasars to find out if our type of quasar is lurking in the present catalogues.

Oort: The subject of the symposium is inextricably tied up with the problem of the formation of galaxies in an expanding universe, and this, in turn, cannot be separated from that of the evolution of the unevenness in the distribution of galaxies and the birth of galaxy clusters. Important progress has been made in this domain by the Soviet astrophysicists, and recently by Gott and by Silk. I wish there would have been time to discuss these investigations properly in the context of the present symposium. A thing that is equally fundamental for the discussion of evolution effects is insight into the process of the formation and maintenance of radio components of galaxies and quasars. Though we know nothing for certain as yet, a discussion of the work on this subject would have been useful.

Longair: I agree completely with Professor Oort's sentiments.